ENERGY GENERATION BY SOLAR WIND ENERGY TOWER

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Abstract— Solar Wind Energy Tower is a newly proposed technology aimed to produce electrical energy by means of cooling large masses of hot and dry air and producing downdraft within a large shaft. Assessment of the Energy Tower potential may shed light on the point of view of this technology as an alternative source for producing renewable electric energy in arid or semi-arid lands. We assess the potential of an Energy Tower, providing evaluations for the net power production and the electricity production cost. In India the highest potential for the energy tower is at Rajasthan where major part of the state, comprises of the arid zone in the west and the semi-arid zone in the mid-west (site: Jaisalmer, average temperature of more than 34℃ during summer and during winters it ranges in between 12℃ to 16℃).The velocity with which the air rushes towards the bottom of the tower, corresponding to 1200m height, is computed as 11.7m/sec. The Energy Tower potentially provides the electricity needs to a millions of consumers at an economically competitive cost where electricity cost estimates range from 2.5 ¢/ kWh up to 7¢/kWh.We analyse the net energy of the downdraft power plant which increases nearly in proportion to the Tower height and the extent of average air cooling. Thus, taller the Tower the more electricity is produced per cubic meter of air or per unit weight of sprayed water.

Keywords— Blades, Cooling Tower, Power Generation.

Nomenclature —
$\theta =$ Potential temperature
$\pi =$ Exner function
g= Gravitational force constant = 9.81 m/s^2
T=Temperature ($°C$)
L = precipitation mass mixing ratio (kg/kg)
ω_0 =the velocity at the surface(m/sec)
v_f = Terminal fall velocity of the water drop (m/s) = 5 m/s
R = Precipitation Intensity (mm/hr) = 30 mm/hr
v_{10}= Average wind flow at 10 m height (m/s) = 4.38 m/s
ω_H =Velocity at height H (m/s)
$\Delta\,\theta$ = Temperature difference of air parcel with ambient air (K) = -1K
$\bar{\theta}_v$ = Ambient of environment (K) = 300 K
g=Gravitational force constant = 9.81 m/s2
H = Height of Tower (m)=1200m
H_{10} =10 m
α= Hellman exponent = 0.16
n_t = Maximum theoretical efficiency of wind high speed rotor = 59%
ρ_o = Density of air (kg/m3) = 1.2 (kg/m^3)
A_c = The cross-sectional area of the main shaft [m^2]
n_t = The efficiency of the turbine - transmission - generator aggregate ≈ 0.85
F= the energy loss coefficient

I. INTRODUCTION

Energy tower is a freshly proposed technology which is based on the thermodynamic principlewhich incorporatesthe temperature difference between hot and cool masses. This temperature difference is the main driver of the turbines and as a result, generation of energy takes place. Over and above the age old sources of wind, hydro-power and bio-mass, the "Energy Towers", is the most economical technology of all the technologies which are being developed to produce environmentally clean electricity using non conventional sources in the arid and semi-arid areas. Moreover, it does not require a solar radiation collector and it works profusely the whole day. Phillip Carlson evolved the concept for the downdraft energy tower in the year 1975. Researchers at Israel's Technion amplified on the idea in 2001.Energy towers are hollow and vertical towers constructed in dry arid regions with heights of 400 meters or more.
Convective downdrafts are driven by cooling as a consequence of melting and evaporation of precipitation pressure forces and condensate loading. As water droplets fall from a cloud into sub saturated air, some are evaporated. Latent heat is therefore removed from the environment, constructing a bubble of air that is cooler than the neighbouring air. Then, this negatively buoyant parcel falls down as long as it remains cooler than its environment

Advantages:

- **Renewable energy without the need for a solar collector**: The most brilliant feature of the Energy Towers is that akin to wind energy, hydropower and biomass, there is no requirement of collectors in order to trap the solar radiation.
- **Comparison with other solar technologies: The** Energy Towers predicted cost of electricity is the least among all renewable sources with the exception of some hydro power stations under very favourable conditions. Among the non-renewable energy sources, the energy generated by energy tower has the lowest cost.
- **The "Energy Towers" potential:** In India, the Energy Towers' likely may provide

electricity to over a billion people at the West European level of utilizatiion.

