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Performance Analysis of a Commercial Scale Solar Chimney Power Plant in Oman

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ABSTRACT

This paper presents a performance study of a commercial-scale solar chimney power plant under Oman climate conditions. A simple mathematical model is presented and validated against the Manzanares prototype and is used to estimate the solar chimney performance parameters for a full-scale commercial power plant to be located in Marmul, Oman. This location is suitable for solar power application owing to its high solar resource and geographical characteristics. Averaged solar data from NASA POWER database was retrieved and synthesized to generate the annual hourly radiation. The model yielded estimates of the collector efficiency, updraft velocity and potential electrical energy that can be generated. The capacity factor and land use requirement were also determined and compared with other solar power technologies in use today.

1. Introduction

Solar energy is one of the most environmentally friendly renewable energy sources available today. It may be used to generate electricity in two ways: through photovoltaic effect and through solar thermal cycle. A solar chimney power plant is a type of solar thermal energy conversion system that operates on air standard cycle which can be modeled by the Bryton cycle [1]. In a solar chimney power plant, electricity can be generated with a very small temperature differential unlike concentrating solar systems [2]. A solar chimney power plant consists mainly of a solar collector, a chimney, and a turbine as illustrated in Figure 1. Solar radiation is transmitted through the glass roof of the collector and absorbed by an absorber surface. As air in the collector gets warmer, it is buoyed upward through the chimney where a centrally located turbine-generator converts the kinetic energy of moving air into electrical energy. The earliest solar working prototype of a solar chimney power plant was designed and built in Manzanares, Spain. It has a chimney height of 194.6 m, a chimney radius of 5.08 m, and a collector radius of 122 m. It produced a peak power of 50 kWe and was able to generate 44 MWh per year [3]. Solar power applications such as solar chimney power plants have significant potential in the Arab Gulf region due to their abundant solar resource. Oman is located in the Arabian Peninsula's extreme south-eastern corner, spanning latitudes 16.40 to 26.20 degrees

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north and longitudes 51.50 to 59.40 degrees east with a 316 km-long coastline stretches northward from the Arabian Sea and the Indian Ocean's entry in the extreme south-west to the Sea of Oman and Musandam. The overall area is about 309,500 km^2 with a population of 4,617,927 people as of the 2020 Census [4]. Summers are often hot and humid, while winters are mild owing to its geographical location. Oman is also developing a national energy strategy that aims to achieve 10% of renewable energy in generating electricity by 2030 [5]. The majority of technical study publications imply that Oman is one of the top solar energy locations in the world [6]. In Oman, solar radiation levels in July vary between 5.5 to 6 KWh/m^2 per day and 2.5 to 3 KWh/m^2 per day in January [7]. As a result, it can be a viable option for supplying electric power. Areas of highest solar density are the desert areas while the coastal areas in the southern part of Oman have the lowest solar density. Marmul, Fahud, Sohar, and Qairoon Hairiti are considered excellent sites in Oman for solar power due to their high solar radiation levels [8]. Additionally, the absence of rain and cloudy skies generally throughout the year and the presence of vast areas of flatlands and deserts make large-scale solar energy exploration an attractive opportunity for development.

Several studies have been conducted on solar chimney power plants. Das and Chandramohan [9] have recently reviewed solar updraft power tower technology including the thermodynamic analysis, current status, recent advances, and major challenges and opportunities. Ikhlef and Larbi [10] have conducted a technical and economic feasibility study of the Manzanares power plant. They developed a mathematical model which evaluates the annual power performance. They were able to compare the profitability of the solar chimney compared with conventional power plants in the Maghreb region. Hammadi [11] developed a similar mathematical model to study the effect of various parameters on the power output of a solar chimney under Basrah climate conditions.

The technical and economic feasibility and sustainability of solar chimney power plant have also been studied. Emergy indicators of sustainability in terms of environmental, ecological, and regional development of solar chimney power plants have been studied, and was found that sustainability increases as size increases [12]. They also investigated the sustainability of solar chimneys using environmental and economic indicators as well as its economic feasibility by estimating the levelized cost of energy. It was concluded that an increased size increases efficiency and decreases the levelized cost [13]. The economic viability of solar chimney in Rajasthan, India has also been investigated [14]. The potential of solar chimneys for application in rural areas has been studied by Onyango and Ochieng. They developed a model to determine the physical viable dimensions of chimney and collector for practical application [15].

