SPECIAL PROJECT INTERIM REPORT

Interim Reports should be 2 to 10 pages in length, depending on importance of the project. All the following mandatory information needs to be provided.

Reporting year	2006
Project Title:	Evaluation of the Global Potential of Energy Towers SPDEGPET
Computer Project Account:	SPDEGPET
Principal Investigator(s):	Dr. Gregor Czisch
Affiliation:	IEE-RE, Universität Kassel
Start date of the project:	2001
Expected end date:	2012

Computer resources allocated/used for the current year and the previous one

(if applicable)
Please answer for all project resources

		Previous year		**Current year**	
		Allocated	Used	Allocated	Used
High Performance Computing Facility	(units)	33	0	33	0
Data storage capacity	(Gbytes)	10	0	10	0

Summary of project objectives

(10 lines max)

The goal of this 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 world 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.

Summary of results of the current year (from July of previous year to June of current year)

This section should comprise 1 to 8 pages and can be replaced by a short summary plus an existing scientific report on the project

See next and following pages.

Evaluation of the potential of electricity by using technology of "Energy Towers" for the Middle East and India-Pakistan

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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.

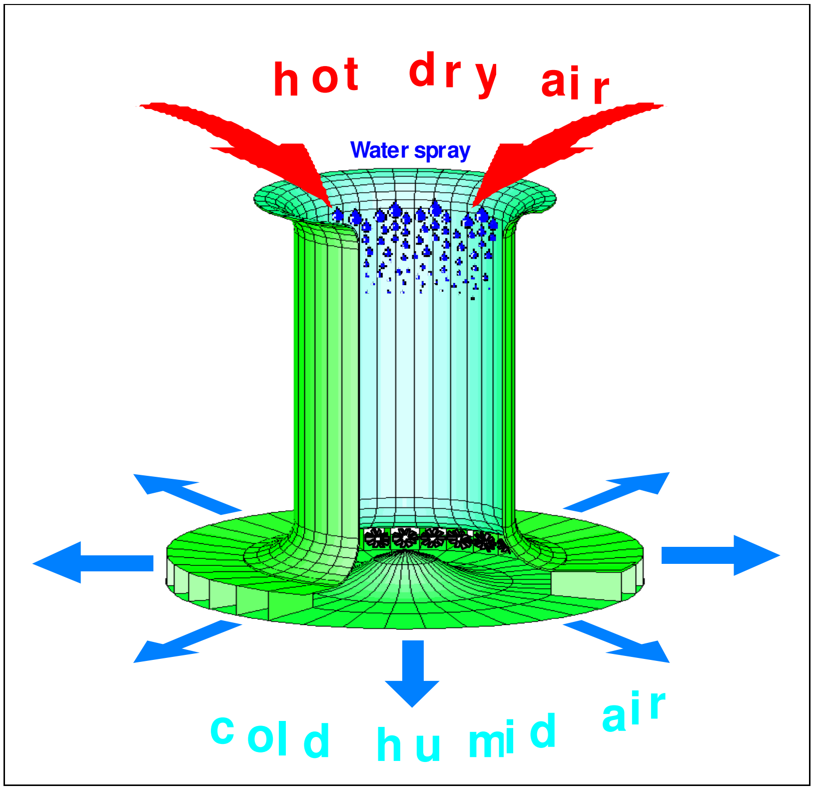

Figure 1.1 - Illustration of an ET

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 two main aspects of the potential of Energy Tower, the net power production and the energy production cost.

2. The Model for the Evaluation of the Energy Towers Potential

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. 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.