- **Desalinization:** Desalinization of sea water can be assimilated into the Tower, and it can be installed step by step in phases.
- **Reliability**: The cost of electricity production was calculated in a highly authentic manner. Furthermore, the future plan of work proposes as a first stage to get quotations from suppliers, thus minimizing even further the uncertainty in the predicted electricity production cost.
- Furthermore, it generates humidity in the surrounding area, leading to good weather conditions in the area at its vicinity.

B. WORKING PRINCIPLE

The occurrence of a downdraft by a water spray has been well known for decades. In the last few years it has been studied largely due to its effect on aviation. It is eminently referred to as "wind shear" (see figure 1).

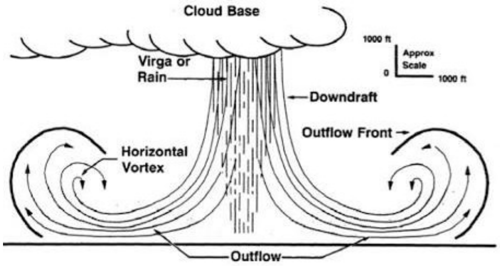


Figure 1: Wind shear effect

Now, wind shearing effect can be defined as change in the speed or direction of wind due to an increase in height. The "Energy Towers" technology is an attempt to show the same process inside a tall cylinder with an open top, having large diameter and openings around the bottom (see figure 2). The rain is replaced by a continuous sprinkle of water at the top. The water partially evaporates and brings down the temperature of the air from dry bulb temperature to its "wet bulb" temperature. The cooled air is comparatively denser. For instance, air cooled by 12 centigrade is approximately 4% heavier than the ambient air. The denser air then falls down and comes out at the bottom which is utilised in running the turbines. More dry and warm air is drawn in from the top and the process continuesinfinitely.

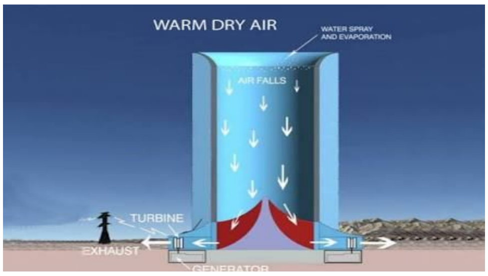


Figure 2: Working of Energy Tower

The particular planttakes advantage of that pressure difference which arises as a consequence of hot air which is outside the tower and the air inside which is cooled and it helps to run a few turbines. The tower has to be huge, to maximize the efficiency of the tower. The energy that is extracted from the air is basically derived from the sun; therefore, it can be taken into account as a form of solar energy.

III. VELOCITY OF DOWNDRAFT AIR PARCEL

Using conservation of momentum and a parameterization for the precipitation loading, the equation explaining the vertical motion of an air parcel in a given environment is gathered. Subsequently, this vertical momentum equation is integrated to achieve an equation for the velocity of a downdraft.

1. *Vertical momentum equation:*

In year 1992 James R. Holton gives equation for the conservation of momentum of an air parcel which is considered for the vertical motion only is given as :

$$\frac{dw}{dt} = -\theta \frac{\partial \pi}{\partial z} - g$$

Where,

$\theta =$ Potential temperature

$\pi =$ Exner function

The Potential temperature of an air parcel at a particular pressure P is the temperature that the parcel would acquire if adiabatically brought to a standard reference Pressure P_o, usually 1000 millibars.**The exner function** can be viewed as non-dimensional pressure, it is an important parameter in atmospheric modelling.

Here, potential temperature (θ) and exner function (π) are defined as follows:

$$\theta = T.\left(\frac{Po}{P}\right)^k$$

$$\pi = Cp\left(\frac{P}{Po}\right)^k$$

$$k = \frac{Cp - Cv}{Cp}$$

k is a constant ,which is defined in terms of the specific heat at constant pressure (C_p) and at constant volume (C_v),is equal to 2/7 for a diatomic gas.P_o is reference pressure, which is usually about 1000hPa.

