INTERIM REPORT

Evaluation of the potential of electricity and desalinated water supply by using technology of "Energy Towers" for Australia and America

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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 down-draft 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 (Figure 1.1). 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 and conveyance. The ET technology employs solar energy indirectly and therefore promises the production of electric energy day & night, without the need to construct solar collectors.

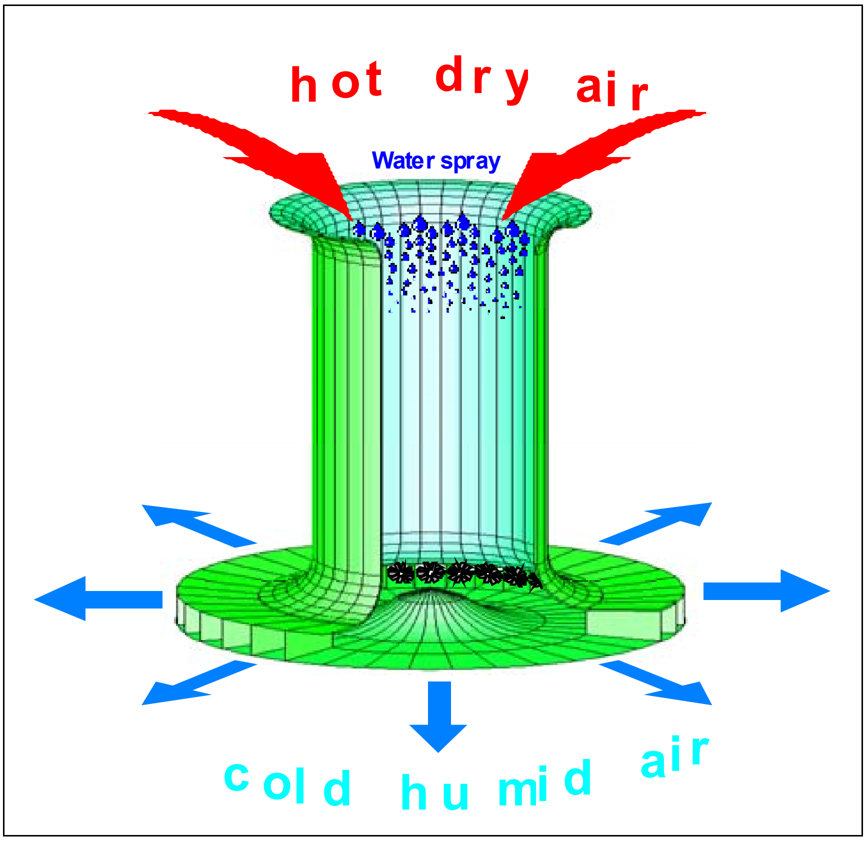

Figure 1.1: Illustration of an ET

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

Naturally, air characteristics vary in space and time; therefore Energy Tower’s gross power production fluctuates diurnally and seasonally. 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 three main aspects of the potential of Energy Tower, the net power production and the energy production cost and possible production of sea water desalination assuming we use 20% of the produced electricity for this purpose.

2. The Model for the Evaluation of the Energy Tower Potential (detailed example for the Australian continent)

2.1 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, the group has explored various aspects of the ET, including the formulation of several models for the air flow simulation and the corresponding power outputs. The Technion group improved the cost effectiveness by a factor of 1:7. 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 a year. 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 compared with a one dimensional flow model, which in turn had to be compared for validity with a the most accurate three dimensional computational fluid dynamics model which took five days computations of 5 parallel computers. This is per one tower at one point in time and a set of climatic parameters at least 5 elevations. Instead to simplify, the ETP model uses two groups of input variables, meteorological and topographic. The meteorological parameters include the air properties at the tower's top only: temperature [K], relative humidity [%], and air pressure [hPa] (all at ~1300 m 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 degrees. Coefficients for the energy losses were studied previously by an axi-symetric 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:

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

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:

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

Where: η_p is the efficiency of the pumping system [-]. Equation (1) results from an analysis conducted in our lab, which shows that the term $2/3E_{net}$ in parenthesis gives the theoretical maximum possible deliverable power where the remaining $1/3E_{net}$ is energy losses (Zaslavsky et al , 2003, Zaslavsky & 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 ±10%. However, the possible inaccuracy is small enough to provide the right relative ranking of different sites within a much smaller computation effort. Table 2.1 lists (a) the input parameters and (b) the state variables of the ETP model, with an example of possible values calculated for an ET of 1200[m] height and 400[m] diameter.

Table 2.1: Input parameters (a) and state variables(b) of the ETP model with example values

	Input parameter	**Unit**	**Value**
1	Height of site above water source	[m]	80
2	Distance between site and water source	[km]	50
3	Air temperature at the top of the ET	[K]	283.15
4	Air relative humidity at the top of the ET	[%]	30
5	Air pressure at the top of the ET	[hPa]	820

	State variable	**Unit**	**Value**
1	Total pumping head	[m]	1445
2	Energy gain due to air cooling (E_C)	[Pa]	428.5
3	Energy gain due to the droplets drag effect (E_r)	[Pa]	27
4	pumping energy (E_p)	[Pa]	126.8
5	Net Energy (E_{net})	[Pa]	318
6	Energy losses (E_{loss})	[Pa]	102
7	Net power	[MW]	311.5
8	Gross power	[MW]	550
10	Air velocity at the ET's bottom	[m/s]	17.8
11	Water discharge	[ton/s]	14.2

2.2 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 Figure 2.1.

