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Vortex process for capturing mechanical energy during upward heat-convection in the atmosphere

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Abstract

Mechanical energy is produced when heat is carried upward by convection in the atmosphere. Processes for controlling and concentrating where the mechanical energy is produced could be a method of harnessing solar energy. A process for producing and controlling a tornado-like vortex and thereby concentrating the mechanical energy where it can be captured is proposed. The vortex process is compared with the solar chimney phenomenon which shares the same thermodynamic basis. The physical tube of the solar chimney is replaced with a vortex and the atmospheric boundary layer acts as the solar collector. The work produced when air rises from the bottom to the top of the troposphere is typically 1500 J kg^{-1}, about the same as the work produced when a kilogram of water is lowered 150 m. The work can be transferred downward to the surface, where it can be captured. A vortex-power station could have an electrical capacity of 100 MW. Developing the process will require cooperation between the meteorology and engineering disciplines. © 1999 Elsevier Science Ltd. All rights reserved.

1. Introduction

Mechanical energy is produced when heat is carried upwards by convection in the atmosphere. The Manzanares solar chimney, shown in Fig. 1 [1], was built in Spain in the 1980s and consisted of a vertical tube 200 m high and 10 m in diameter with a turbine installed inside its base. The chimney was surrounded by a solar collector, a transparent plastic roof 240 m in diameter supported 2 m above the ground. The air flowed through the open rim of the collector and up the chimney. The solar collector increased the air temperature by some 20°C; the upward velocity in the chimney was

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Nomenclature

CAPE	Convective available potential energy (J kg^{-1})
C_p	Specific heat of air (1006 J K^{-1} kg^{-1})
g	Acceleration of gravity (9.8 m s^{-2})
h	Enthalpy (J kg^{-1})
m	Mixing ratio (g kg^{-1})
n_c	Carnot efficiency
P	Pressure (kPa)
q	Heat (J kg^{-1})
r	Radius (m)
s	Entropy (J K^{-1} kg^{-1})
T	Temperature (K or °C)
T_c	Cold-source temperature (K)
T_h	Hot-source temperature (K)
U	Relative humidity (%)
υ	Velocity (m s^{-1})
υ_t	Tangential component of velocity (m s^{-1})
υ_{tm}	Maximum tangential component of velocity (m s^{-1})
w_b	Work of buoyancy (J kg^{-1})
w_x	Kinetic energy of air at restriction outlet (J kg^{-1})
z	Height of tube or vortex (m)
ρ	Density (kg m^{-3})

typically 10 m s^{-1}. The total insolation on top of the collector was 45 MW and the turbine generated 48 kW of electrical power for an overall efficiency of ~0.1%. The operating conditions shown in Fig. 1 are based on those described in Ref. [2].

2. Vortex power-station

A power station using a controlled tornado-like vortex instead of a physical tube was proposed in Ref. [3]. The centrifugal force in the annular vortex replaces the physical tube. There is also no need for a covered solar collector because the boundary layer acts as the solar collector. The vortex could extend from the earth's surface up to the tropopause and the heat to work conversion efficiency could be 15%.

The proposed vortex power station is shown in Fig. 2. The vortex would be started by heating the air in a circular station with fuel while giving the air converging towards the centre of the station angular velocity by having the air pass through a rotating perforated screen. Once the vortex is established it would persist without

