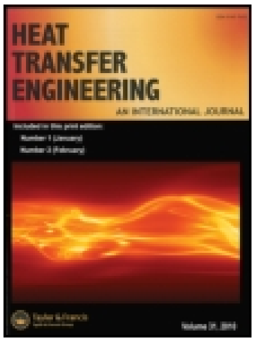

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A Novel Solar Thermal Power Plant with Floating Chimney Stiffened onto a Mountainside and Potential of the Power Generation in China's Deserts

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A novel solar thermal power plant with a floating chimney stiffened on a mountainside segment by segment is proposed. The novel power plant is suitable for the special topography in China (i.e., a vast desert belt surrounded by high mountain chains up to thousands of meters). An investigation of its performance is carried out using a simple mathematical model. The levelized electricity cost and the potential of the proposed solar chimney power generation in the large desert regions in Northwest China are also estimated. The results show that the levelized electricity cost of the proposed power generation is competitive with that of clean coal power plant, that the potential power obtained from the proposed power plant in the Taklamakan Desert or the Badain Jaran Desert can satisfy the total electricity consumption in China, and that the total potential power in the twelve deserts and sands, reaching 25,761 TWh per year, can even supply the electric power needs over the world, which are rapidly increasing.

INTRODUCTION

Several systems for thermal power generation involving solar chimneys have been proposed in recent years. Schlaich [1] designed the first vertical solar chimney power plant. Papageorgiou [2–5] introduced a novel floating solar chimney with lifting gas in its walls instead of a vertical concrete solar chimney, conducted theoretical analyses of its performance, and estimated its cost. Bilgen and Rheault [6] proposed a solar chimney power plant with a sloping solar collector constructed up a mountainside and did a simulation using a mathematical model. Günther [7] introduced the idea of a sloping solar chimney supported by a mountainside in 1931.

The floating solar chimney is an innovative concept. Its great advantage is that it can extend thousands of meters without the technical restrictions or geological limitations [2] encountered by a vertical concrete solar chimney. However, the structure is not suitable for sites where bad weather usually or suddenly occurs, such as winds more than 25 m sec^{-1}, heavy snow falls, sand or dust storms, and heavy hailstorms [8]. Consequently, it would be dangerous in deserts where the weather is unsuitable or varies acutely. In most deserts in China, there are strong winds and sand and dust storms.

To solve the above problem, a novel solar thermal power plant with a floating chimney stiffened by attachment to a mountainside is proposed in this paper, building on the concept of Bilgen and Rheault [6] and Günther [7]. We also estimate the potential for using the proposed technology to generate electricity in China and the levelized electricity costs.

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DESCRIPTION OF A SOLAR THERMAL POWER PLANT WITH A FLOATING CHIMNEY STABILIZED BY ATTACHMENT TO A MOUNTAIN

The proposed solar power plant with a floating chimney stiffened by attachment to a mountainside is shown in Figure 1. It consists of a wide solar collector, a floating chimney stiffened by

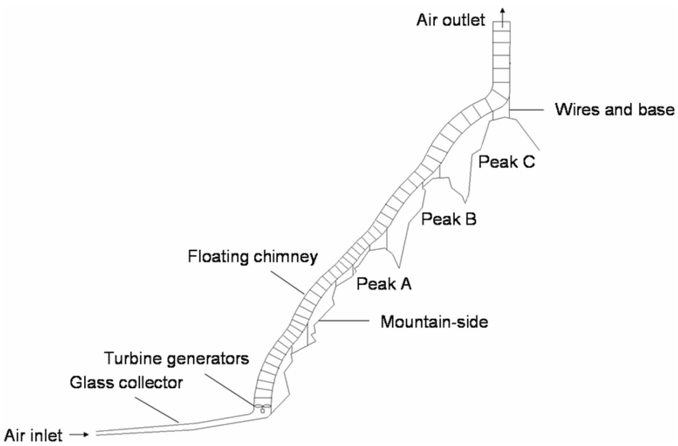

Figure 1 Novel solar thermal power plant with a floating chimney stiffened on a mountainside, segment by segment.

attachment to a mountainside, and turbine generators. The wide solar collector is constructed on the desert floor, and a floating chimney extending from one side of the collector is constructed and attached, segment by segment, to a large adjacent mountainside. Turbine generators are installed at the base of the floating chimney.