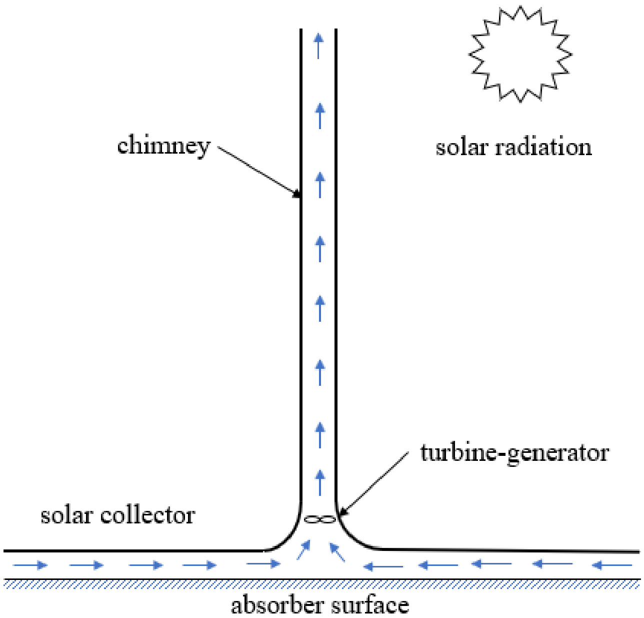

Fig. 1. A solar chimney power plant

Meanwhile, investigations of solar chimney under Oman climate condition are limited. Husain *et al.,* [16] created a CFD model to investigate the effects of inlet velocity to the power generated. A small-scale solar updraft tower was experimentally investigated by Adamsab *et al.,* [17] under Oman meteorological conditions. Hamdan [18] conducted an analysis of a solar chimney using a simplified thermodynamic model under selected Arab gulf region climate conditions. He concluded that chimney height and turbine head have a significant effect on efficiency while chimney diameter and collector have a less significant effect.

This study will focus on the performance analysis of a solar chimney power plant in Marmul, Oman. A simple mathematical model will be presented and location-specific solar radiation and temperature data will be used to determine collector efficiency, updraft velocity, and potential electrical energy output. This performance investigation will help gain insight into the technical feasibility of solar chimney power plant in Oman.

2. Mathematical Model

The thermo-fluid model presented in this paper assumes the following

i. Uniform radiative heating on the collector
ii. Chimney walls are adiabatic
iii. Flow of air is steady and frictionless

2.1 Solar Collector

The heat balance equation in the solar collector is given by

$$mC_p(T_c - T_o) = \alpha I A_c - U A_c (T_c - T_o) \quad (1)$$

This equation implies that the heat gained by the air in the collector is equal to the net solar radiation that reaches the absorber plate less the convection and radiation losses. The overall loss coefficient U includes both wind convection and radiation losses. The estimate of U uses Klein's equation quoted by Duffie and Beckman [19]. For a solar collector with single glass cover placed horizontally, U can be estimated from

$$U = \left(\frac{1}{\frac{520}{T_p}\left[\frac{T_p - T_o}{1+f}\right]^e} + \frac{1}{h_w} \right)^{-1} + \frac{\sigma(T_p+T_o)(T_p{}^2+T_o{}^2)}{\frac{1}{\varepsilon_{p+0.00591h_w}} + \frac{1+f+0.133\varepsilon_p}{\varepsilon_g} - 1} \quad (2)$$

where $h_w = 5.7 + V_i$ and V_i is the air velocity at the collector inlet.

The efficiency of the solar collector which is the ratio of the thermal energy gained by the air to the incident solar radiation can be expressed as

$$\eta_c = \frac{mC_p\Delta T}{\pi R^2 I} \quad (3)$$

The heat absorbed by the solar collector can thus be evaluated by

$$Q = \eta_c A_c I \quad (4)$$

2.2 Chimney

The maximum velocity in the chimney can be evaluated from

$$v_{max} = \sqrt{2gH\left(1 - \frac{T_0}{T_c}\right)} \quad (5)$$

The pressure difference between the outlet of the collector and the ambient is calculated from

$$\Delta p = 0.00353gH\left\{\left(\frac{\pi R^2 I\eta_c}{C_p m}\right) - \left(\frac{gH}{C_p}\right) + \left(\frac{\gamma H}{2}\right)\right\} \quad (6)$$