According to Boussinesq approximation, in which each variable is split into a reference state and a small time-dependent divergence from this state, is then applied:

$$\theta(z,t) \equiv \bar{\theta}(z) + \theta'(z,t)$$

$$\pi(z,t) \equiv \bar{\pi}(z) + \pi'(z,t)$$

$$\frac{\partial \bar{\pi}}{\partial z} = -\frac{g}{\bar{\theta}}$$

Hydrostatic balance for the reference states (in the last equation) implies that $\omega_0 = 0$, and therefore w $=\omega_0$ (z; t). Using the expressions for θ and π and the assumption that $\theta' \ll \bar{\theta}$ and $\pi' \ll \bar{\pi}$, the basic equation can be rewritten into:

$$\frac{dw}{dt} = -\bar{\theta}\frac{\partial \pi'}{\partial z} + g\frac{\theta'}{\bar{\theta}}$$

The second term on the right hand side of this equation reflects the buoyancy of the air parcel while the first term is the vertical pressure gradient force on that parcel. The effects of water vapour and precipitation on the equation of w is not considered yet. Density of the air is reduced due to the presence of water vapours which results in slightly higher temperature to the air parcel. The virtual temperature defined as:

$$\theta_v = \frac{1 + r_v/\varepsilon}{1 + r_v}$$

The precipitation loading's effect on the vertical motion of the air parcel, i.e., downward acceleration due to viscous forces, is limited by the term $-$gL,where L is the precipitation mass mixing ratio (kg/kg). The final vertical momentum expression for an air parcel thus becomes:

$$\frac{d\omega}{dt} = -\bar{\theta}_v\frac{\partial \pi'}{\partial z} + g\frac{\theta'_v}{\bar{\theta}_v} - gL$$

2. *Integration of momentum equation:*

The left hand side of the vertical momentum equation, which is totalvertical acceleration, can be rewritten as:

$$\frac{d\omega}{dt} = \frac{\partial \omega}{\partial t} + \omega\frac{\partial \omega}{\partial z} \approx \omega\frac{\partial \omega}{\partial z} = \frac{1}{2}\frac{\partial \omega^2}{\partial z}$$

The neglect of the explicit time-derivative of ω corresponds to the assumption that the surrounding of the air parcel is static on the time scale of the downdraft and only depends on the vertical coordinate z. Introduction of this equation in the vertical momentum equation and subsequent integration over the vertical coordinate results in:

$$\omega^2(z) = \omega_o^2 + 2g\int_0^z \frac{\theta_v'}{\bar{\theta}_v}dz - 2g\int_0^z L\,dz$$

In case of downdraft which starts at height H above the surface, the velocity at the surface(ω_o) ,which is deflected by the surface in horizontal direction can be achieved from the integrated vertical momentum equation :

$$\omega_0^2 = -2g\int_0^H \frac{\theta_v'}{\bar{\theta}_v}dz + 2g\int_0^H L dz + \omega_H^2$$

From the above equation of vertical momentum, it appears that three processes contribute to the terminal velocity of a downdraft. These processes are from left-to-right in the right-hand side of the last equation: (negative) buoyancy due to evaporation or melting of precipitation, precipitation loading, and incorporation of horizontal momentum.

3. *Estimation of individual parts:*

The maximum velocity of the convective wind gust is assumed to be equal to the maximum downdraft velocity, which probably holds true for the innermost air parcels of the downdraft/wind gust.