A large body of air is heated by the absorber under the collector and enters into and flows up the floating chimney because of its buoyancy. The updraught drives the turbine generators to generate electricity, and the rising air finally flows out from the top of the chimney.

The unique and novel features of this design are as follows:

- The collector is constructed on the slightly waved topography of a desert; the slowly climbing topography at the mountain foot also acts as a guide to airflow.
- The chimney segments are made to be curved, and the transition sections between collector and chimney and between adjacent chimney segments should not be angled but well rounded, with the aim of minimizing resistance to airflow.
- The chimney is attached to the mountainside using tight wires and small bases. Furthermore, unlike Bilgen and Rheault's concept of constructing a sloping collector on a continuous mountainside, the floating chimney may be attached to successively higher peaks, as seen in Figures 1a–1c.
- The top segment is usually constructed at the peak of mountain. Thus, the total height of the chimney is equal to height of the peak plus the height of the topmost chimney segment.
- As for a vast desert, several chimneys can be distributed around the desert only if the desert is surrounded by mountains.

A novel power system attaining the floating solar chimney to a high mountain has the following attractive safety and economic features:

- Desert regions, which are free and relatively flat, are ideal construction sites. Desert regions in China occur mainly in the northwest, an area of 171 million hectares [9]. These large deserts are surrounded by barren mountains thousands of meters high, such as the Kunlun Shan, Tian Shan, Qilian Shan, Altun Shan, and Helan Shan. Furthermore, solar radiation in the desert regions is abundant, with annual global incident radiation usually more than 6500 MJ m^{-2} [10]. Diurnal temperature ranges are usually greater than 20°C in most parts of these desert regions. For example, the diurnal temperature range reached 32.3°C in Minqin, Gansu on March 15th, 1995 [11]. Large diurnal ranges, helping the continuous operation of the turbines after sunset, are a valuable resource for solar chimney power generation. The special topography and climate of this region makes it the most suitable construction site in China for such power plants. The use of uncultivated deserts and barren mountains avoids purchasing land for the establishment of construction sites for solar thermal power plants and provides an effective approach to the exploitation of uncultivated deserts and barren mountains.
- The novel floating chimney can in principle extend several thousands of meters up a high enough mountain in northwest China. This would substantially improve the energy conversion efficiency of the power system. A floating chimney up to thousands of meters eliminates the difficulty and the danger of constructing gigantic vertical concrete chimneys. Humans have no experience of constructing free-standing towers of 1000 m or more.

Thus, the floating chimney would avoid the risk and increase the probability of being able to build such a gigantic chimney.

HEAT TRANSFER MECHANISM

Energy conversion by the proposed power system can be divided into three phases: the collector converts solar energy to thermal energy of the air, the chimney converts thermal energy to kinetic energy of flowing air, and the turbine generators convert the kinetic energy of airflow to electric power.

Pretorius and Kröger [12] developed a detailed model to simulate the air flow and heat transfer in solar chimney power plants. Thermal storage is not considered in the model because the total potential power in a year is simply estimated in the analysis based on the annual global solar radiation.

Here, a simple mathematical model is presented, which will be used to evaluate the performance of the proposed power system. The following assumptions are made:

- The air follows the ideal gas law.
- Only the buoyancy force is considered.
- The wall of the floating chimney is considered as a perfect heat insulator.
- The flow in the collector is considered as a flow between two parallel plates.

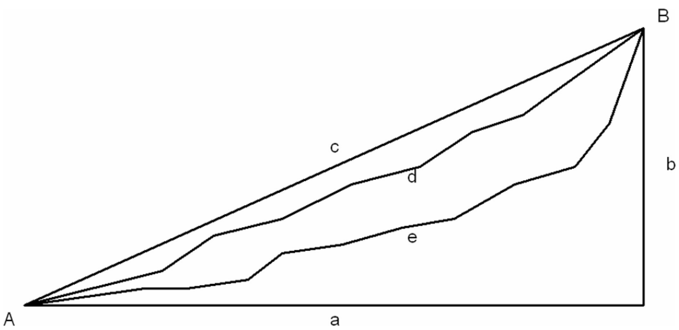

Figure 2 Diagram of crawling route of a floating chimney against several mountain peaks: a, horizontal distance between collector outlet and the base of top chimney segment; b, height between collector outlet and the base of top chimney segment; c, the shortest distance between collector outlet and the base of top chimney segment; d & e, length of chimney against several mountain peaks.

