

Assessment of an “Energy Tower” potential in Australia using a mathematical model and GIS

T. Altmann *, Y. Carmel, R. Guetta, D. Zaslavsky, Y. Doytsher

Faculty of Civil & Environmental Engineering, Technion, Haifa 3200, Israel

Received 8 October 2003; received in revised form 10 June 2004; accepted 20 August 2004

Available online 19 October 2004

Communicated by: Associate Editor David Mills

Abstract

“Energy Tower” is a technology for producing renewable and clean electricity by means of cooling hot and dry air, which is continuously supplied to arid lands. We assess the potential of an Energy Tower by incorporating topographic and meteorological parameters into a computational model, providing evaluations for the net power production and the electricity production cost. We formulate a highly simplified model for the Energy Tower’s flow, setup and process a spatial dataset of topographic and Meteorological upper air parameters. The model was applied to the Australian continent. A model simulation of one annual cycle enabled the ranking and selection of promising sites. The highest potential for energy towers is in the Port Hedland region, where favorable meteorological and topographic conditions would result in high average net power ($\approx 370 \pm 160$ MW), potentially providing the electricity needs of ~ 0.5 million people, for an economically competitive costs (3.5¢kWh).

© 2004 Elsevier Ltd. All rights reserved.

Keywords: Energy Tower; GIS; Technology Assessment; Mathematical model; Electricity; Australia; Power production

1. Introduction

‘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 outlook of this technology as an alternative source for producing renewable electric energy in arid or semi-arid lands.

The principal concept of an Energy Tower (ET hereafter) is to cool hot and dry air by evaporation of a fine water spray. The cooled and denser air flows downward within a tall (1200 m) and large diameter (400 m) shaft of a Tower. At the bottom outlet the high velocity airflow actuates turbines to generate electricity (Fig. 1). The water required for the air cooling may be fresh or salty. The water discharge is pumped and conveyed from the water source (lake or sea) by a pumping system. The ET technology employs solar energy indirectly and therefore promises the production of electric energy day & night, without the need to construct solar collectors.

The power production of an Energy Tower depends on several factors. The Tower’s gross power is determined

* Corresponding author. Tel.: +972 4 8293337; fax: +972 4 8292746.

E-mail address: taland@tx.technion.ac.il (T. Altmann).

Nomenclature

A_c	cross-sectional area of the main shaft (m^2)	E_r	drag effect energy per unit volume (Pa)
$C_{\text{construction}}$	total construction cost of an ET power plant (M\$)	E_{year}	net annual electric energy (kWh)
$C_{\text{electricity}}$	estimated electricity cost (¢/kWh)	F	empiric energy loss coefficient (–)
$C_{\text{O\&M}}$	operation and maintenance costs (¢/kWh)	GP_{avg}	average gross power (MW)
D	distance between water source and the ET site (km)	$GP_{\text{installed}}$	installed gross power (MW)
E_C	energy gain due to air-cooling per unit volume (Pa)	GP_{std}	standard deviation of the gross power (MW)
E_{loss}	total energy losses of the airflow per unit volume (Pa)	i	rate of interest (%)
E_{net}	net mechanical energy per unit volume (Pa)	n	life expectancy (years)
E_p	pumping energy per unit volume (Pa)	$PP_{\text{installed}}$	installed pumping power (MW)
		ρ	average air density (kg/m^3)
		η_p	efficiency of the pumping system (–)
		η_t	efficiency of the turbine transmission generator aggregate (–)

mainly by the properties of the surrounding air, mainly its temperature, humidity, and pressure. Hotter and dryer air will result in a higher temperature-difference between the air inside and outside the Tower, and therefore increase the gross power production of the Tower. The Tower's net power is the gross power minus the power re-directed to pumping of water from the water source up to the Tower's top.

Naturally, air characteristics vary in space and time, therefore Energy Tower's gross power production fluctuates diurnally and annually. Moreover, the Tower's net power is also dependant upon site location and elevation relative to the water source. Consequently, the Energy Tower's performance would vary greatly in different locations. Thus, a critical preliminary step in the

planning of a commercial application is the mapping of the expected potential of an Energy Tower across a whole region. This kind of analysis would enable the ranking and locating of promising sites.

The goal of the present study is to incorporate the important parameters that affect the power production of an Energy Tower into a model capable of calculating the "Energy Tower potential" for an entire region across a whole year. Here, we evaluate two aspects of the potential of Energy Tower, the net power production and the energy production cost.

2. The Energy Tower's Production model (ETP)

The phenomenon of a downward wind shear caused by cloud rain has been well known for centuries. The first to suggest the use of this phenomenon for producing electricity was Philip Carlson (1975). The same principle was developed independently by a research group headed by Prof. Dan Zaslavsky at the Technion, Israel Institute of Technology. Since 1982, this group has explored various aspects of the ET, including the formulation of several models for the air flow simulation and the corresponding power outputs.

