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Research Paper

Performance Evaluation of Solar Chimney Power Plants in Egypt

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Abstract: *Power generating technology based on renewable energy resources will definitely become a new trend of future energy utilization. The solar chimney power plant is a natural draft device which provides an upward momentum to the in-flowing air by firstly converting solar energy into thermal energy in the solar collector. Secondly the generated thermal energy is converted into kinetic energy in the chimney and ultimately into electric energy using a combination of a wind turbine and a generator. The purpose of this study is to evaluate the performance of solar chimney power plants in some locations in Egypt theoretically and to make an approximation of the quantity of the generated electrical energy. A simple mathematical model based on the energy balance was developed to estimate the power output of solar chimneys as well as to observe the effect of various ambient conditions and structural dimensions on the power generation. It was found that, the wind speed inside chimney reaches more than 7 times of the value of free wind speed outside chimney. The solar chimney power plant with 500 m chimney height, 50 m chimney diameter and 3000 m collector diameter is capable of producing yearly between 1.6-1.7 × 10^8 kW hr in the selected locations in Egypt. Therefore the use of solar chimney power plants in many locations in Egypt will be attractive. It can cover a considerable section of the increasing demand to energy. It can save the use of conventional sources of energy like oil and natural gas and consequently reduces the emissions of harmful gases.*

Keywords: Renewable Energy, Solar Energy, Solar Chimney, Draft Tower, Wind Energy.

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1. Introduction:

In recent years, rapid developments of global economy and increase in population and living standards have been posing great pressure on natural resources. Fossil fuels are therefore being exhausted at a fast rate. The utilization of fossil fuels together with net deforestation has induced considerable climate change in warming the atmosphere by releasing greenhouse gases which may produce many negative effects including receding of glaciers, rise in sea level, loss of biodiversity, extinction of animals, and acidification of oceans [1-3]. Therefore, it is urgent to develop the technologies utilizing renewable and clean energy sources to solve these problems. Solar chimney power technology is a promising large-scale power technology [4–6], which absorbs direct and diffused solar radiation and converts parts of solar energy into electric power free of green house gases emissions.

In 1931, a description of a solar chimney power plant was presented by Guenther [7]. The basic study on the solar chimney concept was performed by Schlaich in the seventies of the twentieth century and in 1981 he began the construction of a pilot solar chimney power plant in Mansanares, Spain, as a result of a joint venture between the German government and a Spanish utility. A 36-kW pilot plant was built, which produced electricity for seven years, thus proving the efficiency and reliability of this novel technology. The chimney tower was 194.6 m high, and the collector had a radius of 122 m. The prototype solar chimney power plant at Manzanares in Spain showed that the solar chimney is a practical technology capable of generating electrical power from the sun [5]. Different types of small-scale solar chimney devices with power outputs not exceeding 10 W were demonstrated by [8, 9]. A mathematical model to study the effects of various environment and geometry conditions on the heat and flow characteristics and power output of a solar chimney were developed by [10-12]. They also developed three model solar chimneys in Florida and reported experimental data to use in assessing the viability of the solar chimney concept. A simplified theory, some practical experience results and a detailed economic analysis of solar chimneys for the design of commercial solar chimney power plant systems were presented by [13, 14]. Many attempts have been made to evaluate the performance of solar chimney power plants in some parts of the world [15-19]

The most suitable construction sites of large-scale solar chimney power plants (SCPP) are located in vast desert regions where land may be free [20]. The technologies for the SCPP components are simple and reliable, accessible to the technologically less developed countries, which are sunny and often have limited raw material resources. Little maintenance and no combustible fuel and cooling water are needed for SCPPs. A major problem of SCPP is its low conversion efficiency as determined by the thermal performance of the system. However, the conversion efficiency of SCPP increases with the solar chimney height. For commercial power plants producing energy economically, not only is a large collector area necessary for collecting solar energy, but also a high huge solar chimney is required to obtain a large driving force and to produce a large volumetric flow to drive big turbines. Furthermore, higher conversion efficiency for large-scale SCPP will also lead to a certain reduction in the energy cost.