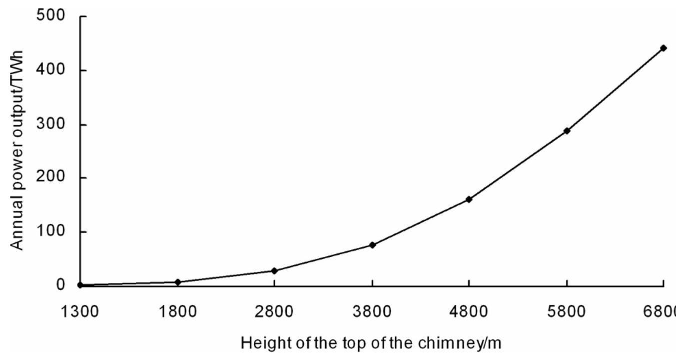

Figure 3 Variations in annual power output with height of the top of the chimney.

RESULTS AND DISCUSSION

Performance

In related work, Schlaich et al. [13] designed a 100 MW power plant, which had a 1000 m tall chimney 110 m in diameter, and a 200 MW power plant, which had a 1000 m tall chimney 120 m in diameter. Von Backström et al. [14] investigated the performance of a 200 MW power plant 1500 m in height and 160 m in diameter. In order to evaluate conveniently the performance of solar chimney power plant, the ratio of chimney length to the effective diameter of the total internal cross-section area of chimney is kept constant at 9, and the height of the top chimney segment is kept constant at 800 m in the analysis.

Figure 2 shows the diagram of crawling route of a floating chimney against several mountain peaks. In the figure, the relations among a, b, c, and d or e, which correspond to the caption of Figure 2, can be expressed as,

$$c \leq d \leq a + b \tag{1}$$

In order to calculate conveniently, the mean of them is used to estimate the length of the floating chimney against several mountain peaks in the analyses,

$$L = \frac{a + b + c}{2} \tag{2}$$

Taking a 10,000 km^2 desert surrounded by high mountains as an example, with a mean latitude 40°N and an annual solar radiation = 1800 kWh m^{-2}, we have calculated the performance of a hypothetical power plant with a collector constructed on the desert floor and the chimney constructed against a mountainside of different heights.

Figure 3 shows variations in power output with the height of the top of the chimney from 1300 m to 6800 m. As expected, with an increase in height, the power output increases.

Figure 4 shows variations in efficiency and limited efficiency with height of the mountain. The maximum theoretical efficiency of converting heat energy of airflow to electric power is given by the following equation [1]:

$$\eta_{\mathrm{Max}} = \frac{gH}{c_p T_0} \tag{3}$$

The limited efficiency of the power system is the product of the collector efficiency and the Carnot efficiency. As shown in Figure 4, the efficiency of the proposed power system is far less than the limited efficiency. However, compared with the energy conversion efficiency of a 200 MW power output proposed by Schlaich et al. [13] with only a 1000 m high chimney, which reached about 0.78%, the energy conversion efficiency of the proposed power system is high, as the combination of the floating chimney and the mountain up to thousands of meters high produces a larger “chimney” effect.