In order to estimate net power production of an ET for an entire region for a whole year, a model should calculate net power production for each location, several times per day, 365 days. Obviously, this requires the formulation of a highly simplified model capable of producing fairly accurate estimates in a short run-time. Towards this end, we devised the model called ETP (Energy Tower Production) model. Basically, the ETP model gives an analytical expression for the major process occurring in the ET. The ETP model results were

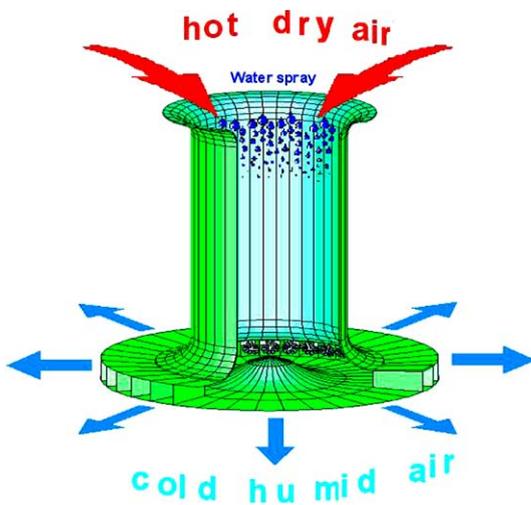


Fig. 1. Illustration of an ET.

compared with a one dimensional flow model, which in turn had to be compared for validity with an even more accurate three dimensional computerized fluid dynamics model.

The ETP model uses two groups of input variables, meteorological and topographic. The meteorological parameters include the air properties at the tower's top: temperature (K), relative humidity (%), and air pressure (hPa) (all at ~1300m above ground). The topographic variables include site elevation (m) and distance (km) between the site and the nearest water source. The models outputs are net power production (MW), gross power (MW), pumping power (MW) and water discharge (ton/s).

The ETP model formulates four energy terms expressed in pressure units (energy per unit volume): The energy gain due to air-cooling (E_C (Pa)), which is defined as the excess of static pressure due to cooled air column inside the ET. The drag effect energy (E_r (Pa)) exerted on the air by the un-evaporated water droplets falling along the tower at a constant velocity. The pumping energy (E_p (Pa)) expressed as a function of the total pumping head and the total energy losses of the airflow (E_{loss} (Pa)).

The energy losses in the ET are due to friction and turbulence of the flow and mainly due to local energy losses at the ET's inlet and outlet, where the air flow is turning by 90°. Coefficients for the energy losses were studied previously by an axi-symmetric numerical model and were compared to results of an ET's laboratory model in a wind tunnel (Mezhibovski, 1999). Here we assumed the total energy losses to be proportional to the air's kinetic energy with an empiric constant $F = 0.8$.

The calculation of the energy gain due to air cooling and drag effect (E_C and E_r) are based on the approximation of two air temperature profiles inside and outside the ET. Next, the model solves the four energy terms (E_C , E_r , E_p and E_{loss}) for the thermodynamic optimum. This yields the maximum net power using the following equation:

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

where A_c is the cross-sectional area of the main shaft (m^2), η_t is the efficiency of the turbine transmission generator aggregate (–), ρ is the average air density (kg/m^3), F is the empiric energy loss coefficient (–), and E_{net} is the net mechanical energy per unit volume (Pa). E_{net} is defined as the following sum:

$$E_{\text{net}}[\text{Pa}] = E_C + E_r - \frac{E_p}{\eta_p} \quad (2)$$

where η_p is the efficiency of the pumping system (–).

Eq. (1) results from an analysis conducted in our lab, which shows that the term $2/3 E_{\text{net}}$ in parenthesis gives the theoretical maximum possible deliverable power where the remaining $1/3 E_{\text{net}}$ is energy losses (Zaslavsky et al., 2003; Zaslavsky and Guetta, 1999).

Comparison of the ETP Model output results with those of the detailed one dimensional model (Gutman et al., 2003) indicated differences in the range of $\pm 10\%$. However, the possible inaccuracy is small enough to provide the right relative ranking of different sites within a much smaller computation effort. Table 1 lists (a) the input parameters and (b) the state variables of the

Table 1
Input parameters (a) and state variables (b) of the ETP model with example values

		Value	Unit
<i>(a) Input parameter</i>			
Height of site above water source	1	80	m
Distance between site and water source	2	50	km
Air temperature at the top of the ET	3	283.15	K
Air relative humidity at the top of the ET	4	30	%
Air pressure at the top of the ET	5	820	hPa
<i>(b) State variable</i>			
Total pumping head	1	1445	m
Energy gain due to air cooling (E_C)	2	428.5	Pa
Energy gain due to the droplets drag effect (E_r)	3	27	Pa
Pumping energy (E_p)	4	126.8	Pa
Net Energy (E_{net})	5	318	Pa
Energy losses (E_{loss})	6	102	Pa
Net power	7	311.5	MW
Gross power	8	550	MW
Air velocity at the ET's bottom	10	17.8	m/s
Water discharge	11	14.2	ton/s

ETP model, with an example of possible values calculated for an ET of 1200m height and 400m diameter.