Wind velocity at ground level,

$$\omega_o = \sqrt{NAPE + LOAD + HMOM}$$

Where,

NAPE: Negative available potential energy also called as the negative buoyancy process occurs due to the evaporation or cooling of the ambient hot air.

$$\text{NAPE} \equiv 2g\int_0^H -\frac{\theta_v'}{\bar{\theta}_v}dz$$

$$\approx \frac{2g}{\bar{\theta}_v}\int_0^H -\theta_v'\,dz$$

Assume that the lapse rate of the temperature difference is constant and that the temperature difference at the origin of the downdraft is zero:

$$\text{NAPE} = -\frac{2gH\Delta\theta_s}{\bar{\theta}_v}$$

LOAD: Load is the term used for precipitation loading and refers to the mixing of the kg of water vapour per kg of the air. The precipitation loading can be determined using the rainfall intensity obtained from a numerical weather prediction model or radar observations:

$$\text{LOAD} \approx 2gLH = \frac{2gMH}{\rho_o}$$

$$\text{LOAD} = \frac{2gRH}{3600\rho_o v_f} = 5.63\frac{RH}{v_f}$$

HMOM:Is the maximum horizontal momentum that can be incorporated by the downdraft has to be determined by numerical weather prediction models:

$$\text{HMOM} = \omega_H^2$$

Calculated for (Site: Jaisalmer, Rajasthan, India):

NAPE= $32.7\,m^2/s^2$
LOAD= $16.89\,m^2/s^2$
HMOM= ω_H^2

$$\omega_H^2 = \omega_{10}\left(\frac{H}{H_{10}}\right)^{\alpha}$$

HMOM= $88.73\, m^2/s^2$

Calculation of velocity:

$$\omega_0 = \sqrt{NAPE + LOAD + HMOM}$$

$$\omega_0 = \sqrt{32.7 + 16.89 + 88.73}$$

$$\omega_0 = 11.7 m/s$$

IV. ENERGY CALCULATION

The net deliverable power N [Watts] of an downdraft Energy Tower can be expressed very closely by the following equation:

$$N = A_c n_t\left(\frac{2}{3}E_{net}\right)\frac{1}{\sqrt{F\rho}}$$

The above equation is a result of an analysis showing that the term $\frac{2}{3}E_{net}$ in parenthesis gives the theoretical maximum possible deliverable power and that exactly $\frac{1}{3}$ Enet is devoted to energy losses. E_{net} is the net mechanical specific energy [Pascals] of sprayed water ,it can be computed as:

$$E_{net} = \left(E_c + \frac{E_{pump}}{n_t} + E_R\right)$$

Where,

E_c =Excess static pressure of a cooled air column.
$\frac{E_{pump}}{n_t}$ =The pumping energy required for spraying a certain amount of water per cubic meter of air.
E_R =The recovered energy of the non-evaporated sprayed water

$$E_{losses} = \left(\frac{Q}{A_c}\right)^2 F\rho$$

Where,
Q is the rate of air flow [m^3/sec]
F is the energy loss coefficient
The rate of air flow (Q) and energy loss coefficient (F) can be expressed as:

$$Q = \left[\left(\frac{2}{3}\right)E_{net}\right]^{\frac{1}{2}}\frac{1}{\sqrt{F\rho}}$$

$$F = \left(\frac{A_c}{A_d}\right)^2 + f$$

Here $A_c and A_d$ is the kinetic energy loss coefficient and f is the energy loss due to fiction

Interestingly, the ratio N/Q is

$$\frac{N}{Q} = n_t\left(\frac{2}{3}E_{net}\right)$$

Independent on the loss coefficient F.

E_{net} increases more or less in proportion to the Tower height and the extent of average air cooling. Thus, the taller the Tower the more electricity is produced per cubic meter of air or per unit weight of sprayed water.