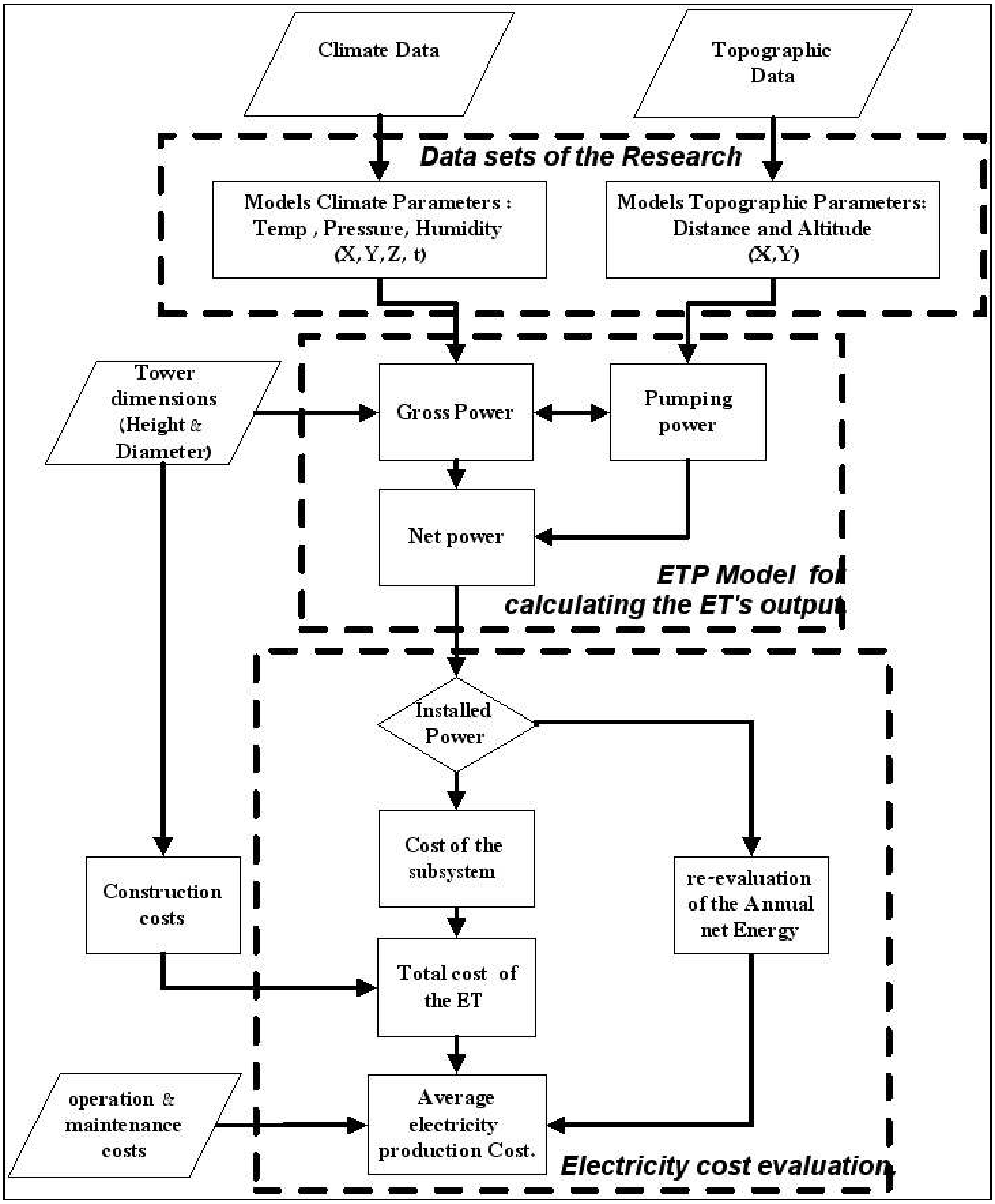

Figure 2.1- Flow chart of the steps to evaluate the Energy Tower Potential

Setup of a meteorological and topographic dataset

A very thorough study of the computation procedure ETP was applied in the Asian continent. 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.

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).

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 Asia (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	Number of units for construction

		[$/unit]	
Tower Construction	Evaluated cost for the steel space frame construction (including chimney, diffuser and systems support).	2000 [$/ton]	191,300 [ton]
	Framework cover	$13\ [\$/\mathrm{m}^2]$	$3.355\mathrm{e}{+}6\ [\mathrm{m}^2]$
	Concrete foundation	$165\ [\$/\mathrm{m}^3]$	$140{,}500\ [\mathrm{m}^3]$
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 picks 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 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:

$$\mathrm{GP}_{\mathrm{installed}}[\mathrm{MW}] = 0.7(\mathrm{GP}_{\mathrm{avg}} + 3\mathrm{GP}_{\mathrm{std}}) \tag{4}$$

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.

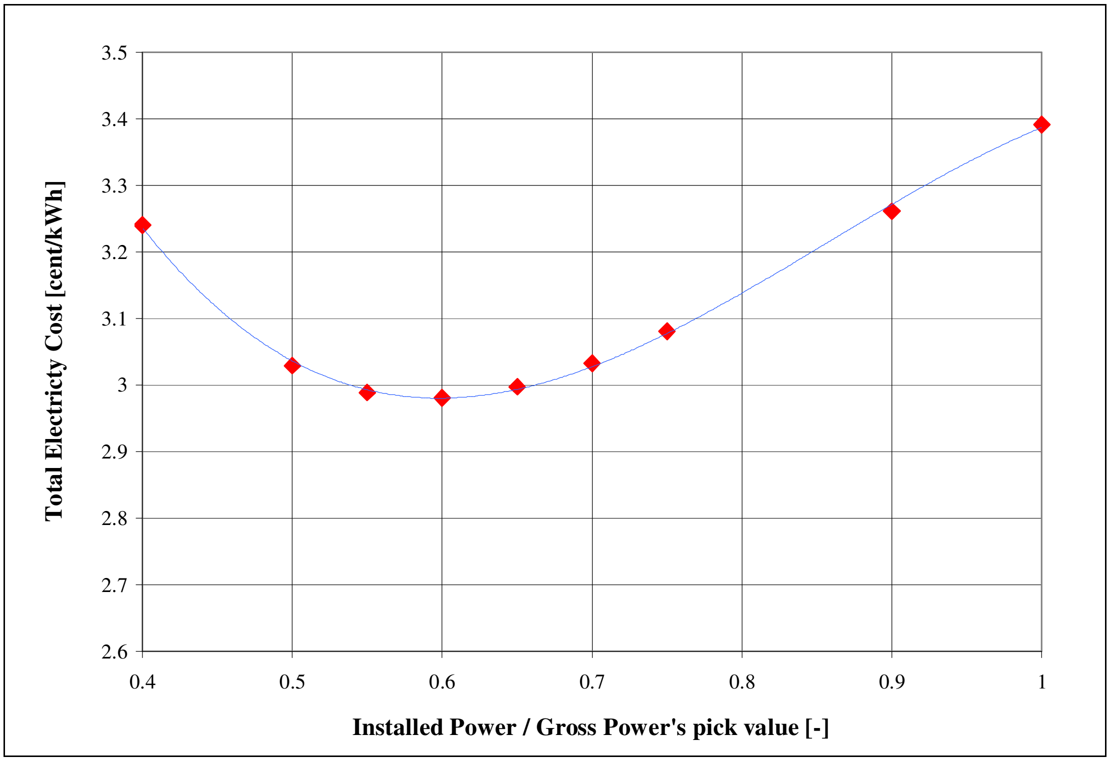

Figure 2.2 -Total electricity cost for different installed power ratios [¢/kWh]

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.

