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Energy Performance Analysis of a Solar Chimney Power Plant with and without Thermal Storage System

IKHLEF Khaoula[#1], LARBI Salah[#2]

[#]*École Nationale Polytechnique d'Alger (ENP), Laboratoire de Génie Mécanique et Développement (LGMD)*
10 Avenue Hassen Badi, BP182, El Harrach, Alger, Algérie

[1]khaoula.ikhlef@g.enp.edu.dz

[2]salah.larbi@g.enp.edu.dz

Abstract— **The present work is dedicated to the performance analysis of solar chimney power plants with and without thermal storage system. The performance prediction is carried out according to Schlaich's and Hammadi's mathematical models. The analysis is based on variable solar incident radiation along the day. Obtained results enable us to understand the influence of meteorological conditions, the importance of the thermal storage system and evaluate the effect of geometrical parameters on the power production. Good agreement is observed between the results of this study and those obtained experimentally and theoretically from the literature review.**

Keywords— **Solar Chimney power plant; Energetic performances analysis; Thermal storage; Mathematical model; Sites of Algeria.**

Nomenclature

A_{coll}	Collector area	m^2
Cp_a	Specific heat of air	J/kg K
Cp_s	Specific heat of water-storage	J/kg K
D_{coll}	Solar collector diameter	m
G	Solar intensity	W/m^2
H_{coll}	Height of the collector	m
H_t	Tower height	m
H_s	Water-storage layer thickness	m
h_i	Heat transfer coefficient of inside collector	W/m^2 K
h_∞	Heat transfer coefficient of outside collector	W/m^2 K
k_a	Thermal conductivity of air	W/m^2 K
$\dot{m}_a$	Air mass flow rate	kg/s
t	Time	S
$T_{a,i}$	Air temperature at the collector inlet	K
$T_{a,0}$	Air temperature at the collector outlet	K
T_∞	Ambient temperature	K
T_s	Water-storage temperature	K
$\bar{u}_{coll}$	Average air velocity in the collector	m/s
u_t	Air velocity in the solar tower	m/s
u_{wind}	Wind velocity	m/s
α	Absorptivity of water-storage	/
ρ_a	Air density in the collector	kg/m^3
ρ_s	Water-storage density	kg/m^3
η_{tg}	Turbine-generator efficiency	/
$\Delta\tau$	Day length	hr

I. Introduction

In order to ensure sustainable development and to diversify its energy needs, the world is engaged in an important program of development of renewable energies. To meet its energy needs, it aims to significantly increase the contribution of renewable energies. One of the options that will help meet these demands is the solar chimney power plant (SCPP). The SCPP is a device of renewable energy power plant that transforms solar energy into electricity.

The solar chimney offers a method for large-scale generation of electricity from solar energy. Air is heated near the ground by trapping solar radiation in a flat circular glass-roof greenhouse. The heated air rises in the tower, and the updraft is used to drive a turbine.

The idea of the chimney solar power plant was originally proposed by two German engineers, Jorg Schlaich and Rudolf Bergermann in 1976 [1]. In 1979, they developed the first prototype with a maximum power of 50kW produced in Manzanares, south of Madrid, Spain. It consisted of a chimney with a radius of 5m and a height of 195m and a collector with a radius of 120m and a variable height between 2m at the entrance and 6m at the junction with the chimney. The installation was operational from 1982 until 1989. Tests have shown that the installation works reliably and therefore that the concept is technically viable [2, 3]. The energy balance, design criteria and cost analysis were discussed in the work of Haaf et al. [2]. An analysis showed that the cost of generating electricity from the plant was 25 DM/kWh (0.098 USD/kWh based on the 1983 average exchange rate).

