Energy Conversion and Management 126 (2016) 1013–1027

Contents lists available at ScienceDirect

Energy Conversion and Management

journal homepage: www.elsevier.com/locate/enconman

# A new economic feasibility approach for solar chimney power plant design

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ARTICLE INFO

*Article history:*
Received 19 June 2016
Received in revised form 23 August 2016
Accepted 26 August 2016

*Keywords:*
Solar chimney power plant
Electricity generation
Optimal dimensions
Nonlinear optimization
Economic feasibility

ABSTRACT

Solar chimney power plants have been accepted as one of the promising technologies for solar energy utilization. The objective of this study is to propose an effective approach to simultaneously determine the optimal dimensions of the solar chimney power plant and the economic feasibility of the proposed plant. For this purpose, a two-stage economic feasibility approach is proposed based on a new nonlinear programming model. In the first stage, the proposed optimization model which determines the optimal plant dimensions that not only minimize the discounted total cost of the system, but also satisfy the energy demand within a specified reliability taking into account the stochasticity of solar radiation and ambient temperature is solved using a commercial optimization solver that guarantees finding the global optimum. In the second stage, the net present value of building the plant is computed by deducting the discounted total cost found in the first stage from the present value of revenues obtained due to selling the electricity generated by the plant. The proposed approach is novel because it determines the optimal dimensions of the plant together with its economic feasibility by taking into account the energy demand and uncertainty in solar radiation and ambient temperature. The proposed approach is applied on a study in Potiskum, Nigeria, which reveals that building a plant with a collector diameter of 1128 m and chimney height of 715 m to Potiskum would be profitable for investors at an annual rate of return of 3% and would provide electrification to about 7500 people with a high level of reliability. The proposed approach is benchmarked with an intuitive approach and an approach that does not consider uncertainty in solar radiation and ambient temperature. The results clearly revealed the value of the proposed approach. Managerial insights on the impact of the efficiency of the collector, the efficiency of the turbine, electricity price, electricity demand, meteorological conditions, and discount rate on the size of the plant and the net present value are obtained through detailed sensitivity analyses.



## 1. Introduction

The increasing demand for electricity has motivated considerable research interest in a wide range of engineering applications aimed at providing a sustainable solution for the energy security problem. The wider utilization of renewable energy sources of solar, wind, biomass and geothermal is currently being propelled not only by the environmental concern of conventional thermal fossil fuels which contribute approximately 80% of the global energy [1], but also by the continuous upsurge in their price trend resulting from the increasing population induced demand. The solar energy among other choices seems to be promising and ultimately has been accepted as one of the future alternatives for electricity generation [2]. An increase in the use of solar energy and other renewable technologies could decrease the environmental pollution and the dependence on the finite fossil fuel resources. The problems of huge capital cost, enormous land area requirement, and reliability associated with solar energy systems have widely been addressed through robust design, optimization and formulation of new concepts using cheap and hybrid materials [1,3]. Moreover, there have been these kinds of studies assessing the techno-economic feasibility and lifecycle of renewable energy technologies [4–6]. Solar chimney power plant (SCPP) offers a unique opportunity to generate electricity by combining relatively simple and reliable old technologies of the solar thermal collector, chimney and turbine as shown in Fig. 1.

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http://dx.doi.org/10.1016/j.enconman.2016.08.080
0196-8904/

**Nomenclature**

*Acronyms*

| | |
|---|---|
| NPV | net present value (€) |
| SCPP | solar chimney power plant |
| TC | discounted total cost (€) |
| TMY | typical meteorological year |

*Indices*

| | |
|---|---|
| $j$ | days of the year |
| $m$ | months of the service life of plant |

