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Technco-Economic Aspect Analysis of Solar Chimney Power Plants

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Abstract— **The present work is devoted totechno-economic analysis of the solar chimney power plant (SCPP) of Manzanares site. A mathematical model is presented to describe the solar chimney power plant mechanism. The technical study is carried out in order to analyse the annual performances and studying the effect of various parameters on power output.The economic study is based on the calculation of the LCOE "Levelized Cost of Energy" which corresponds to the complete price of energy over the lifetime of the equipment. A profitability study of the prototype of Manzanares is developed for Maghreb countries such as Algeria, Tunisia and Morocco as well as for some European countries: Spain, Germany and Denmark.The technical study demonstrates that the capacity of the power generation depends on several parameters such as solarradiation and duration of sunshine. For Maghreb countries, the economic study reveals illustrates that the cost of the kWh produced by the solar chimney isunprofitable (negative return) in contrast to European countries where it is profitablethat is with positive return.**

Keywords— **Renewable energies, Solar chimney power plant, Technico-economic study, Mathematical modelling.**

Symbol	Signification	Units
Technical		
A_{ch}	Cross sectional area of the solar chimney	$[m^2]$
A_{coll}	Area of the solar collector	$[m^2]$
C_p	Specific heat of air	$[KJ/Kg\ K]$
G	Solar heat flux	$[W/m^2]$
H	Solar chimney height	$[m]$
h	Outflow heat transfer coefficient	$[W/m^2\ K]$
$\dot{m}$	Air mass flow rate	$[Kg/s]$
P_{max}	Max. output mechanical power	$[W]$
P_e	Electric power produced	$[W]$
Q	Heat absorbed by air in the collector	$[W]$
T_{coll}	Temperature of air in the collector	$[K]$
T_0	Ambient temperature	$[K]$
u	Air velocity of the solar chimney	$[m/s]$
α	Absorbance of the solar collector	
η_{coll}	Efficiency of solar collector	
η_e	Electrical generator efficiency	
ρ_{coll}	Air density in the collector	$[Kg/m^3]$
ρ_0	Ambient air density	$[Kg/m^3]$
ΔP	Pressure difference between the chimney base and the surroundings	
Economical		
I	Total investment cost	[Mio. €]
r	Discount rate	[%]
n	Expected lifetime of power station	[year]
M_y	Annual operation & maintenance cost	[Mio. €/a]
E_y	Electrical energy generated in the year	[kWh]

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 first SCPP prototype was proposed by Schlaich and built in 1982 in Manzanares, Spain [1, 2].In 1983 Krisst demonstrated a 'back yard type' device with a power output of 10W in West Hartford, Connecticut, USA [3]. In a later study 1984, Haaf reported preliminary test results of the plant built in Spain[2]. In 1985Kulunkproduced a micro scale electric power plant of 0.14 W in Izmit, Turkey[4]. The governing differential equations were developed by Padki and Sherif in 1988 to describe the chimney performance [5]. In 1991Yan et al. reported on a more comprehensive analytical model in which practical correlations were used to derive equations for the air flow rate, air velocity, power output and thermofluid efficiency [6]. One year later, Padki and Sherif briefly discussed the effects of the geometrical and operating parameters on the chimney performance [7]. In 1997Kreetzpresented a numerical model for the use of water storage in the collector. His calculations showed the possibility of a continuous day and night operation of the solar chimney [8]. In 1999 Bernardes et al. presented a theoretical analysis of a solar chimney operating on natural laminar convection in the steady state [9]. In 2000 Gannon and Backstrom developed an analysis of the solar chimney including chimney friction, exit kinetic losses and a simple model of the solar collector [10, 11]. More thorough analyses of solar chimney power plant performance were conducted by Kroger and Buys (2001) and Gannon and Von Backstrom (2002) studied the performance of turbines employed in solar chimney power plants [12]. In 2003 Bernardes et al. developed an analytical and numerical model for a solar chimney power plant, comparing simulation predictions to experimental results from the prototype plant at Manzanares [13]. One year later Pastohr et al. conducted a basic CFD analysis on the solar chimney power plant and compared their