ANALYSES

Desert regions [9] in China cover 171 million hectares, accounting for 18% of the Chinese land area. The deserts are mainly located between 35°N and 56°N. They comprise a vast desert belt, 4500 km from east to west, 600 km from south to north, west to the Tarim Basin and east to the Song Nen Plain, and they enlarge by 2460 km^2 per year. The investment costs of a power plant with a large collector constructed on a desert and with lots of floating chimneys constructed against a

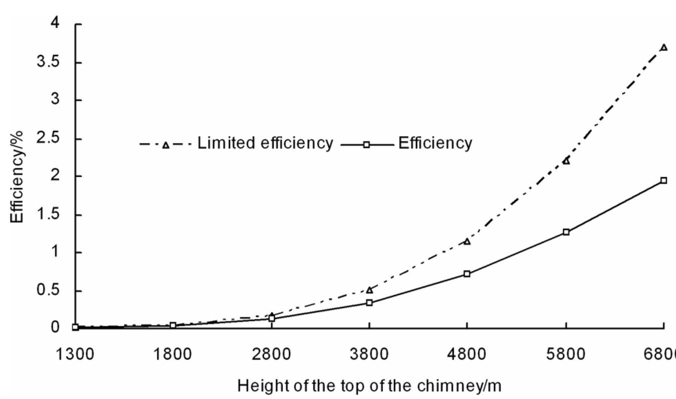

Figure 4 Variations in efficiency and limited efficiency with height of the mountainside.

Table 1 Features of the Eight Largest Deserts and Four Largest Sands in China and the Adjacent Mountains

Desert and sand	Location	Mean latitude	Annual global solar radiation##/ kWh m^{-2}	Area/ thousand km^2	Mean height above sea level/km	a/km	b/km	a/km	b/km	a/km	b/km	a/km	b/km	a/km	b/km	a/km	b/km	a/km	b/km
Taklamakan Desert	Sinkiang	39° N	1700	337.6	0.9	0.5|||	1.5	1.1	2	13.75	3	22	4	44	5	63.25	6	66	7.719*
Chaidamu Desert	Qinghai	37°30' N	1800	34.9	3	5.6	4	15.75	5	28	5.798†								
Gurbantunggut Desert	Sinkiang	45°15' N	1600	48.8	0.45	0.5	1	1.1	2	8.25	3		4	20.9	5	24.75	5.445‡		
Sand Dunes Desert	Sinkiang, Gansu	39°35' N	1800	19.5	1.1	0.5	1.5	4.4	2	46.75	4	51.15	5	52.25	5.798†				
Badain Jaran Desert	Inner Mongolia, Gansu	40°12' N	1800	44.3	1.45	0.5	1.5	3.5	2§	8.75	3	12.25	3.616||	26.25	4	40.25	5.547#		
Tengger Desert	Inner Mongolia, Gansu, Ningxia	38°30' N	1800	42.7	1.4	0.5	1.5	8.75	2	17.5	3	25	3.556**						
Horqin Sandy Sand	Inner Mongolia, Jilin, Niaoning	41°28' N	1600	50.6	0.2	0.9	1.5	10	2.029††										
Mu Us Sandy Sand	Inner Mongolia, Shanxi, Ningxia	38°36' N	1800	32.1	1.45	1.25	2	52.5	3	56.25	3.556**								
Otindag Sandy Sand	Inner Mongolia	42°42' N	1700	23.8	1.2	0.5	1.5	10	2.029††										
Hulunbeier Sand	Inner Mongolia	48°18' N	1500	10	0.675	0.5	1	35	1.5	45	1.712‡‡								
Ulan Buh Desert	Inner Mongolia	40° N	1800	11.5	1.1	0.5	1.5	2.5	2	15.625	3	25.625	3.556**						
Kubuqi Desert	Inner Mongolia	40°24' N	1800	1.86	1.1	20	2.324§§												

*Kongur Shan; †Altun Shan; ‡Bogda Feng; Bulai Shan; ||Longshou Shan; #Qilian Shan; **Helan Shan; ††Huanggangliang, the second peak of Daxinganling; ‡‡Taipingling; §§Dahuabei Shan

|||The distances are considered to be 0.5 km when the horizontal distances from the edge of the desert, which is usually located at the mountain foot to an height where the top chimney segment is located, are less than 0.5 km.

A value of annual global solar radiation is selected among the records of annual global solar radiation in the past.