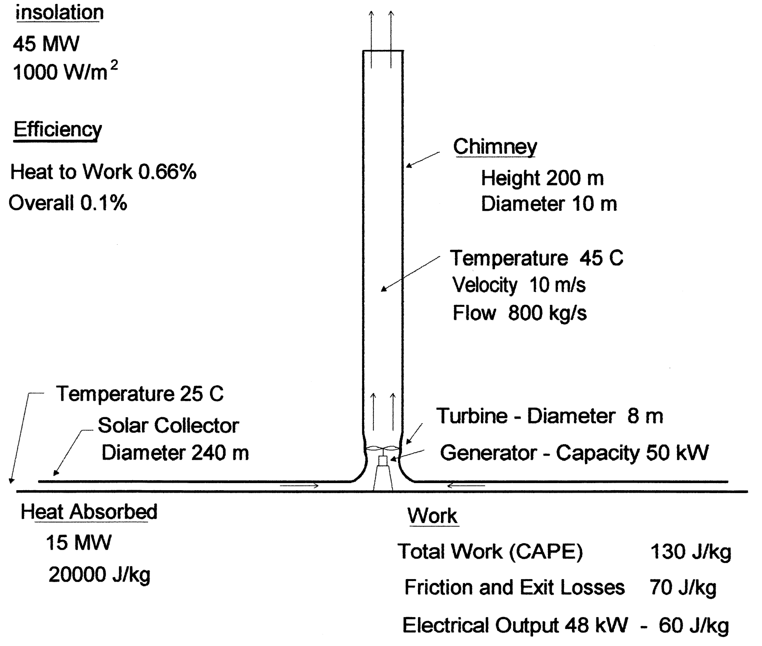

Fig. 1. Manzanares solar-chimney.

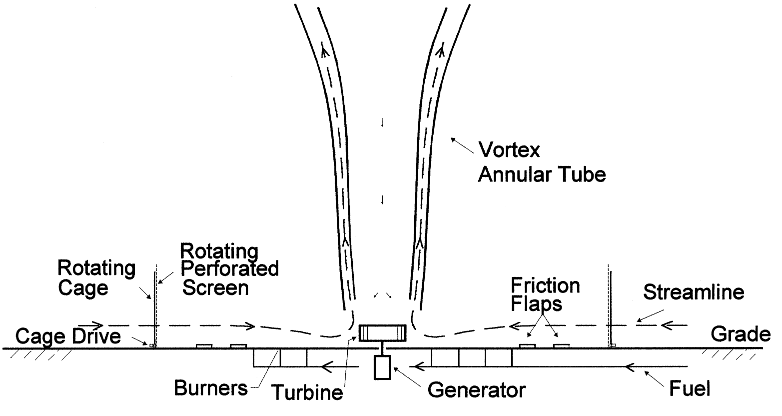

Fig. 2. Vortex power-station.

fuel and its base would remain at the centre of the station. An optional vertical-axis turbine located in the centre of the station would generate electricity. The earlier proposal used fixed deflectors instead of a rotating screen [3]. However, a rotating screen would provide more positive control during development.

A medium size vortex power-station could be 300 m in diameter, and the perforated rotating screen could be 50 m high. The vortex could be 80 m in diameter at its base. The turbine could produce 100 MW of electrical power from a vortex the size of a small tornado. The heat needed to sustain the vortex, after heating with the fuel has stopped, would be derived from the sensible and latent heat content of the air at the bottom of the atmosphere.

The process could be used to produce convective vortices ranging in size from dust devils to medium-size tornadoes. Tornadoes are dangerous, but the process could be developed safely by using physical models of increasing size, first indoors and then outdoors. Some dust devils are less than a metre in diameter. Under optimal conditions, it should be possible to start a self-sustaining vortex to demonstrate the concept with a station 30 m in diameter. Large stations could be tested safely by supplying heat continuously under stable atmospheric conditions.

3. Physical models

Fire whirls have been produced by burning fuel in the centre of a rotating screen [4]. The author has built a 30 cm diameter model—essentially a small-scale version of Fig. 2. The model consisted of a circular plate, with a 20 cm high vertical perforated-screen attached to its edge. The screen was an ordinary metallic bug-screen. The plate was placed on a turntable; there is no need to rotate the base, but on such a small model, it is simply easier to rotate both the screen and the base. The vortex was produced by burning liquid fuel on the base of the model while the screen was rotating. The fuel could be placed either in a circular cavity at the centre of the model or in an annular groove just inside the screen. The vortex stayed in the centre of the model. The vortex, which was 1–5 cm in diameter was stable and visible to a height of 1 m because of the colour of the flame and smoke. Some vortices extended to a height of up to 2 m. The model was only used indoors because small vortices are easily disturbed by stray air currents.

The air converging towards the base of the vortex is entrained sideways as it passes through the small openings of the screen and acquires a tangential component of velocity approaching the tangential velocity of the screen. The tangential velocity of the air just inside the screen was measured to be 87% of the screen tangential velocity by [4]. As the air converges from the rotating screen, its tangential component of velocity increases to conserve the angular momentum acquired at the screen, except in the layer adjacent to the surface, where tangential velocity is reduced by friction. As a result convergence is limited to the thin surface layer.