The objective of this paper is to investigate the opportunity for electric energy production in some parts of Egypt and to approximate the quantity of the produced electric energy. The objective of this paper also is to analysis the effect of some physical parameters, such as ambient temperature and solar radiation, on the power output of solar chimney power plants. A general and simplified mathematical model of a solar chimney power plant will be established and analysed for the selected locations in Egypt.

2. System Descriptions:

The solar chimney power plant combines three familiar components: a solar collector, a solar chimney, and power conversion unit which include one or several turbine generators. The turbines are driven by air flow produced by buoyancy resulting from greenhouse effect inside the collector (Fig. 1). The main function of solar chimney systems is to convert solar energy into electrical energy. In the collector, the solar energy will be transformed into heat energy. The chimney converts the generated heat energy into kinetic energy, which will be transformed into electric energy by using a combination of a wind turbine and a generator.

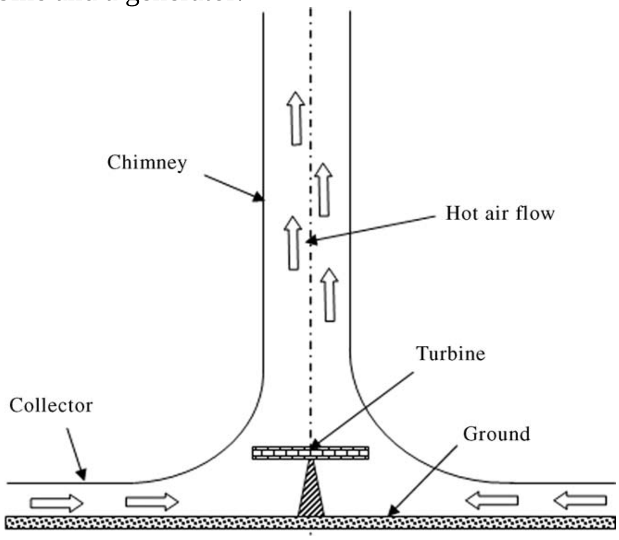


Fig. 1: Schematic illustration of a solar chimney power plant

The collector in solar chimney system consists of support matrix, column structure and transparent roof. A large air collector is formed, when a transparent glass or plastic roof supported above the ground by column structure and support matrix is stretched out horizontally many meters. The height of the roof slowly increases along a radius from the periphery to the center to guide inward airflow with minimum friction losses. This glass or plastic roof allows the transmission of the shorter wavelength solar radiation but blocks the longer wave length radiation emitted by the ground. As a result, the ground under the roof heats up, which, in turn, heats the air flowing radially above it. The soil surface under the collector cover works as a storage medium, which saves a part of the incoming solar radiation during a day and releases it later during the night. This mechanism is capable of providing a continuous supply of power all year round.

The chimney situated in the collector centre is the actual thermal engine of the solar chimney power plant. The up thrust of the air heated in the collector is proportional to the rise in air temperature flowing in the collector and its volumetric flow rate.

Suitable turbines located at the base of chimney convert kinetic energy of the up-flowing air inside chimney to mechanical power in the form of rotational energy. The typical solar chimney turbine is of the axial flow type. The principle of operation of these turbines is similar to the turbo-generators used in hydroelectric power stations, where the static pressure is converted into mechanical work. The power output achieved is proportional to the product of the volume flow rate and the pressure drop across the turbine. The air flow through the turbine can be regulated by varying the turbine blades pitch angle. This mechanical energy can be converted into electric energy by coupling the turbine to the generator. Solar chimneys do not necessarily need direct sunlight. They can exploit a component of the diffused radiation when the sky is cloudy. The lack of system dependence on the natural occurrence of wind, which is intermittent, makes it a very attractive development [4, 21]

3. Mathematical Analysis:

The power output of a solar chimney depends on parameters such as the ambient conditions and structural dimensions of the system. The former includes quantities such as the solar radiation intensity and ambient temperature, whereas the latter includes the height and radius of both the chimney and collector.