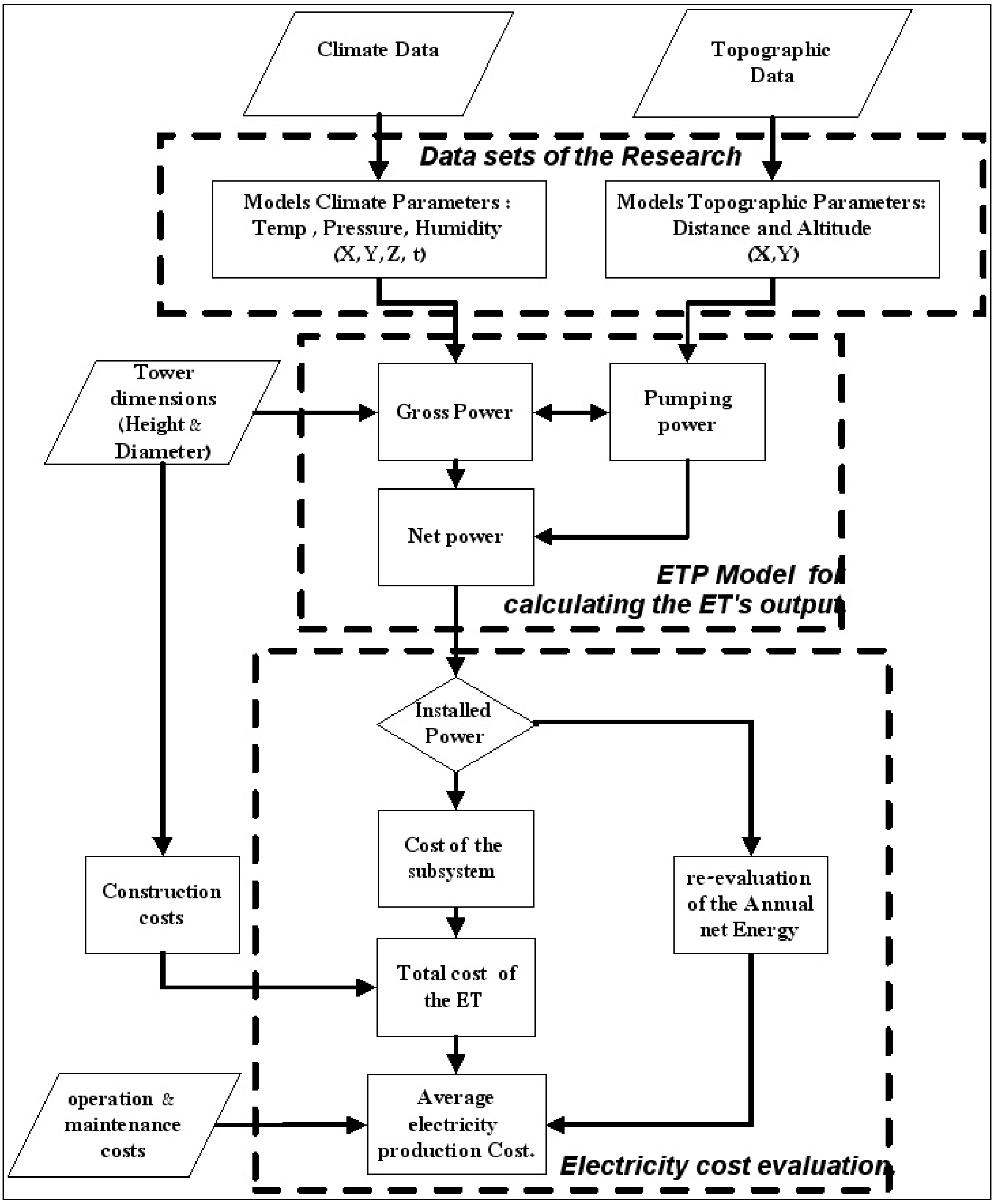

Figure 2.1: Flow chart of the steps to evaluate the Energy Tower Potential

Setup of a meteorological and topographic dataset

A very thorough study of the computation procedure ETP was applied first in the Australian continent, part of which is brought in the following. The first step was 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 6 hr 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 *231X180* cells, where cell size is approximately 20X20 km (0.2X0.2[deg]). 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 (≈1km). The lowest location within a cell would be optimal for the ET operation, since it minimizes the pumping energy. Thus, each 20×20 km cell was assigned the minimum elevation value of the original 1 km DEM (Figure 2.2). The distance (*D*) to water source was calculated as the Euclidean distance between each cell and the nearest sea-cell.

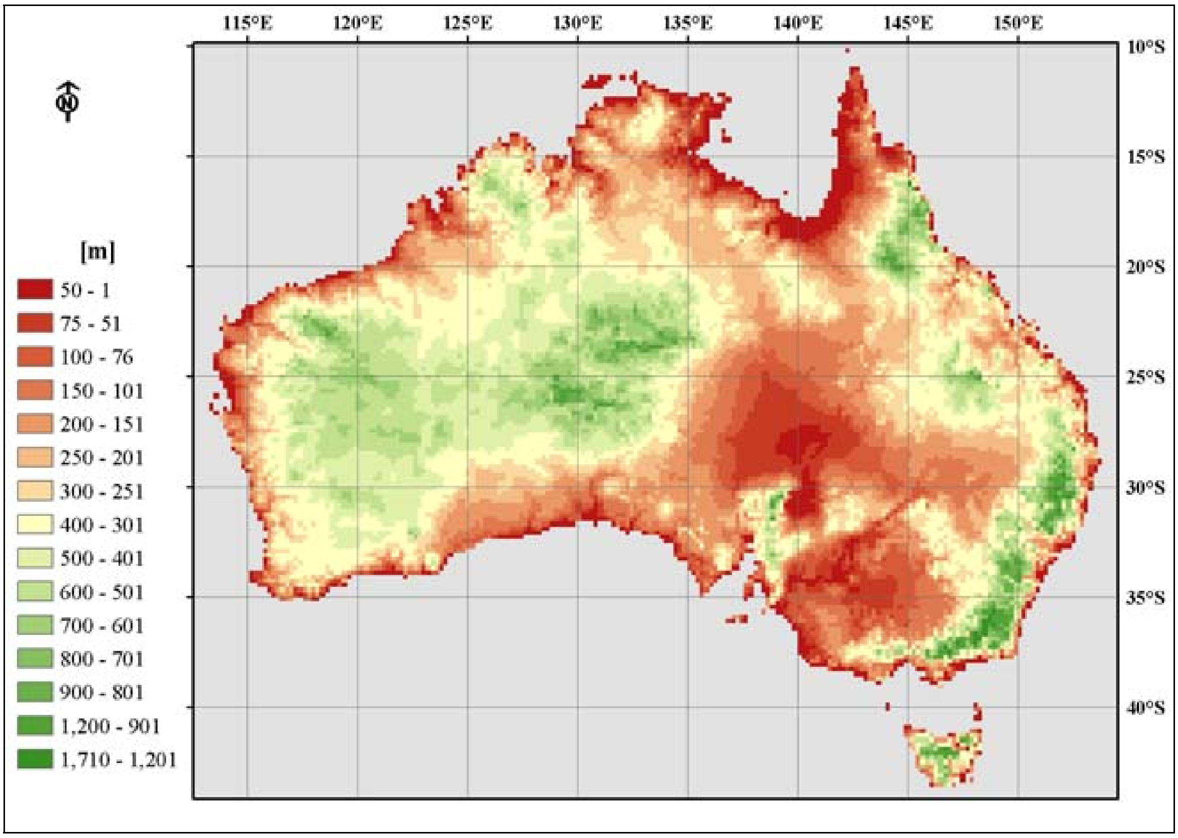

Figure 2.2: Height difference between the Tower's site and Water Source [m]

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 700 [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 output of this process is maps of meteorological parameters at the same resolution as the elevation data, namely 20x20 [km^2] (Figure 2.3 illustrates the temperature at Tower's top for the entire continent).

