Energy towers
A renewable energy technology for producing electricity and desalinated water in arid climates

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ABSTRACT

“Energy Towers” is the name of a technology which was developed at the Technion--Israel Institute of Technology, to produce electricity in arid lands, taking its predicament - a lot of hot dry air - and turning it into an asset. “Energy Towers” is an economically promising technology to produce environmentally clean electricity using renewable sources. It does not require a solar radiation collector and it works continuously day and night. It is also capable of producing 20 times more than all the electricity produced today around the world. The principle is that a vertical hollow shaft is constructed between 600-1200 m high and between 100-400 m in diameter and water (usually sea water or brackish water) is sprayed at the top opening. The water partially evaporates, cooling the air. The cooled air is heavier and sinks down, the air flows at high rates, moving turbines and electricity generators through openings near the shaft’s bottom. The Energy Towers, is in fact, a wind producing machine working 24 hours a day. The projected cost of electricity of a tower of 1200 m high and 400 m diameter in Eilat, Southern Israel, was found to be 2.47 – 3.88 ¢/kWh at 5% and 10% discount rate, respectively, slightly less than the average electricity costs of coal fired and natural gas combined cycle stations favorable conditions. The theoretical potential in a recent global estimate for Energy Towers was found to be 230,000 billion kWh /year. There are additional benefits to the Energy Towers such as a sea water desalination at a low price.

1. THE “ENERGY TOWERS” TECHNOLOGY

The basic principle of the Energy Towers operation is very simple. A very tall and large diameter cylindrical chimney is built (see figure 1). The chimney is built in a hot and dry area and not too far from and too high above a large source of water. The source is mostly the ocean and large volume of brackish water, such as agricultural drainage along large rivers. The water is pumped up and sprayed from the chimney’s top. Part of the water evaporates and cools the air. The cold air flows down (just the opposite of regular chimneys where hot air flows up). The cold air flows out of openings in the chimney’s bottom and turns turbines that rotate electrical generators. The spray of unevaporated water is collected and sent back to the sea. As long as the energy invested in water pumping and spray leaves enough extra energy produced, the Energy Towers may be considered useful.

Fig. 1 The Principle of Energy Towers

The phenomenon of a downdraft by a water spray has been well known for centuries. In the last three decades it has been studied extensively due to its effect on aviation. It is often referred to as “wind shear”. The “Energy Towers” technology is an attempt to contain the process of wind shear inside a tall and large diameter hollow shaft with an open top and openings around the bottom. The rain is replaced by a continuous spray of water at the top. The water partially evaporates and cools the air from dry bulb temperature to close to its “wet bulb” temperature. The cooled air is denser. As an example, air cooled by 12°C is approximately 4% heavier than the ambient air. The heavier air then falls down and comes out at the bottom. More dry and warm air is sucked in from the top and the process continues endlessly. A part of the produced power is used to pump water from a water source to the bottom of the tower from there to the top of the tower to be sprayed across the diameter
of the shaft. A rough breakup of the energy components under conditions in the south part of the Arava Valley in Israel (1200 m tower, 40 km away from the sea and 80 m above sea level) is given in Figure 2.

Fig. 2 Components of Mechanical Energy

Under a wide range of conditions one can produce more electricity than is needed for pumping. For example, in the south Arava, north of Eilat, the mechanical energy is divided about 4/9 for electricity delivery, 3/9 for pumping and 2/9 energy losses as the air flows through the shaft. (See Figure 2).

The net deliverable power \( N \) [W] of an Energy Tower can be expressed very closely by the following expression:

\[
N = Q \left[ \eta_t \left( E_c - E_f \right) - E_p \right]
\]

By differentiating (2) w.r.t. \( Q \) the optimum value of \( N \) can be obtained:

\[
N_{opt} = A_c \eta_t \left( \frac{2}{3} E_{net} \right)^{1/2} \frac{1}{\sqrt{F \rho}}
\]

with

\[
E_{net} = E_c - \frac{E_f}{\eta_t}
\]

where:

- \( A_c \): the cross-sectional area of the main shaft [m\(^2\)];
- \( \eta_t \): the efficiency of the turbine-generator aggregate [-];
- \( E_c \): the excess static pressure of a cooled air column [Pa];
- \( E_f \): the pumping energy for spraying per unit volume of air [Pa];
- \( \rho \): the average air density [kg/m\(^3\)];
- \( F \): the energy loss coefficient [-];
- \( Q \): the air flow rate [m/s]

This formula is a result of an analysis showing that the term \( 2 E_{net}/3 \) in parenthesis gives the theoretical maximum possible net deliverable power and that exactly \( E_{net}/3 \) goes to energy losses. The rate of air flow \( Q \) can then be expressed by:

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

Interestingly, the ratio \( N/Q \) is independent of the loss coefficient \( F \).

\[
\frac{N}{Q} = \eta_t \left( \frac{2}{3} E_{net} \right)
\]

\( E_{net} \) 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. Figure 3 shows the air temperatures inside and outside the tower for different spray droplets diameters. The right hand line shows the temperature of the outside air, assuming here that it follows a dry adiabatic distribution, i.e. a constant temperature gradient of approx. 1°C /100 m. The other lines, on the left, are the cooler inside air. These lines approach asymptotically a wet adiabatic distribution with a temperature gradient of slightly less than 0.5°C /100 meters. In Figure 3, the cooling rates with spray droplets of 100 microns in diameter, 300 microns and 500 microns are observed. The more water sprayed and the finer the droplets, the more efficient the cooling. However, more energy is then used for pumping. The extent of the usable potential of the mechanical work depends on the area between the left side lines and the right side line, which expresses how much the inside air column is cooler and heavier than the outside air. The optimal droplet size must be chosen between smaller droplets for better cooling and larger droplets for lower energy spending for pumping and spraying.