A very small turbine was installed in the centre of the model to test a method of extracting energy. The turbine was 4 cm in diameter and sat on the tip of a pin. For the turbine test, the fuel was burned in the annular groove located just inside the screen. The speed of rotation of the turbine was estimated at over 1000 rpm, i.e. much higher than the speed of rotation of the turntable, which ranged from 30 to 80 rpm. The flame would cling to the surface of the plate and impinge directly on the turbine. The turbine behaved like a cup anemometer caught in a rotating flow.

4. Thermodynamic basis

The work of buoyancy (w_b) produced when air is raised can be calculated by applying the total energy equation to the process shown in Fig. 3. The total energy equation is

$$W_b = q - \Delta h - \Delta gz - \frac{\Delta v^2}{2} \tag{1}$$

where the deltas are for the approximate parameters between the inlet and outlet conditions labelled 1 and 2 in Fig. 3, where q is the heat received during processes 1–2, h is the enthalpy of the raised air including the enthalpy of its water content; g is the acceleration of gravity; z is the height of the tube, and v is the velocity. For an adiabatic process, (i.e. $q=0$), with negligible inlet and outlet velocities ($v \rightarrow 0$), the total energy equation reduces to

$$W_b = -\Delta h - \Delta gz \tag{2}$$

The work is equal to the decrease in enthalpy of the air minus the increase in potential energy of the air. The work is a maximum when the process is frictionless and reversible, when the expansion is isentropic. The maximum work is, therefore, equal to the reduction in enthalpy minus the increase in potential energy in an constant entropy process, (i.e. s = constant).

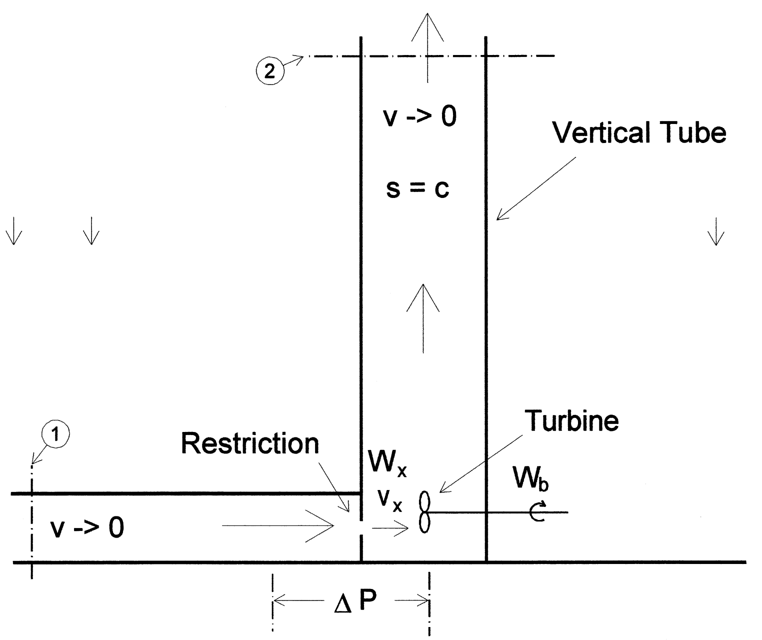

Fig. 3. Vertical tube with turbine at its base.

The work due to buoyancy (w_b) is equivalent to the convective available potential energy (CAPE) [5], which is widely used in meteorology, and which is the integral part of the force of buoyancy times the distance moved. During periods of insolation, CAPE is typically 1200–2200 J kg^{-1} [6]. The average CAPE during a recent month of observation in an oceanic tropical area was 1920 J kg^{-1} [7]. The maximum work of buoyancy is readily calculated from atmospheric soundings. The following oceanic tropical conditions will be used to demonstrate the technique by calculating the work produced when air is raised from the surface to the 20 kPa level. The conditions are: $P_1 = 101$ kPa; $T_1 = 27°C$; $U_1 = 80\%$ corresponding to $m_1 = 18.18$ g kg^{-1}; $P_2 = 20$ kPa and $z_2 = 12400$. In tropical oceanic areas, the level of neutral buoyancy is usually above the 20 kPa level and the elevation of the 20 kPa level is typically 12400 m. The corresponding energy variables are: $h_1 = 73485$ J kg^{-1}, $h_2 = -51954$ J kg^{-1}, $s_1 = s_2 = 256.7$ J kg^{-1}, $\Delta h = 125440$ J kg^{-1} $\Delta gz = 123730$ J kg^{-1}. The work of expansion when the air is expanded from 101 to 20 kPa is 125440 J kg^{-1}, but 123730 J kg^{-1} is required to lift a kilogramme of air including its water content to the 20 kPa level. The net work is therefore: $w_b = 1710$ J kg^{-1}.