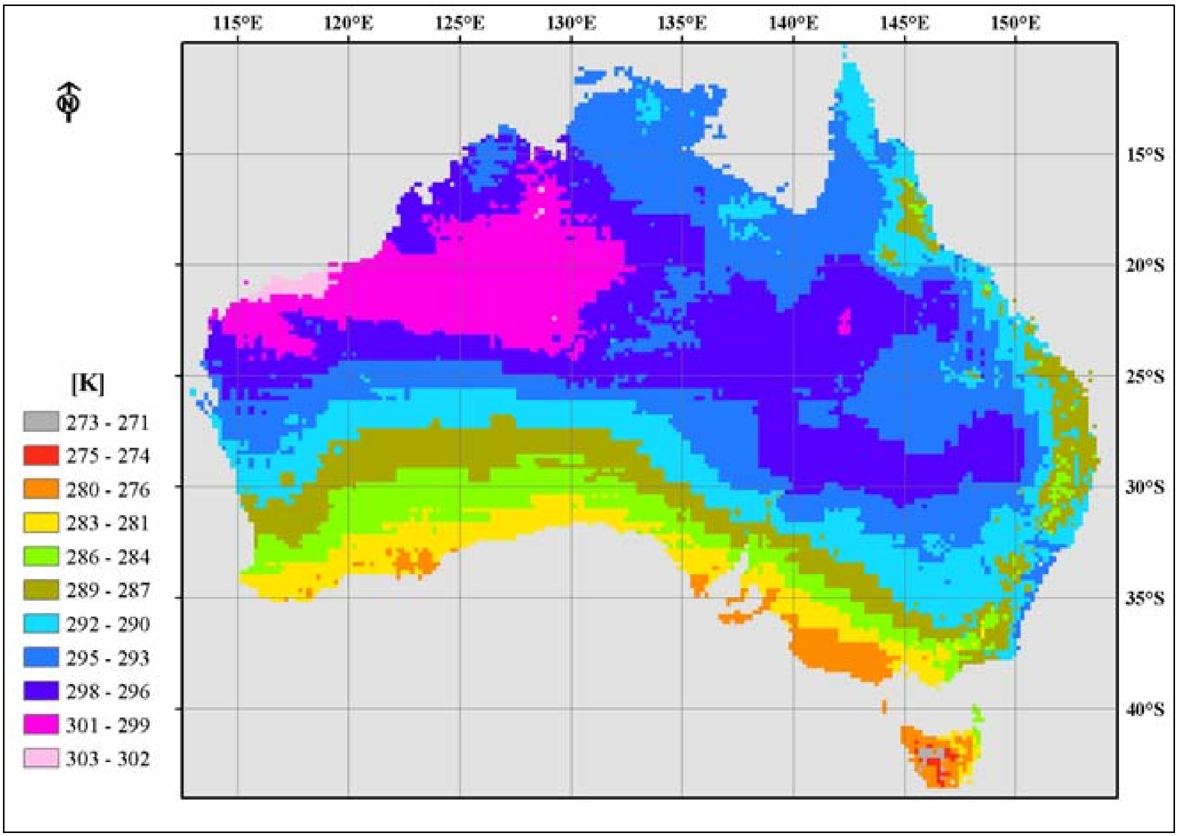

Figure 2.3: Air Temperature at the Tower's top at the resolution of the processed data, 0.2deg [^oK]

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 X 365). Monthly average, seasonal average and annual average maps, as well as maps of the variability of these parameters were then constructed.

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 2.2.

Table 2.2: 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 (ϕ2600mm) & 80% concrete open canal (wall slope 1:4 and 4 m width)	0.2*5,500+0.8* 1,000 [k\$/km]	D [km]
	Water Pumping from water source up to the ET top	400[\$/kW]	$PP_{installed}$ [kW]
Water Spray System	Including: 1,000,000 Sprayers, 20,000 m of water pipes (ϕ200-ϕ2000 mm), support beams and controllers.	38[M\$]	1 [per ET]
Power Pack	An array of 100 Wind Turbine	124 [\$/kW]	$GP_{installed}$ [kW]
	Generators	182 [\$/kW]	$GP_{installed}$ [kW]
	Transmissions	10[\$/kW]	$GP_{installed}$ [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]

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 peak would 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-Headland is illustrated in Figure 2.4. Here, the minimum electricity cost occurs where the installed power is 0.6 of the gross power's peak 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:

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

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.

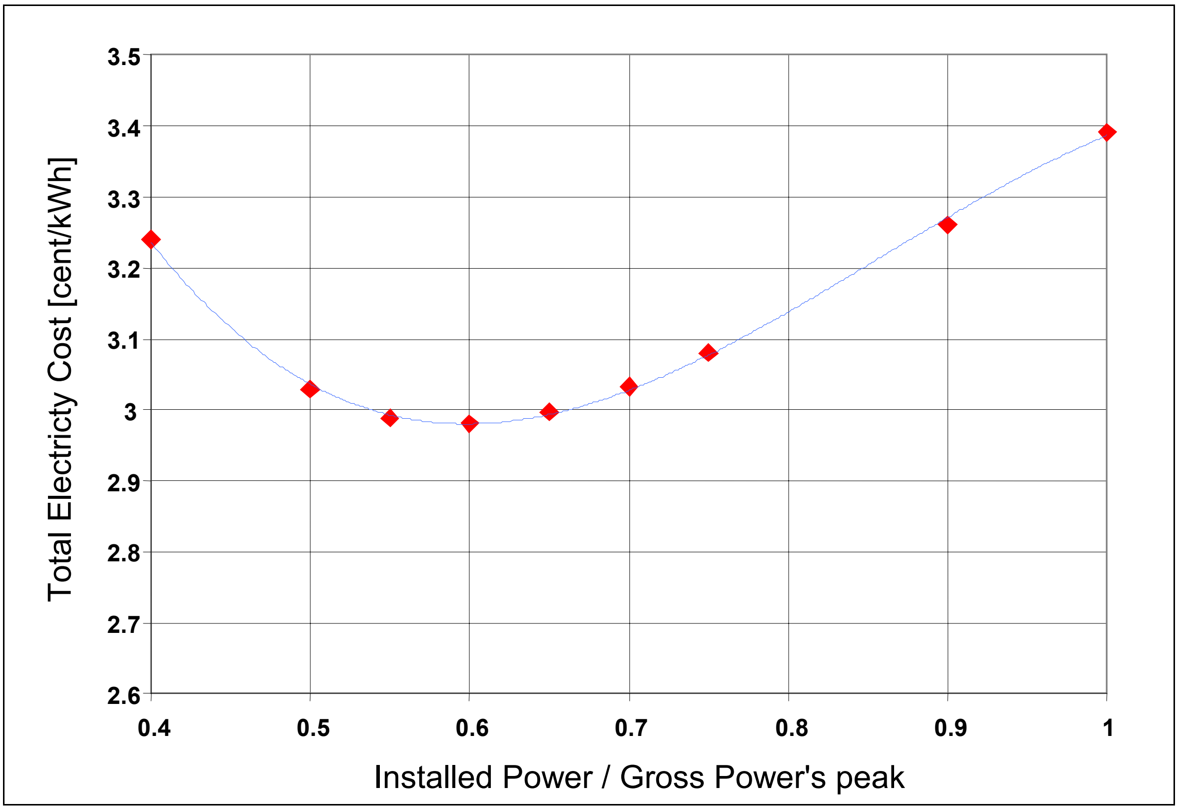

Figure 2.4: Total electricity cost for different installed power ratios projected with interest rate of 10% and 30 years life expectancy [¢/kWh]

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 ($C_{electricity}$) consisted of the parameters expressed in equation (5)

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

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

2.3 Detailed example of the results for the Australian continent

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 (Figure 2.5) 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 characterized by high gross power, 620 - 694[MW] (marked as areas A, B, C and D in Figure 2.5).