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results to another simple model[14]. In 2005Schlaichet al. presented the theory, practical experience, and economy of solar chimney power plants to give a guide for the design of 200-MW commercial solar chimney power plant systems [15]. In the same year a mathematical model was developed by Bilgen and Rheaultfor evaluating the performance of solar chimney power plants at high latitudes [16]. A refined numerical model for simulating large solar chimney plants was presented by Pretorius and Kroger in 2006 [17]. In 2008Ming et al. presented a numerical analysis of the flow and heat transfer characteristics in a solar chimney power plant with an energy storage layer [18]. Zhou et al. (2007), Ketlogetswe et al. (2008) and Ferreira et al. (2008) conducted experimental analyses on solar chimney systems [19, 20, 21]. Koonsrisuk and Chitsomboon (2007) and later Zhou et al. (2009) performed numerical simulations of solar chimneys using a commercial CFD software [22, 23]. In 2010Bernardes et al. evaluated the operational control strategies applicable to solar chimney power plants andKoonsrisuket al. described the constructal-theory search for the geometry of a solar chimney [24, 25]. So far, some experimental studies have been carried out and several solar chimney pilots in different sizes were constructed Kasaeian et al. (2011), Mehla et al. (2011), Zuo et al. (2012), Kalash et al. (2013), Li and Liu (2014) and Rekaby (2016)[26, 27, 28, 29, 30, 31]. 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.A mathematical model was established by Siyang andDennis (2017) toanalysethe hydrodynamic features of a series of divergent chimneys in a SCPP [32]. 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 [33]. 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 [34].The effect of latent heat storage (LHS) on a solar chimney pilot was studied experimentally by NiloufarFadaeia and AlibakhshKasaeian (2018) [35].Mathematical models of the solar double-chimney power plant (SDCPP) are established and its performances are analysed by FeiCao et al. (2018) [36].

The article presents a theoretical study and economics of the solar chimney power plant of Manzanares: First a simplified theoretical model of the solar chimney is described. Then the economic study which is based on the profitability calculation of the chimney of manzanares in several countries for the future commercial systems of solar chimney.

II. MATHEMATICAL MODEL

The analysis presented in this paper is based on the following simplifying assumptions [37]:

1- Uniform heating of the solar collector surface.
2- No temperature gradient of the air inside the collector.
3- No heat loss from the chimney walls.
4- Friction losses of the flowing air in the chimney are neglected.

A. Technical Model

A.1. The Solar Collector

The heat balance equation of the collector can be simplified as:

$$\alpha\, G\, A_{coll} - h\, A_{coll}\,(T_{coll} - T_0) = \dot{m} C_p\,(T_{coll} - T_0) \qquad (1)$$

Where:

$$\dot{m} = \rho_{coll}\, A_{ch}\, u \qquad (2)$$

The efficiency of the solar collector can be defined as:

$$\eta_{coll} = \alpha - \frac{h\,(T_{coll} - T_0)}{G} \qquad (3)$$

A.2. TheChimney

Pressure developed due to the air density between entrance at temperature T_{coll} and exit at T_0 in the chimney is calculated as:

$$\Delta P = g \int_0^H (\rho_0 - \rho_{coll})\, dz \qquad (4)$$

For a vertical adiabatic chimney, the integrating equation (4) gives:

$$\Delta P = g\,(\rho_0 - \rho_{coll})\, H \qquad (5)$$

The air velocity in the chimney can be evaluated using Bernoulli equation as follows:

$$u = \sqrt{2\, \Delta P / \rho_{coll}} \qquad (6)$$

Substitution of equation (5) into equation (6) gives:

$$u = \sqrt{\frac{2\, g\, H\,(\rho_0 - \rho_{coll})}{\rho_{coll}}} \qquad (7)$$

Using the following approximation for ideal gas:

$$\frac{\rho_0 - \rho_{coll}}{\rho_{coll}} \approx \frac{T_{coll} - T_0}{T_0} \qquad (8)$$