The effect of sounding properties is difficult to see from Eq. (2), but is readily appreciated by applying Eq. (2) to different conditions. Increasing the temperature of the surface air by 1°C at a constant mixing ratio increases w_b by 250 J kg^{-1}. Increasing the relative humidity of the surface air by 5% at a constant temperature increase w_b by 585 J kg^{-1}. Increasing the mixing ratio of the surface air by 1 g kg^{-1} at a constant temperature increase w_b by 517 J kg^{-1}. Increasing the temperature of the surface air by 1°C at a constant relative-humidity increases w_b by 825 J kg^{-1} because both the temperature and the mixing-ratio increase. A small change in the air temperature has a large effect on the work of buoyancy. Decreasing the temperature of the surface air by 2°C at constant relative-humidity, would reduce w_b to near zero. Decreasing the average temperature of the sounding by approximately 2°C, without changing the surface air conditions, decreases the level of the 20 kPa surface by 100 m and increases w_b by 1000 J kg^{-1}.

The thermodynamic basis of the process was described in Refs. [5] and [8], which showed that the heat-to-work conversion efficiency of the atmosphere is approximately 15%. The work produced when heat is transported upward by convection is essentially equal to the work that would be produced if heat were transported by a Carnot engine. The Carnot efficiency (n_c) is given by

$$n_c = \frac{T_h - T_c}{T_h} \tag{3}$$

where T_h and T_c are the absolute temperatures at which heat is received and given up. The troposphere receives heat at an average temperature of 20°C and gives heat up at an average of −20°C giving a Carnot efficiency of 15%. Approximately 15% of the heat carried upward by convection is converted to work, irrespective of whether the heat is carried as sensible or latent heat. The same conclusion was reached independently by others [9]. The work dissipated when heat is carried upward by convection is the product of the entropy produced when work dissipates and of the absolute temperature at which the work dissipates [8], a conclusion also reached independently [10].

Ordinary engines need a heat source at a temperature higher than ambient because the cold source is at ambient temperature. The solar chimney and the vortex power station can use heat received near ambient temperature because the cold source temperature is lower than the ambient temperature. The cold source is the troposphere, i.e. the Earth's heat sink, which radiates heat to space and is at an average temperature of −20°C.

The physical basis of the solar chimney is well established and is essentially the same as that of the natural-draft chimney [2]. The heat-to-work conversion efficiency of the solar chimney is the Carnot efficiency using the ambient temperatures at the bottom and top of the tube for the hot and cold source-temperatures respectively. The heat-to-work conversion efficiency of the solar chimney is

$$n = \frac{gz}{C_p T_1} \approx 33 \times 10^{-6} z \tag{4}$$

where C_p is the specific heat at constant pressure of air, and T_1 is the base ambient temperature [2].

The conversion efficiency of the 200 m Manzanares solar chimney was 0.66%. A collector efficiency of 33% and friction and exit losses of 50% reduced the overall efficiency of the Manzanares chimney to 0.1%. In the Manzanares solar chimney, the temperature of the air in the chimney was 20°C higher than the ambient temperature for a height of 200 m, so giving a w_b of 130 J kg^{-1}. In the vortex power-station, the rising annulus of air would be at 1 to 5°C higher than the ambient temperature for a height of 12 km, so giving a w_b of 400–2000 J kg^{-1}.