2. POWER CALCULATIONS

The power and the flow were computed using different methods: an analytic method, calculation of a one-dimensional model, two-dimensional formulations of the flow with cylindrical symmetry and a three dimensional flow simulation using two modern techniques of computational fluid dynamics (CFD). This may be especially useful for cases with strong outside wind and for regulating both the water spray distribution at the top
and the turbines around the bottom for maximum net deliverable electricity output. Many wind tunnel tests were made and also experiments in a model 1:50 to investigate the loss coefficient and the dynamics of the droplets (evaporation, coalescence).

Estimates for a tower of the following dimensions in the south Arava, near Yotvata, 40 km north of the Eilat Bay and 80 m above sea level are shown in Table 1.

Table 1 - Main dimensions and performances of Energy Tower in Eilat (Israel)

<table>
<thead>
<tr>
<th>Diameter (m)</th>
<th>Height (m)</th>
<th>Installed  turbine capacity (MW)</th>
<th>Installed pumping capacity (MW)</th>
<th>Annual deliverable electricity (95% availability) (kWh)</th>
</tr>
</thead>
<tbody>
<tr>
<td>100</td>
<td>1200</td>
<td>135.8</td>
<td>589</td>
<td>3.09x10^9</td>
</tr>
<tr>
<td>150</td>
<td>186.3</td>
<td>1374</td>
<td>589</td>
<td>3.09x10^9</td>
</tr>
<tr>
<td>200</td>
<td>242.9</td>
<td>1374</td>
<td>589</td>
<td>3.09x10^9</td>
</tr>
<tr>
<td>250</td>
<td>309.0</td>
<td>1374</td>
<td>589</td>
<td>3.09x10^9</td>
</tr>
<tr>
<td>300</td>
<td>371.4</td>
<td>1374</td>
<td>589</td>
<td>3.09x10^9</td>
</tr>
<tr>
<td>350</td>
<td>437.8</td>
<td>1374</td>
<td>589</td>
<td>3.09x10^9</td>
</tr>
</tbody>
</table>

Notably, the net deliverable power increases roughly with the linear dimension of the Tower. If the same proportion is maintained between the height and the diameter the power increases very close to the third power of linear dimension. As the rate of flow of air and the rate of water spray increased as the square root of the height. Then the net deliverable output increases linearly with the Towers height. This is at least one reason to have tall Towers. Table 2 shows the computed net deliverable power for different Towers dimensions.

3. THE ELECTRICITY COSTS

The estimated production cost of the deliverable electricity with 30 years projected life, 5% interest, 9.1% interest during construction and 0.556 $/kWh operation and maintenance expense can be shown to vary with tower height and tower. As we have shown, the increase of the thermodynamic efficiency corresponds roughly to the height of the tower. However, the net deliverable power grows at a power higher than 3 of a characteristic linear dimension of the tower. As far as the electricity cost is concerned, there is a very wide and flat minimal range between the heights of roughly 700 m and 1400 m and for diameters of 200 to 500 meters. At the optimal dimensions, the cost of electricity is 2.47 $/kWh with a discount rate of 5%, and 3.88 $/kWh at a 10% discount rate. This competes with every known technology, with the possible exception of very large hydro-power projects, especially cheap combined cycle projects with closely available natural gas sources. The disadvantage of the Energy Towers, at least in their early application, is that they are not as economically attractive at very small dimensions and very small investments. The gross advantage is that other benefits are expected in addition to income from electricity sale. In most cases, these benefits may accrue to at least 2-3 $/kWh and in some cases even twice as much.

