Solar chimney power generation project—The case for Botswana

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Abstract

Import of a huge proportion of electrical energy from the Southern African Power Pool, and the geographical location and population distribution of Botswana stimulated the need to consider renewable energy as an alternative to imported power. The paper describes a systematic experimental study on a mini-solar chimney system. Particular attention is given to measurements of air velocity, temperature and solar radiation. The results for the selected 5 and 6 clear days of October and November, respectively, are presented. These results enable the relationship between average insolation, temperature difference and velocity for selected clear days to be discussed.

Keywords: Renewable energy; Solar chimney

Contents

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1. Introduction

Botswana Power Corporation (BPC) oversees electricity generation, transmission, distribution and import from abroad. The Morupule electricity generating plant is the sole electrical generating plant in the country. The facility is a coal-fired steam plant with a maximum generating capacity of 132 MW. The plant employs an air-cooled condenser system, owing to the shortage of a clean water supply for an evaporative cooling system. Although the same system is used the world over, it is believed that relatively high summer air temperatures (above 33 °C) in most parts of Botswana adversely affect the overall performance of the plant. Such observation is based on the fact that the water outlet temperature from the condenser is believed to be above 100 °C.

It should be noted that presently the electrical system's maximum demand for the entire country is around 402 MW, that is, 270 MW more than the local generating capacity [10]. The data in Fig. 1 show the maximum electrical demand projected into the future to 2012. It should be noted that the data for 2005–2012, as shown in Fig. 1, are predicted data.

It is evident that the future demands for electrical energy in Botswana will continue to increase. This raises several questions, the primary one being how the local power generating company (BPC) plans to achieve the demand mentioned earlier. In response to some of the above observations, it is pertinent to mention that Botswana is a signatory to the Southern African Power Pool (SAPP), which was created in 1995 (SAPP annual report 2005). It is noted that some SAPP member states presently generate electrical energy above their maximum demand. The data in Fig. 2 demonstrate maximum electrical generation and demand levels for selected SAPP member states.

Currently, Botswana's internal generation (at the Morupule coal-fired power plant) satisfies only 33% of its demand [11]. The country imports its additional electrical energy requirements to meet its maximum demand from Eskom of the Republic of South Africa and NamPower of Namibia. It is to be noted that the installed capacity and maximum demand for power from Republic of South Africa, are the largest among the SAPP community. As of 2006 its installed capacity stands at 42 GW, while its maximum demand

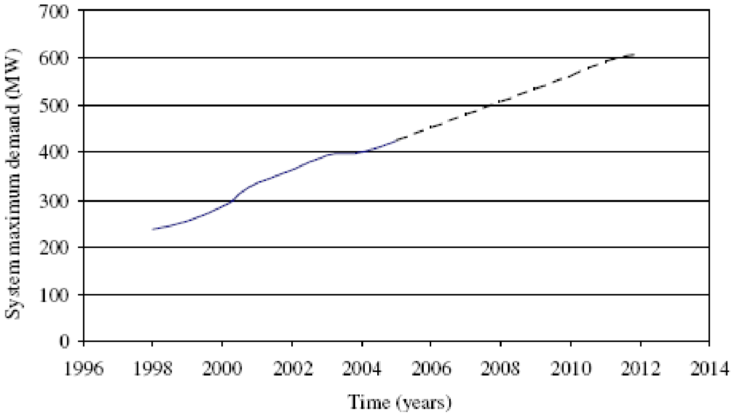

Fig. 1. Botswana's electrical system maximum demand and projection data. *Source*: Southern African Power Pool (SAPP) annual report 2005.