2.3 Turbine

The maximum power output of the turbine located near the bottom of the chimney as recommended by Schlaich [20] is

$$P_{max} = \frac{2}{3}v\mathrm{A}\Delta p \quad (7)$$

If the generator has an efficiency of η_e, the electrical power output produced becomes

$$P_e = \eta_e P_{max} \quad (8)$$

3. Results

3.1 Model Validation

Results of the mathematical model were compared against published data from the Manzanares prototype and is shown in Table 1 [3]. The comparison shows that the results derived from the present mathematical model are in good agreement with published data obtained from the Manzanares prototype.

3.2 Solar Radiation in Marmul, Oman

The average daily solar radiation per month in Marmul is shown in Table 2. The data was taken from NASA's Surface Solar Energy Data Set or (NASA POWER) which provides monthly average solar radiation data anywhere on earth averaged for a period of 22 years.

Table 1
Comparison of published and model data

Data	Manzanares Prototype [3]	Present model
Ambient temperature (K)	300	300
Solar radiation (W/m^2)	1000	1000
Wind velocity (m/s)	15	14.0
Temperature difference (K)	20	19.6
Collector efficiency	0.32	0.4
Power output (kWe)	50	49.2

To generate synthetic hourly solar data from the monthly average data, HOMER software was used which employs an algorithm based on the work of Graham and Hollands [21]. His method employs a stochastic approach for creating synthetic sets of hourly solar irradiation values, useful in solar simulation work. For Marmul, a total of 8760 hourly radiation values were generated. The hourly radiation data generated for Marmul for the month of May where peak radiation occurs and December, where solar radiation is least is shown in Table 2. This hourly solar irradiation data together with the local ambient temperature data is used as inputs to the mathematical model developed in order to estimate the electrical power generated by the solar chimney power plant.

Table 2
Monthly average daily radiation and ambient temperature in Marmul

Month	Daily radiation (KW/m^2/day)	Ambient temperature (K)
Jan	5.24	292.3
Feb	5.86	294.3
Mar	6.58	301.5
Apr	7.20	297.5
May	7.55	304.4
Jun	6.84	305.8
Jul	6.63	304.9
Aug	6.59	304.1
Sep	6.74	302.8
Oct	6.34	299.9
Nov	5.53	296.9
Dec	4.97	293.7

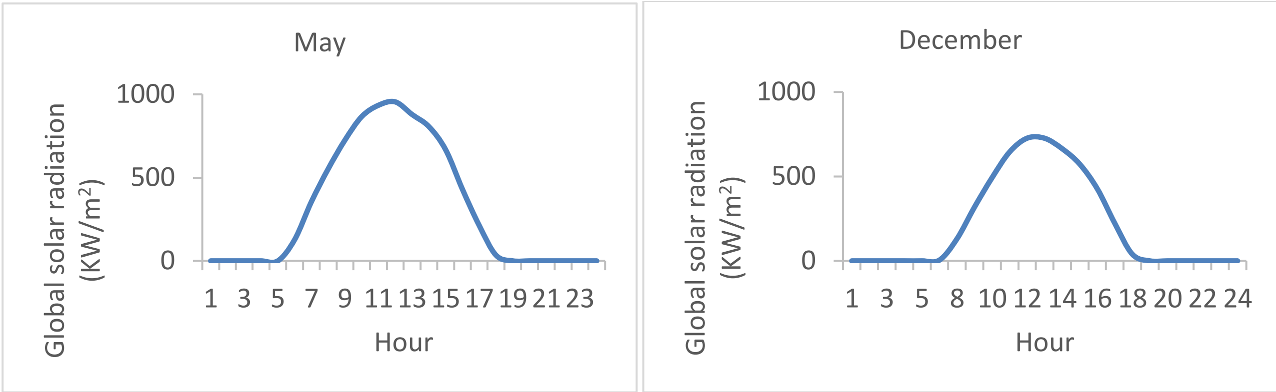

Fig. 2. Synthesized hourly solar radiation in Marmul for May and December

3.3 Performance Results

The physical dimensions of full-scale solar chimney power plant to be analyzed is shown in Table 3. These parameters were based on the commercial-scale power plant suggested by Schlaich *et al.,* [3,22]. According to them, solar chimney plants of this size are capable of generating energy at costs comparable to conventional power plants. The construction of a solar chimney power plant of this scale can be a challenge but can be built today owing to the advancement of construction technologies similar to building tall skyscrapers.