In order to make the interrelationships comprehensible, the fundamental dependencies and influence of the essential parameters on the predictable power output of a solar chimney power plant are presented here in a simplified form for the three main components of the solar chimney power plant: the solar collector, the chimney and the wind turbine. The performance of solar chimney power plant is based on the mathematical model described in [4].

A. The Solar Collector

A solar chimney collector converts available solar radiation G onto the collector surface A_{coll} into heat output. The collector efficiency can be expressed as a ratio of the heat output of the collector as heated air $\dot{Q}$ and the solar radiation G times A_{coll}

$$\eta_{coll} = \frac{\dot{Q}}{A_{coll}.G} \tag{1}$$

Heat output $\dot{Q}$ at the outflow from the collector under steady conditions can then be expressed as a product of the mass flow $\dot{m}$, the specific heat of air c_p and the temperature difference between collector inflow and outflow ΔT

$$\dot{Q} = \dot{m}.c_p.\Delta T \tag{2}$$

Where

$$\dot{m} = \rho_{coll}.v_c.A_c \tag{3}$$

With ρ_{coll} density of air at temperature $T_0 + \Delta T$ at collector outflow/chimney inflow, $v_{coll} = v_c$ is the air speed at collector outflow/chimney inflow, and A_c chimney cross section area.

For collector efficiency this gives

$$\eta_{coll} = \frac{\rho_{coll}.v_c.A_c.c_p.\Delta T}{A_{coll}.G} \tag{4}$$

To evaluate collector performance, it is necessary to know the mean plate temperature, which could be estimated by the method recommended in [22] as follows.
For the heat balance at the collector

$$\dot{Q} = G.A_{coll}.\tau.\alpha - U_l.A_{coll}.(T_p - T_{amb}) \tag{5}$$

Here α represents the effective absorption coefficient of the collector, taken as 0.9; τ is the transmissivity of the collector glazing, taken as 0.88; T_p is the plate temperature; T_{amb} is ambient temperature and U_l is the overall heat loss coefficient. The overall heat loss coefficient, in W/m^2K, of a single glazed collector can be obtained from the following relation [22]

$$U_l = 5.5 + 0.024\,t_p \tag{6}$$

Where t_p is the plate temperature in ^oC.
The heat transfer to the air inside collector from the plate is

$$\dot{Q} = h.A_{coll}.(T_p - T_2) \tag{7}$$

Where h is the convective heat coefficient between plate and air and T_2 is the temperature of air inside the collector.

B. The Chimney

The chimney converts the heat flow $\dot{Q}$ produced by the collector into kinetic energy and potential energy. Thus the density difference of the air caused by temperature rise in the collector works as driving force. A pressure difference ΔP_{tot} is produced between chimney base (collector outflow) and the surroundings

$$\Delta P_{tot} = g.\int_0^{H_c} (\rho_e - \rho_c).dh \tag{8}$$

With g acceleration due to gravity, H_c chimney height, ρ_e air density in outer environment and ρ_c air density in the chimney. The total pressure difference causing the draught in the chimney increases with chimney height and the density difference. It can be divided into a static and a dynamic component, neglecting friction loss

$$\Delta P_{tot} = \Delta P_s + \Delta P_d \tag{9}$$

The static pressure difference drops at the turbine; the dynamic component describes the kinetic energy of the airflow.