*Parameters*

| | |
|---|---|
| $A_{coll}$ | area of the solar collector ($m^2$) |
| $C_{black,tube}$ | unit cost of black tube for water storage (€/$m^3$) |
| $C_{ch}$ | capital cost of chimney (€) |
| $C_{coll}$ | capital cost of collector (€) |
| $C_{electricity}$ | unit price of electricity (€/kWh) |
| $C_{tur}$ | capital cost of turbine (€) |
| $C_{water}$ | unit cost of water (€/$m^3$) |
| $CC_{sc}$ | unit capital cost of chimney due to material and construction costs (€/$m^3$) |
| $C_p$ | specific heat capacity (J/kg·K) |
| $C_{O\&M}$ | cost of system operation and maintenance (€) |
| $D_{ch}$ | diameter of the chimney (m) |
| $\bar{E}$ | average daily energy demand (kWh) |
| $E_j$ | energy demand in day $j$ (kWh) |
| $EP_j$ | amount of energy produced in day $j$ (kWh) |
| $g$ | gravitational constant, 9.81 (m/$s^2$) |
| $G_h$ | solar radiation (W/$m^2$) |
| $h_1, h_2$ | heat transfer coefficients (W/$m^2$·K) |
| $H_{coll}$ | height of the collector (m) |
| $H_{sl}$ | height of the water storage layer (m) |
| $i$ | monthly discount rate |
| $J_m$ | set containing all days of month $m$ |
| $L_{ch}$ | lower bound for chimney height (m) |
| $L_{coll}$ | lower bound for collector diameter (m) |
| $\eta_{ch}$ | efficiency of chimney |
| $\eta_{coll}$ | efficiency of the solar collector |
| $\bar{\eta}_{coll}$ | average daily efficiency of the solar collector |
| $\eta_{tur}$ | efficiency of the turbine |
| $n_{hour}$ | number of sunshine hours |
| $\bar{n}_{hour}$ | average daily sunshine hours |
| $\theta_{1-r}$ | value at which the probability of $X$ being less than or equal to $(C_p\bar{E})/(A_{coll}\, g\, H_{ch}\bar{\eta}_{coll}\eta_{tur}\bar{n}_{hour})$ is equal to $1-r$ |
| $\rho$ | air density (kg/$m^3$) |
| $r$ | desired system reliability |
| $r_{real}$ | realized system reliability |
| $T_a$ | ambient temperature of the location (K) |
| $T_c$ | temperature of the glass collector (K) |
| $T_f$ | air flow temperature (K) |
| $T_p$ | temperature of the absorber (K) |
| $U_{ch}$ | upper bound for chimney height (m) |
| $U_{coll}$ | upper bound for collector diameter (m) |
| $P_{ele}$ | power output from the SCPP (kW) |
| $Pt_{coll}CC_{sc}$ | product of capital cost of the collector per square meter and the specific capital cost of chimney |
| $Pt_{Hcoll}$ | percent age capital cost for every one meter height of the collector inlet |
| $Pt_{O\&M}$ | percentage capital cost of the system |
| $Pt_{tg}$ | percentage capital cost of collector and chimney |
| $Rev_m$ | revenue obtained from the energy produced in month $m$ (€) |
| $S$ | number of months in the service life of SCPP |
| $X$ | continuous random variable denoting the ratio of solar radiation to ambient temperature (W/$m^2$·K) |

*Variables*

| | |
|---|---|
| $D_{coll}$ | diameter of the solar collector (m) |
| $H_{ch}$ | height of chimney (m) |
| $Z$ | objective function value (€) |

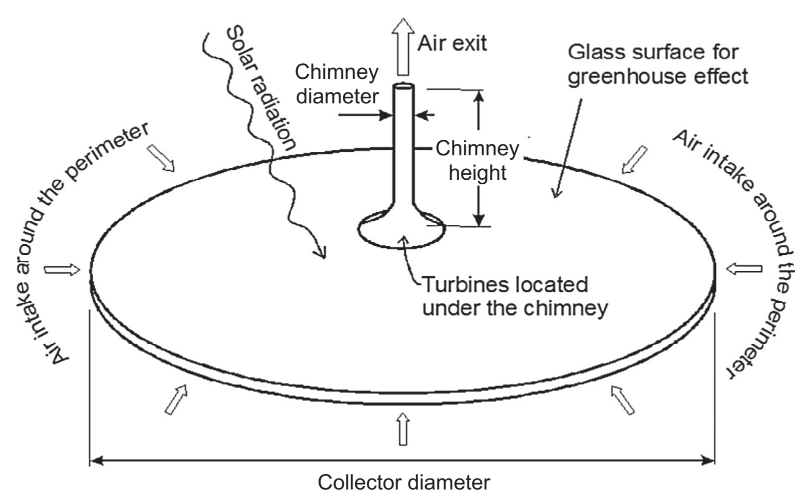


**Fig. 1.** Schematic of a solar chimney power plant, adapted from [7].

SCPP has numerous advantages over other solar energy utilization alternatives, such as; (i) the ability to utilize global solar radiation, (ii) the high reliability due to low rotating part, (iii) not using scarce water resources for heat rejection during operation, (iv) the ability to work during nights by using the natural ground as a storage medium, (v) the use of the greenhouse effect for drying of agricultural produce, (vi) the low operation and maintenance cost of the system, and (vii) high durability and long lifecycle time [8–10]. Therefore, SCPP has attracted much attention for electricity generation. As a result, experimental studies involving SCPP are