Table 2 Parameters of Possible Plants in the Sand Dunes Desert

Height above sea level at base of top chimney segment/m	1500	2000	4000	4500
Collector area/km^2	19500	19500	19500	19500
Chimney length/km	2.5	5.7	49.0	51.5
Number of chimneys	4	17	1319	1455
Annual power output/TWh	1.3	11.7	930.9	964
Investment cost/10^9 U.S. dollars	324	328	1071	1158
LEC/U.S. dollars kWh^{-1}	18.72	2.042	0.095	0.099
Efficiency of system/%	0.004	0.033	2.652	2.746

mountainside are high. In order to produce an adequate profit, our analysis mainly focuses on the eight largest deserts and the four largest sands, comprising a total area of 67.4 million hectares [11].

Table 1 lists the detailed features of the areas analyzed, including annual global solar radiation, mean height (the arithmetic mean of the north end and the south end), the heights between collector outlets and the base of top chimney segments, and the corresponding horizontal distances between them.

COST ESTIMATE

To determine the economic potential of such a power plant, a thorough cost study is needed. In order to estimate the levelized electricity cost (LEC) of a proposed power plant, it is necessary to consider its investment cost, operation and maintenance costs, depreciation period, lifespan, inflation rate, and interest rate. Schlaich et al. [13, 15] and Bernardes [16] estimated the costs of components for grade-MW power plants, including a plastic covering for the collector, and Fluri et al. [17] estimated the costs of a power plant including a glass covering for the collector. Papageorgiou [4, 5] estimated the cost of materials to construct a floating chimney. Their work gave approximate costs of the collector and the chimney per square meter, and the power conversion unit (PCU) per kW rated power. (A conversion rate between the Euro and the U.S. dollar is used in the analysis: 1.2 U.S. dollars = 1 Euro.) Generally, there are two kinds of collector cover materials: glass and plastic film. We consider a glass cover because a plastic film would be readily destroyed in deserts where the weather is usually bad. In the work, the cost of collector includes the cost of materials (i.e., glass, column system and support matrix, construction costs, and transport costs [17]). The cost of materials of the floating chimney is estimated from the shape C of the chimney wall construction and for the case of NH_3 as the lifting gas [4]. The construction and transport cost of the floating chimney is estimated as 20% of its material cost [4]. The cost of the PCU, including turbines, generators, electronic control equipment, and grid feed-in apparatus, is estimated at a cost of 488.4 U.S. dollars per kW rated power based on wind turbine costs in around the year 2002 [17]. The operation and maintenance costs are calculated at 13.96 U.S. dollars per kW rated power [15].

The Sand Dunes Desert (area: 19,500 km^2; average latitude: 39° 35′ N; annual global solar radiation: 1800 kWh m^{-2}) and the adjacent mountainside 4000 m in height above sea level are selected for the hypothetical construction sites of a collector and the top chimney segments for a rough cost estimate. The length of chimney is calculated from Eq. (2) to be about 49 km with a height of 2900 m and a horizontal distance of 46.75 km between collector outlet and the base of the top chimney segment, plus the height of the top chimney segment of 800 m.

In this economic assessment, a land cost has not been added into the investment cost because the construction sites are considered to be free desert regions and mountains. The depreciation period of the plant is considered to be 30 years, the nominal interest rate as 6%, and the inflation rate as 3.5%.

In the paper, the cost of electricity is calculated by employing the equations used by Fluri et al. [17]. The present equivalent value of the total cost over the life span of the plant, C_{pv}, is calculated using

$$C_{pv} = \frac{C_r}{f-i}\left(\left(\frac{1+f}{1+i}\right)^n - 1\right) + C_{iv} \tag{4}$$

where C_r is the cash flow at the end of the first year (i.e., the operation and maintenance cost in the first year), C_{iv} is the capital cost, f is the inflation rate, i is the interest rate, and n is the lifespan in years. An equivalent annual cost over the life span C_{tot} can be calculated from

$$C_{tot} = C_{pv}\left(\frac{i(1+i)^n}{(1+i)^n - 1}\right) \tag{5}$$

LEC is obtained as

$$\text{LEC} = \frac{C_{tot}}{P} \tag{6}$$

where P is the annual power output.

Based on the above, the LEC of the proposed power plant can be calculated to be 0.095 U.S. dollar kWh^{-1}, which is competitive with a clean coal power plant, the LEC of which reaches 0.11 U.S. dollar kWh^{-1} plus the cost of CO_2 disposal [18].

