The Wind from the Sun Power Plant

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Abstract – *Wind from the Sun* is a new method for producing electric power from a solar/wind hybrid system. Energy from sunlight is converted to heat by a large solar collector. The solar collector heats the air above it and the heated air rises. Cooler air moves in to replace the rising hot air and a cycle begins. The solar collector continually heats the air, which rises and is replaced by cooler air. The heated rising air decreases the air pressure above the collector. The rising hot air over the collector has a lower air pressure than the cooler air over the land away from the collector. A large diameter pipe (or "air channel") connects the lower air pressure, near the center of the collector, to the higher air pressure, a short distance away from the collector. Air moves from high to low air pressure through the air channel. Inside the air channel, pressure-staged wind turbines convert the wind's mechanical energy into electricity.

1. Introduction

In nature, it is solar power that creates wind power. Consider the example of the sea breeze. The sun heats both land and sea, but the land heats up more quickly and reaches a higher temperature than the sea. The air over the land becomes hotter than the air over the sea and the hot air rises, creating an area of lower air pressure (close to the surface). Air moves from the area of higher pressure over the sea to the area of lower pressure over the land. The cool sea air heats up as it moves over the land and so it rises, creating a cycle. The result of this cycle is a steady wind moving from the sea to the land.

In this example from nature, the land is acting like a solar collector, changing sunlight into heat. The heated land heats the air and creates a wind. This wind energy can be harvested by wind turbines. A *Wind from the Sun* power plant would imitate this same type of system that occurs in nature, but with a greater degree of control and predictability. This will result in a more reliable wind with a higher average wind speed.

2. The Solar Collector

2.1 Materials

The solar collector must have low reflectivity. In other words, it must be a dark color, so that most of the sunlight that strikes it will be changed into heat, instead of being reflected. A matte (not shiny) black color will work best.

Any matte black color will absorb, rather than reflect, visible light. However, in order to convert as much of the sun's energy to heat as possible, the solar collector must also absorb light well in the ultraviolet and infrared wavelengths. The energy from sunlight is approximately 5% ultraviolet light, 44% visible light, and 51% infrared light. A carbon-based pigment (known commercially as "carbon black") will absorb greater than 90% of the energy from light across the spectrum of ultraviolet, visible, and infrared wavelengths [1]. Carbon black is a common pigment used in industrial paints.

Any one of a large number of different materials could be covered with carbon black pigment for use in the solar collector. The solar collector material does not need to have high thermal mass. Since the goal is to transfer the heat from the collector to the air, the collector does not need to retain the heat.

Black ceramic gravel is heavy enough not to blow away in the wind, will allow rainfall to pass through to the ground beneath, and can be spread over a large area of land by machinery, requiring much less manual labor. It is also less expensive to manufacture than many other materials. Black ceramic gravel is one of the better materials for the solar collector. The black color would have to come from carbon black pigment, either painted on the ceramic after firing, or fired into the clay itself.

2.2 Size

The optimum size of the collector depends on a number of factors. Since a *Wind from the Sun* power plant has not yet been built, the optimum size can only be estimated at this point in time. A comparison with a similar technology, the Solar Chimney power plant, will give us a reasonable starting point for such an estimate.

The Solar Chimney power plant operates on similar principles to the *Wind from the Sun* power plant. Both use a solar collector to heat air. Both generate wind from the rising of the heated air. According to Schlaich, a Solar Chimney power plant with a solar collector of 4000 meters in diameter and a 1500 meter tall chimney will produce 600 GWh/y [2]. The area of such a collector would be approximately 12.566 million square meters (πr^2). A Solar Chimney power plant is planned for Mildura, Australia. That power plant will have a 4000 meter diameter collector and a chimney about 1000 meters high. The estimated power output is just under 500 GWh/year, due to the shorter chimney [3].

A *Wind from the Sun* power plant would ideally be located in an area of the world with solar radiation of 2300 kWh/m^2y or greater. The system's energy input can be determined by multiplying the area of the solar collector (12.566 x 10^6 m^2) by the amount of solar radiation (2300 kWh/m^2y), giving us a value of 28,900 GWh/year. The energy input times the efficiency of the system gives us the power output. In the above examples of Solar Chimney power plants, the efficiency of the first power plant would be 2.07%; whereas, the efficiency of the second power plant will be about 1.7%. The efficiency is calculated by dividing power output (600 and 500 GWh/y, respectively) by power input (28,900 GWh/y). For the *Wind from the Sun* power plant, the efficiency has not yet been determined. But, even with a low overall efficiency, a sufficient amount of power might be obtained from such a system.