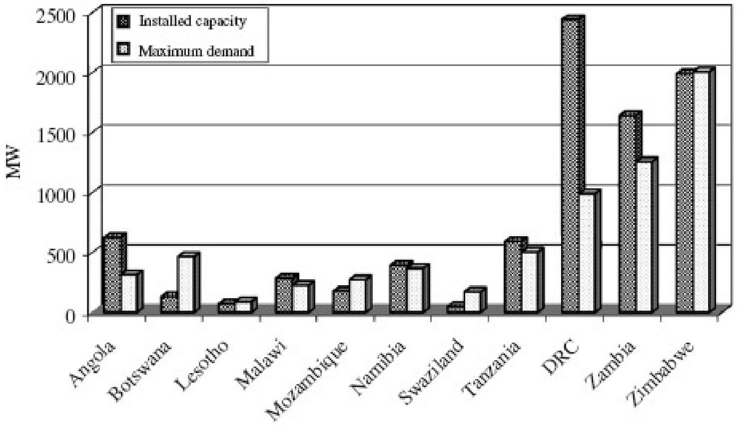

Fig. 2. Installed capacity and maximum demand in SAPP member states (excluded is the Republic of South Africa, which has an installed capacity of 42 GW and a maximum demand of 32 GW). *Source*: SAPP annual report 2005.

is around 32 GW. As a result, the Republic of South Africa has an apparent excess capacity of around 10 GW, which currently supplies the region around it, Botswana included. It is believed that this was the main rational for the creation of SAPP as mentioned earlier. Looking at the whole SAPP region, already in 2001, demand exceeded supply, and this is due to power rehabilitation projects.

It is pertinent to mention that the energy policy instruments in some Southern African Development Community (SADC) [1] countries, Botswana and Republic of South Africa included, are now placing more emphasis on increased access to the national electricity grid. To carry out their mandates, many SADC member states have established special programmes. In the context of Botswana, the programme is referred to as Rural Electrification. On the basis of this programme, the government together with the internal electricity generator and transmitter (BPC) provide funds for expansion of the national electricity grid network to more than 15 villages on an annual basis [2]. In Republic of South Africa, the same approach achieved a target of approximately 2.8 million households connected to the electricity grid between 1994 and 1999 [3]. The rapid development of the Rural Electrification Programme in the Republic of South Africa is explained by the backlogs experienced by the historically disadvantaged communities, both in urban and in rural environments. In Namibia [4], available evidence indicates that the government annually commits between US $1.8 and 2.7 million for the expansion of the rural electrification network [5].

On the basis of the above observations and available evidence, there is a growing threat that the SADC region may face a shortage of electrical energy in the not very distant future. The situation would adversely affect member states, Botswana included, with high electricity demands which are usually above their internal electricity generation capacities. Among SADC member states, Botswana has one of the highest electricity demand growth rates, 6%, while the Republic of South Africa presently stands at 3% (SAPP report 2005). This also raises several questions, the primary one relates to the future electricity generation strategies for Botswana, to satisfy its ever-increasing electrical energy requirements. The paper discusses a systematic experimental study on solar chimney technology in Botswana. Particular attention is given to the measurements of irradiation solar energy, collector temperature and chimney air velocity. The results provide indicators which can be used to predict the performance of a full-scale plant using this technology.

2. Solar-tower technology

A technology of solar chimney power generation is not new in power generation sector, world over. Available evidence indicates that one of the earliest descriptions of the solar chimney power station was written in 1931 by a German researcher, Günter [6]. The concept was refined by the German professor, Schlaich [7], who also discussed the transferability of the results from the Manzanares plant. In 1981, a large experimental plant was constructed on a pilot in Manzanares, Spain, as a result of a joint venture between the German government and a Spanish utility. It had a greenhouse with a radius of 122 m and a chimney 194.6 m high. It produced an upwind velocity of 15 m/s [8]. In 2002, the Australian government issued permission for the development of a 1000 m high by 7 km diameter solar chimney plant. It is predicted that the facility will produce a power output of 200 MW [9].

The sun's radiation heats a large body of air, which is then forced by buoyancy forces to move as a hot wind through large turbines to generate electrical energy. Solar chimney power plants, with an output of 5–200 MW, require a transparent roof several kilometres in diameter, and the tube has to be as high as possible to achieve a large output. With the use of materials of better absorbing radiation, both the diameter of the base of the chimney as well as its height may be substantially reduced. On this basis, solar chimney plants are appropriate on land with no natural vegetation, such as desert regions. Such conditions compare favourably well with the conditions found in most parts of Botswana. The Kalahari Desert in Botswana occupies approximately 70% of the country. On the basis of the above, and particularly on the need for plans for long-term energy strategies, a decision was taken by the government of Botswana through its Ministry of Science and Technology to design and build a small-scale solar chimney system for research.