3. Methods

We applied the ETP model to the entire Australian continent. The position of Australia across the Tropic of Capricorn, zone of descending dry air results in extensive arid and semi-arid regions in the continent. Evaluation of the Energy Tower potential involves a sequence of steps illustrated in Fig. 2.

3.1. Setup of a meteorological and topographic dataset

The first step is the processing of raw Topographic and Meteorological data sources, to set up an input dataset for the ETP model. This dataset includes the two topographic parameters (distance and height above sea level) and the three meteorological parameters (Temperature, Relative humidity and air pressure at the Tower's top), all at a temporal resolution of 6hr and a spatial resolution of 0.2 deg. The entire dataset was integrated into a GIS in the format of Lat/Lon grid layers of 231×180 cells, where cell size is approximately 20×20 km (0.2×0.2 (deg)).

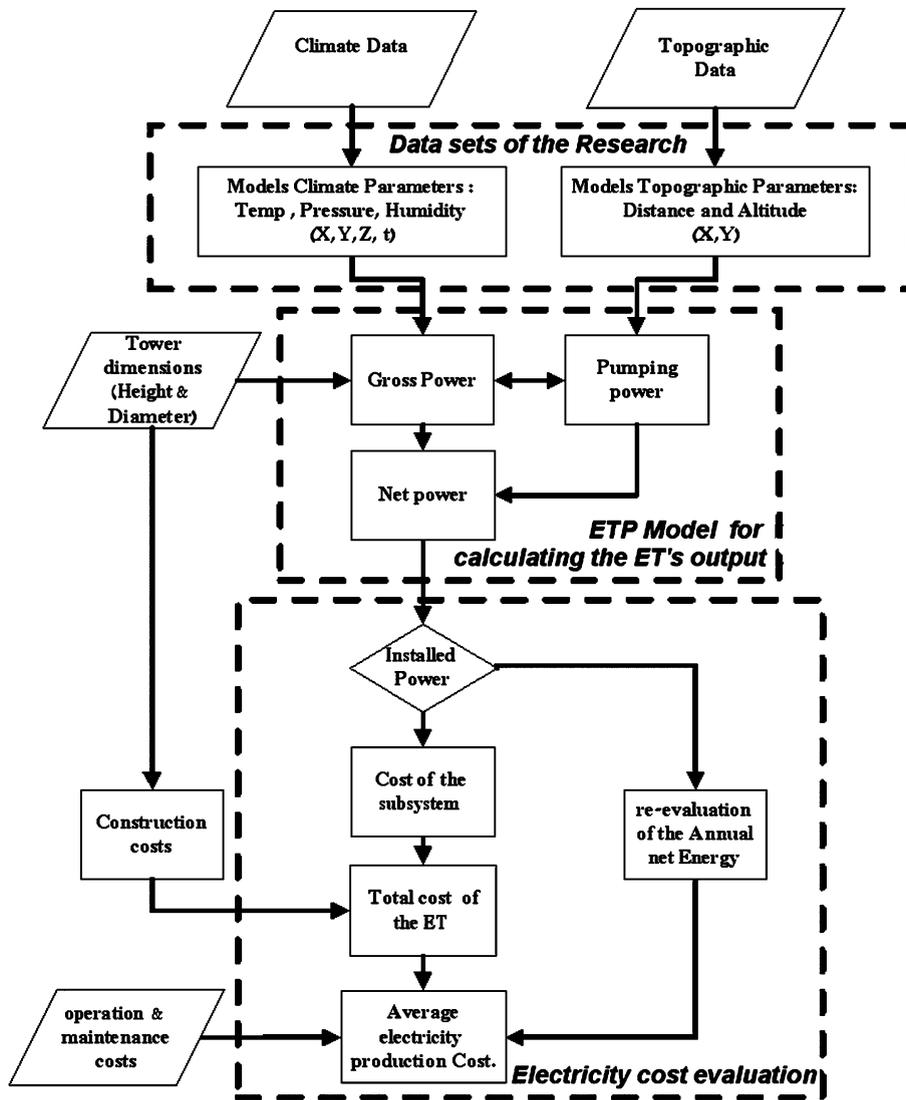


Fig. 2. Flow chart of the steps to evaluate the Energy Tower Potential.

The topographic data source is the Digital Elevation Model GTOPO30 produced by the U.S Geological Survey (USGS, 2003), where elevations are regularly spaced at 30-arc seconds (≈ 1 km). The lowest location within a cell would be optimal for the ET operation, since it minimizes the pumping energy. Thus, each 20 km^2 cell was assigned the minimum elevation value of the original 1 km DEM (Fig. 3). The distance (D) to water source was calculated as the Euclidean distance between each cell and the nearest sea-cell.