Increasing the area of the solar collector will increase the power input, and, assuming the same degree of efficiency, would increase the power output proportionately. A solar collector with a diameter of 5000 meters will have an area of about 19.635 x 10^6 square meters, a 56% greater area than the 4000 meter diameter collector. Power output should be at least 56% greater. A 7000 meter diameter collector will have an area 3 times the size of the 4000 meter collector, and should produce at least 3 times the power.

2.3 Temperature

In the case of the sea breeze, the temperature difference between two areas, land and sea, creates wind. Similarly, the temperature difference between the solar collector and the surrounding land drives the system, producing wind and power. The solar collector must become significantly hotter than the surrounding land in order to create wind. For a sea breeze, a typical temperature difference is 10^o C and a typical wind speed is 12 m/s [4].

The solar collector will tend to be hotter towards its center and cooler towards its perimeter. A smaller solar collector loses some heat to its perimeter. A larger collector has less perimeter per unit area and so loses less heat to its perimeter, making the center of the collector hotter than the perimeter. The center of a very large solar collector will reach a significantly higher temperature than the outer edges of the collector. However, the crucial temperature difference is in the air.

3. The Air Above the Solar Collector

3.1 Air Temperature

The air temperature above the solar collector is the result of the amount of energy from the sun which is converted to heat by the collector and transferred to the air above. Solar radiation in the southwestern United States averages between 5 and 10 kWh/m^2day from March through September, and 4 to 5 kWh/m^2day in February and October. In August, solar radiation averages between 6 and 8 kWh/m^2day [5].

Consider the following case. The average solar radiation on a particular day is 5000 Wh/m^2. The size of the solar collector is 12.566 x 10^6 m^2. Thus the solar collector receives 6.283 x 10^{10} Watt-hours of energy input on that day (solar radiation times area). The solar collector converts this energy to heat with about a 90% efficiency, so the amount of energy converted to heat is 5.6547 x 10^{10} Watt-hours.

To determine the amount of air which can be heated on such a day, we use Equation (1) below.

$$Q = C \cdot M \cdot \Delta T \qquad (1)$$

In Equation (1), Q is the heat added to the air by the solar collector, C is the specific heat of the air, M is the mass of the air, and ΔT is the change in temperature. The energy input in Watt-hours can be converted to Joules. Watts stands for Joules/second. The conversion leaves us with the value for Q (heat added) in Joules:

$$3600 \text{ seconds/hour} \cdot 5.6547 \times 10^{10} \text{ Joules-hours/second} = 2.0357 \times 10^{14} \text{ Joules} = Q \qquad (2)$$

If the change in air temperature is a typical temperature difference needed to produce a strong sea breeze, then ΔT is 10^{o} C. Of course, more air could be heated to a lower temperature, or less air to a higher temperature, with the same energy input. Also, in a real world system, it is not the case that an amount of air is heated to any one temperature. Rather, there are gradations of temperature found in the volume of air over the collector, that air is moving constantly, and the temperature of that air is changing over time. But, if we begin by simply calculating how much air can be heated to a particular temperature by the collector, we can see whether enough air can be heated to drive the system.

The specific heat of the air will change over time, because the air is being heated and so undergoes changes in density, pressure, and temperature. However, to simplify the equation, we will choose a single conservative number for the specific heat of air within the range of densities, pressures, and temperatures, which the air will move through. The specific heat of dry air at a constant pressure and a temperature of 30^{o} C is about 1005 Joules/kg · C [6]. Using Equation (1) gives us the following:

$$2.0357 \times 10^{14} \text{ Joules} = 1005 \text{ Joules/kg C} \cdot M \cdot 10^{o}\text{C} \qquad (3)$$

$$M = 2.0256 \times 10^{10} \text{ kg}$$

From Equation (3), we see that the mass of air which this size solar collector can heat by 10^{o} C, on a day with a moderate amount of solar radiation, is rather large—20 billion kilograms of air. The volume of the air heated can be determined by dividing mass by density. The density of air at 30^{o} C is 1.165 kg/m^{3}, but the air is now 40^{o} C, so the density has changed to 1.127 kg/m^{3} [7].