Table 3
Commercial scale dimensions of solar chimney power plant used in this study

Parameter	Size
Capacity (MW)	200
Chimney height (m)	1000
Chimney diameter (m)	120
Collector diameter (m)	7000
Collector height (m)	3

The mathematical model was used to perform stepwise hourly calculations of performance parameters such as velocity, collector efficiency, power, and energy output. Figure 3 shows the efficiency of the collector for the months of May and December. It illustrates that collector efficiency follows the variation of solar radiation where it is low at minimal solar radiation levels and peaks around noon when solar radiation is maximum and then decreases as radiation also diminishes. Collector efficiency is generally greater in May when peak monthly radiation occurs, however, the peak efficiency for both months May and December has marginal difference.

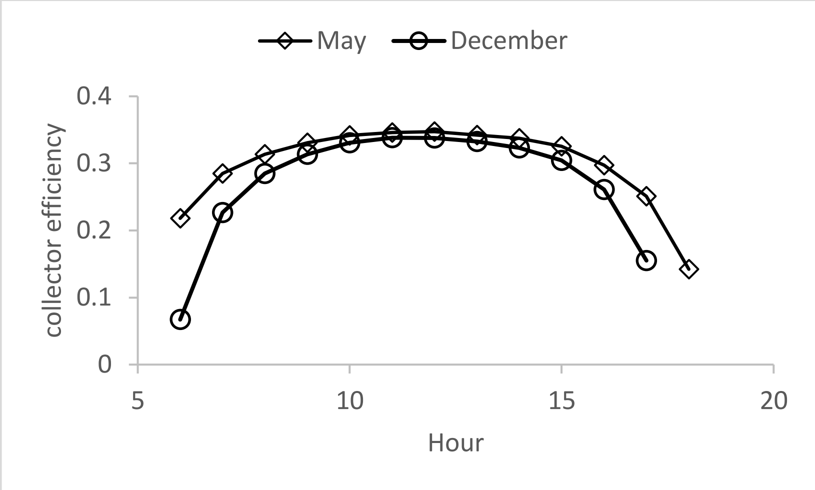

Fig. 3. Collector efficiency for May and December

Figure 4 shows the hourly variation of maximum updraft velocity developed in the chimney for the months of May and June. The updraft velocity follows a similar variation to that of solar radiation where the peak occurs at maximum irradiation time. Updraft velocities of more than 40 m/s can be induced in the chimney depending on the heat gained by the air. Also, even at low radiation levels early in the day or late afternoon, air flow can be induced in the solar chimney to produce sufficient velocities suitable to rotate the air turbine.

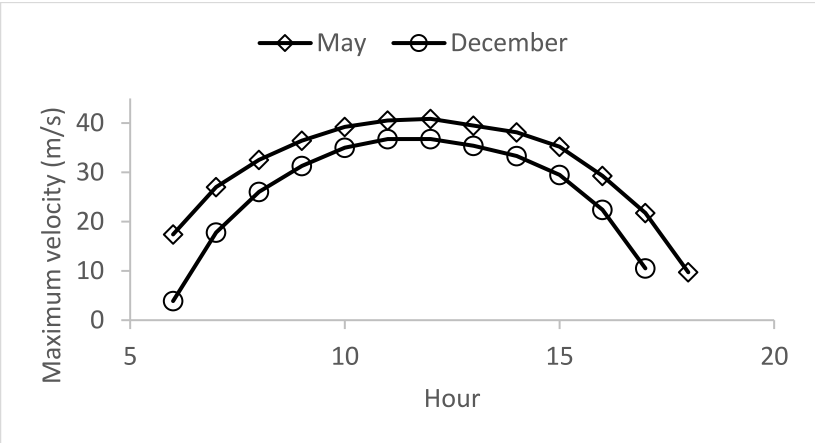

Fig. 4. Maximum updraft velocity for May and December

Figure 5 depicts the estimated monthly energy output for a 200 MW solar chimney power plant in Marmul, Oman. The variation of energy output follows the variation of the average daily radiation as shown in Table 2. A peak energy production of 53.5 GWh can be generated in the month of May while the lowest energy production occurs in December at 35.5 GWh. Annually, the total energy production for this installation is estimated at 531.4 GWh per year. Based on 2019 per capita electricity consumption of Oman, it has the potential to serve up to 15,100 households [23].