The air velocity in the chimney can be written as:

$$u = \sqrt{\frac{2\, g\, H\,(T_{coll} - T_0)}{T_0}} \qquad (9)$$

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Combine equations (1) and (9) yields:

$$\frac{u^2 T_0}{2\, g\, H} - \frac{\alpha\, G\, A_{coll}}{h\, A_{coll} + \rho_{coll} A_{ch}\, u\, C_p} = 0 \quad (10)$$

$$\rho_{coll} A_{ch} C_p T_0\, u^3 + h\, A_{coll} T_0\, u^2 - 2\, g\, H\, \alpha\, G\, A_{coll} = 0$$

The last equation can be solved numerically to evaluate the air velocity through the chimney. Taking the value of heat transfer coefficient:

$h = 5.7 + 3.8 * U_{wind}$

A.3. TheTurbine

Turbines are located at the bottom of the chimney. The maximum mechanical power taken up by the turbines as recommended by Schlaich [38] is:

$$P_{max} = {}^{2}/_{3}\, u\, A_{ch} \Delta P \quad (11)$$

Where:

$$\Delta P = \rho_{coll}\, g\, H \frac{T_{coll} - T_0}{T_0} \quad (12)$$

The heat absorbed by the solar collector can be written as:

$$Q = \eta_{coll} A_{coll}\, G \quad (13)$$

Substitution of equations (12) and (13) into equation (11) gives:

$$P_{max} = \frac{2}{3} \eta_{coll} \frac{g}{C_p T_0} H\, A_{coll}\, G \quad (14)$$

If the generator efficiency defined as ηe, the electric power from the solar chimney becomes:

$$P_e = \eta_e\, P_{max} \quad (15)$$

B. *Economical Model* [39]

The levelized cost of electricity (LCOE) is given by:

$$LCOE = \frac{I.\frac{(1+r)^n .\, r}{(1+r)^n - 1} + M_y}{E_y} \quad (16)$$

According to the formulation above, if the mass flow rate is known or assumed then the power output can be determined. The different steps of the power output computation are:

1. Choose a density;
2. Calculate u using Eq. (10);
3. Calculate T_{coll} using Eq. (9);
4. Calculate ρ_{coll} using Eq. (8) and perform the iteration;
5. Calculate η_{coll} using Eq. (3);
6. Calculate P_{max} using Eq. (14);
7. Calculate P_e using Eq. (15).

A flowchart for these procedures is illustrated in **Fig. 1** [37].

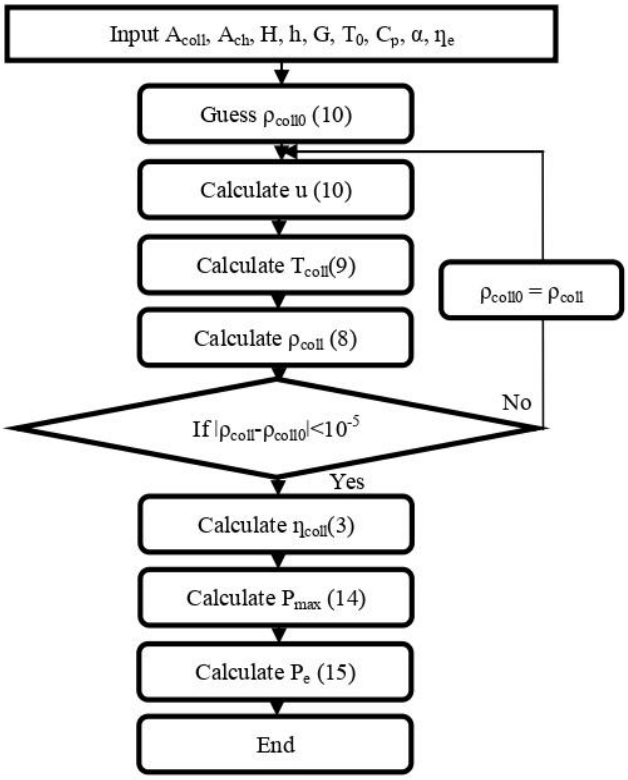

Fig. 1Flow chart of computational procedure [37].