$$\frac{2.0256 \times 10^{10} \text{ kg}}{1.127 \text{ kg/m}^3} = 1.797 \times 10^{10} \text{ m}^3 \qquad (4)$$

Equation (4) gives us the volume of air heated by 10^{o} C on a day with an average solar radiation of 5000 Wh/m^{2}, about 18 billion cubic meters of air. Solar radiation in the southwestern United States can reach as high as 10,000 Wh/m^{2}day, which would double the amount of air heated per day to approximately 36 billion cubic meters.

Of course, the above calculations are a simplification, which provides only a rough estimate of the amount of air this system can effect. In the real world, not all the air is heated to exactly the same temperature. Also, the amount of solar radiation increases as the day approaches solar transit (apparent solar noon) and decreases as the day approaches sunset. The result is that the amount of air heated increases and decreases, the temperature of the ambient air, as well as the heated air, increases and decreases, and the wind speed and amount of power produced follows the same pattern.

3.2 Air Movement

The air movement over the collector is complex. Hot air rises, so the air over the collector will rise upwards. However, a number of factors make the rising column of air above the collector significantly narrower than the collector's diameter.

First, the solar collector is hotter towards its center than towards its perimeter. As a result, the air over the center of the collector will also be hotter than the air over the perimeter. Hotter air rises faster. The hotter air over the center rises faster than the air over the perimeter, causing the air over the perimeter to curve inwards as well as upwards.

Second, as the hot air over the solar collector rises, it is replaced by the cooler air over the area of land surrounding the collector. The air moves inward from 360 degrees around the collector. The air increases in temperature as it spends more time over the collector, and so the air has a greater tendency to rise the longer it spends over the collector. As a result, the path of the air curves from horizontal to vertical. Thus the air is hotter over the center of the collector both because the center of the collector itself is hotter and because the air in the center has spent more time over the collector.

Third, the rising air in the center meets with less resistance as it rises, because it is surrounded by air that is also rising. This factor also causes the air towards the center to rise faster, drawing in air from the perimeter, and again narrowing the rising column of air.

As a result of the above factors, the rising column of air is much narrower than the collector itself and the wind speed of this updraft is much greater than if the air over the collector simply rose straight upwards. This narrow column of rising air is like a virtual chimney over the collector through which air heated by the collector flows.

Furthermore, the air mass over the solar collector is so large that, in addition to moving inwards and upwards, it also rotates. This rotation is a common weather phenomenon, due to the Coriolis effect. Wind tends to rotate around any low pressure area, counterclockwise in the Northern hemisphere, clockwise in the Southern hemisphere. The solar collector is designed to create just such a low pressure area, so we must expect some rotation of the air.

3.3 Air Pressure

In a closed container, when we increase temperature, volume remains the same, so pressure must increase to balance the system. However, in the case of a solar collector in the open air, the collector increases the air temperature, causing air volume to increase and pressure to decrease. The decrease in air pressure is what drives the *Wind from the Sun* system. This same decrease in air pressure is seen in nature in the case of a sea breeze.

Calculating the change in pressure in a system open to the atmosphere is complex. The pressure is affected by the changing temperature of the solar collector, by changes in atmospheric pressure, surface winds, and humidity. In addition, the solar collector causes a strong updraft, which contributes to the decrease in pressure over the collector. Future experiments are needed to quantify the solar collector’s effect on the air pressure over the collector. What is clear, though, even at this point in time, is that the solar collector will decrease the air pressure over the collector.

4. Air Channels

4.1 Pressure Difference

Air flows into the solar collector from the surrounding land from 360 degrees around the collector. One could generate power by placing conventional open-air wind turbines in a circle around the collector. However, this would require many wind turbines. Also, the wind speed in the open air around the collector is significantly less than the air velocity through the air channel.