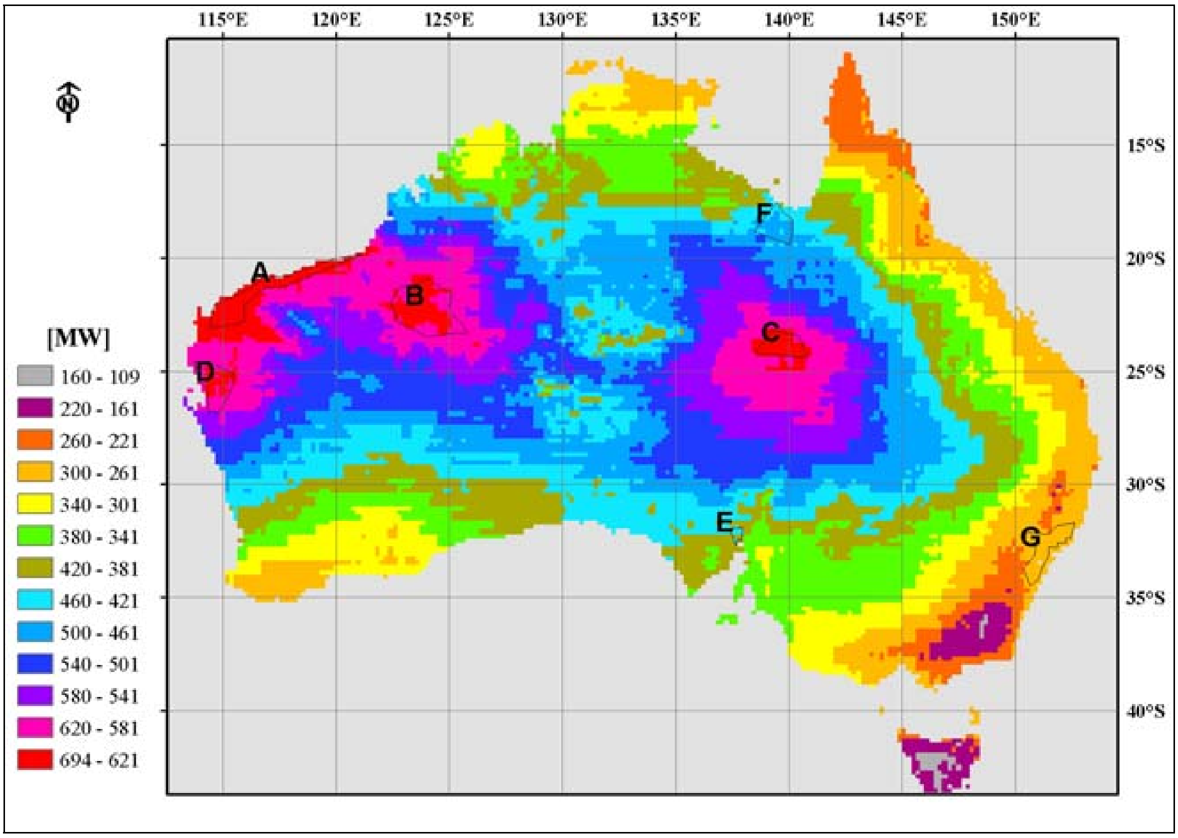

Figure 2.5: Annual average Gross Power of the "Energy Tower" for 1993 [MW]

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).

Net power

Net power is the difference between the gross power and pumping power. The map of average annual net power (Figure 2.6) 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 west coast.

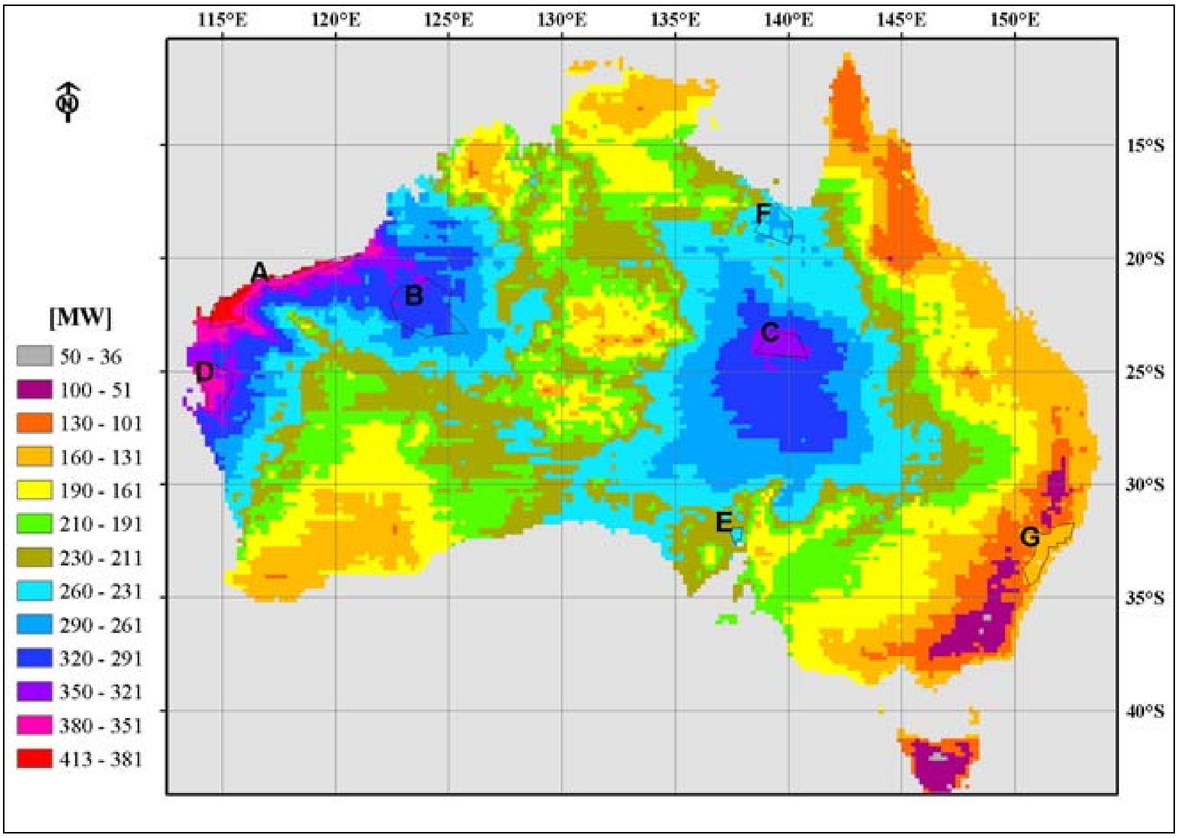

Figure 2.6: Annual average Net Power of the "Energy Tower" for 1993 [MW]

Table 2.3 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% difference 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 closely (Table 2.3). 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 2.3 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.

Table 2.3: Summary of the parameters and ET outputs of zones A-G

Area of interest	Avg. Distance	Avg. height	Annual avg. temperature	Annual avg. humidity	Annual avg. Gross power	Annual avg. Net power	Std. of the net power
	Topography		Properties of the air at the ET's top		ETP model outputs		
	[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

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

Electricity cost

Electricity cost estimates (Figure 2.7) 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 environmentally superior but also economically competitive to costs of fossil electricity sources (Table 2.4).

Table 2.4: Characteristic electricity production costs [¢/kW] 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

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, 50[km] 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 [cent/kWh]). These costs are based on a 10% interest rate, which is a conservative value (OECD 1998). If lower interest rates are available, then the relative advantage of ET over fossil sources increases further.