The net mechanical specific(E_{net}) energy is a certain fraction of the heat taken out of the air and is about 0.7 to 0.8 times the highly familiar term (T_{max} - T_{min})/Tmax which is in our case dependent only on the Tower height H .

$$E_{net} = .7/.8 \times \frac{T_{max} - T_{min}}{T_{max}}$$

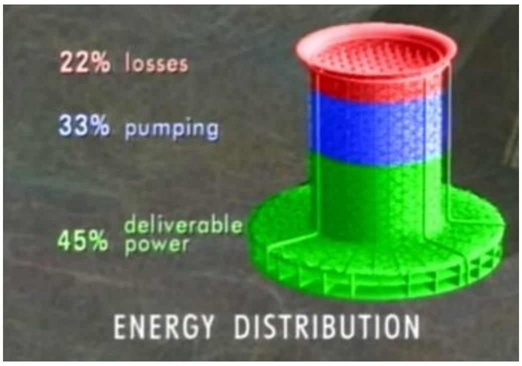
T_{max} is the outside air temperature at the shaft bottom and T_{min} is the outside air temperature at the shaft top. The whole efficiency term of turning heat to mechanical energy is roughly equal to:

$$n_f = .7/.8 \times \frac{H}{100}$$

Where,

H is the shaft's effective height is in meters.

Interestingly, the overall efficiency for turning heat into mechanical energy for 668 m cooling height is only 2.8% and the efficiency to net deliverable electricity is about 1.2%.



E. COST OF ENERGY FOR CONSUMER FROM AN ENERGY TOWER PLANT:

The total cost of an Energy Tower power plant is summarized with the following equation:

$$C_{construction}[M\square] = 22478 + 0.32GP_{installed} + 0.4PP_{installed} + 171 * D$$

Where,

22478[M▪]:-is a fixed construction cost of the Tower, the spray system and the operational reservoir.
$[GP_{installed}(MW)]$: is the costs of the turbine and generators power system as a function of the installed gross Power.
$[PP_{installed}(MW)]$: are the costs of the pumping system as a function of the installed pumping power.

$[171 * D(km)]$: are the construction costs of the water conduit from the water source to the Energy Tower site as a function of the distance between them.

Subsystem	Unit description	Evaluated cost Per unit (□/unit)	Number of units For construction
Tower construction	Evaluated cost for the steel space frame construction (including chimney, diffuser and systems support Framework cover Concrete foundation	60000 (□/ton)	191,300 (ton)
Water Supply	Operational reservoir (1,000,000m3) and water uptake structure	1200 (M□)	+1 (per ET)
	Water conduit: 20% pipes (/2600mm) & 80% concrete open canal (wall slope 1:4 and 4m width)	0.2*330+0.8* 60(M□/km)	D (km)
	Water Pumping from water source up to the ET top	24000 (□/kW)	$PP_{installed}(kW)$
Water Spray System	Including:1,000,000Sprayers, 20,000m of water pipes (/200-/2000mm), support beams and controllers	2000 (M□)	1 (per ET)
Power Pack	An array of 50 Wind Turbine Generators	7500 (□/kW)	$GP_{installed}(kW)$
		10,900 (□/kW)	$GP_{installed}(kW)$
	Transmissions	600 (□/kW)	$GP_{installed}(kW)$
Brine disposal system	Brine reservoir (500,000m3) Ground sealing and drainage of the ET surroundings.	6000 (M□)	1 (per ET)
	Brine disposal conduit (half the price of the Water conduit).	57(M□/km)	D (km)
Infrastructure	Land. Roads, fence, buildings etc.	1800 (M□)	1 (per ET)

The above table describes the cost of energy tower subsystem.

$$C_{construction} = 22478 + 0.32 * 9500 + 0.4 * 12000 + 171 * 10$$

$$C_{construction} = 32028\ M□$$

The cost of electricity by a energy tower can be expressed as:$C_{electricity} = \frac{\frac{i(1+i)^n}{(1+i)^n-1} C_{construction} + C_{o\&m}}{E_{year}}$