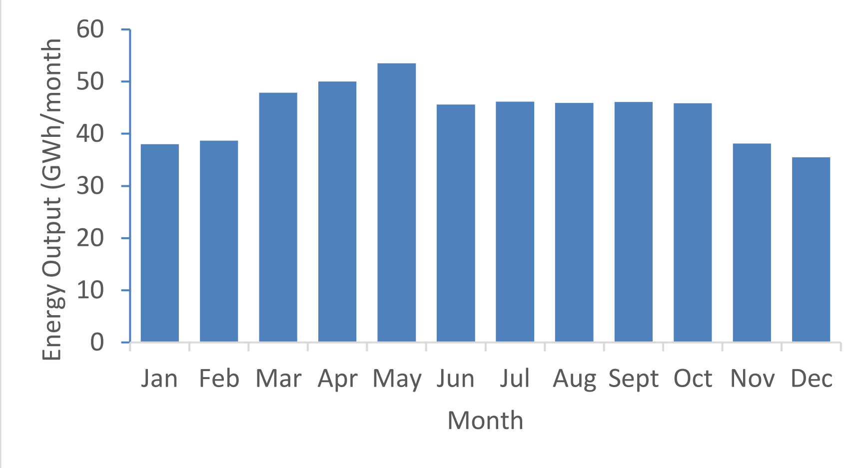

Fig. 5. Monthly energy output

3.4 Comparison with Other Solar Technologies

Capacity factor is a measure of how much energy is generated by a power plant compared with its maximum capacity. The capacity factor is given by

$$Capacity\ factor = \frac{energy\ generated}{capacity\ x\ 8760} \qquad (9)$$

The land use requirement provides a reliable comparison between various solar technologies with different capacity factors and is useful in the evaluation of land-use impacts. It can be reported either on a capacity or generation basis. Generation-based land requirement is the area of land required to generate a unit of energy over a period of time. Table 4 shows the comparison of the solar chimney power plant's capacity factor and land use requirement with that of other solar power technologies. The capacity factor for the solar chimney is greater than that of a solar photovoltaic system and slightly less than that of a concentrating solar power system (CSP). The solar chimney can generate electricity even at low radiation levels as low flow velocity can be induced sufficient enough to rotate the turbine-generator. In this present analysis of solar chimney power plant, there is no thermal storage. If thermal storage is wanted, tubes filled with heat-absorbing liquid can be laid on the ground. When air starts to cool at night, the liquid in the tubes releases the heat stored. By using heat storage, the capacity factor can be further increased as heat otherwise lost to the ground can be captured and used to heat the air at night to produce air flow. Meanwhile, the land required for solar chimney is 94008 m^2/GWh significantly higher than that of solar photovoltaic and CSP. This is attributed to the lower over-all conversion efficiency of a solar chimney power plant. However, the impacts associated with the use of the land can be reduced if it is built on desert plains such as in Marmul.

Table 4
Comparison of solar chimney power plant with other solar power technologies

Parameter	Solar photovoltaic	CSP	Solar chimney (Marmul)
Capacity factor	10-21% [24]	32% [25]	30.3%
Land use requirement (m^2/GWh per year)	13,759 [26]	14,164 [26]	72,420

4. Conclusions

A solar chimney power plant is an attractive option for power generation that requires low temperature heating. In this study, a mathematical model of a solar chimney power plant is presented to determine the performance parameters of a commercial scale solar chimney power plant in Marmul, Oman. Modeling results show that a chimney power plant with a chimney height and diameter of 1000 m and 120 m respectively and a collector diameter of 7000 m can produce about 40 m/s of updraft air velocity in the chimney enough to drive an air turbine-generator. The total energy generated is highly dependent on the intensity of solar radiation. It is estimated that 531.4 GWh of energy can be generated per year which is adequate to supply the requirement of 15,100 Omani households. The capacity factor for this facility is close to 30% comparable to that of a concentrating solar power plant. The land use requirement however is significantly larger compared to both solar photovoltaics and concentrating solar power due to its lower over-all conversion efficiency.

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