3. Maps and Tables for the Evaluation of the ENERGY TOWERS Potential in the Middle East and India-Pakistan

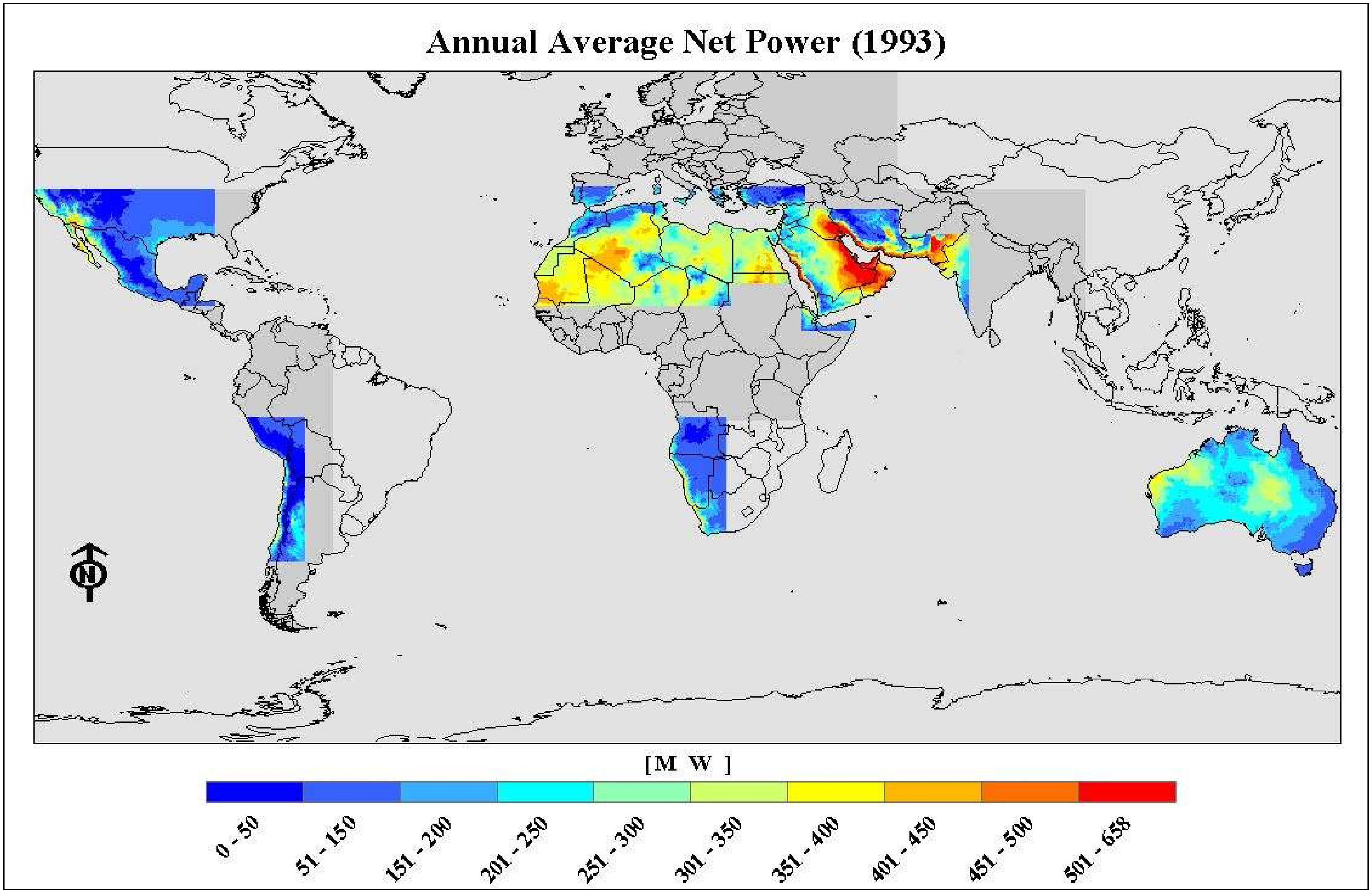

Figure 3.1- Evaluation of the annual average net power production of the "Energy Towers" for year 1993 on a global map