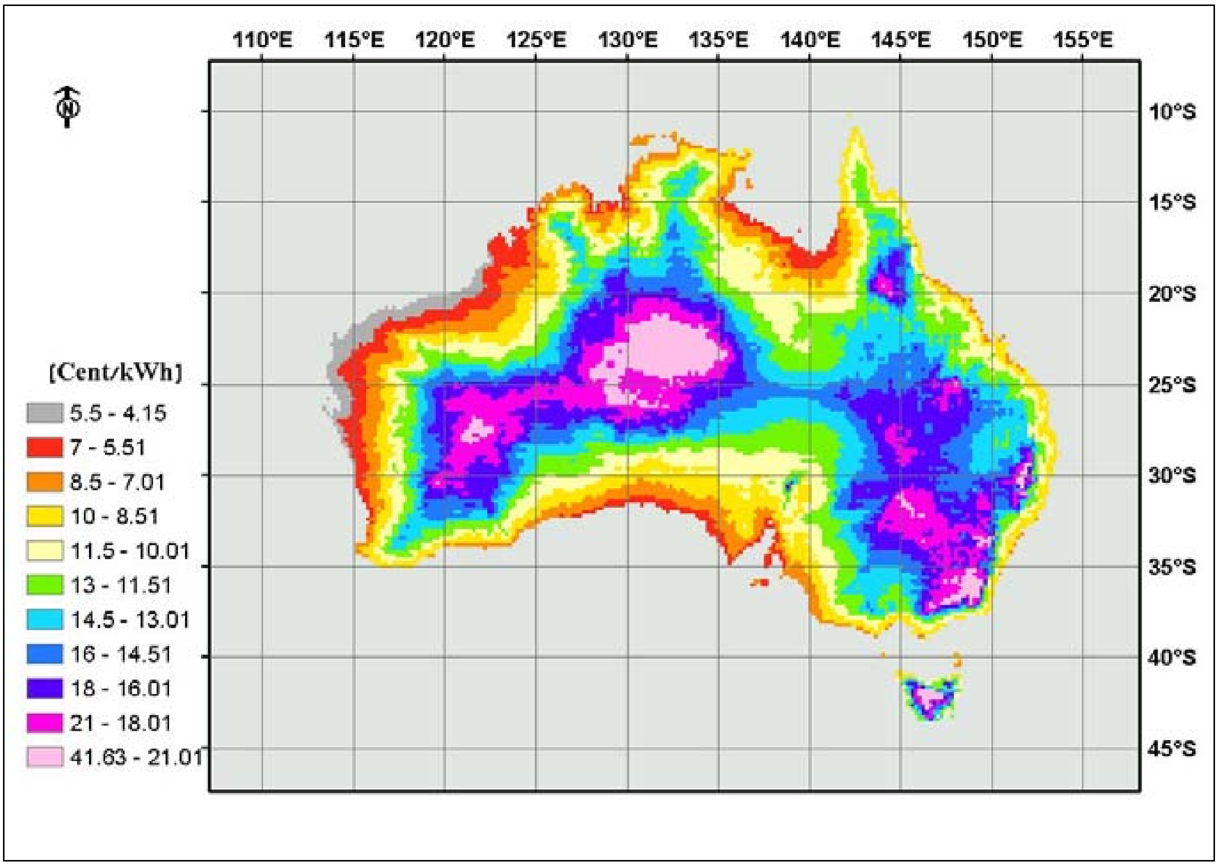

Figure 2.7: Electricity Cost projected with interest rate of 10% and 30 years life expectancy [¢/kWh]

Table 2.5: Summary table for the evaluation of Energy Towers' potential in ***Australia***

Range net power	**Average net power**	**Area in this region**	**Annual energy for this area in this region**	**Number of required Energy Towers**	**Potential number of people at 6,000 kWh per year**
[MW]	**[MW]**	**[10^3 km^2]**	**[10^9kWh/year]**	**[-]**	**[millions]**
450-400	406	5.6	50	14	8
400-350	368	80	645	200	107
350-300	315	441.2	3044	1103	507
300-250	273	1067.6	6383	2669	1064
250-200	223	2283.6	11152	5709	1859
TOTAL		**3878**	**21,274**	**9695**	**3,545**

2.4 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 Headland area), characterized by favorable meteorological and topographic conditions, a single ET would supply constantly high net power (≈370 ± 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 (≈230 ± 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).

3. Maps and summary tables for the evaluation of the global Energy Tower potential in California, Mexico, Chile and Peru

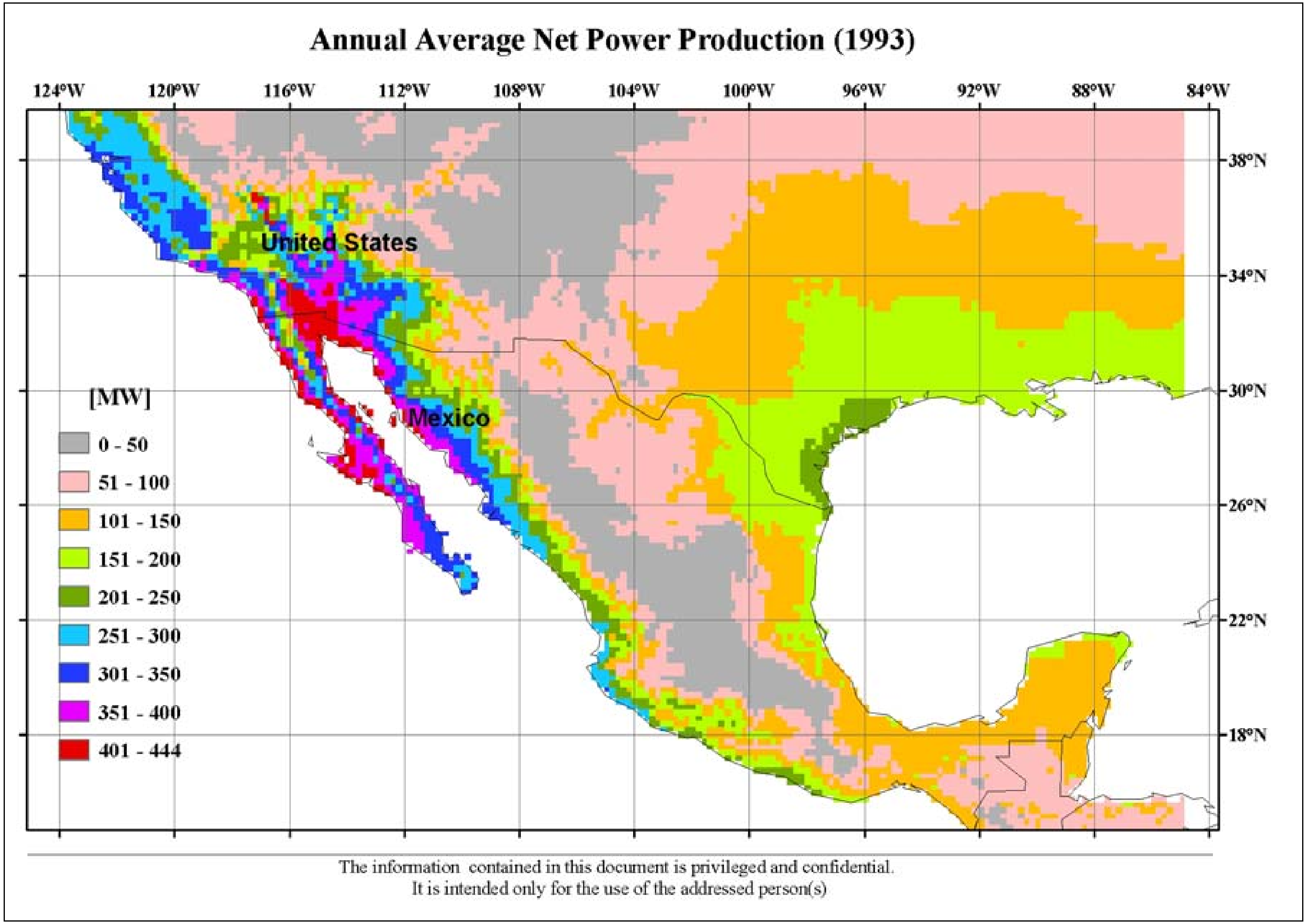

Figure 3.5- Evaluation of the annual average net power production of the "Energy Towers" (year 1993) for ***California and Mexico***