4. SOURCE OF ENERGY AND ESTIMATED POTENTIAL

The source of heat is a global air cyclic flow named after its discoverer George Hadley (1735). Hot and humid air rises above the equatorial belt. The rising air cools, vapor condenses and rain is shed. The rate of air cooling rising cooling with moisture condensation is about half a centigrade every 100 m. The air then turns south and descends back to the earth’s surface from a height of up to 10 km., at a latitude between 15 degrees and 35 degrees north or south. This belt moves a little from season to season. The descending air warms up, this time a full centigrade every 100 m. The air then turns south and descends back to the earth’s surface from a height of up to 10 km., at a latitude between 15 degrees and 35 degrees north or south. This belt moves a little from season to season. The descending air warms up, this time a full centigrade every 100 m. High pressure air belts are formed. Finally, the air turns back towards the equator picking up moisture and heat again. The areas of air descent turn into arid lands. There are several estimates of the heat transfer which results from the Hadley Cell circulation. One estimate is over 17 million square km. of extreme desert and some 25 million square km. of arid lands have been formed by the descending air and extra heat. The heat transfer is estimated between 2 and 4x10^16 kWh/year. This assumes a typical rate of air descent is 1 cm/s and the cooling rate is 10-12°C, over the arid areas. The overall efficiency of turning this heat into electricity with of about 1000 m is in the order of
1%. The theoretical potential of producing electricity is then 2-4x10^{14} kWh/year. The present global consumption of electricity is about 8000 billion kWh a year, one part in 25 to one part in 50 of the estimated global potential. (Another source estimates the global electricity consumption as 13000 billions kWh/year). Assuming the future use of all human beings of 5000 kWh/year/capita for 8 billion people, this theoretical quantity is sufficient for 5-10 times more than the population of the globe. The development team prepared an estimate of the world potential using a satellite set of measurement data (ECMWF) over 10 years, every hour, and at several elevations. In these somewhat simplified and conservative computations only data of 1200 m above the local ground level were taken into consideration with distances and elevations from and above a water source. The computation was made for a base line design tower of 1200 m height and 400 m diameter, it assumed a very inefficient water conveyance to the Tower of about one percent head losses. The results are summarized in Table 3 and are organized in power groups of 50 MW average output from 200 MW and up to 600 MW. The number of possible towers was calculated assuming that each tower requires on the average a 400 square km open sky space for importing sufficient hot and dry air. This is a very conservative assumption. One can crowd Towers in a space less than 20X20 km. For example, into a Valley, such as the Arava Valley, the Towers create a sink to the hot air over a much narrower space and thus the installation of a Tower at the vicinity of highly elevated ground can be avoided. Thus, one can utilize less distant and topographically lower ground, and not give up much area as in the computation that led to Table 3. Hot air flows not only vertically, but drains from the surrounding. Thus, Table 3 brings a relatively conservative estimate. It may be, of course, offset to some degree due to different existing land uses that prevent construction of Towers everywhere.

Each value from the satellite data represents 1.125x1.125 degrees or approximately 125x125 km. In such a square, it is possible to find points where the output can be much higher than the average. The total annual power in this table is about 2.3 X 10^{14} kWh/year, about 1% of the heat flow through the Hadley Cell circulation. Thus, we roughly confirm our two former estimates at least by an order of magnitude, and show that they are very conservative. The summary results at the bottom of Table 3 are of extreme interest. The world potential, assuming 200 MW as the low economic limit, is 230,000 X 10^{6} kWh/year, sufficient for 46 billion inhabitants at the level of Western Europe. Eventually it might be possible that areas of less optimal climatic conditions, allowing outputs between 100 and 200 MW, become worthwhile. Characteristic areas with such lower performance are to be found in south Europe, Texas, southern and western parts of India, very large parts of Australia, etc. Another very interesting possibility is the extremely low projected cost of electricity production in some locations. Theoretically, some 756 towers at costs lower than 1.9 €/kWh at 5% discount rate. In Table 4 the total potential for different regions in the world is shown. The area in North Africa that could be installed with at least 300 MW and up could supply 3.58 billion people electricity at a European consumption level. At the same time, cheap sea water desalination could provide water at volumes 15-20 times the Nile River, just by using 20% of the electricity. Energy Towers at the southern part of Europe have poorer climatic conditions. Over half billion people can still be provided with electricity at somewhat higher production cost, but smaller transmission costs. The electricity produced in California and Mexico could serve 1.2 billion people at this low rate of 4.5 €/kWh or less at the power station gate.

5. FRINGE BENEFITS

5.1 Desalination of sea water

The desalination of sea water in combination with the Energy Towers can save a large part of the initial investment. This is especially effective with Reverse Osmosis which is the preferred method today. A detailed analysis showed saving of nearly half of the investment and about one third of the energy outlay.

5.2 Reduction of pollutants and greenhouse emissions

The Energy Towers alone can gradually provide a solution for nearly two thirds of the necessary reduction in
the greenhouse gases due to the electricity production. Considering 2.5% annual increase in electricity demand and 2% power stations replacement, the use of fuel for electricity would be 4.5% less per year.

6. CONCLUSIONS

A major problem of the modern world is to produce cheap and clean energy in a large scale. The Energy Tower is a promising clean technology method of utilizing solar power that can be used in hot, dry climates to produce energy at cost that can easily compete with conventional methods of energy production based on fossil fuels – while offering a number of possible benefits, mainly desalination but also elimination of greenhouse gases. The problems connected with their functioning have been researched and it is thought that the project is ready for the building of a prototype plant. The Energy Towers projected cost of electricity production is the lowest among all renewable sources with the exception of some large hydro-power stations under very favourable conditions.

The theoretical potential in a recent global estimate for Energy Towers, with a net average output ranging between 200 and 600 MW for station, was found to be 230,000 billion kwh/year.

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