The power contained in the flow is the product of total pressure difference and the volumetric flow rate of air

$$P_{tot} = \Delta P_{tot}.v_c.A_c \tag{10}$$

From which the efficiency of the chimney can be established

$$\eta_c = \frac{P_{tot}}{\dot{Q}} \tag{11}$$

C. The Wind Turbine

The wind turbine generator fitted at the base of the chimney converts free convection flow into rotational energy. The pressure drop ΔP_s across the turbine can be expressed from Bernoulli equation

$$\Delta P_s = \Delta P_{tot} - \frac{1}{2}\rho_c.v_c^2 \tag{12}$$

The theoretical useful power P_{wt} at the turbine becomes

$$P_{wt} = v_c.A_c.\Delta P_s \tag{13}$$

From the above equations the power of wind turbine will be zero at ΔP_s=0 and at ΔP_s= ΔP_{tot}. It takes a maximum between these extremes at

$$v_{c.mp} = \sqrt{\frac{2\,\Delta P_{tot}}{3\,\rho_c}} \tag{14}$$

The maximum power is achieved when two thirds of the total pressure difference is utilized by the turbine and can be expressed as

$$P_{wt.\max} = \frac{2}{3} . \eta_{coll} . \eta_c . A_{coll} . G \qquad (15)$$

The maximum electrical power from the solar chimney is obtained by multiplying Eq. (15) by wind turbine efficiency that contains both blade, transmission and generator efficiency.

4. Results and Discussion:

The above-mentioned mathematical model was used to estimate the performance of solar chimney power plant in some locations in Egypt theoretically. For assumed initial values of collector radius of 1500 m, chimney radius of 25 m, and height of chimney of 500 m, the above equations were solved together by iteration methods. The calculations were performed for six locations covered a large part of Egypt, Hurghada, Ras Banas, Kharga, Suez, Aswan and New Valley.

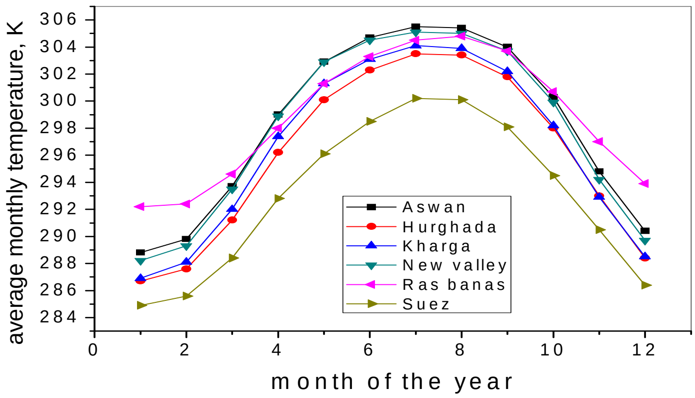


Fig. 2: Average monthly temperature in the selected locations

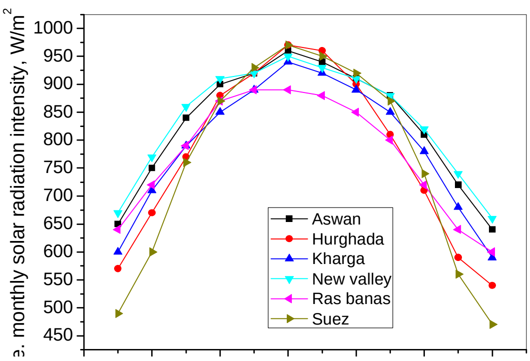


Fig. 3: Average monthly solar radiation intensity in the selected locations

Figure 2 shows the monthly average air temperature in these locations at 10 m above the surface of the earth. Aswan in south is the location with average higher temperature while Suez in north has the lowest average temperature. The monthly averaged midday insolation incident on a horizontal surface measured by NASA in these locations is shown in Fig. 3 [23]. These values were used in the calculations of average monthly power generation in each location. The expected average monthly power output in the six selected locations is given in Fig. 4. In all locations, the generated power in spring and summer months is found to be higher than its value in other months. The generated power from these locations reaches its maximum value between 20 and 23 MW in June.