The data source for the upper air parameters is the ERA15 Re-Analysis Project retrieved from the MARS-data Storage and Retrieval System, developed by the European Center for Medium-Range Weather Forecasts (ECMWF, 2003). The ERA15 archive specifies numerous weather parameters from December 1978 to February 1994. Three upper air parameters were retrieved: the geopotential (m^2/s^2), the dry bulb temperature (K) and the relative humidity (%), at five air pressure levels: 1000, 925, 850, 775 and 70 hPa every six hours during the year 1993. The ERA-15 atmospheric model is at a spatial resolution of 1.125 long/lat degree. Cell-specific elevation data served to calculate the meteorological parameters, temperature, humidity and pressure at the tower top, using a linear interpolation between air pressure levels. The outputs of this process are maps of meteorological parameters at the same resolution as the elevation data, namely $20 \times 20\text{ km}^2$ (Fig. 4 illustrates the temperature at Tower's top for the entire continent).

3.2. Application of the ETP model and evaluation of the power potential

The next step of the Energy Tower potential assessment was to run the ETP model with the entire input dataset. Model output was time-series maps of Gross Power, Pumping Power, and Net Power for Australia (4 maps per day \times 365). Monthly average, seasonal average and annual average maps, as well as maps of the variability of these parameters were then constructed.

3.3. Evaluation of the electricity cost

The third and last step is the estimation of the energy cost. This step is based on estimates of several parameters and considerations which are all detailed in Table 2. The total cost of an ET power plant was summarized with the following equation:

$$C_{\text{construction}} [\text{M\$}] = 648 + 0.32\text{GP}_{\text{Installed}} + 0.4\text{PP}_{\text{Installed}} + 2.85D \quad (3)$$

Where: 648 [M\$] is a fixed construction cost of the Tower, the spray system and the operational reservoir. The second term is the costs of the turbine and generators power system as a function of the installed gross power ($\text{GP}_{\text{installed}}$ (MW)). The next term expresses the costs of the pumping system as a function of the installed pumping power ($\text{PP}_{\text{installed}}$ (MW)), and the last term stands for the construction costs of the water conduit from the water source to the ET site as a function of

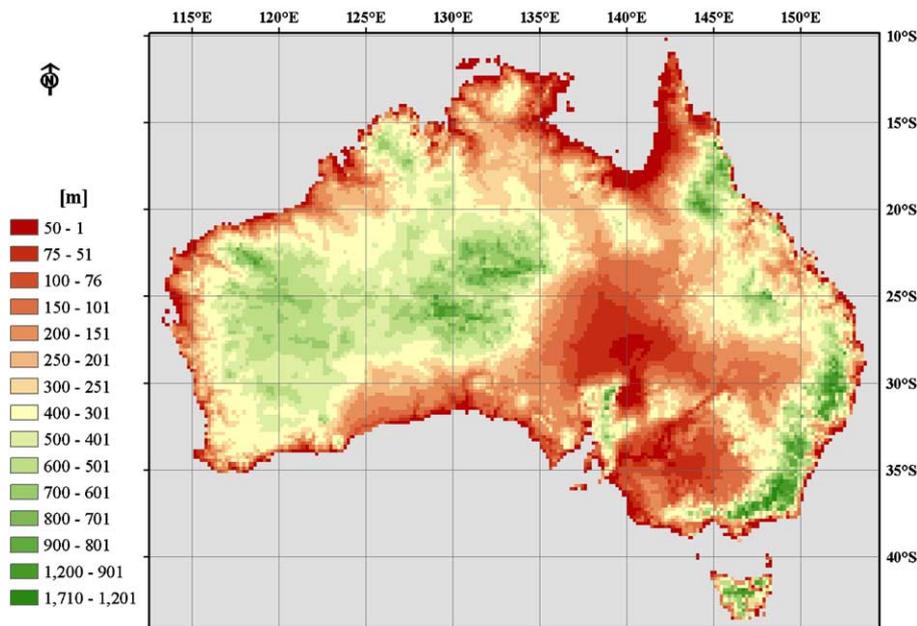


Fig. 3. Height difference between the Tower's site and Water Source (m).