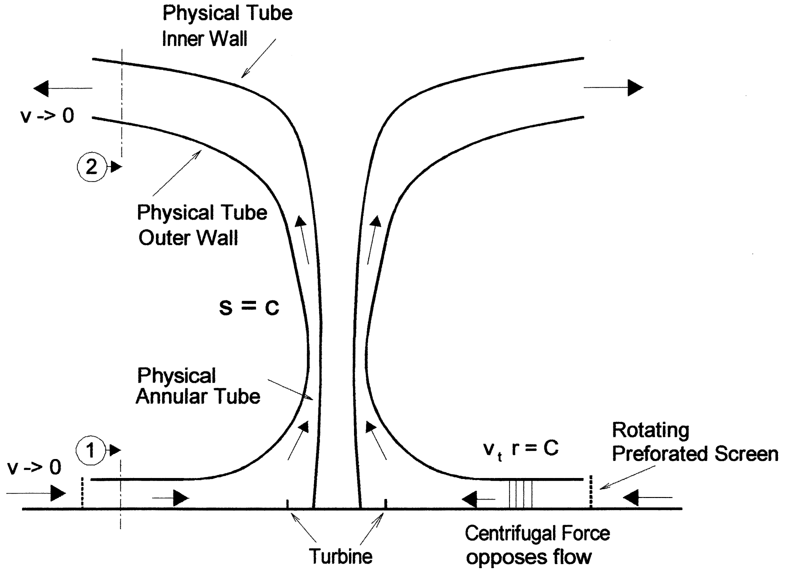

Fig. 4. Physical annular tube process.

The turbine in Fig. 3 is essentially a restriction, where kinetic energy (w_x) is produced, followed by a blade, where kinetic energy is captured, i.e. $w_b = w_x$. The fact that work is produced when heat is carried upwards by convection is well recognized [6,7]. The major obstacle to the acceptance of the feasibility of the vortex power-station is the lack of recognition of the fact that the work of buoyancy can be transferred to the point where the flow is restricted rather than be dissipated where the expansion occurs. The pressure reduction at the base of the tube in Fig. 3 is equal to the weight per unit area of a column of ambient air of the same height as the chimney minus the weight per unit area of the air inside the chimney. The fact that the kinetic energy (w_x) calculated from the pressure difference at the base of the tube (ΔP) is identical to the work of buoyancy calculated from Eq. (2) demonstrates that the work of buoyancy can be transferred downwards. The base pressure reduction (ΔP) in the previous example is 1.94 kPa. The kinetic energy of the surface air after going through a restriction with a 1.94 kPa pressure differential would be 1710 J kg^{-1}.

A good way to understand the operation of a convective vortex is to start with a physical annular tube, and consider what happens when the air converging towards the base of the tube has a tangential velocity (v_t). The upflow can take place in the annular tube shown in Fig. 4 rather than in the circular tube shown in Fig. 3 because the shape of the chimney does not change the thermodynamic process. The upward flow takes place in the annulus between the two tubes; there is no flow in the central tube which is closed at the bottom. As the air converges towards the annular tube, its tangential velocity increases to conserve angular momentum acquired in passing through the screen; ($v_t r$ = constant), where r is the radial distance from the vortex axis. The pressure differential due to the centrifugal force in the converging air is $\rho \upsilon_{tm}^2/2$. In a frictionless flow, the radial flow would stop once the centrifugal force is equal to the pressure reduction at the base of the tube. Further convergence can only occur after friction has reduced the tangential velocity sufficiently for the centrifugal force to become less than the base pressure differential. Convergence is therefore limited to the thin layer against the Earth's surface, because above this boundary-layer friction is negligible.

The air rising in the annulus retains some tangential velocity and the centrifugal force produced by the rising and spiralling air opposes the radial pressure-differential. If the physical tube were to vanish or lose its radial strength after the vortex is established, the diameter of the annulus would adjust itself so that radial pressure differential is balanced by centrifugal force. Once the radial pressure-balance is established, there would be no further convergence at intermediate levels. The vortex would diverge at high elevation as the pressure differential due to density difference decreases and becomes less than the centrifugal force.

A vortex behaves like a dynamic pipe: a vortex in cyclostropic balance permits little or no radial flow into its core because the radial pressure gradient force is in stable equilibrium with the centrifugal force; the cyclostropic balance is upset in the surface layer because friction reduces the tangential wind and centrifugal force [11]. Work dissipation in tornadoes and hurricanes is concentrated near the surface [12].

The upward velocity of non-rotating updrafts is limited by entrainment and drag, the work of buoyancy is not transferred downward to the surface [13]. Friction losses are higher in discontinuous updrafts than in a continuous vortex-flow [13]. The thermodynamic basis of the process is described in more details in the manuscript: "Thermodynamic cycle of the atmospheric upward heat conversion process" available from the author.