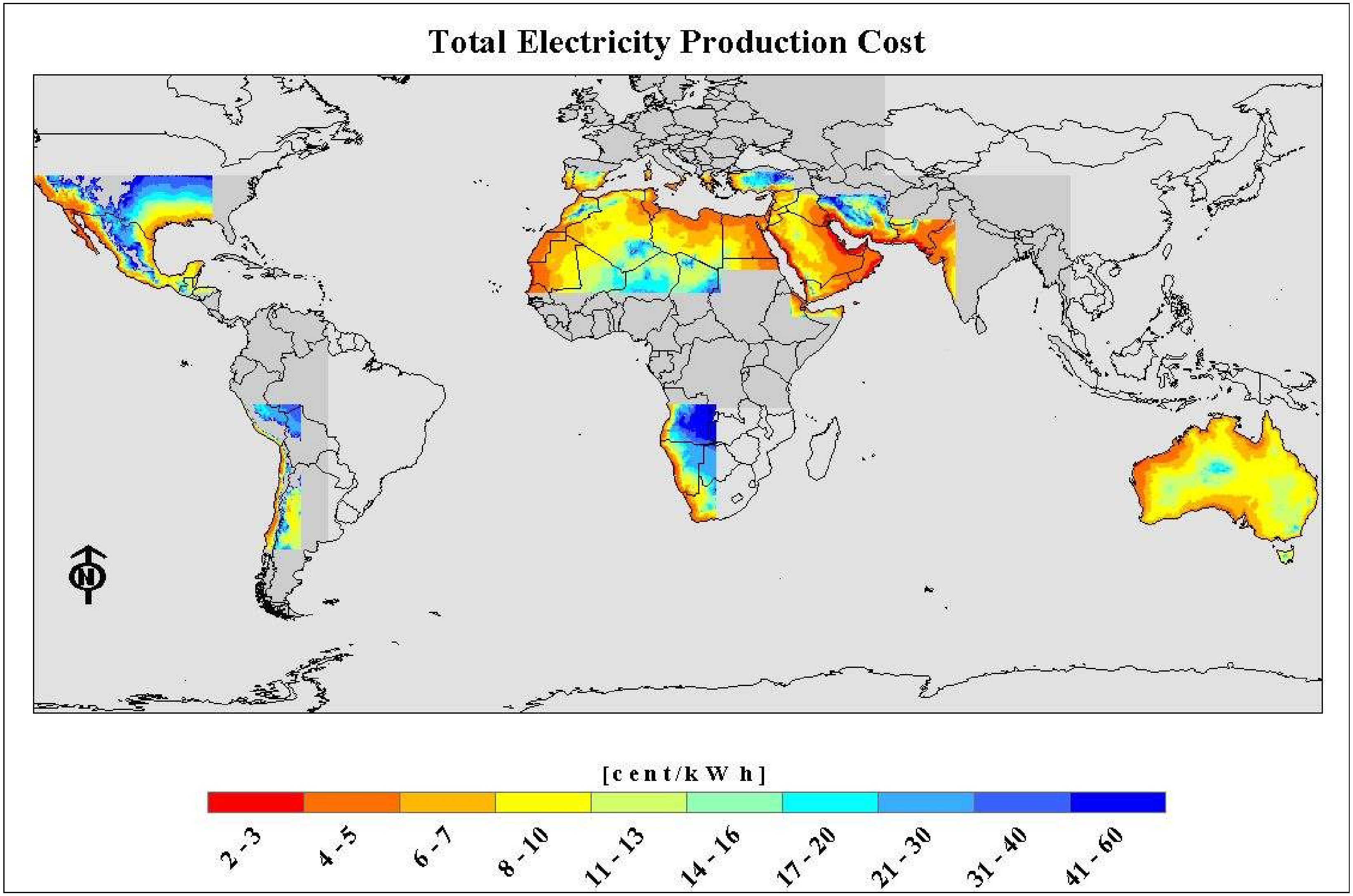

Figure 3.2 – Evaluation of the electricity production cost for year 1993 on a global map