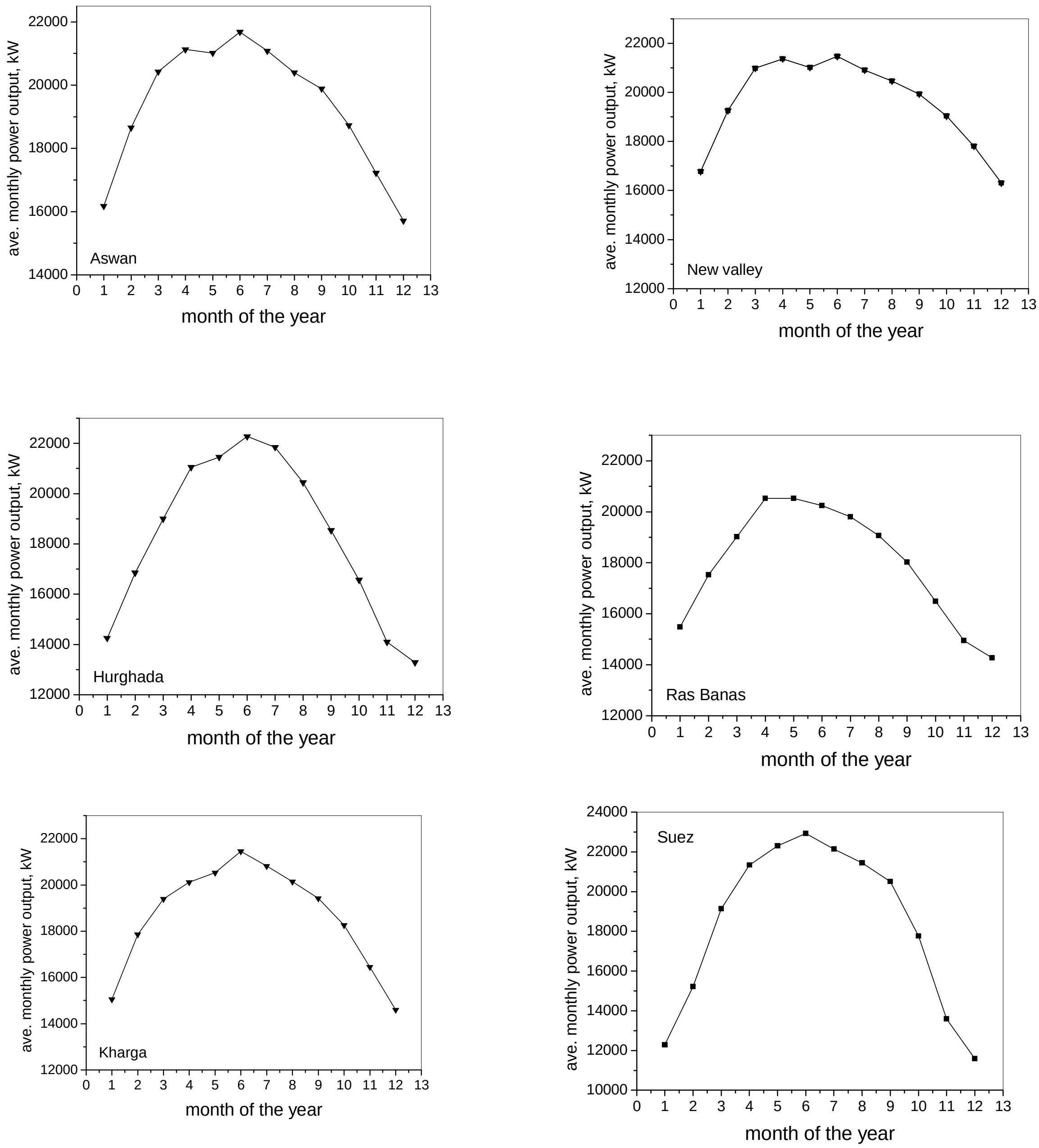
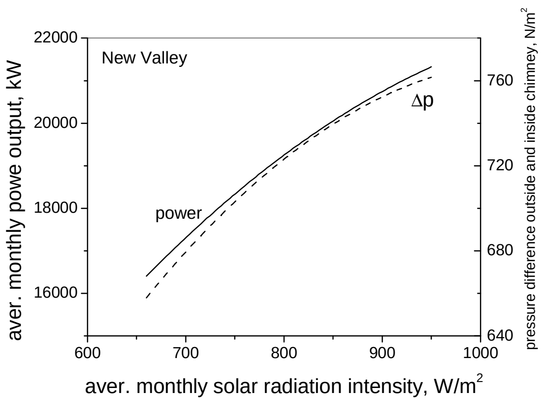


Fig. 4: Variation of average monthly power output in Aswan, Hurghada, Kharga, New Valley, Ras Banas and Suez.