3. Description of apparatus

A small-scale solar chimney was constructed with an inside diameter of 2 m and a height of 22 m. The chimney was manufactured from glass reinforced polyester material, with a collection base area of approximately 160 m^2. The collector section was opened at ground level around its outer edge by approximately 10 cm, in order to allow the airflow into the system. The roof was made of a 5 mm thick clear glass that was supported by a steel framework. The floor was made of two layers of compacted soil approximately 10 mm thick and a layer of crushed stones. The layer of crushed stones was spread evenly on the top surface of the compacted soil layer. All these were done to increase the absorption of incident solar radiation. The bottom end of the chimney was bolted on top of a concrete stand, and anchored to the ground supports using wires. This was done to ensure that the chimney axis lay in the vertical direction with the nozzle located 2.8 m from the ground.

A Kestel 600 Head (48 VDC) turbine with six fixed blades was installed at the exit end of the nozzle. In order to monitor the performance of the facility, several parameters were measured including air velocity, temperature and solar irradiation. A total of 11 sensors of

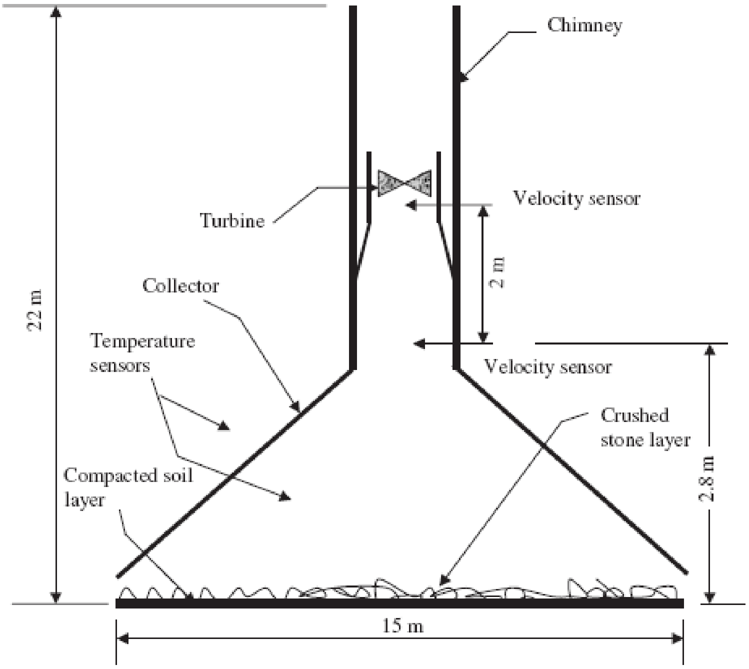

Fig. 3. Schematic arrangement of the solar chimney used for the study.

three different types were used. There were two velocity sensors, two temperature sensors, and seven solar irradiation sensors. Solar irradiation sensors were employed to monitor solar energy from seven positions, Global, Diffuse and Albedo included. It should be noted that four of the irradiation sensors were located in a manner that their location corresponded to the faces of the glass collector. Irradiation sensors were placed approximately 2 m from the glass collector, in order to avoid shading and reflection from the glass collector. The positions of some sensors are shown in Fig. 3.

The data on temperature, velocity and irradiation were recorded using a DL2e data logger. This data logger offered important data acquisition and smoothing features, including the capability to use time and boxcar integrators, and to calculate the time averages of the measured properties. Point measurements of temperature, velocity and irradiation were sampled at 30 s intervals and averaged over 30 min. The measured data for each test run were then downloaded onto a laptop through a RS232 to a USB connection and analysed.