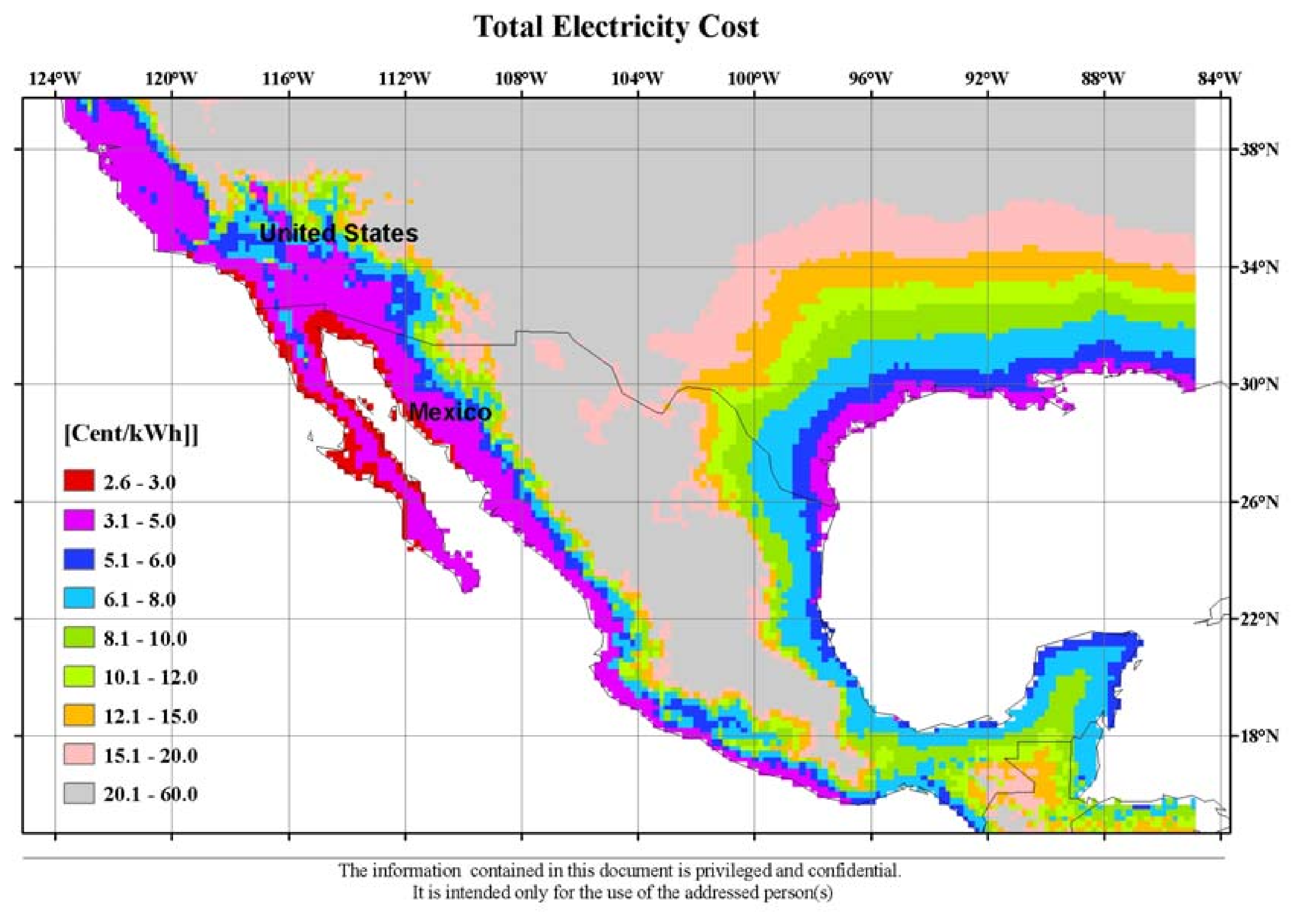

Figure 3.6- Evaluation of the electricity production cost projected with interest rate of 10% and 30 years life expectancy (year 1993) for ***California and Mexico***

Table 3.1: Summary table for the evaluation of Energy Towers' potential in ***California-Mexico***

Range net power	**Average net power**	**Area in this region**	**Annual energy for this area in this region**	**Number of required Energy Towers**	**Potential number of people at 6,000 kWh per year**
[MW]	**[MW]**	**[10^3 km^2]**	**[10^9kWh/year]**	**[-]**	**[millions]**
450-400	413	62.4	564	156	94
400-350	374	102	835	255	139
350-300	321	142.8	1005	357	167
300-250	276	170.4	1029	426	171
250-200	220	208	1003	520	167
TOTAL		**686**	**4435**	**1714**	**739**

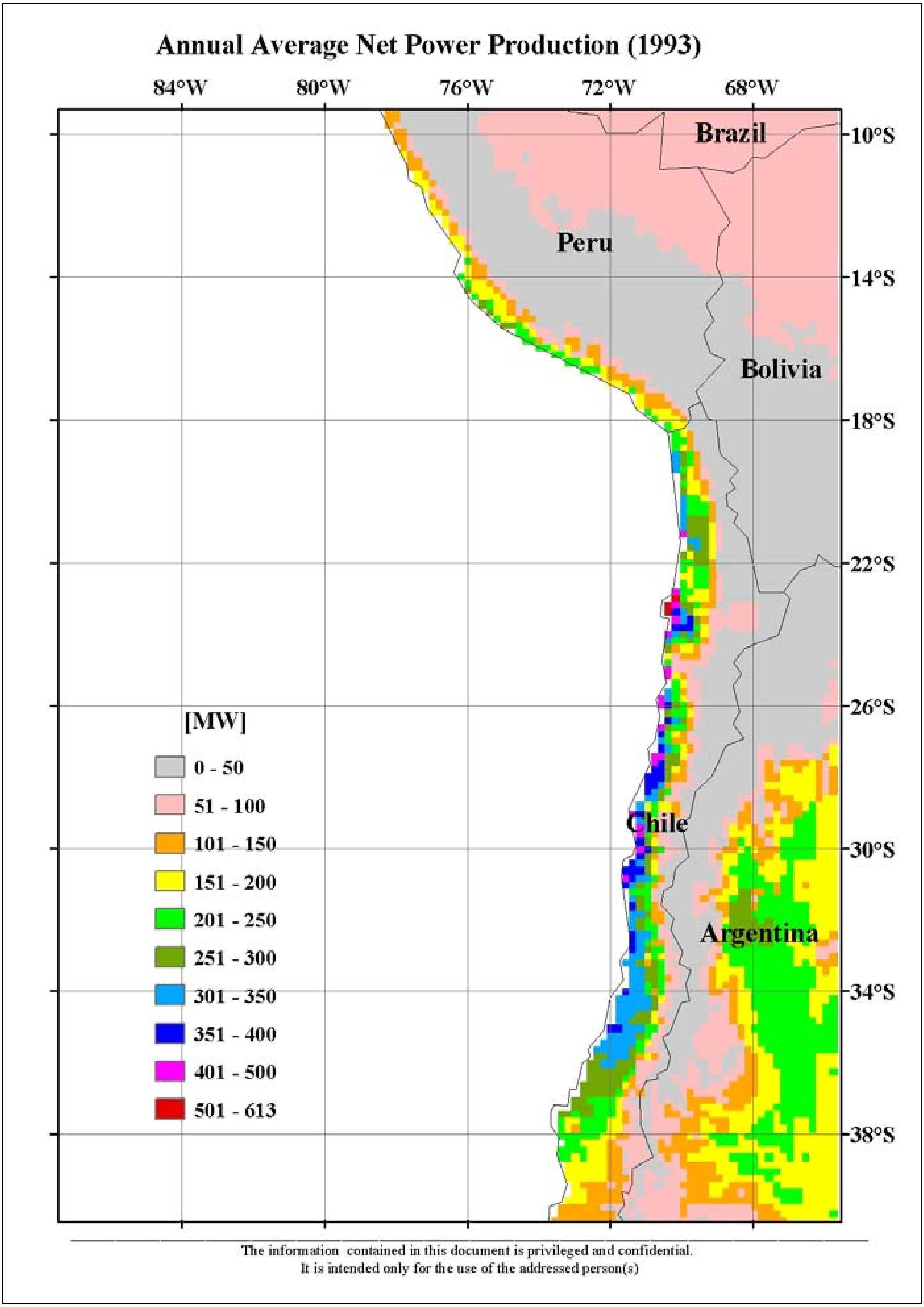

Figure 3.7- Evaluation of the annual average net power production of the "Energy Towers" (year 1993) for ***Chile-Peru***