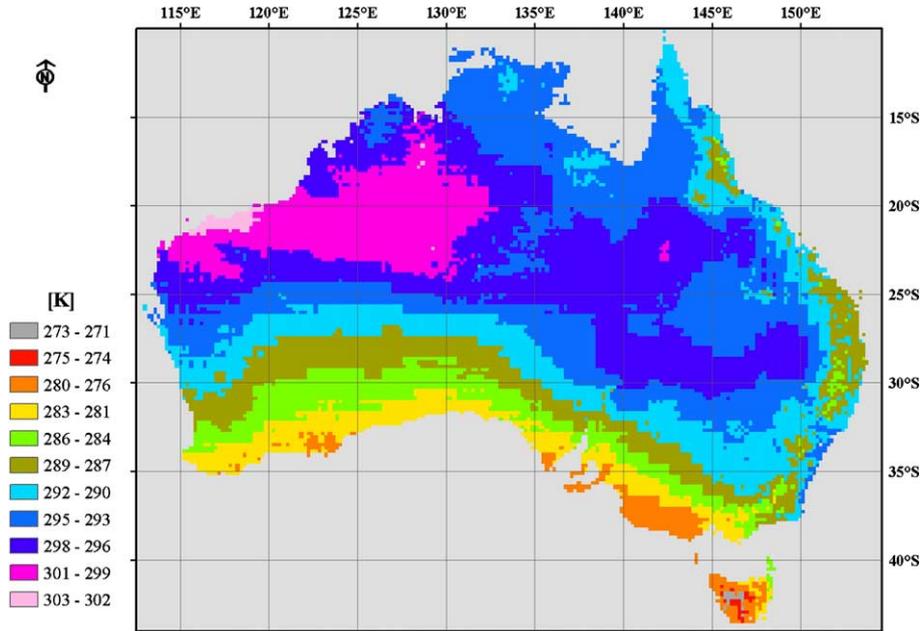


Fig. 4. Air Temperature at the Tower's top at the resolution of the processed data, 0.2 deg (K).

the distance between them (D (km)). Table 2 details the above mentioned costs.

The installed gross and pumping power is the machine capacity mounted at an ET site. Installing large

capacities would enable large electricity production during rare events of favorable meteorological conditions (the hottest, driest day). On the other hand, providing the ET with capacities fitting to exceptional peaks would

Table 2
Estimated costs of the Energy Tower's subsystems

Sub System	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)	2000 (\$/ton)	191,300 (ton)
	Framework cover	13 (\$/m ²)	3.355e+6 (m ²)
	Concrete foundation	165 (m ³)	140,500 (m ³)
Water Supply	Operational reservoir (1,000,000 m ³) and water uptake structure	21.8 (M\$)	1 (per ET)
	Water conduit: 20% pipes (ϕ 2600mm) & 80% concrete open canal (wall slope 1:4 and 4m width)	0.2*5,500+0.8*1,000 (k\$/km)	D (km)
Water Spray System	Water Pumping from water source up to the ET top	400 (\$/kW)	$PP_{\text{installed}}$ (kW)
	Including: 1,000,000 Sprayers, 20,000m of water pipes (ϕ 200- ϕ 2000mm), support beams and controllers	38 (M\$)	1 (per ET)
Power Pack	An array of 50 Wind Turbine	124 (\$/kW)	$GP_{\text{installed}}$ (kW)
	Generators	182 (\$/kW)	$GP_{\text{installed}}$ (kW)
	Transmissions	10 (\$/kW)	$GP_{\text{installed}}$ (kW)
Brine disposal system	Brine reservoir (500,000 m ³) Ground sealing and drainage of the ET surroundings	109 (M\$)	1 (per ET)
	Brine disposal conduit (half the price of the Water conduit)	950 (k\$/km)	D (km)
Infrastructure	Land, Roads, fence, buildings etc.	30 (M\$)	1 (per ET)

imply higher construction cost. The optimal solution for this tradeoff depends on site-specific topography and power fluctuations, and thus varies from site to site. The variation of the total electricity cost as a function of the installed power at site located close to Port Hedland is illustrated in Fig. 5. Here, the minimum electricity cost occurs where the installed power is 0.6 of the gross power's pick value. For the purpose of the present study, we applied a rule of thumb that sets the installed gross power at 0.7 of the sub-maximum gross power, defined as:

$$GP_{\text{installed}} [\text{MW}] = 0.7(GP_{\text{avg}} + 3GP_{\text{std}}) \quad (4)$$

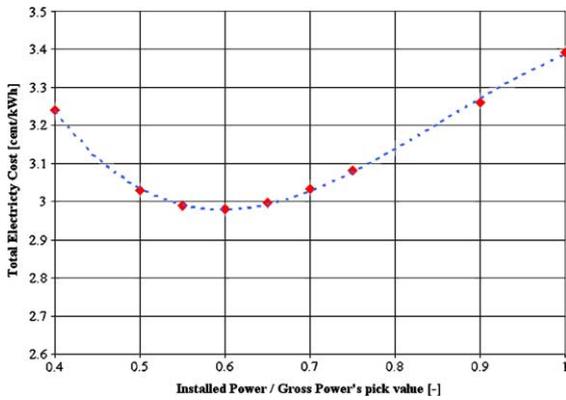


Fig. 5. Total electricity cost for different installed power ratios (¢/kWh).

Where GP_{avg} is the average gross power (MW), GP_{std} is the standard deviation of the gross power (MW) and 0.7 is the reduction coefficient.