4. Experimental procedure

In order to obtain comprehensive data on the performance of the solar chimney, data were collected under three different operating conditions. First, point measurements of air velocity at the sampling points were recorded, when both the turbine and the nozzle were installed. The turbine was then removed and other sets of data were recorded. Finally, both the turbine and the nozzle were removed and a third set of data was recorded. Prior to each test condition, each sensor was then tested so that all the relevant data could be recorded. When all the initial tests were done, automatic measurements of air velocity, temperatures and solar irradiation were initiated.

5. Results and discussion

Several tests were conducted in a systematic study of solar chimney technology. The experimental data were collected as discussed earlier, leading to the results showing daily variation of total global insolation, collector temperature, temperature difference and air velocity. For simplicity, only a sample of the results obtained from these experiments have been presented and discussed in this section. This enables the main findings of the study to be identified and explained. It should be explained that turbine power could not be recorded during a systematic study of solar chimney technology due to limited test facilities. For this reason, no turbine power data can be included in Figs. 4–6. To provide sufficient experimental data and to allow sensible average values for solar irradiation, temperature difference and air velocity, a data sampling size of 5 clear days of October and November was used to generate the results in Figs. 4–6.

The results in Fig. 4 show insolation, temperature difference and velocity for the selected 5 clear days of October 2005 when the turbine was installed. It can be observed that between approximately 6:00 and 8:00 h air velocity reached a maximum, corresponding to an increase in solar energy from approximately 100 to 500 W/m^2. The air velocity then remains nearly constant until approximately 14:00 h, despite the increase in solar energy to a maximum peak of 950 W/m^2 recorded approximately at 12:00 h. All these lead to the conclusion that approximately 47% of incoming solar energy is absorbed by the ground

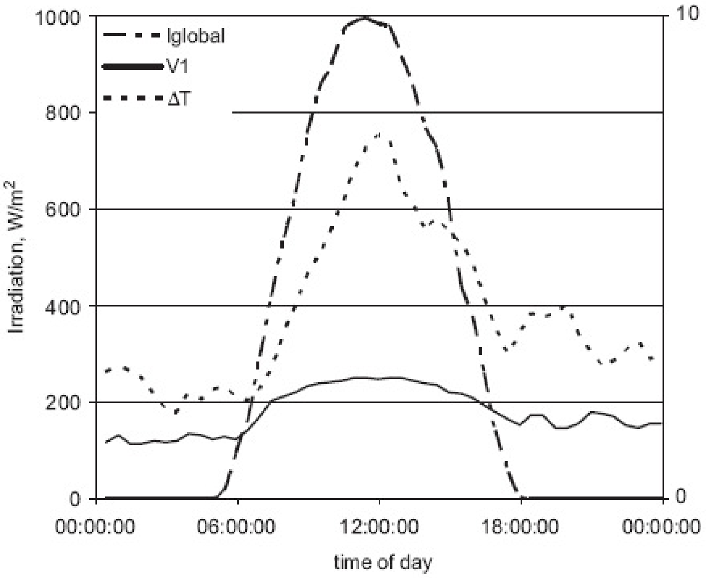

Fig. 4. Average insolation, temperature difference and velocity for selected 5 clear days of October (with turbine installed).