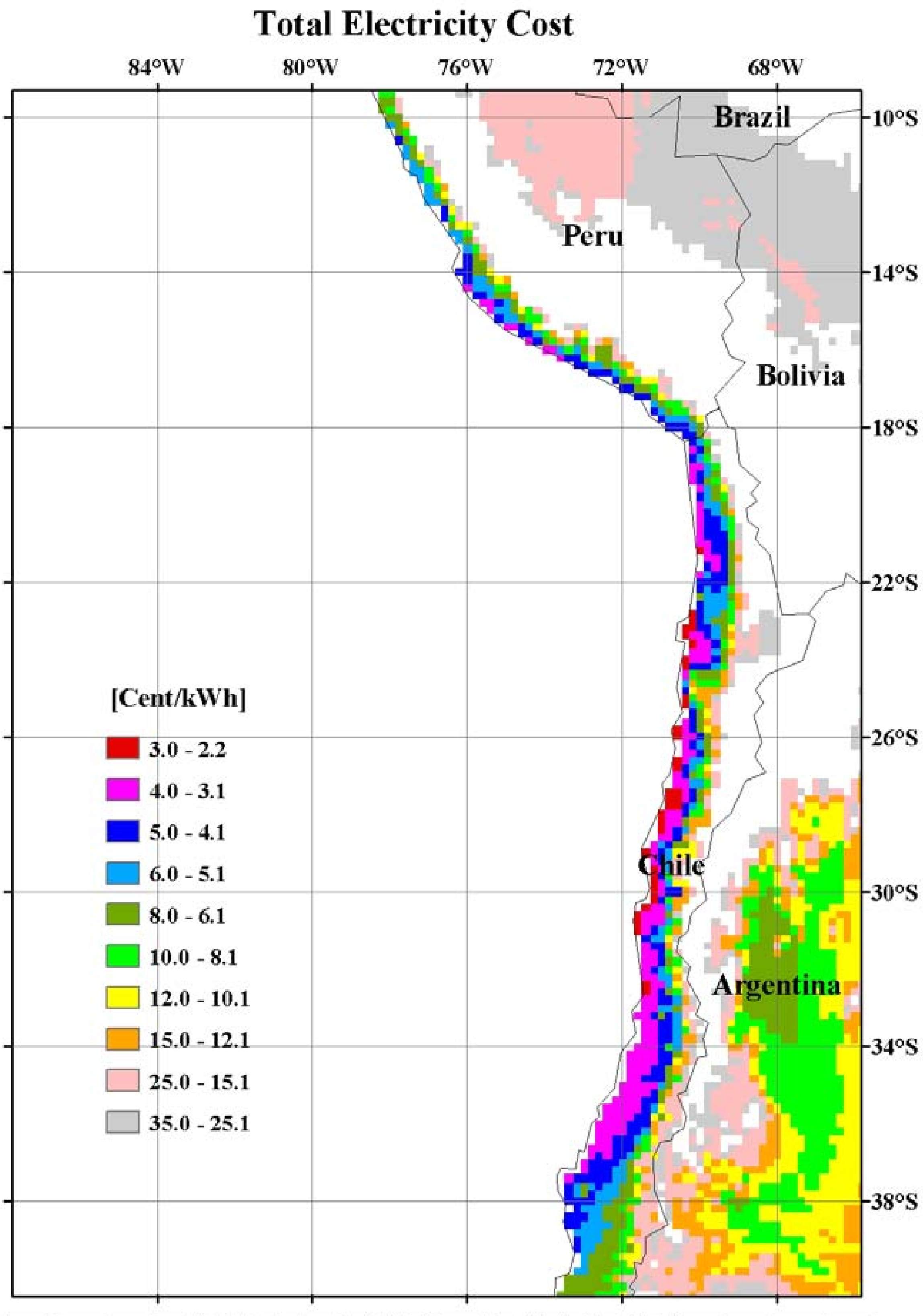

Figure 3.8- Evaluation of the electricity production cost projected with interest rate of 10% and 30 years life expectancy (year 1993) for ***Chile-Peru***

Table 3.2: Summary table for the evaluation of Energy Towers' potential in ***Chile-Peru***

Range net power	**Average net power**	**Area in this region**	**Annual energy for this area in this region**	**Number of required Energy Towers**	**Potential number of people at 6,000 kWh per year**
[MW]	**[MW]**	**[10^3 km^2]**	**[10^9kWh/year]**	**[-]**	**[millions]**
600-613	613	0.40	5.4	1	1
550-600	590	0.40	5.2	1	1
500-550	523	0.40	4.6	1	1
450-500	462	2.80	28.4	7	5
400-450	419	4.40	40.4	11	7
350-400	370	14.00	113.6	35	19
300-350	324	36.00	255.7	90	43
250-300	270	58.80	348.3	147	58
200-250	218	199.20	951.7	498	159
TOTAL		**316.40**	**1753.14**	**791.00**	**292.19**

4. Evaluation for the Desalinated Water Supply for California, Mexico, Chile and Peru

The computation of sea desalinated water assumed that 20% of the power produced will be used for it and the power consumption will be 3 kWh per cubic meter desalinated, then the water quantity was divided by 1000 to find out how many people could be served, 1000 cubic meter per person per year is a very rich state as far as water is concerned. To find the overall potential one has to multiply by the number of small 20×20 km squares.

First consider in the last way in the middle east over 200,000 people set in one square or over 200 million cubic meters per square spread over 400 square kilometer, it means more than half a meter water covering the whole land.

Taking the total electricity in a year over north Africa 59676×10^9 kWh/year can easily provide nearly 10 billion people with electricity. This means that the whole of Europe and Africa can be provided by cheap and clean electricity. Moreover, let us say that only one billion people will be provided with 6000×10^9 kWh per year. Take 3 kWh per cubic meter and only 20% of this power for water desalination and we shall have 400×10^9 cubic meter per year, nearly 6 times the Nile for local water supply.

Taking 1753×10^9 kWh/year in Chile and Peru to supply electricity fully for to 290 10^6 people. When with 20% of the electricity we can provide the same number of people with 403 m^3/ capita/year. (Israel has only about 350 m^3/capita before desalination.

