International Conference on Green Energy & Environmental Engineering (GEEE-2018)
Proceedings of Engineering and Technology – PET
Vol.37 pp.30-33

TECHNICO-ECONOMIC ASPECT ANALYSIS IN THE DESIGN OF SOLAR CHIMNEY POWER PLANTS

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***Abstract*—The present work is dedicated to the techno-economic analysis of the solar chimney power plant (SCPP) of Manzananares site. This site is located in the south region of Spain. Manzanares. This prototype reached a production of 44MWh/year with a power peak of 50kW [7]. A mathematical model [1] was presented to describe the solar chimney power plant mechanism in detail, establish a technical study, evaluate the annual performances, and study 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.**

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

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 [3, 4]. Research works were conducted on the power plant and it proved that the SCPP concept is technically viable for power generation [5]. There are normally three methods in studying the performance characteristics of a solar chimney power plant: analytical method, numerical method and methods based on similarity theory [6].

The Manzanares solar updraft tower (Spain, 150 km 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 45 000m². It reached a production of 44MWh/year, for a peak power of 50kW [7].

TABLE I
Technical data of Manzanares prototype [7].

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

II. Mathematical Model

The analysis presented in this paper is based on the following simplifying assumptions [1]:

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.

ISSN 2356-5608

International Conference on Green Energy & Environmental Engineering (GEEE-2018)
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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:

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

Where:

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

The efficiency of the solar collector can be defined as:

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

A.2. The Chimney

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

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

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

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

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

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

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

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

Using the following approximation for ideal gas:

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

The air velocity in the chimney can be written as:

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

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. The Turbine

Turbines are located at the bottom of the chimney. The maximum mechanical power taken up by the turbines as recommended by Schlaich [9] 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 [2]

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** [1].

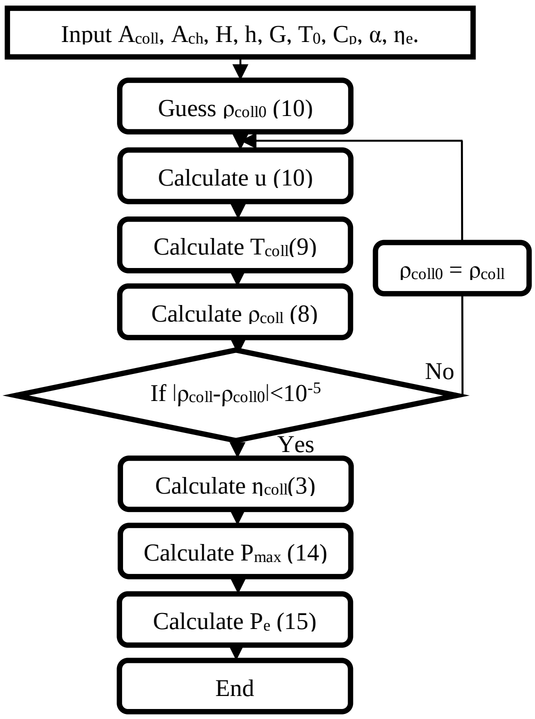

Fig. 1 Flow chart of computational procedure [1].

III. Results And Discussion

A. Technical Model

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

ISSN 2356-5608

International Conference on Green Energy & Environmental Engineering (GEEE-2018)
Proceedings of Engineering and Technology – PET
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with period data (1991-2010). These are illustrated in the following table:

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 in Table 3.

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

Technical sheet	Experiments [7]	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 2 illustrate the SCCP performances such as the power and efficiency. In general, the output power increase during the summer months as solar heat flux increases which generates the increase of the efficiency.

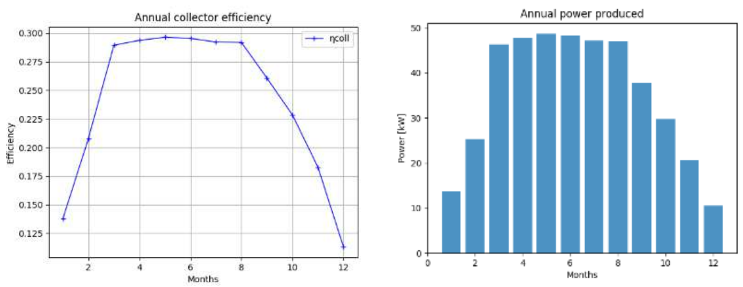

Fig. 2 Average monthly power production and efficiency of the Manzanares solar chimney power plant.

Figure 3 presents a comparison between measured and calculated average monthly energy outputs, showing that there is 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.

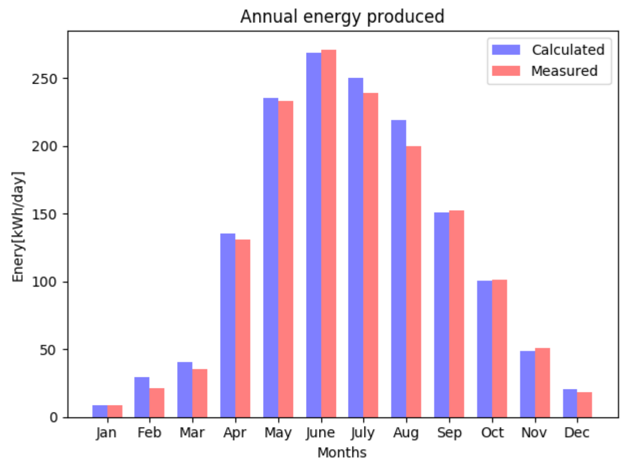

Fig. 3. Comparison between measured and calculated monthly energy outputs for Manzanares solar power plant.

3.2. 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 [8].

To give an overview, typical dimensions for selected solar updraft tower capacities are given in Table 4 [10].

TABLE IV
TYPICAL DIMENSIONS AND ELECTRICITY OUTPUT

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

ISSN 2356-5608

International Conference on Green Energy & Environmental Engineering (GEEE-2018)
Proceedings of Engineering and Technology – PET
Vol.37 pp.30-33

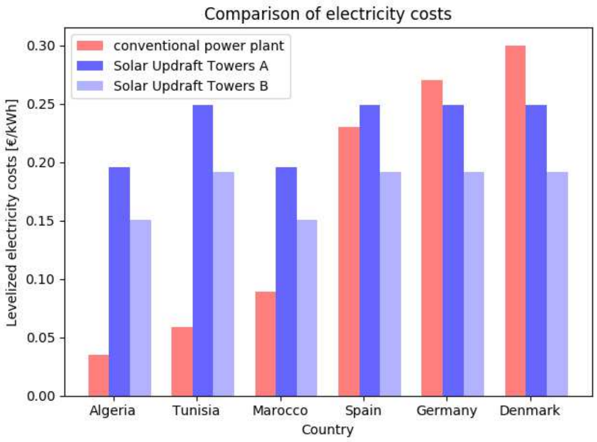

Fig. 4. Comparison of electricity cost.
A assuming weighted average cost of capital of 8 % and a depreciation time of 25 years
B assuming weighted average cost of capital of 5 % and a depreciation time of 25 years

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 technical-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 Table 3.

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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ISSN 2356-5608