Following the correction of the installed gross and pumping power the net annual electric energy (E_{year}) was then re-evaluated for the entire continent. Finally, the assessment of the electricity cost ($C_{\text{electricity}}$) consisted of the parameters expressed in Eq. (5)

$$C_{\text{electricity}} = \frac{\frac{i(1+i)^n}{(1+i)^n - 1} C_{\text{construction}} + C_{\text{O\&M}}}{E_{\text{year}}} \quad (5)$$

Where: $i = 10\%$ rate of interest, $n = 30$ years life expectancy and $C_{\text{O\&M}} = 0.49$ ¢/kWh operation and maintenance costs.

4. Results

4.1. Gross power

The Gross power production of the ET is determined by the properties of the surrounding air. In the ETP model, these properties are represented by the temperature, humidity, and air pressure at the Tower's top. Not surprisingly, the pattern of the annual average gross power (Fig. 6) indicates that areas of high gross power are found in regions that are dominated by a combination of high temperature and low humidity, namely the arid parts of the continent. Four areas of interest were

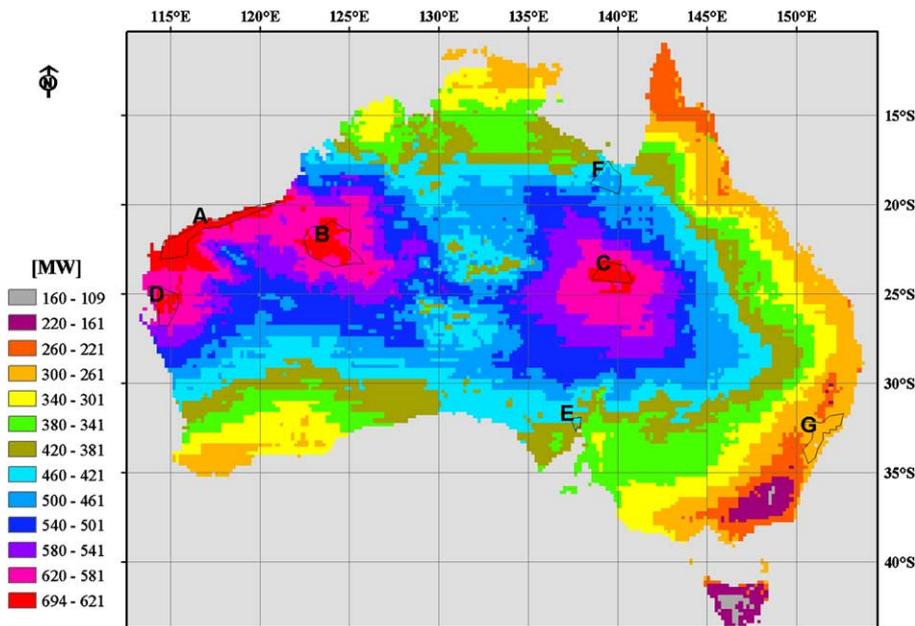


Fig. 6. Annual average Gross Power of the “Energy Tower” for 1993 (MW).

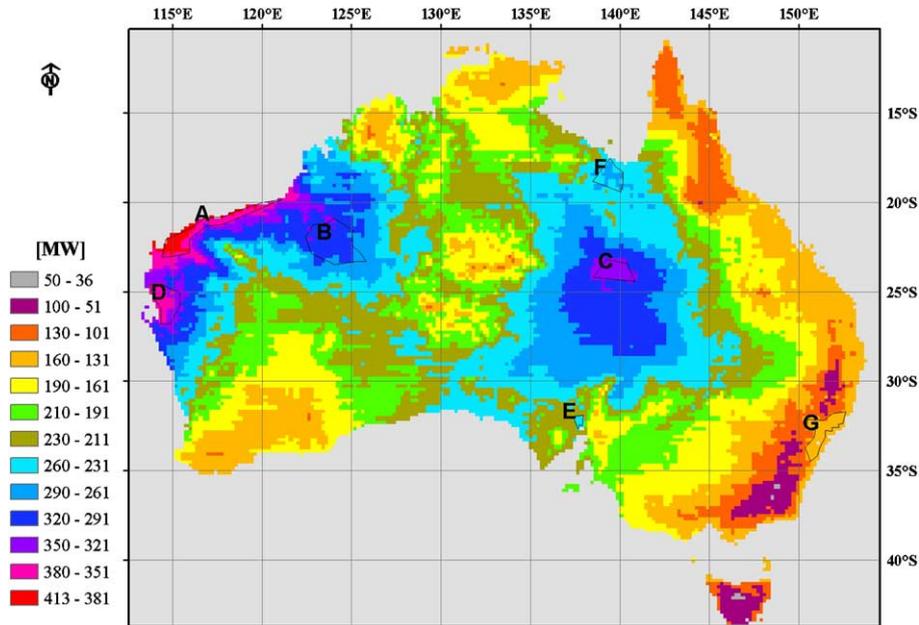


Fig. 7. Annual average Net Power of the “Energy Tower” for 1993 (MW).

characterized by high gross power, 620–694 MW (marked as areas A, B, C and D in Fig. 6).