Where,

E_{year} =The net annual electric energy(2654*10^6 kWh)

i = 10% rate of interest

n = 50 years life expectancy

$C_{o\&m=}$ 0.294 ▪ /kWh operation and maintenance costs

$$C_{electricity} = \frac{\frac{0.1(1+0.1)^{50}}{(1+0.1)^{50}-1} * 32028 + 0.294 * 2654}{2654}$$

$$C_{elecricity} = 1.511\ □/kWh \cong 2.3¢$$

V. RESULT

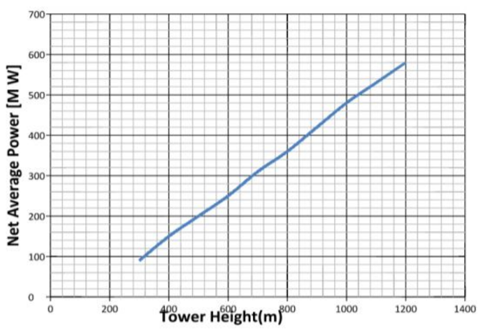


Fig 3variation of net average power in megawatts vsheight(metres)

Figure 3 shows the variation of net average power in megawatts with height in metres. As per the figure it can be notably seen that the net deliverable energy increases linearly with height, where energy is directly proportional to the net average power and this is one of the reasons of construction of tall towers.

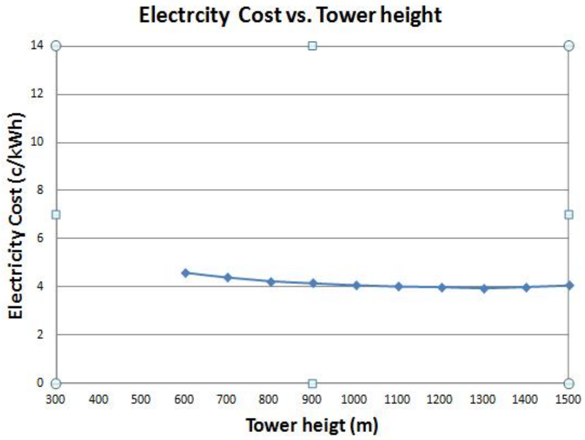


Figure 4:variation of electrical cost with height

Figure 4 shows the variation of electrical cost with height at an interest rate of 5%. As its already known that the increase of the thermodynamic efficiency corresponds roughly to the height of the tower. , therefore with an increase in height the cost decreasesand finally becomes independent of the total height.

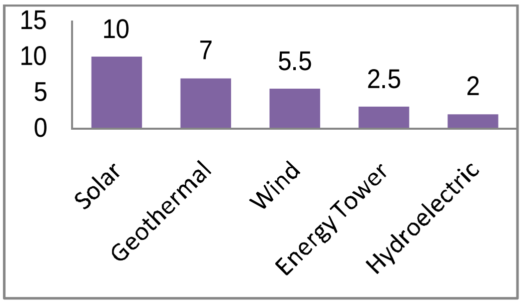


Figure 5 comparison among electricity generation costs of different power plants in cents

Figure 5 shows the comparison among different electricity generation costs in cents. An Energy Tower's projected cost of electricity production is the lowest of all current renewable sources, with the exception of some very large hydro-power stations under very favourable conditions This infers that Energy Towers, apart from being environmentally friendly , are even pocket friendly with a minimal cost varying between 3 cents/Kwh to wind speed, the power generation is maximum in June and on average throughout the summer.

The velocity of the downdraft air parcel, as computed, has come out to be 11.7 m/sec. In India, As per the

CONCLUSION

The "Energy Tower" technology is in effect the containment of the process of wind shear inside a tall and large diameter hollow shaft with an open top and openings around the bottom. Energy tower's efficiency or the net power output is mostly dependent upon the height of the tower and the temperature difference between the downdraft energy tower and its environment. An appropriate temperature difference leads to an increase in the velocity of the downdraft.
Magnitudes of downdrafts are associated with steeper environmental lapse rates, higher amounts of rainwater, and higher environmental relative humidity. Negative buoyancy is enhanced in moist environments because the water vapour increases the environmental virtual temperature. The intensity of the wind produced can be varied using these parameters. Accordingly, stronger downdrafts develop when the relative humidity is high since the ambient air is virtually warmer than the descending air parcel.
A parallel effort should be made to continue the scientific efforts to further refine various design elements, to use the knowledge and technological advances, which has been developed recently in related applications

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