Atit and Tawit [4] carried out a study to compare the performance of chimney solar power plants using five simple theoretical models, proposed in the literature. The parameters used in the study were the different geometric parameters, vegetation and insolation. Gholamalizadeh and his collaborators [5] presented a comprehensive analytical and numerical analysis to predict the performance of a chimney solar power plant in Kerman. Chiemeka and Atikol [6] studied the feasibility of installing a chimney solar power plant (SCPP)

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under the conditions of Northern Cyprus as well as the efficiency of the installation for different dimensions such as the diameter of the collectors and the height of the chimney. Atit and Tawit [7] determined a dimensional analysis combining eight primitive variables into a single dimensionless variable, which establishes a dynamic similarity between a prototype and its scaled models. The basic physical conditions of thermodynamic fluid processes in chimney solar power plants, including the transfer of solar radiation and the numerical difficulties expected in numerical simulation are summarized in the work of Wilfried B. Krätzig [8]. Bernardes et al. [9] conducted a comparison study of the methods used to calculate the heat fluxes in the collector and their effects on the performance of the chimney solar power plant.

Chimney solar power plants are also studied numerically using the commercial code ANSYS Fluent [10]. The study encompasses a wide range of scales with tower heights varying between 1m and 1000m. The optimization of the major components of the geometry of the SCPP to study and improve the flow characteristics inside the latter is carried out in Sandeep's work using a CFD code from ANSYS CFX [11]. Fei Cao et al. [12] designed a program, based on TRNSYS, to simulate the performance of a chimney solar power plant. The observation made is that energy production in a CCS is more relevant to local solar irradiation than at room temperature. Jing-yin Li et al. [13] proposed a complete theoretical model for the evaluation of the performance of a chimney solar power plant (CSC), which was verified by the experimental data of the Spanish prototype. This model takes into account the effects of fluid flow and heat loss and temperature drops inside and outside the chimney. Shadi et al. [14] developed a pilot installation of a chimney solar power plant on the southern campus of the University of Damascus in Syria. The solar collector considered is tilted 35° to the south with an approximate area of 12.5m2. The diameter of the chimney is 0.31m and its height is 9m. Although the measurements were taken during the winter, the air temperature increased to reach a maximum value of 19 ° C, which generates an air speed rising in the chimney reaching a maximum value of 2.9 m/s.

Kasaeian and his collaborators [15] built a pilot chimney solar power plant with a collector 10m in diameter and a chimney 12m high. The temperature gradient obtained between the outlet of the collector and the atmosphere reaches 25°C. A maximum air speed of 3m/s was recorded in the chimney, while the speed at the inlet of the collector was zero. Hurtado et al. [16], in their work, analyzed the thermodynamic behavior and the power that can generate a chimney solar power plant taking into account the ground as a heat storage system, through numerical modeling in non-stationary conditions. The influence of the thermal inertia of the ground allows a gain of 10% in the power generated by the turbines. Bernardes et al. [17] performed numerical simulations to study the performance of two output power control systems applicable to chimney solar power plants. The independent control variable used is either the volume flow rate or the pressure drop across the turbine. The values found in the literature for the optimal ratio of pressure drop at the turbine to the pressure potential vary between 2/3 and 0.97. It is shown that the optimal ratio is not constant throughout the day and that it depends on the heat transfer coefficients applied at the level of the collector. Their study is a contribution to the understanding of the performance and control of the chimney solar power plant and can be useful in the design of turbines intended for the chimney solar power plant. Maia et al. [18] carried out an exergetic and energetic study of the air flow inside a chimney solar power plant. The results obtained show that the losses of exercise were lower and the yield was higher by considering the lowest ambient temperature as a reference temperature, compared to the instantaneous ambient temperature. Mehran and his collaborators [19] built a pilot chimney solar power plant with a 3m diameter collector and a 2m high chimney at the University of Tehran, Iran. The temperature difference between the chimney entrance and the ambient was 26.31°C. The output data for different header heights has been obtained and the report shows that reducing the input size has a positive effect on plant performance. The recirculation of the air flow at the chimney entrance is not observed and they found that this phenomenon is directly related to the geometry of the structure. The maximum air speed is 1.3 m/s reached inside the chimney while the speed at the inlet of the collector was around zero. Xinping et al. [20] presented a correlation model between the atmospheric fluid flow and the fluid flow inside a chimney solar power plant (SUT) assuming that at the entrance to the plant the fluid is compressible. The results showed that the flow of the wind had a great influence on the speed of entry of the fluid into the manifold. With an increase in the wind flow speed, the fluid flow speed inside the plant increases. Atit [21] proposes a study of a chimney solar power plant with an inclined external surface of the collector. This will reduce the height of the chimney and the cost of construction.