The pumping power is calculated as a function of cell elevation, its distance from sea and water discharge. The first two parameters are determined by topography, while water discharge is determined by climate conditions (hot and dry air conditions result in increased evaporation, and thus require transport of more water).

4.2. Net power

Net power is a function of both gross power and pumping power. The map of average annual net power (Fig. 7) reveals two separate areas that would yield the highest net power, areas A and D. In these areas the

average net power of an Energy Tower is estimated to be above 350 MW. Areas of low net power production, 36–160 (MW) are stretched along the continent’s east coast.

Table 3 presents various model outputs for areas of interest A through G. Comparison of areas A to D explains the contribution of the topographic and meteorological parameters to the resulting net power. For example there is a ~5% between gross power production of areas A and B due to climate conditions. For the net power this difference rises up to ~20% mainly because of topographic differences. In contrast, area D has a relatively low gross power but high net power for the same reason. Three additional areas of interest were delineated on the map, and their properties were investigated

Table 3
Summary of the parameters and ET outputs of zones A–G

Area of interest	Topography	Properties of the air at the ET’s top	Annual avg. temperature	Annual avg. humidity	Annual avg. gross power	Annual avg. net power	Std. of the net power
	Avg. distance (km)						
	(km)	(m)	(C)	(%)	(MW)	(MW)	(%)
A	50	67	19.2	39.0	654	377	44.3
B	416	316	18.4	39.0	623	306	51.0
C	684	107	17.9	38.6	626	324	46.5
D	66	68	16.4	40.7	618	355	54.0
E	95	24	11.6	53.0	419	236	60.0
F	117	60	19.2	53.4	470	261	57.2
G	85	94	9.8	66.0	275	142	62.9

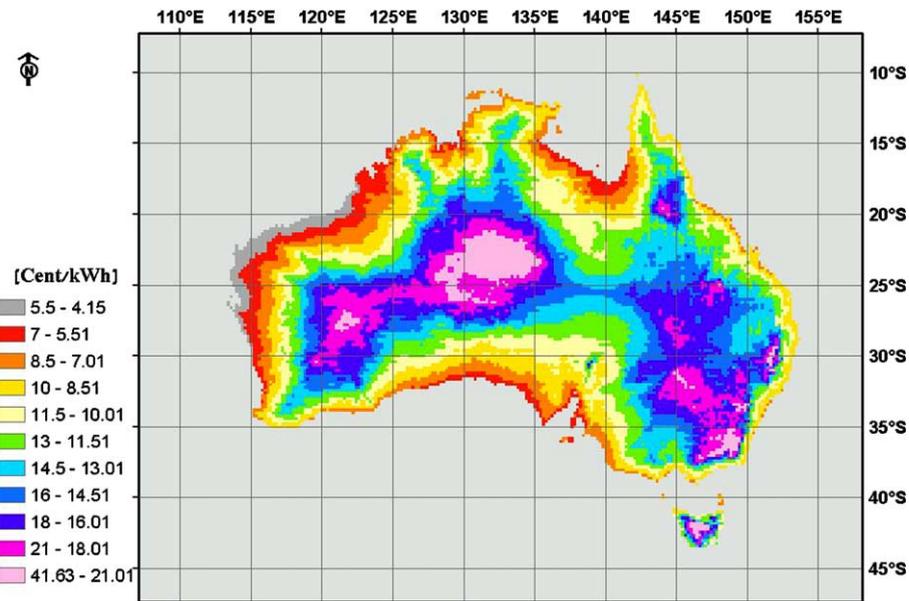


Fig. 8. Electricity Cost projected with interest rate of 10% and 30 years life expectancy (¢/kWh).

closely (Table 3). Areas E and F were explored because of their proximity to population centers and area G was explored as an example for an unsuitable location. Another important feature documented in the Table 3 is the standard deviation of the net power production, indicating the reliability of electricity supply. Our results show that area A stands out not only for high net power but also for low variations in power production, promising a relatively stable generation of electricity. There are several ways to adapt the slight daily power fluctuations to the demand curve, mainly by built-in pumped storage which is applicable near mountain ranges. There are also ways to adapt the seasonal power fluctuations to reduce the standard deviation, but these are beyond the scope of this work.

Analysis of specific sites was performed as well. A single grid cell was selected in area A, close to Port Hedland (Lat: 20.3S, Long: 119.5), located 44km south of the Indian Ocean. Net power production of an ET at this site is estimated to be on average 370MW, where 95% of the time, net power will not drop below 137MW. The estimated net deliverable annual energy is summed up to 3.5 billion (kWh/year). Assuming an annual consumption of 6000kWh/year per capita, our calculations reveal that a single ET on site may serve a population of approximately half a million people.