A better way to take advantage of the air changes caused by the solar collector is to build a large-diameter air channel, connecting the area of lower air pressure over the center of the collector to an area of higher air pressure over the land surrounding the collector. The air pressure at the collector end of the air channel remains lower than the air pressure at the other end of the collector, because the solar collector continually heats (and thus expands) the air over the collector.

Given a tubular or rectangular air channel with a lower air pressure at one end and a higher air pressure at the other end, air must move through the air channel from high to low pressure. The air channel contains wind turbines, which provide some resistance to the air movement. Even so, the difference in air pressure continually drives air through the air channel and past the wind turbines.

Why should air flow through the air channel despite significant resistance from the turbines?—because the collector maintains a constant pressure difference from one end of the air channel to the other. The air inside the channel must move from high to low pressure. The pressure difference determines the air speed within the channel. The fact that the area over the collector is the path of least resistance for the air, does not matter. The air within the channel must obey the laws of physics and move from high to low pressure.

4.2 Air Channel Size

The size of the air channel will depend upon the size of the collector. In the case of a solar collector with a diameter of 4000 meters, the air channel would be approx. 2000 meters in length, extending from a point 500 meters away from the collector to a point 500 meters from the center of the collector. The length and position of the air channel should be chosen so as to maximize the air pressure difference from one end of the collector to the other. Further data is needed to determine optimum length and position for the air channel. A larger collector could support more than one air channel.

The cross-sectional area of the air channel must be within certain parameters. If it is too small, then the amount of power produced will also be small. If it is too large, the large volume of air flowing into the center of the collector will cool the collector, reducing the air pressure difference and decreasing the air velocity. In general, the cross-sectional area should be chosen so as to maximize air velocity through the air channel. The available power from the wind (P_1), per square meter of cross-sectional area, depends on the cube of the wind velocity (V^3) and the air density (D), as shown in Equation (5) below [8]. For the sake of simplicity, cross-sectional area of the air channel is assumed to be equal to the area swept by the blades of the wind turbines in the air channel.

$$P_1 = 0.5 \cdot D \cdot V^3 \qquad (5)$$

To find the power available for any cross-sectional area (A), we multiply by the power available in the wind (P_1) from Equation (5). Since velocity is cubed, increasing the wind velocity has a much greater effect on power than increasing the area. It is, therefore, much preferable to have a faster wind traveling through a narrower air channel, than to have a slower wind and a wider air channel. A narrower air channel also means that there are fewer wind turbines. This translates into lower costs for turbines and for the construction of the air channel.

4.3 Wind Velocity

The wind velocity (V) through the air channel depends mainly on the total pressure difference (ΔP_{tot}) from one end of the air channel to the other. Air density (D) is a much less significant factor. In Equation (5), velocity is multiplied by air density, so that a greater air density would seem to increase power. However, Equation (6) below shows that the square root of the air density affects the velocity [9]. Since that velocity is cubed in Equation (5), overall, a greater air density provides less power. Higher air temperature generally results in lower air density, which, in this system, will provide higher air velocity and greater power.

$$V = \sqrt{\frac{2}{3}\frac{\Delta P_{tot}}{D}} \qquad (6)$$

Equation (6) can be solved for the total pressure difference (ΔP_{tot}), giving us Equation (7) below.

$$\Delta P_{tot} = V^2 \cdot D \cdot 3/2 \qquad (7)$$

This equation assumes that the wind turbine extracts the theoretical maximum power by reducing pressure across the turbine (ΔP_s) by 2/3rds of the total pressure difference (ΔP_{tot}) [10]. Table (1) below compares total air pressure difference (ΔP_{tot}) and air velocity (V) through the air channel, to power available in the wind per square meter (P_1), to swept area of the wind turbines (A) and total power output (P_2). Air density is assumed to be 1.165 kg/m^3 (the value for 30 degrees Celsius and standard atmospheric pressure). Note that a 50% increase in velocity increases power output by 3.375 times. Total power output (P_2) is simply the product of the power of the wind per square meter and the total swept area (A) of the turbines. Note that total power output is the theoretical maximum, actual power output will be less than is theoretically possible.