Atit and Tawit [22], in this study, theoretically modeled the solar collector, the chimney and the turbine. The model is used to predict the performance characteristics of large chimney solar power plants thus showing the size of the power plant, the pressure drop factor at the turbine level and the solar flux are important parameters for improving the performance of the latter. In addition, the study proposes, to meet the electricity demand of a typical village in Thailand, a power plant with a 200m radius collector and a 400m high chimney. In addition, it is shown that the optimal ratio between the suction pressure of the turbine and the drive pressure available for the proposed installation is approximately 0.84. The purpose of the study proposed by Roozbeh et al. [23] is to carry out a more detailed digital analysis of a chimney solar power plant. A mathematical model based on Navier-Stokes equations, continuity and energy equations has been developed to describe the mechanism of the chimney solar power plant in detail. Two different numerical simulations were carried out for the geometry of the prototype in Manzanares, Spain. First, the equations governing the flow were solved numerically using an iterative technique.

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In 2010 Bernardes et al. evaluated the operational control strategies applicable to solar chimney power plants and Koonsrisuk et al. described the constructal-theory search for the geometry of a solar chimney [2, 3]. So far, some experimental studies have been carried out and several solar chimney pilots in different sizes were constructed [24-31] Zhou et al. (2007), Mawire et al. (2008), Kasaeian et al. (2011), Mehla et al. (2011), Zuo et al. (2012), Kalash et al. (2013), Li and Liu (2014) and Rekaby (2016). In those researches, the influence of geometrical and climatic parameters on the solar chimney performance was evaluated and temperature distributions in whole system were reported. Siyang and Dennis (2017) to analyse the hydrodynamic features of a series of divergent chimneys in a SCPP [34] established a mathematical model. In the same year, a comprehensive and updated review that includes most of the experimental, analytical and simulation studies, the solar chimney applications, hybrid systems and geographical case studies based on extended references with different focuses in different sections [35]. One year later, the effect of the chimney configuration on the solar chimney power plant performance was investigated by Bouabidi (2018) et al. A series of numerical simulations were conducted to simulate the turbulent flow and an experimental setup was developed in Tunisia to carry out several measurements [36]. Niloufar Fadaeia and Alibakhsh Kasaeian (2018) studied the effect of latent heat storage (LHS) on a solar chimney pilot experimentally [37]. Mathematical models of the solar double-chimney power plant (SDCPP) are established and its performances are analyzed by Fei Cao and his collaborators (2018) [38].

This paper presents a theoretical study of the solar chimney power plant of Manzanares installed in the southern region of Algeria (Adrar). A simplified theoretical model of the solar chimney power plant is described to evaluate the power produced with and without storage system and to estimate the effect of geometrical parameters on the power production of the power plant. The results show that the tower tall, the tower diameter, the collector diameter and the thickness of the water-storage have a significant effect on the power production.

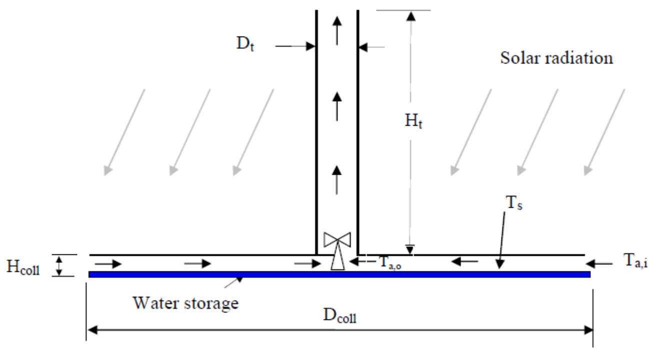

Fig. 1 The solar chimney.

II. Mathematical Model

A. Schlaich Model

The schleich model has previously been presented in the article "Technico-economic aspect analysis in the design of solar chimney power plants" [39].