In reality, the lifespan of a glass collector could be far more than 30 years [1, 15, 19]. The LEC would be reduced with an increase in lifespan.

Table 3 LEC Estimate and the Potential Solar Chimney Power Generation in the Eight Largest Deserts and the Four Largest Sands in China

Desert and Sand	Taklamakan Desert	Chaidamu Desert	Gurbantunggut Desert	Sand Dunes Desert	Badain Jaran Desert	Tengger Desert	Horqin Sandy Sand	Mu Us Sandy Sand	Otindag Sandy Sand	Hulunbeier Sand	Ulan Buh Desert	Kubuqi Desert	Total
Collector area/km^2	337600	34900	48800	19500	44300	42700	50600	32100	23800	10000	11500	18600	
Height above sea level at base of top chimney segment/m	7719	5798	5445	4000	5547	3556	2029	3556	2029	1712	3556	2324	
Temperature rise of collector inward flow at solar radiation of 1000 W m^{-2}/K	42	38.9	37.7	17.1	31.0	42.8	35.0	23.1	34.6	15.5	26.9	39.6	
Collector efficiency/%	26.7	30.4	22.3	49.7	38.6	20.2	2.3	49.3	3.5	44.0	41.7	22.3	
Chimney length/km	70.4	30.3	28.3	49.0	43.1	26.9	11.8	58.1	11.2	46.3	27.7	21.4	
Number of chimneys	2718	502	439	1319	1021	396	76	1853	69	1177	421	252	
Annual power output/TWh	16230	1283	1554	935	2290	902	98	1406	50	211	483	321	25761
Collector cost/10^9 U.S. dollars	5602	579	810	324	735	709	840	533	395	166	191	309	
Chimney cost/10^9 U.S. dollars	1462	116	95	717	337	81	7	823	6	417	89	41	
Turbine cost/10^9 U.S. dollars	4663	348	474	254	621	245	30	381	14	69	131	87	
Investment cost/10^9 U.S. dollars	11727	1044	1379	1071	1693	1035	876	1737	415	651	411	437	
LEC/U.S. dollars kW h^{-1}	0.06	0.07	0.08	0.11	0.07	0.10	0.66	0.10	0.62	0.24	0.07	0.11	
Efficiency/%	2.8	2.0	2.0	2.7	2.9	1.2	0.1	2.4	0.1	1.4	2.3	1.0	
Limited efficiency/%	6.6	3.6	4.2	9.4	6.1	1.9	0.2	4.7	0.2	2.6	4.4	1.5	

Note. Nominal interest rate = 6%, inflation rate = 3.5%, plant depreciation period = 30 years.

There is abundant labor available in China with low wages, and there is advanced engineering technology, which will produce a large reduction of investment costs and LEC.

Many mountains or many locations at different heights on a mountainside facing deserts could be selected for the site of the top chimney segment, which would lead to different power outputs and different costs. Taking the Sand Dunes Desert, with a height above sea level of 1100 m, as an example, we have carried out a dimensional optimization of the proposed power plant. Table 2 shows parameters of possible plants in the Sand Dunes Desert.

As shown in Table 2, the LEC decreases from 18.72 U.S. dollars kWh^{-1} for a 2.5 km long chimney to 0.095 U.S. dollar kWh^{-1} for a 49 km long chimney, but then increases to 0.099 U.S. dollar kWh^{-1} for a 51.5 km long chimney. The lowest LEC is for the combination of a collector in the desert and a 49 km long chimney, the top segment of which is located at an adjacent mountainside 4000 m in height above sea level. This depends on the LEC being determined by the investment cost and the power output. Larger height may improve the energy conversion efficiency of the plant, so reducing the LEC, but too large a height also results in the greater cost of an increase in chimney length. In order to construct the top segment on a mountainside 4500 m in height above sea level for obtaining more power, a 51.5 km long chimney is needed, which is higher than the 49 km obtained when the top segment is constructed on an adjacent mountainside 4000 m in height above sea level. The increase in chimney length results in the increase from 0.095 U.S. dollar kWh^{-1} to 0.099 U.S. dollar kWh^{-1} in LEC. This shows that an excessively long chimney produces less profit, even though more power is obtained. In all cases, they are competitive with clean coal power plants and other power technologies.