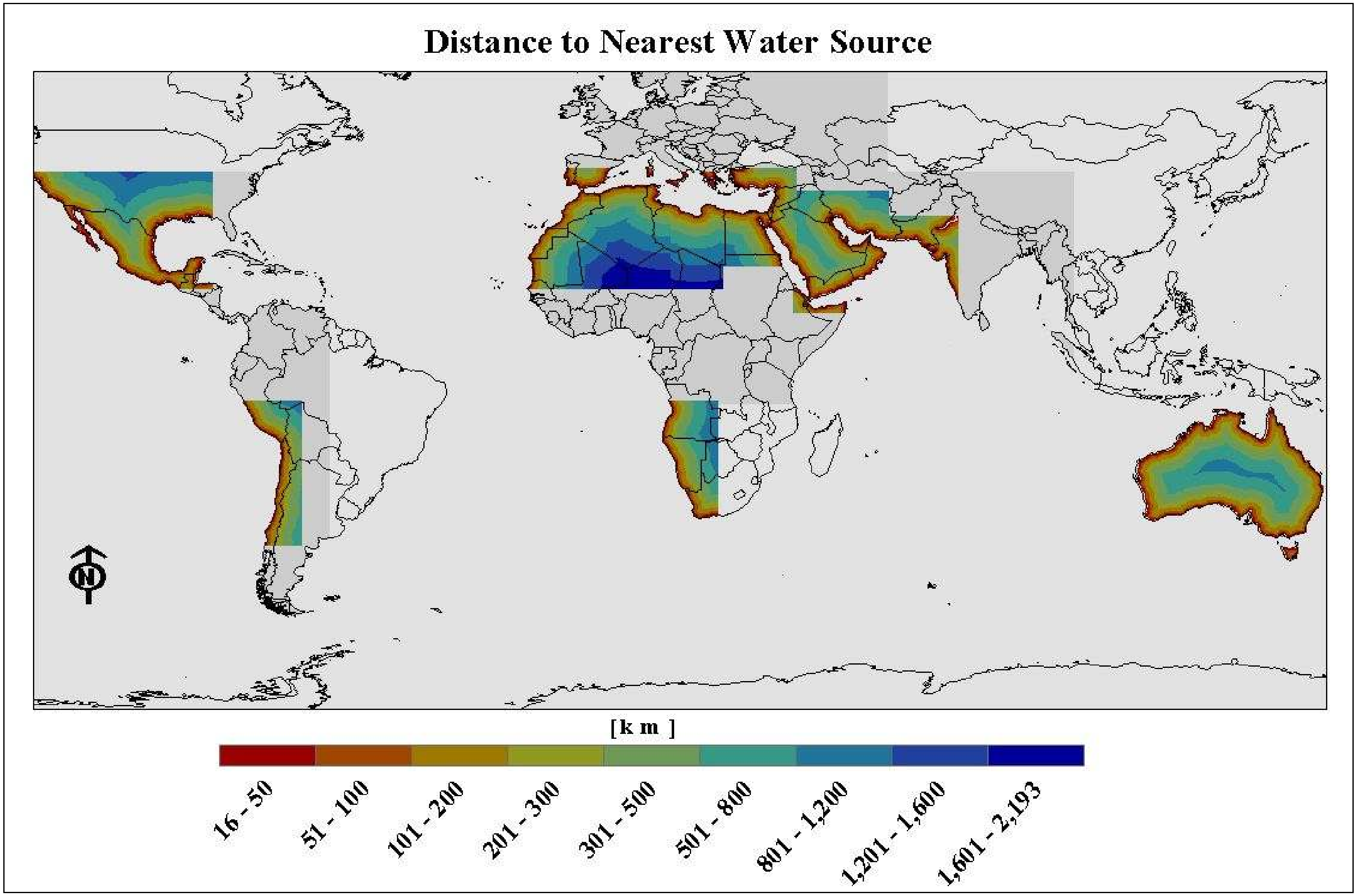

Figure 3.3- An illustration for the calculated distance between nearest water source and the potential sites