B. Hammadi Model [43]

The simplified heat balance equation of the solar collector shown in Fig. 1 is given as:

$$\alpha\, G\, A_{coll} - h_i\, A_{coll}\,(T_s - T_a) = m_s\, Cp_s \frac{dT_s}{dt} \qquad (1)$$

Where:

$$m_s = \rho_s\, A_{coll}\, H_s \qquad (2)$$

And the energy equation for the air stream through the collector is:

$$h_i\, A_{coll}(T_s - T_a) - h_\infty\, A_{coll}(T_a - T_\infty) = \dot{m}_a Cp_a\left(T_{a,0} - T_{a,i}\right) \qquad (3)$$

Where:

$$T_a = \frac{T_{a,0} + T_{a,i}}{2} \qquad (4)$$

Substitution of equations (2),(3), and (4) into equation(1) gives the following time dependent differential equation:

In replacing $T_{a,0} = 2\,Ta - T_{a,i}$ dans (3), the result obtained with equation (2) is injected into equation (1):

$$\frac{dT_s}{dt} = \frac{\alpha G}{\rho_s\, Cp_s\, H_s} - \frac{h_i}{\rho_s\, Cp_s\, H_s}\left[T_s - \frac{\left(\frac{\dot{m}_a Cp_a}{A_{coll}}\right)T_{a,i} + \frac{1}{2}(h_i T_s + h_\infty T_\infty)}{\left(\frac{\dot{m}_a Cp_a}{A_{coll}}\right) + \frac{1}{2}(h_i + h_\infty)}\right] \qquad (5)$$

The inside heat transfer coefficient (hi) is taken as [40].

$$h_i = \frac{\left(f/_8\right)(Re - 1000)\,Pr}{1 + 12.7\sqrt{f/_8}\left(Pr^{2/3} - 1\right)}\frac{k}{D_h} \qquad (6)$$

Where:

$$f = [0.79\ln(Re) - 1.64]^{-2} \qquad (7)$$

Where Dh is the hydraulic diameter of the solar collector by considering the flow through the collector as flow between parallel plates of infinite width;

$$D_h = 2H_{coll} \qquad (8)$$

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And:

$$Re = \frac{\rho_a \, \bar{u}_{coll} D_h}{\mu_a} \tag{9}$$

From the continuity equation:

$$\dot{m}_a = \rho_{a,o} \frac{\pi}{4} D_t^2 \, u_t = \rho_a \, \pi \, D_{coll} \, H_{coll} \, u_{coll} \tag{10}$$

Where:

$$\rho_a = \frac{\rho_{a,i} + \rho_{a,o}}{2} \tag{11}$$

The average air velocity through the collector can be expressed as:

$$\begin{aligned} \bar{u}_{coll} &= \frac{\dot{m}_a}{2 \, \pi \, \rho_a \, (r_{coll} - r_t)} \int_{r_t}^{r_{coll}} \frac{dr}{r} \\ &= \frac{\dot{m}_a}{2 \, \pi \, \rho_a \, (r_{coll} - r_t)} \ln \frac{r_{coll}}{r_t} \end{aligned} \tag{12}$$

Where r_{coll} and r_t are equal to ($D_{coll}/2$) and ($D_t/2$) respectively.

The heat transfer coefficient the collector to the ambient air is given by [40]:

$$h_\infty = 5.7 + 3.8 \, u_{vent} \tag{13}$$

- **The Solar Chimney Tower**

The velocity of the hot air at the collector outlet (tower inlet) can be can be estimated using Bernoulli equation as follows:

$$u_t = \sqrt{\frac{2\Delta p}{\rho_{a,o}}} \tag{14}$$

And the pressure difference due to the between the air at the solar tower base and the ambient air is given by:

$$\Delta p = g \int_0^{H_t} \left(\rho_{a,o} - \rho_\infty\right) dH_t = g \left(\rho_{a,o} - \rho_\infty\right) H_t \tag{15}$$

Thus, the equation (14) can be written in term of temperature difference as follows:

$$u_t = \sqrt{\frac{2g \, H_t \left(T_{a,o} - T_\infty\right)}{T_\infty}} \tag{16}$$