POTENTIAL POWER ESTIMATE

All of the optimal combinations of deserts and adjacent mountains are selected to estimate the total potential of this type of proposed power generation in China. Table 3 gives estimated LEC and estimated potential power obtained from the proposed plant in the eight largest deserts and the four largest sands. The total electricity consumption in China in 2003 reached 1903.16 TWh [19]. This demand would be satisfied by the power obtained from the proposed power plants in either the Taklamakan Desert or the Badain Jaran Desert, or with the power obtained from the plants in two or three other deserts. The total power obtained from the proposed power plants in the eight largest deserts and the four largest sands would reach 25761 TWh per year, which is far more than the world's electricity needs (which increased from 13592 TWh to 15441 TWh between 2000 and 2004) and approaches the electric power needs in 2030 (which are estimated to be around 30116 TWh [20]). Northwestern China can be developed as the solar power-generating base to supply the total power needs of China and the world. In order to realize this, high voltage lines would be needed for transporting electricity from northwest China. Fortunately, some high voltage lines from northwest to east China are being built with the support of the Chinese West-to-East Electricity Transfer Project. Eastward, a high voltage line from Guizhou Province to Guangdong Province was built in 2004 that transports electricity to supply the development of Guangdong Province. An eastward high voltage line from Sinkiang is also being built. Power obtained from the proposed power plant in the deserts could make use of these high voltage lines.

CONCLUSIONS

A vast desert belt, 4500 km from east to west, 600 km from south to north, is surrounded by barren mountains up to thousands of meters high in northwest China. A novel solar chimney power plant has been proposed, suited to this region, which consists of a solar collector constructed on vast desert floor and a floating solar chimney attached to the side of an adjacent high mountain. The energy conversion efficiency of the proposed power system is higher than the efficiency of the concrete vertical chimney, as a floating chimney constructed up a mountain thousands of meters high can produce a larger chimney effect than that of the concrete vertical chimney with less height.

Estimates of LEC show that the power obtained from the proposed plant in this particular topography is competitive with the power of clean coal power plants and other power-supplying plants.

The potential power obtained from the proposed power plants in the Taklamakan Desert, Gurbantunggut Desert, or Badain Jaran Desert can satisfy the total electricity consumption in China. The total potential power, reaching 25761 TWh per year, could even supply the electric power needs of the whole world.

Other alternatives include coal-fired power plants, as well as nuclear and hydroelectric plants. Large amounts of radioactive waste, which are difficult to treat, are emitted from nuclear power plants. The environment is destroyed in the process, and humans are forced to migrate when a dam with a water power plant is built. By contrast, the proposed solar chimney power plant does not have any negative effect on the surroundings. In fact, increased desertification will also be effectively prevented when desert regions are covered by collectors [21].

NOMENCLATURE

a	horizontal distance between collector outlet and the base of top chimney segment, m
b	height between collector outlet and the base of top chimney segment, m
c	the shortest distance between collector outlet and the base of top chimney segment, m
C_{iv}	capital cost, U.S. dollar
c_p	specific heat capacity, 1005 J kg^{-1} K^{-1}

C_{pv} present equivalent value of the total cost, U.S. dollar
C_r cash flow at the end of the first year, U.S. dollar
C_{tot} an equivalent annual cost over the life span, U.S. dollar
d, e length of chimney against several mountain peaks, m
f inflation rate, %
g gravitational acceleration, 9.81 m s^{-2}
H chimney height, m
i interest rate, %
L length of the floating chimney against several mountain peaks, m
LEC electricity cost, U.S. dollar kW h^{-1}
n life span, years
P annual power output, kWh
T_0 ambient temperature, K

Greek Symbol

η_{Max} maximum efficiency, %

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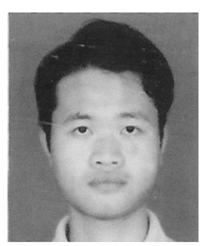

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