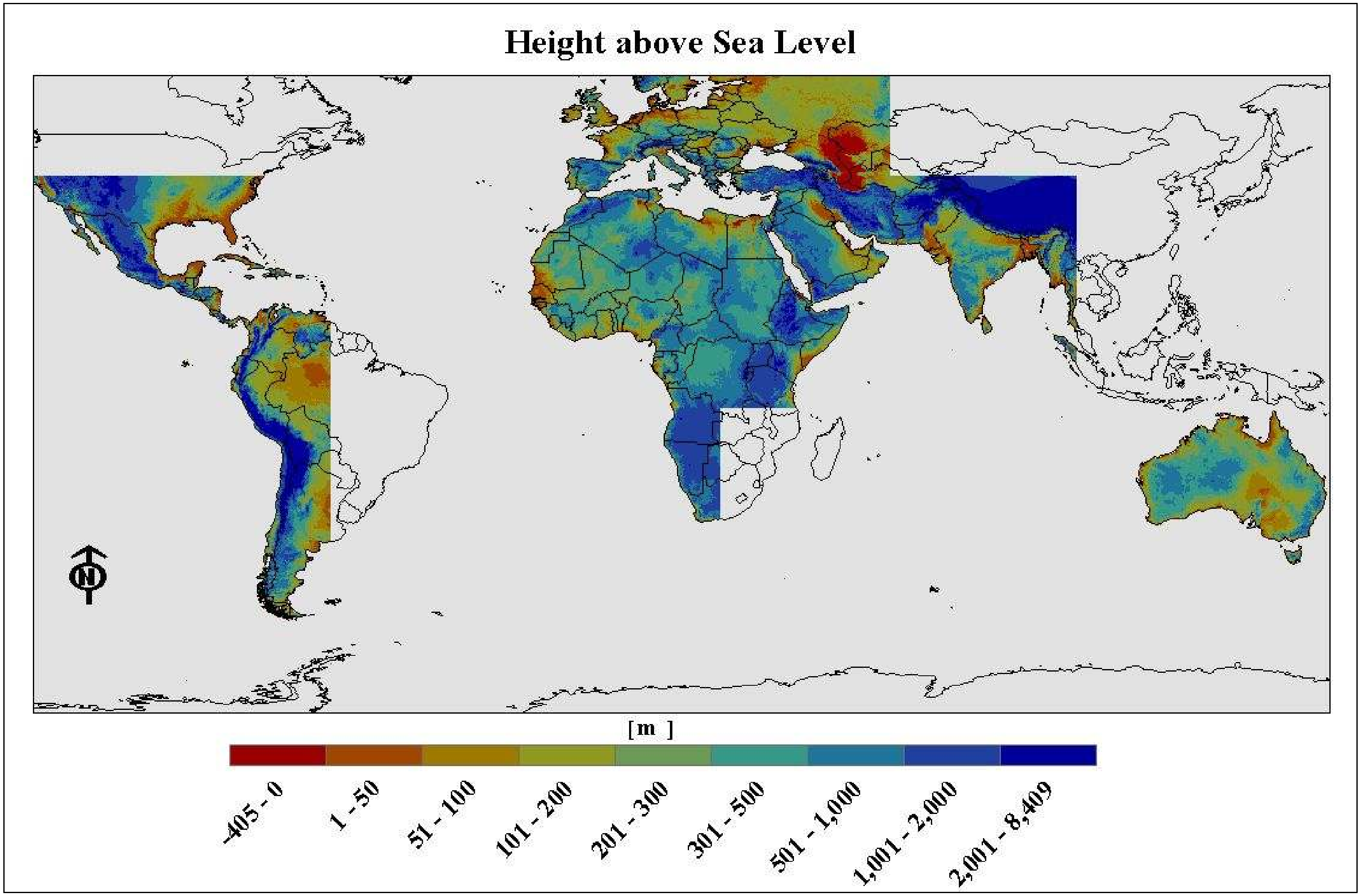

Figure 3.4 - An illustration of the topographic height of the potential sites

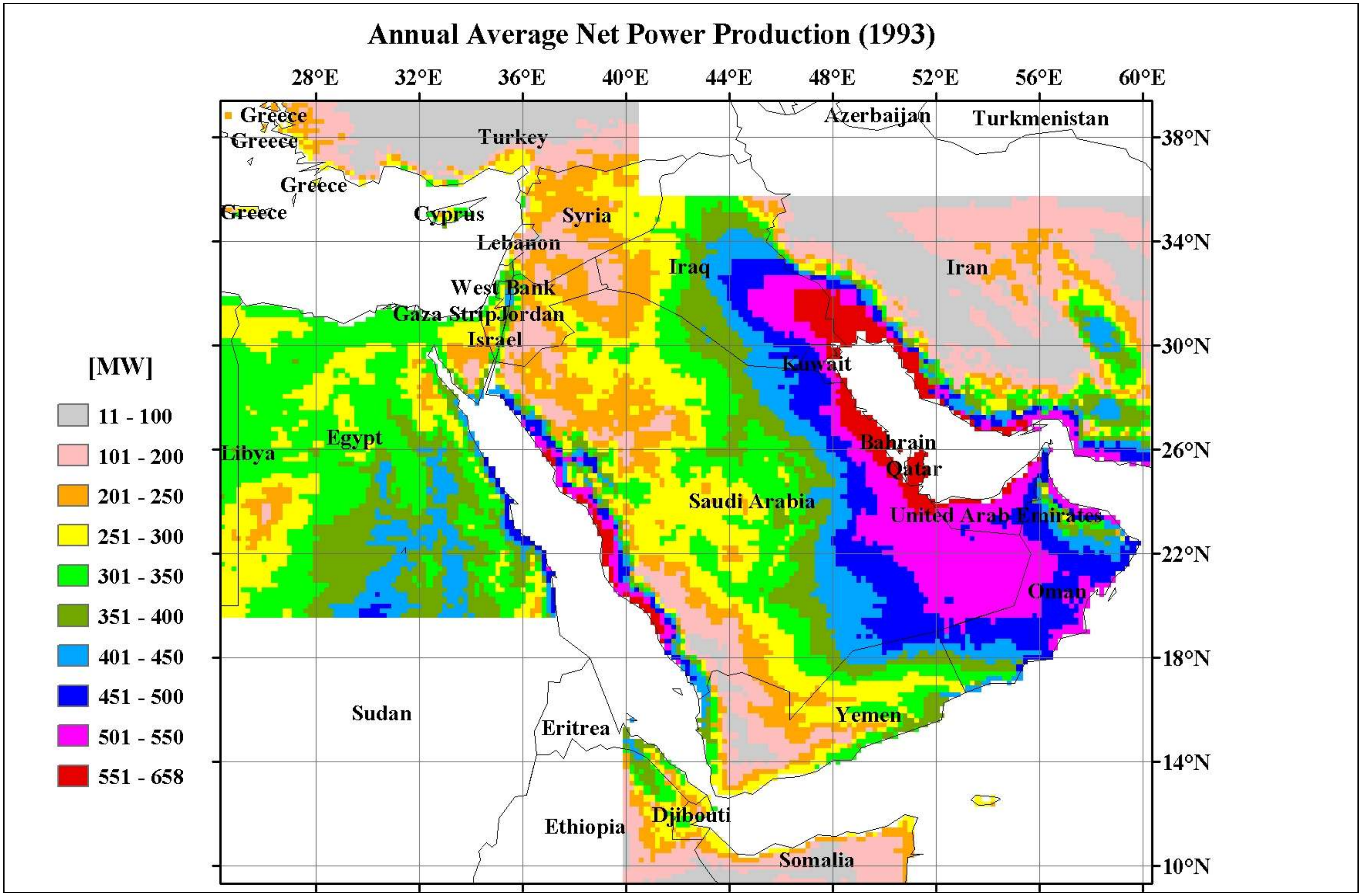

Figure 3.5- Evaluation of the annual average net power production of the "Energy Towers" (year 1993) for the ***Middle East***