The change in average monthly power output and pressure difference outside and inside chimney with solar radiation intensity in some of the selected locations, New Valley and Ras Banas, is illustrated in Fig. 5. There is an increase in both power output and pressure difference with the rise in solar radiation intensity. The same results are obtained for the other locations. Figure 6 clarifies the relation between temperature difference inside and outside chimney and solar radiation intensity in New Valley and Ras Banas. The temperature difference increases with the grow in solar radiation intensity.



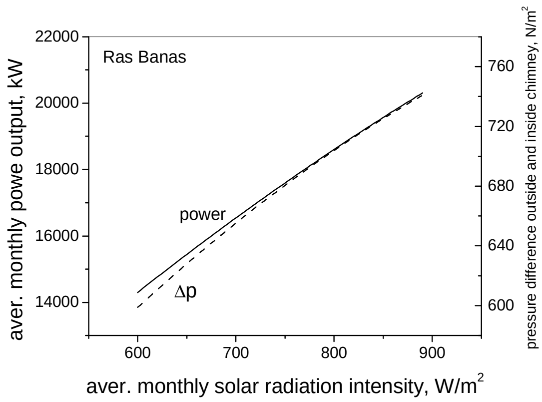
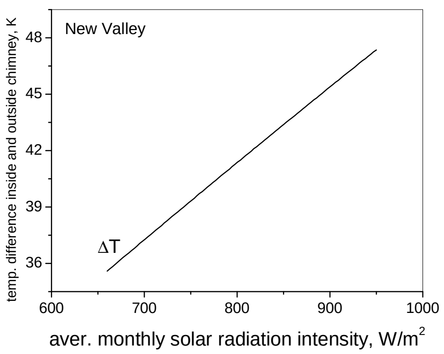


Fig. 5: Change of average monthly power output and pressure difference in New Valley and Ras Banas.



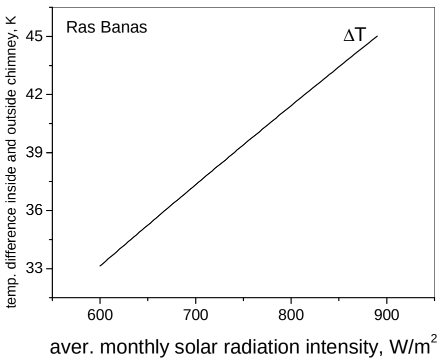


Fig. 6: Variation of temp. difference inside and outside chimney with solar radiation intensity in New Valley and Ras Banas

The variation in wind speed inside and free wind speed outside chimney with the change in solar radiation intensity is plotted in Fig. 7 for New Valley and Ras Banas. It is seen that, due to solar heating in the collector, the wind speed inside chimney becomes more higher than the free wind speed outside. The wind speed inside chimney reaches more than 7 times of the value of free wind speed outside chimney. Therefore, it is correct to say that the solar chimney is a machine for producing wind. The wind speed inside chimney increases also with the rise in solar radiation intensity. The same results are obtained for the other studied locations.