The pressure difference is used to accelerate the air and is thus converted to kinetic energy:

$$P_k = \frac{1}{2} \, \dot{m}_a \, u_t^2 \tag{17}$$

The output electrical power of the plant can be found as [41]:

$$P_e = \frac{1}{3} \eta_{tg} \, \rho_{a,o} \, A_t \, u_t^3 \tag{18}$$

The amount of power varies with the variation of incident solar radiation. The equation that describes the amount and variation of solar radiation incident on a clear day is given by the following sinusoidal relation [42]:

$$G = G_g \sin\left(\frac{\pi \, t}{\Delta\tau}\right) \tag{19}$$

Where Gg is the global solar constant which approximately equal to 1000 W/m^2, t=0 for the sunrise and $\Delta\tau$ is the day length which is given by the difference between the sunrise and the sunset.

III. Results and Discussion

The Manzanares solar chimney (Spain, 150km south of Madrid) was used in this study for the simulation with the meteorological data of Adrar. It is a prototype, built between 1982 and 1989 years. The prototype has a tower of 200m high and a collector of 4000m². It reached a production of 44MWh/year, for a peak power of 50kW [41]. Table 1 gives the technical data of Manzanares prototype.

TABLE I

Technical data of Manzanares prototype [41]

H_T : Tower height [m]	194.6
R_T : Tower radius [m]	5.08
R_C : Mean collector radius [m]	122
H_C : Mean roof height [m]	1.85
U_{vent} : Up wind velocity [m/s]	5
η_e : Turbine efficiency	0.83
α : Friction loss factor	0.9

The technical data injected into the Hammadi program, determined according to an average operating temperature of 300K are:

- The water-storage height 10cm;
- The transmittance and absorbance product of the collector 0.65;
- The absorptivity coefficient of storage water 0.8;
- The density of water 1000 kg/m^3;
- The specific heat of water 4178 J/kg K;
- The density of the ground 1900 kg/m^3;
- The specific heat of the ground 840 J/kg K;
- The thermal conductivity of the ground k = 1.26 W/m K;
- The specific heat of the air 1006 J/kg K;

The maximum horizontal solar irradiation and the ambient temperature of the Adrar region (Algeria) are used to analyze the performance of the solar chimney. Meteorological data are taken by METEONORM 7 software with period data (1991-2010). The month of July was chosen for the simulation because it has the highest irradiance, the meteorological data for the Adrar region are illustrated in Fig 2 and Fig 3:

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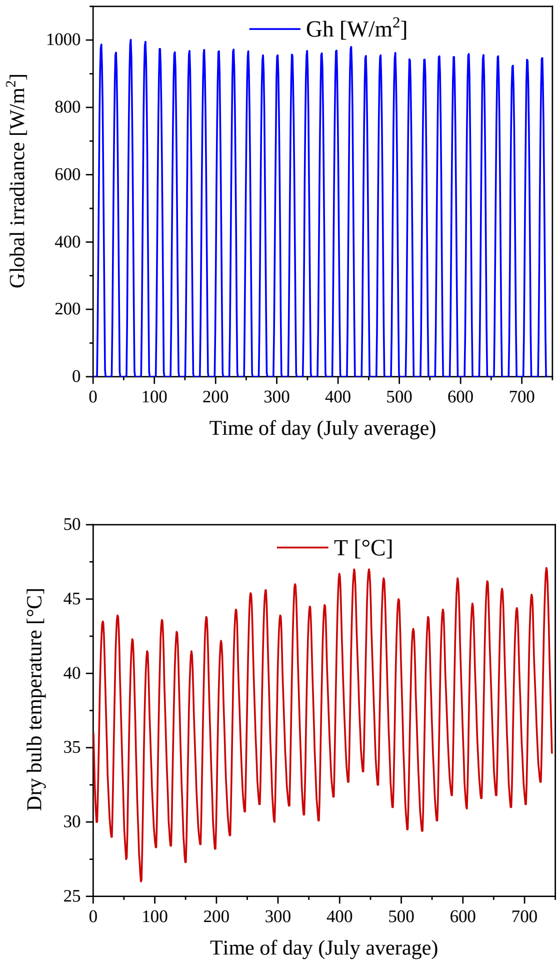

Fig. 2 Hourly average global solar irradiance and temperature for the region of Adrar.