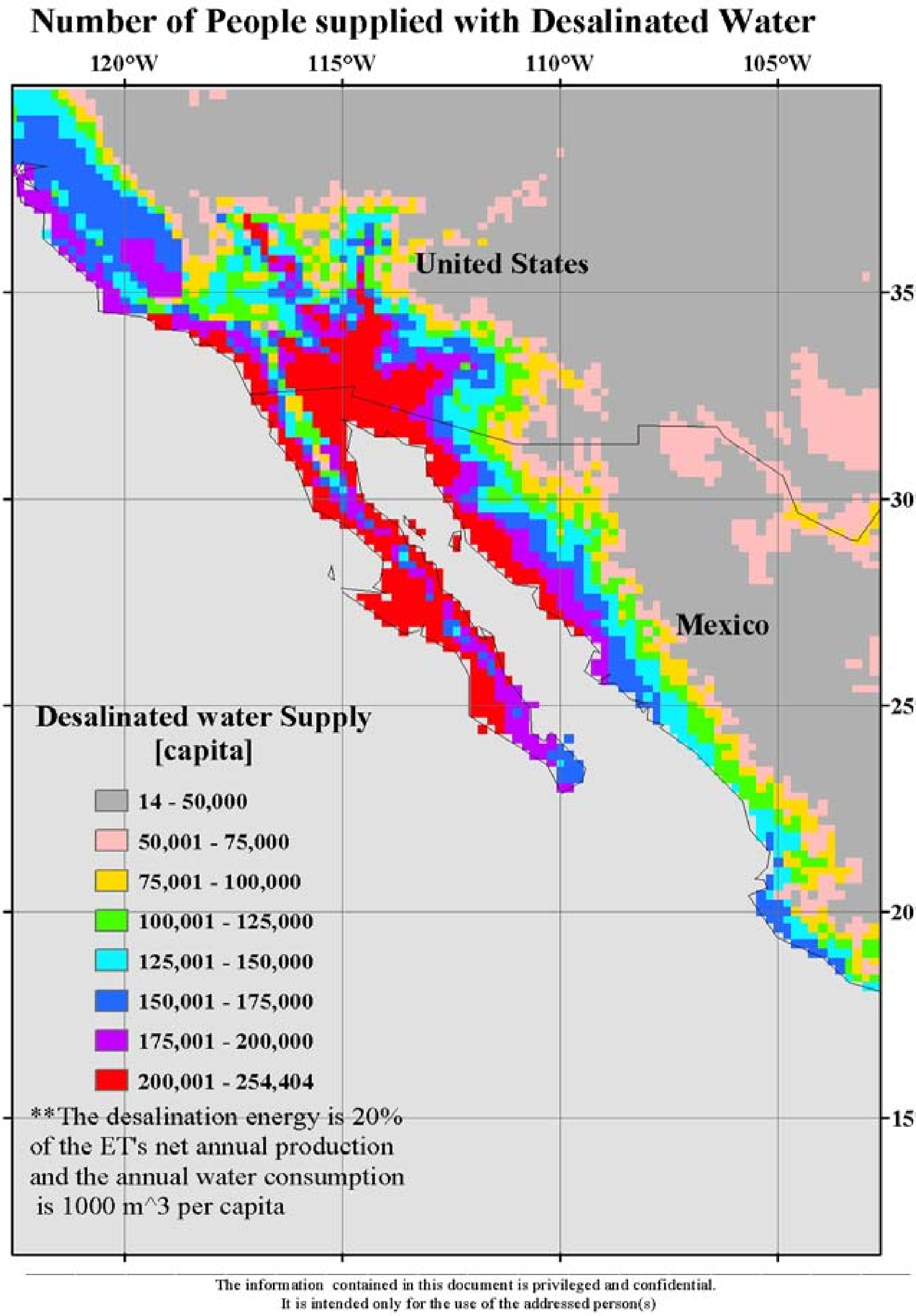

Figure 4.1- Evaluation of number of potentially supplied with desalinated water per 20×20 km square by the "Energy Towers" (year 1993) for California and Mexico

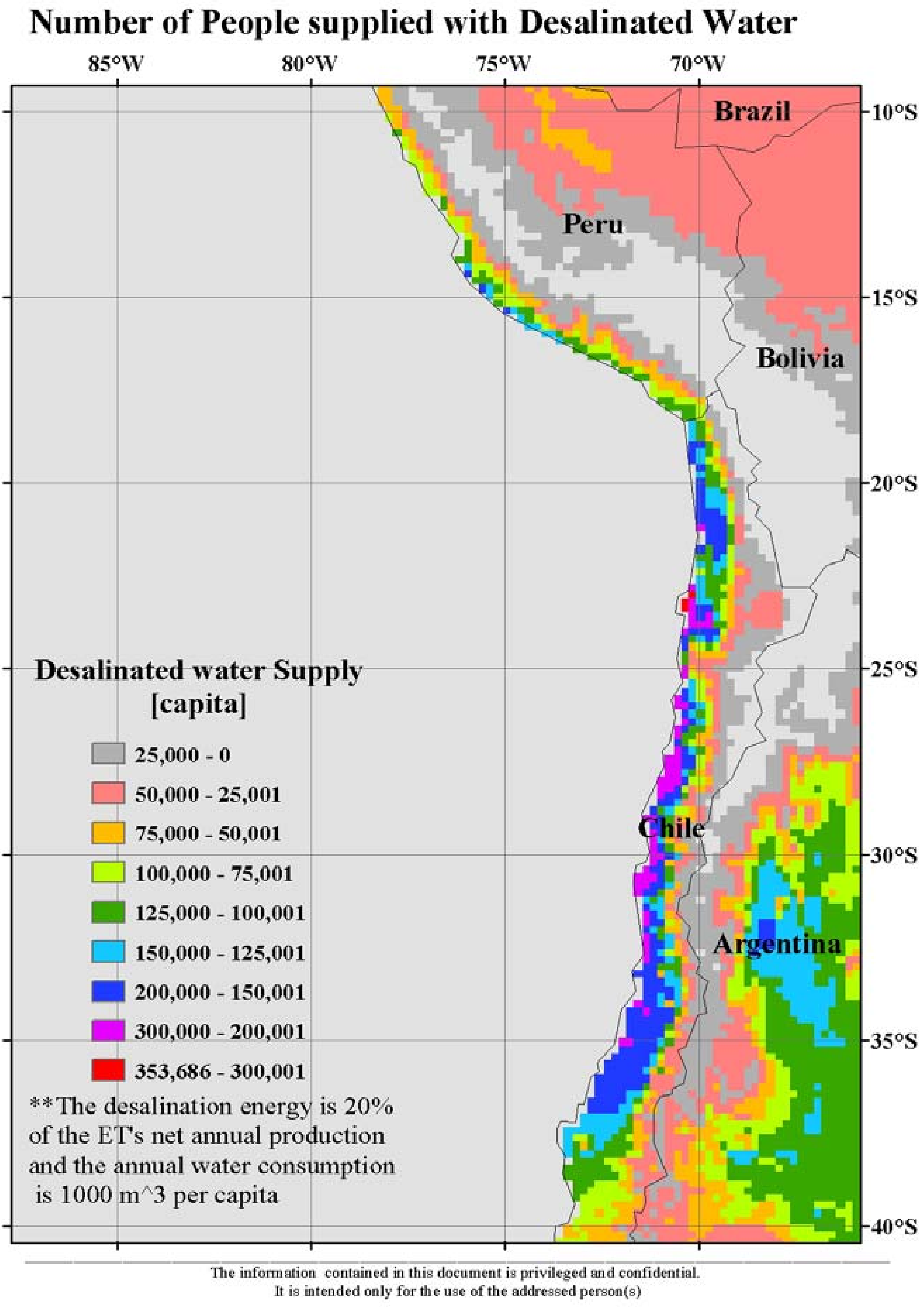

Figure 4.2- Evaluation of number of people potentially supplied with desalinated water per 20×20 km square by the "Energy Towers" (year 1993) for ***Chile-Peru***

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