III. Results And Discussion

The Manzanares solar updraft tower (Spain, 150km south of Madrid) is considered in this study. 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 [37].Table 1 gives the technical data of Manzanares prototype.

TABLE I
TECHNICAL DATA OF MANZANARES PROTOTYPE [37]

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} : Upwind velocity [m/s]	5
η_e : Turbine efficiency	0.83
α : Friction loss factor	0.9

A. Technical results

The maximum horizontal solar irradiation and the ambient temperature of the city of Ciudad Real (Manzanares, Spain) are used to analyze the performance of the solar chimney. Meteorological data are taken by METEONORM 7 software with period data (1991-2010). The technical results are illustrated onTable 2:

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TABLE II
MAXIMUM HORIZONTAL SOLAR IRRADIATION AND MONTHLY AVERAGE TEMPERATURE FOR THE CITY OF MANZANARES.

Month	Solar Heat Gain [W/m²]	Max. Monthly average Temp [K]
1	566	279.25
2	699	281.55
3	928	284.85
4	950	287.15
5	975	291.85
6	993	298.45
7	989	300.85
8	986	300.25
9	870	295.45
10	767	289.55
11	652	283.15
12	531	279.85

To validate the analytical model, the theoretical results were compared with experimental data obtained on Manzanares prototype. The power plant results are given inTable 3.

TABLE IIII
RESULTS COMPARISON BETWEEN EXPERIMENTAL DATA AND CALCULATION (MANZANARES, SAPIN).

Technical sheet	Experiments [1]	Present model
I [W/m²]: Irradiation	1000	975
T_0 [K]: Ambient temperature	302	291.85
η_c: Collector efficiency	0.32	0.29648
Pe [kWe]: Power output	50	48.67137
u [m/s]: Upwind velocity in the collector	15	17.65388
ΔT [K]: Temperature difference(collector / ambient)	20	23.8231

The results displayed in figure 1 and figure 2 illustrate the SCCP performances such as the power and efficiency. The range of electricity production is between 10.5 and 48.7kWe throughout the year. In general, the output power increase during the summer months according to the increases of solar heat flux which generates the increase of the efficiency.

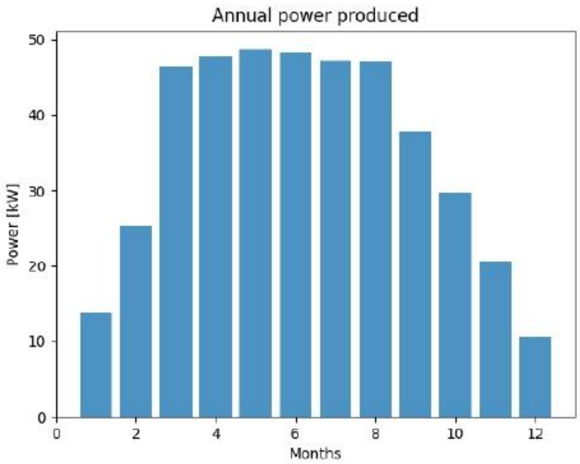

Fig. 2Average monthly power production of the Manzanares solar chimney power plant.

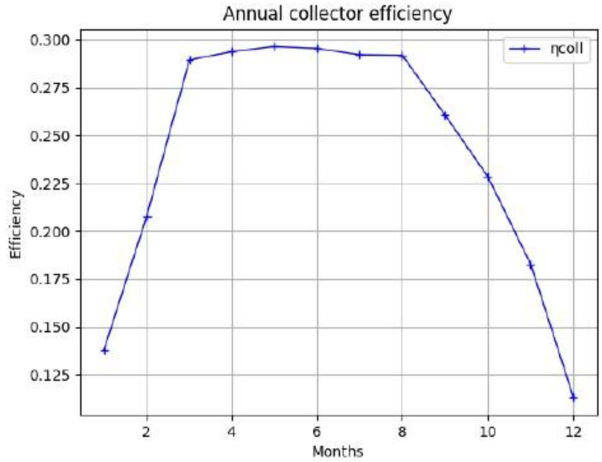

Fig. 3Average monthly efficiency of the Manzanares solar chimney power plant.