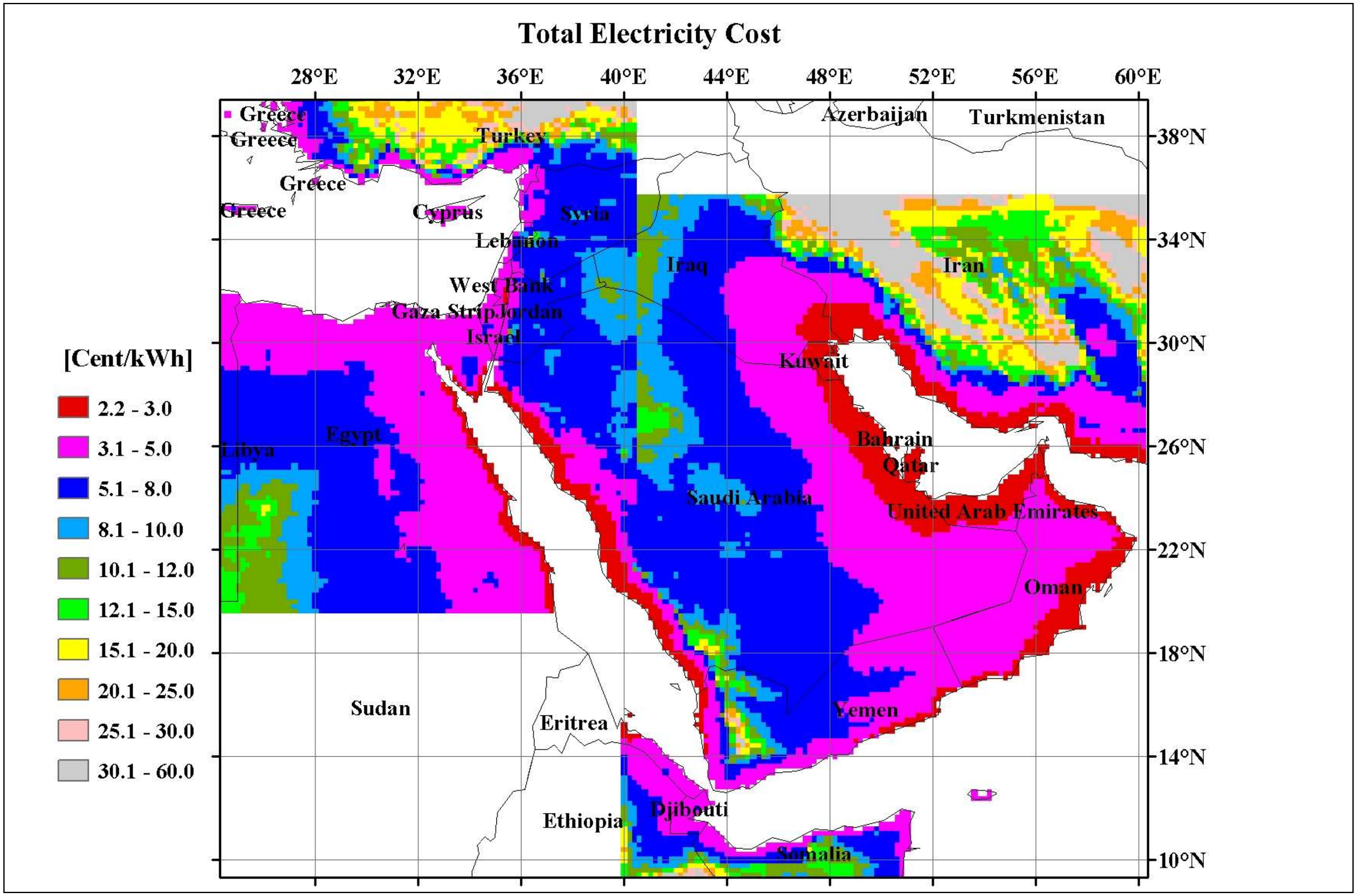

Figure 3.6 - Evaluation of the electricity production cost (year 1993) for the ***Middle East***

Table 3.1 - Summary table for the evaluation of Energy Towers' potential in the ***Middle East***

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]**
650-658	654	1.2	17	3	3
600-650	618	29.2	395	73	66
550-600	570	116.8	1459	292	243
500-550	519	412.4	4686	1031	781
450-500	475	413.2	4302	1033	717
400-450	423	460.8	4266	1152	711
350-400	375	615.6	5053	1539	842
300-350	323	1052.4	7440	2631	1240
250-300	277	942.8	5723	2357	954
200-250	226	631.2	3124	1578	521
TOTAL		**4676**	**36465**	**11689**	**6078**

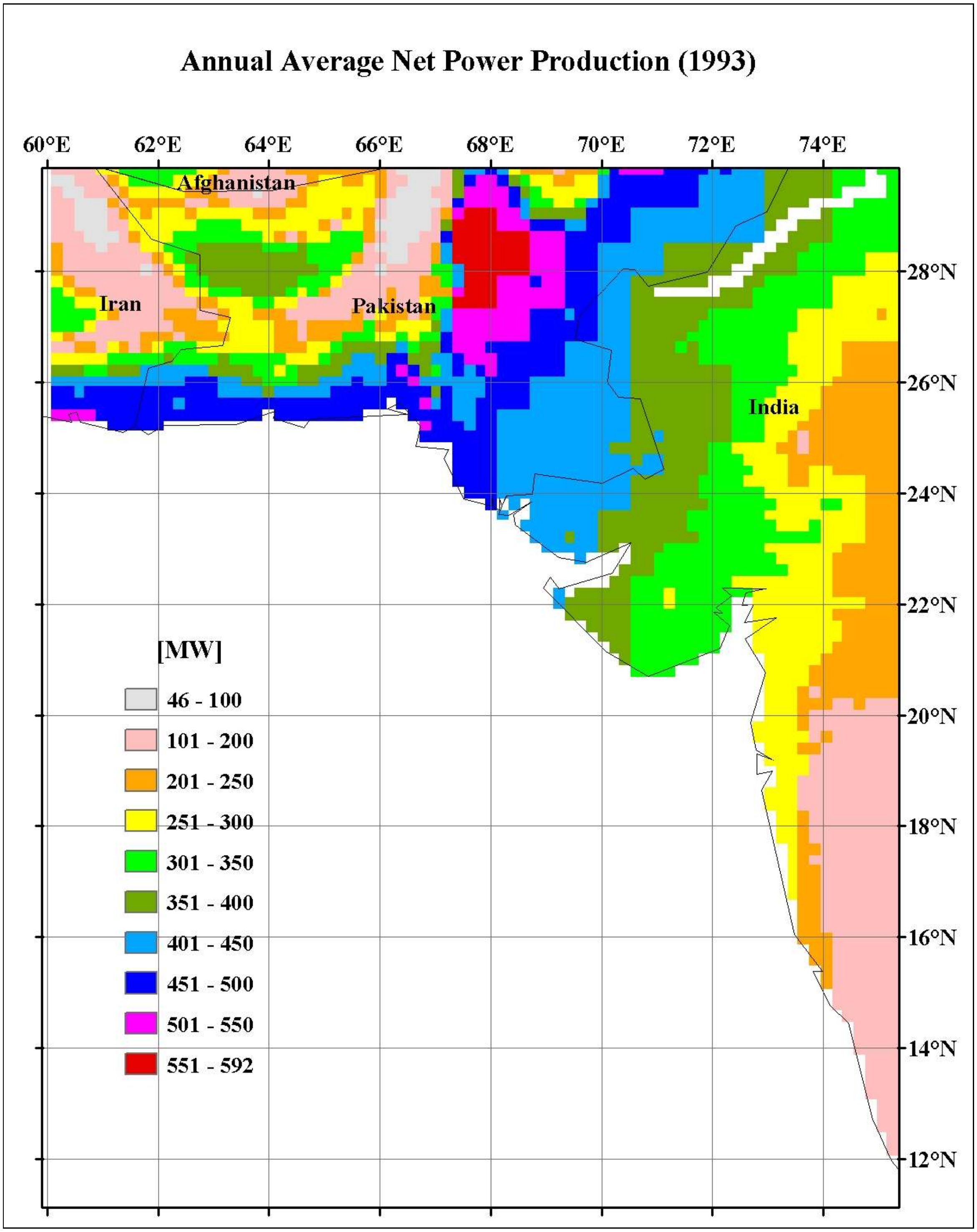

Figure 3.7- Evaluation of the annual average net power production of the "Energy Towers" (year 1993) for ***India-Pakistan***