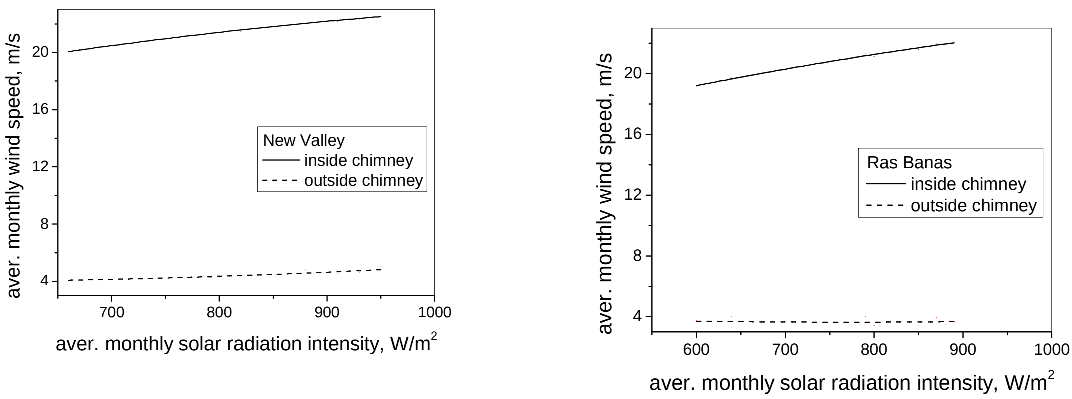


Fig. 7: Variation of average monthly wind speed inside and outside chimney in New Valley and Ras Banas.

The expected yearly energy that can be generated from the studied locations is given in Fig. 8. One can see that, a huge amount of energy can be generated from these locations. The six locations are promising in the field of solar chimney power plants in Egypt. Therefore a part of energy demand in Egypt can be covered through the use of solar chimney power plants. The use of conventional sources of energy, like oil and natural gas, can be reduced. This results in a reduction in the emissions of harmful gases.

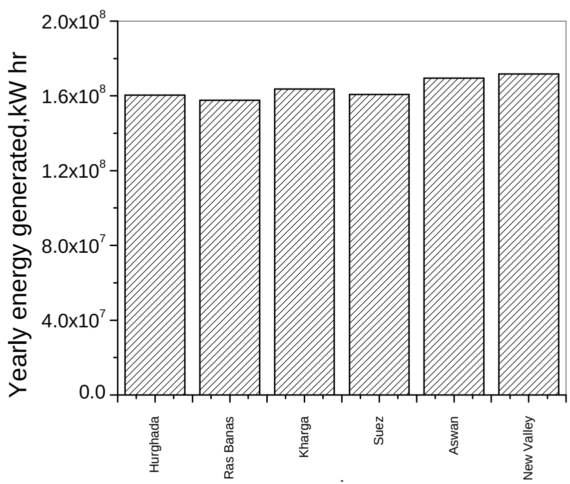


Fig. 8: Yearly energy generated from the studied locations

5. Conclusions:

In this paper a mathematical model has been developed for predicting the performance of solar chimney power plants in some parts of Egypt and for estimating the quantity of the produced electric energy. This mathematical model which based on the energy balance was developed also to examine the effect of various ambient conditions and structural dimensions on the power output. The performance of a power generation in six locations in Egypt, namely, Hurghada, Ras Banas, Kharga, Suez, Aswan and New Valley was studied.

The results showed that a solar chimney power plant with 500 m chimney height, 3000 m collector diameter and 50 m chimney diameter is capable of producing yearly average 18–19.6 MW electric power from the studied locations. In all locations, the generated power in spring and summer months is found to be higher than its value in other months and the generated power from these locations reaches its maximum value between 20 and 23 MW in June. It was shown that New Valley has a higher yearly average power generation of 19.6 MW, while Ras Banas is the location with the lowest yearly average power generation of 18 MW.

The results indicated that the power generation capacity increases with the increase in solar radiation intensity. However, the power generation is slightly affected by changing the ambient temperature.

The expected yearly energy that can be generated from the studied locations is found to be between 1.6-1.7 $\times 10^8$ kW hr. One can see that, a huge amount of clean energy can be generated from these locations. Therefore a part of energy demand in Egypt can be covered through the use of solar chimney power plants. This reduces the use of conventional sources of energy, like oil and natural gas, which considered the main source of the emissions of harmful gases.

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