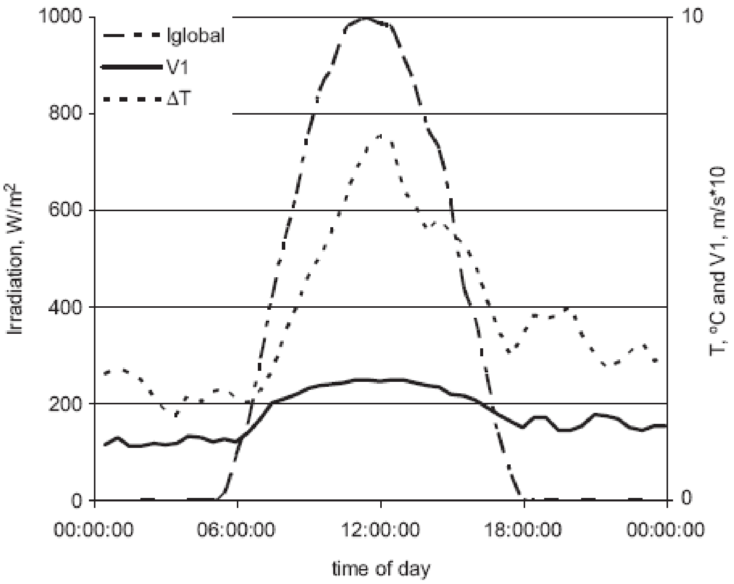

Fig. 5. Average insolation, temperature difference and velocity for selected 6 clear days between 19 and 30 October (with turbine removed).

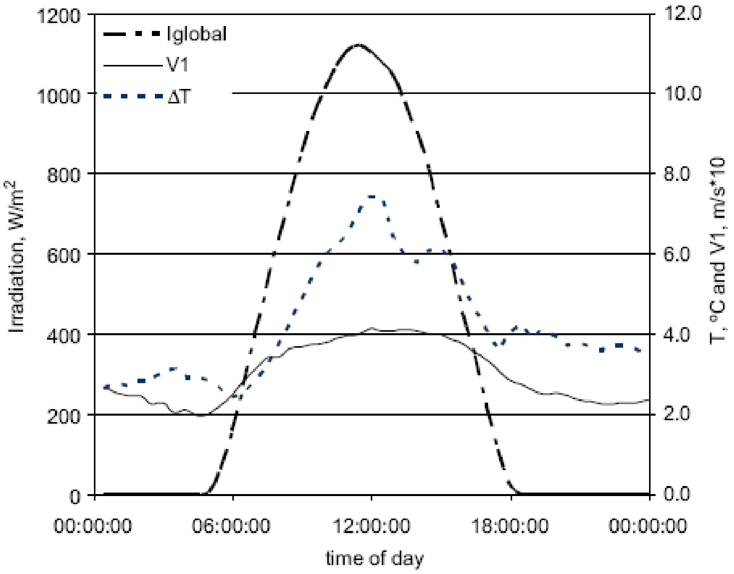

Fig. 6. Average insolation, temperature difference and velocity for 6 days between 14 and 21 November (with turbine and diffuser removed).

which is later released when the local temperature decreases. The peak maximum temperature recorded after the peak maximum irradiation reinforces the observation that the ground absorbs part of the incoming solar energy which is later released, resulting in an increased collector temperature. Figs. 4–6 show variation of the total global insolation, temperature difference and air velocity for the selected clear days. It can be seen that the range of temperature difference was from about 2 °C at 6:00 a.m. to 7.5 °C at noon. Air velocity was in the range 1–2.5 m/s with the diffuser installed and 2–4 m/s with the diffuser removed.

Overall the chimney operated from 7 October until 22 November 2005. The turbine was removed on 17 October, but data were still collected until 4 November, when the diffuser was removed from the system.

References

[1] SADC annual report, 2005.
[2] Energy Affairs Division annual report 2002. Ministry of Minerals, Energy and Water Resources.
[3] Kotz'e IA. The South Africa National Electrification Programme—past lessons and future prospects. South Africa: Department of Minerals and Energy; 2000.
[4] Tobich R. Rural electrification in Namibia. ESI 12002_038_2. ESI Africa, 2001.
[5] 〈http://www.esi-africa.com/last/ESI_1_2002/ESI12002_028_1.htm〉.
[6] Günther H. In Hundert Jahren—Die künftige Energieversorgung der Welt. Stuttgart: Kosmos, Gesselschaft der Naturfreunde, Franckh'sche Verlagshandlung; 1931.
[7] Schlaich J. The solar chimney. Stuttgart, Germany: Axel Menges; 1995.
[8] Pasumarthi N, Sherif SA. Experimental and theoretical performance of a demostration solar chimney model–Part 1: mathematical model development. J Energy Res 1998;22:277–88.
[9] 〈http://www.enviromission.com.au/faqs/faqs.htm〉.
[10] BPC annual report, 2005.
[11] SAPP annual report, 2005.