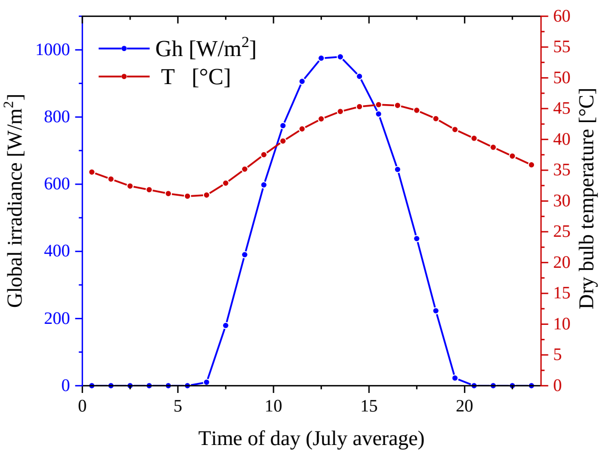

Fig. 3 Daily average global solar irradiance and temperature for the region of Adrar.

In the following analysis, the importance of the power produced by the Manzanares power plant located in the Adrar region with and without a storage system was quantified, and Fig 4 shows the results.

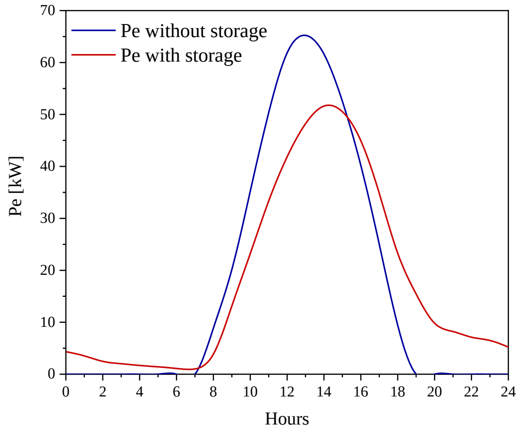

Fig. 4 Power produced with and without storage system (July month).

Figure 4 shows the production of the power plant with and without storage system, the difference can be shown in two ways: a decrease in the peak value and an increase in the min. It can be seen that the power plant with storage system continues to produce energy after the disappearance of the global solar irradiance (null GHI). This generation of energy is provided by the storage system.

In this section, we investigated the effect of the variation of certain technical parameters (geometrical) on the electrical production of the solar chimney power plant equipped with a thermal storage system, by using the meteorological data of the site of Adrar.

- Effect of storage height (Hs):

The model used considers the storage medium as a layer located just above the ground and under the collector, with a height Hs and a surface equal to that of the collector. Fig 5 shows the electric power produced for different storage thickness layers such that the storage thicknesses were considered: 5cm, 15cm and 30cm.

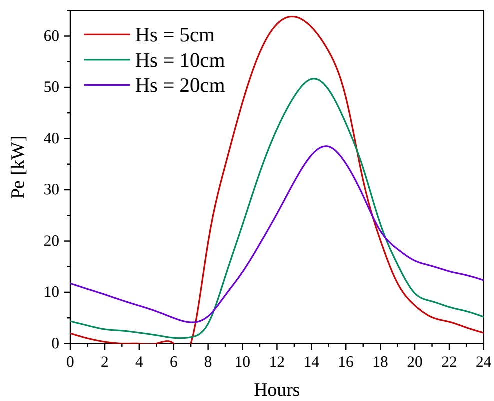

Fig. 5 Effect of storage height on the power production.

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Figure 5 shows the effect of water-storage thickness on the output power. This effect can be shown in two ways: a decrease in the peak value and an increase in the min. The more the storage system increases the more the storage effect becomes important at the ends of the curves and therefore the electric power produced during the non-sunny periods is greater.

- Effect of the diameter of the chimney (D_t):

The diameter of the chimney is one of the essential parameters entering into the study of the feasibility in the construction of solar chimney power plant. Fig 6 shows the results of the electric power produced with the variation of the diameter.