5. Station description

The perforated screen could be mounted on a rotating cage installed on rollers, some of which would be motorized; or it could be suspended inside a ring of fixed posts. The rotating screen could be divided into several horizontal bands whose, speeds of rotation could be controlled individually. The perforated screen could consist of vertical slots a few centimetres wide, separated by thin partitions, with a few layers of fine wire mesh on the inside. The starting fuel could be propane gas. Ten minutes of heating with fuel should be sufficient to establish a self sustaining vortex. Starting a large vortex could require a few tonnes of fuel.

The diameter of the core of the vortex is self regulating. Above the friction layer, the pressure outside the vortex is equal to the pressure inside the vortex plus that due to the centrifugal force. If the core pressure decreases relative to the ambient pressure, the core diameter decreases, the tangential velocity increases to conserve angular momentum, and the centrifugal force increases until a new balance of the radial forces is reached. The air in a vortex rises in an annular tube rather than as a solid cylinder: there can be a slight secondary downward flow near the axis of the vortex.

Once the vortex is established, its size could be controlled by varying the speed of rotation of the screen. Increasing the speed of rotation of the screen would increase the diameter of the vortex, increase the upward air flow, and increase the energy produced. Gradually stopping the screen should stop the vortex. The flow up the vortex could also be manipulated by changing the roughness of the bottom of the station to reduce the angular momentum of the lowest layer. Surface roughness could be manipulated with the adjustable flaps on the floor of the station as shown in Fig. 2. Alternatively, the speed of rotation of the lower band of the rotating screen could be reduced to favour convergence near the surface.

The base of the vortex should stay in the centre of the station. Removing some energy with a turbine could help to hold the base of the vortex in the centre of the station. If necessary, a short tapered column could be installed in the centre of the station to help keep the vortex central. The upper part of the vortex need not be perfectly vertical; it could be deflected from the vertical by a horizontal wind and rise at an angle without adversely affecting energy production. The Manzanares solar chimney, which operated for 7 years, was very easy to control, and the load swings were less severe than in conventional windmills [1]. Controlling a vortex should become easier as its size increases because a large vortex has a high inertia and so is less easily disturbed.

A 100 MW vortex power-station could have an air inflow of 100 000 kg s^{-1} and extract 1000 Joules of mechanical energy per kilogram of rising air. The tangential velocity of the screen would be 5–10 m s^{-1}. The tangential velocity of the air at the turbine could be 50 m s^{-1}, and the upward velocity in the rising air annulus could be 10–30 m s^{-1}.

6. Conclusion

The average upward convective heat flux at the bottom of the atmosphere is ~150 W m^{-2}, and the average work produced in the atmosphere is ~25 W m^{-2} [8]. The total mechanical energy produced in the atmosphere is ~12000 TW (i.e. 25 W $m^{-2} \times 510 \times 10^{12}$ m^2), whereas the total work produced by humans is ~2 TW. The mechanical energy per unit mass produced by raising air with a CAPE system of 1500 J kg^{-1}, is roughly the same as the mechanical energy produced by lowering a kilogram of water 150 m and this mechanical energy can be transferred down to the surface. There is plenty of air at the bottom of the atmosphere with a CAPE system of 1500 J kg^{-1} or higher.

Favourable locations for vortex power-stations are likely to be those with light winds and high insolations, such as are common in low latitudes. Under ideal conditions, producing a dust-devil size vortex to demonstrate the concept should not be difficult. Controlling vortices the size of small tornadoes would be more demanding. Learning to control large vortices under less than ideal conditions would be a major challenge. Developing the process will require determination and cooperation between engineering and atmospheric science disciplines. There will be difficulties to overcome, but they should be no greater than in similar technical enterprises.

The existence of tornadoes proves that low intensity solar radiation can produce highly-concentrated sources of mechanical energy. It should be possible to control a naturally-occurring energy producing process. The controlled vortex process has the potential of providing precipitation as well as energy. There is reluctance to attempt to reproduce a phenomenon as destructive as a tornado, but controlled tornadoes could reduce hazards by relieving instability rather than create hazards. The vortex process would capture the work dissipated by friction in updrafts and not just horizontal wind energy.

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