Figure 4illustrates a comparison between measured and calculated average monthly energy outputs where we notes the good agreement between the theoretical and measured values. The total annual energy measured is around 44,623MWh and the total annual calculated energy is 46,028MWh.

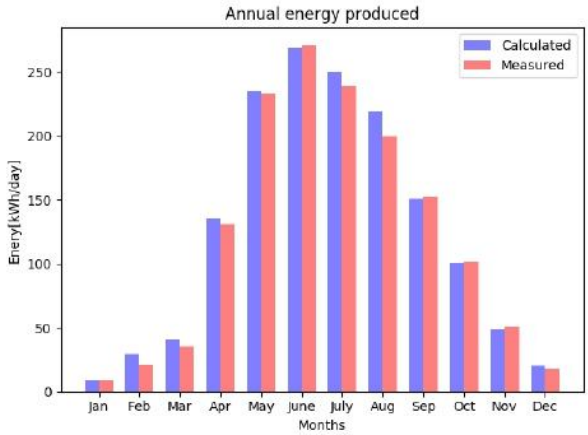

Fig. 4 Comparison between measured and calculated monthly energy outputs for Manzanares solar power plant.

B. Economical results

Electricity produced by the solar updraft tower is proportional to the intensity of global solar radiation, the collector area and tower height. There is in fact no optimum physical size for such plants. Optimal dimensions can be calculated only by including specific component costs (collector, tower, turbines) for individual sites [2].

To give an overview, typical dimensions for selected solar updraft tower capacities are given in Table 4 [40].

TABLE IV
TYPICAL DIMENSIONS AND ELECTRICITY OUTPUT

50 kWe	Ht	Dt	Dc	Pe at 2300 kWh/m²yr	Pe at 1800 kWh/m²yr

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Value	750m	90m	3750m	153GWh/yr	120GWh/yr

Based on specific costs (To produce 50 kW of electricity, the total investment cost is 302Mio € and annual operation & maintenance cost are 1.6Mio €/a) and the dimensions from Table 1, investment costs were calculated for Manzanares solar updraft tower and the results are plotted in the figure 5.

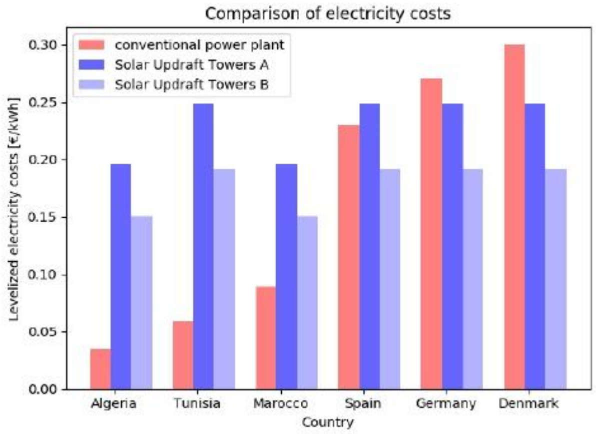

Fig. 5 Comparison of electricity cost.
A assuming weighted average cost of capital of 8 % and a depreciation time of 25 years
B assuming weighted average cost of capital of 5 % and a depreciation time of 25 years

IV. Conclusions

Generation of electricity using solar energy is an alternative for power generation over conventional power plants. Many research works based on numerical and experimental studies are carried out by keeping Manzanares power plant as a reference. It is concluded that such system should be constructed in a very large way to generate large amount of electricity.

The work presented in this study is related to the techno-economic study of the solar chimney of Manzanares. The obtained results show:

1. The generated power depends on the solar irradiance and the ambient temperature.

2. The efficiency both of the collector and the turbine has a significant role in the improvement of the system performances.

3. The mathematical model presented here is relatively simple while provides a very accurate result as shown in Table3.

4. Maghreb countries have really small conventional electricity cost because of natural sources (oil and gas) which makes the solar chimney unprofitable (negative return). On the other hand, the cost of the kWh produced by solar chimneys in Europe is profitable (positive return).

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