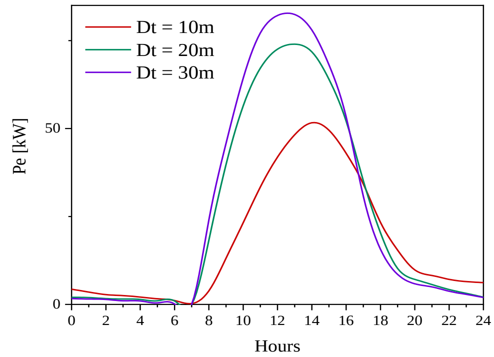

Fig. 6 Effect of the diameter of the chimney on the power production.

Figure 6 shows a significant increase in the power with the tower height due to the increase of the pressure difference between air at the tower base and ambient air as the tower height increases.

- Effect of the height of the chimney (H_t):

The height of the chimney is also considered as one of the parameters entering into the feasibility study of the construction of solar chimney power plant, a very high chimney will require a remarkable investment, an optimization of this parameter is necessary. In this section, we will try to understand the effect of the variation of the height of the chimney on the electricity production of the power plant. Fig 7 shows the results the effect of the variation of the height of the chimney on the power produced.

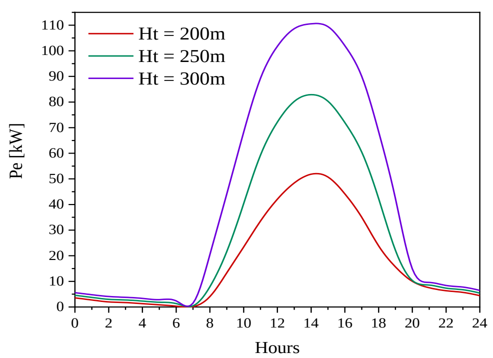

Fig. 7 Effect of the height of the chimney on the power production.

Figure 7 shows that daily electricity production is also directly related to the height of the chimney. It is noted that the higher the height of the chimney, the more the daily electrical power produced increases considerably.

- Effect of collector radius (R_C):

The diameter of the collector represents a fundamental parameter considering the cost necessary for its construction. An optimization of this parameter is necessary to reduce expenses. We will try to understand the effect of the variation of the collector diameter on the electricity production of the solar chimney. Fig 8 shows the effect of collector radius on power produced.

Figure 8 shows that the collector radius has a direct influence on daily electricity production. We notice that the power production of the power plant increases with increasing the collector diameter due to a more solar energy absorbed as the collector area increases.

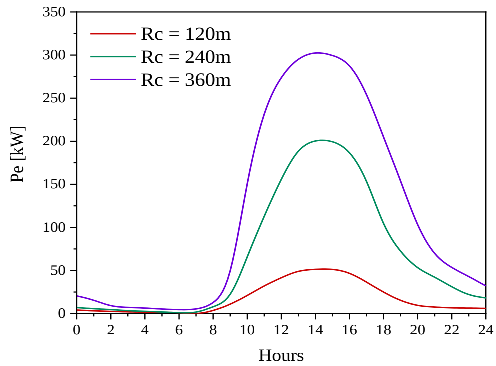

Fig. 8 Effect of collector radius on the power production.

IV. Conclusion

The study presented in this article relates to the analysis of the energy performance of a solar chimney power plant with and without thermal storage support. The site of Adrar was chosen considering the importance of its solar energy potential compared to all regions of Algeria, and the results found shows that:

- The results obtained have shown that thermal storage is the solution to the intermittency of solar radiation such as the storage system increase the power produced during periods of low or no solar irradiance.
- Thermal storage avoids the use of non-renewable energies to guarantee continuous production.
- The optimization study allowed us to understand the variation of the technical parameters on the power produced.

Through the results obtained in this study, it can be noted that a solar chimney plant equipped with a thermal storage system is one of the most interesting alternatives to guarantee a continuous and large-scale energy production. Energy

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performance can be improved either by improving storage systems by acting on the specific heat of the fluids or solids used in the storage or by acting on the sensible and latent heat storage pairing or the combination of both.

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