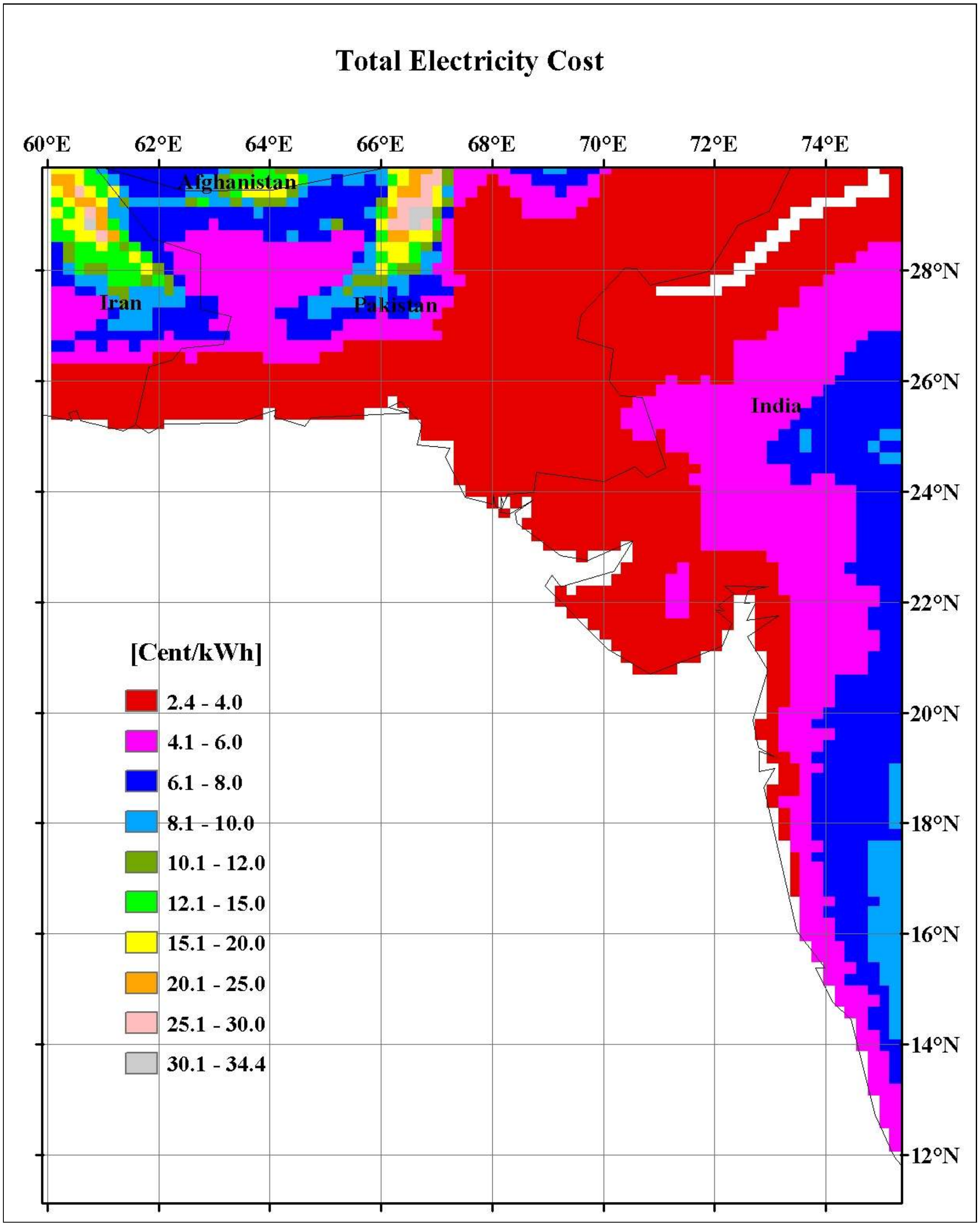

Figure 3.8- Evaluation of the electricity production cost (year 1993) for ***India-Pakistan***

Table 3.2 - Summary table for the evaluation of Energy Towers' potential in ***India-Pakistan***

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]**

550-600	574	17.6	221	44	37
500-550	522	34.8	398	87	66
450-500	472	108.8	1124	272	187
450-400	425	147.6	1373	369	229
400-350	374	153.6	1258	384	210
350-300	324	173.6	1231	434	205
300-250	274	174.4	1048	436	175
250-200	228	154.8	772	387	129
TOTAL		**965**	**7425**	**2413**	**1238**

4. References

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Acknowledgements

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Summary of plans for the continuation of the project

(10 lines max)

The program for the next years is to choose several sites in different regions and using detailed climate data for these sites. The predicted output: location of the tower, energy production along the year (gross power, pumping power, net power), optimized design and operation of the tower, electricity cost, economic analysis.