Table 1: Pressure Difference and Wind Velocity versus Power Output (P_2)

ΔP_{tot} (Pa)	V (m/s)	P_1 (Watts/m^2)	P_2 (MW) (A=10,000 m^2)	P_2 (MW) (A=25,000 m^2)	P_2 (MW) (A=50,000 m^2)
10.92	2.5	9.10	0.091	0.228	0.455
43.69	5.0	72.81	0.728	1.820	3.640
98.30	7.5	245.74	2.46	6.14	12.29
174.75	10.0	582.50	5.82	14.56	29.12
273.05	12.5	1137.70	11.38	28.44	56.88
393.19	15.0	1965.94	19.66	49.15	98.30
535.17	17.5	3121.84	31.22	78.05	156.09
699.00	20.0	4660.00	46.60	116.50	233.00
884.67	22.5	6634.04	66.35	165.88	331.70
1092.19	25.0	9101.56	91.02	227.54	455.08

Air velocity will increase towards solar noon, when solar radiation is greatest, and decrease as sunset approaches. Maximum air velocity will also increase as summer approaches and decrease as winter approaches. Since power is based on the cube of air velocity, more power will be generated in the middle of the day and the middle of the year. However, locations closer to the Equator will have less of a difference in power production between summer and winter.

5. Wind Turbines

Open-air wind turbines, such as those used in wind farms, draw power by decreasing air speed. But pressure-staged wind turbines, such as those used in a Solar Chimney or *Wind from the Sun* power plant, do not decrease wind speed significantly. They draw power by decreasing air pressure. Pressure-staged wind turbines produce several times more power than open-air wind turbines with the same wind velocity and swept area [11].

Most open-air turbines rotate at a set speed. When the wind speed increases beyond the optimum speed (typically about 15 m/s) the open-air turbine does not produce any additional power. The power available in the wind increases by the cube of the wind's velocity, so a faster wind speed offers a large increase in available power. But the open-air turbine cannot harvest that greater available power.

Pressure-staged wind turbines work efficiently over a wide range of wind speeds. When the wind speed increases, the turbine's rotational speed can also increase. (The angle of incline of the turbine blades is adjusted according to the increase or decrease in wind speed.) The ability of the pressure-staged turbine to increase its rotational speed with any increase in wind speed allows it to take advantage of greater available power in higher wind velocities.

6. Alternate Design Possibilities

The above design for a *Wind from the Sun* power plant requires a large area of land to be covered with black ceramic gravel. What would be the effect on the environment of covering thousands of acres of land with gravel? And if the power plant one day had to be dismantled, what would be the cost to remove the gravel? The large solar collector required for a *Wind from the Sun* power plant is a significant concern within this type of solar power.

An alternate design is possible, which either omits the solar collector, or uses a smaller collector. The collector's purpose is to produce an area of lower air pressure relative to the surrounding land. Such pressure differences also occur naturally, as seen in the example of the sea breeze. If the location of the *Wind from the Sun* power plant were chosen astutely, the natural air pressure difference might be sufficient to produce enough power to operate the plant economically.

Most sea breezes are between 0.3 and 1.0 kilometers in depth, yet the wind velocity can exceed 12 m/s [12]. An air channel of less than one kilometer, connecting the air over a large body of water to the air over an adjacent land mass could find a sufficient natural air pressure difference to produce a significant amount of power. And the cost of building the power plant would be reduced significantly because the amount of land required would be lessened, and the expense of a large quantity of black ceramic gravel would be eliminated.

Another possible location with a natural air pressure difference would be at the border between two different types of land topography. The cause of the differing air pressures would generally be the difference in reflectivity of the two areas and differences in how quickly each area is heated by the sun. If the natural difference in air pressure is not sufficient, a solar collector (reduced in size from the power plant described in 1 – 5 above) could augment the natural pressure difference.

7. Conclusions

At this point in time, two conclusions are clear. First, this type of system will produce some power. The sun will heat the collector, which will heat the air. The higher air temperature will expand the air, reducing air pressure. Air must move from high to low pressure, through the air channel and past the wind turbines, producing power. A sea breeze works much the same way and produces significant wind. Some power can certainly be produced in this way.

Second, the system has not been built and tested to a large enough scale to determine how much power will be produced. Will the air pressure difference be large enough to produce significant air velocity through the air channel? Will the system produce enough power to be economical? What are the possible ecological effects of such a large solar collector? Further study is needed to answer these and other questions.

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