4.3. Electricity cost

Electricity cost estimates (Fig. 8) range from 4.5¢/kWh up to 42¢/kWh. This result reveals that at potential sites the costs of ET technology may be not only envi-

Table 4

Characteristic electricity production costs (¢/kWh) projected to 2005 with an interest rate of 10% (OECD, 1998)

Energy source	Range of electricity cost (¢/kWh)	Average electricity cost (¢/kWh)
Coal	3.74–7.61	4.99
Natural gas	2.36–8.44	4.47

ronmentally superior but also economically competitive to costs of fossil electricity sources (Table 4). The pattern of the electricity cost shows the impact of the conduit construction cost, causing a constant increase in costs with distance-from-sea. Note, for example a comparison of two specific sites, one located in area A, 50km away from sea shore and the other in area E directly on coastline. The average net power production of both sites differs by ~32%, yet because of conduit cost and power fluctuations, the sites have the same economic potential (the estimated electricity production cost is ~5.85¢/kWh. These costs are based on a 10% interest rate, which is a conservative value (OECD, 1998). If lower interest rates are available, than the relative advantage of ET over fossil sources increases further.

5. Conclusions

With the advent of GIS, Spatially explicit models are becoming indispensable tools for assessing the potential

of new energy sources (Ariza Lopez et al., 1997), offering important information for decision makers (Voivontas et al., 1998). Here, a set of tools was devised to assess the potential of an Energy Tower to supply environmentally clean and economically profitable electric energy. The computer-based assessment integrated site specific topographic parameters and time dependent air properties into a model producing time sequence maps of ET's power outputs. Implementation of the model resulted in the mapping of both power production and electricity cost for the entire continent of Australia.

The ETP model running time was relatively short. Simulation of a whole year for the entire Australian continent took about one day, compared with an estimated running time of six months for the one dimensional model. This achievement allows the model to be further implemented on yet a larger scale, consisting several years of meteorological data and covering the whole globe.

Analysis of the model outputs characterized specific regions of interest and provided overall ranking of sites in terms of net power production and energy cost. The results depicted vast regions in Australia where arid conditions imply high gross power from Energy Towers. However, part of these areas are characterized also by large distance from water source, and thus high pumping power, which in turn result in relatively low net power. Mapping of the net power and electricity cost indicated at least two regions in Australia (A and E) where the environmental conditions may support profitable Energy Towers. Region A (Port Hedland area), characterized by favorable meteorological and topographic conditions, a single ET would supply constantly high net power ($\approx 370 \pm 160$ MW), providing the electricity needs of ~ 0.5 million people, for an economically competitive costs (4.7¢/kWh). In region E (Port Augusta area), characterized by less favorable environmental conditions (lower temperatures and higher humidity), net power would be lower ($\approx 230 \pm 140$ MW). Yet, its proximity to populated areas and to water source makes of this region compatible to that of region A (7.3¢/kWh).

Acknowledgments

The ECMWF is Acknowledged for the technical support, access to the facilities and cooperation.

References

- Ariza Lopez, F., Lopez, R., Lopez Pinto, A., 1997. Territorial competitiveness of the stand alone photovoltaic systems versus grid electricity supply. A method and a study based on geographical information systems. *Solar Energy* 61, 107–118.
- ECMWF, 2003. European Center for Medium Range Weather Forecasts member state server. ERA Documentation. Available from: <<http://www.ecmwf.int>>.
- Gutman, P.O., Hoersh, E., Guetta, R., Borshchevsky, M., 2003. Control of the Aero-Electric Power Station—an exciting QFT application for the 21st century. *International Journal of Robust and Nonlinear Control* 13, 619–636.
- Mezhibovski, V., 1999. Numerical simulation of the flow in Energy Towers and their surroundings. *Agricultural Engineering*. MSc Thesis, submitted to The Technion—Israel Institute of Technology, Haifa. In Hebrew.
- OECD, IEA, NEA, 1998. Projected Costs of Generating Electricity, update 1998. OECD, Paris.
- Philip Carlson, R., 1975. Power generation through controlled convection (aeroelectric power generation). Lockheed Aircraft Corporation, Burbank, California. US patent # 3,894,393.
- USGS, 2003. EROS Data Center Distributed Active Archive Center. GTOPO30 Documentation. Available from: <<http://edcdaac.usgs.gov/main.html>>.
- Voivontas, D., Tsiligiridis, G., Assimacopoulos, D., 1998. Solar potential for water heating explored by GIS. *Solar Energy* 62, 419–427.
- Zaslavsky, D., Guetta, R., 1999. Energy Towers, volume I: Summary. A report submitted to the Ministry of National Infrastructure. Technion—Israel Institute of Technology, Haifa.
- Zaslavsky, D., Guetta, R., Hitron, R., Krivchenko, G., Burt, M., Poreh, M., 2003. Renewable resource hydro/aero-power generation plant and method of generating hydro/aero-power. Sharav Sluices LTD., Haifa IL. US patent # 6,647,717 B2.