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# Techno-economic optimization for the design of solar chimney power plants

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ABSTRACT

This paper aims to propose a methodology for optimization of solar chimney power plants taking into account the techno-economic parameters. The indicator used for optimization is the comparison between the actual achieved simple payback period for the design and the minimum possible (optimum) simple payback period as a reference. An optimization model was executed for different twelve designs in the range 5–200 MW to cover reinforced concrete chimney, sloped collector, and floating chimney. The height of the chimney was optimized and the associated collector area was calculated accordingly. Relationships between payback periods, electricity price, and the peak power capacity of each power plant were developed. The resulted payback periods for the floating chimney power plants were the shortest compared to the other studied designs. For a solar chimney power plant with 100 MW at electricity price 0.10 USD/kWh, the simple payback period for the reference case was 4.29 years for floating chimney design compared to 23.47 and 16.88 years for reinforced concrete chimney and sloped collector design, respectively. After design optimization for 100 MW power plant of each of reinforced concrete, sloped collector, and floating chimney, a save of 19.63, 2.22, and 2.24 million USD, respectively from the initial cost of the reference case is achieved. Sensitivity analysis was conducted in this study to evaluate the impacts of varied running cost, solar radiation, and electricity price on the payback periods of solar chimney power plant. Floating chimney design is still performing after applying the highest ratio of annual running cost to the annual revenue. The sensitivity analysis showed that at the same solar radiation and electricity price, the simple payback period for 200 MW with sloped collector design would almost have the double simple payback period for 5 MW with floating chimney design.


## 1. Introduction

The energy demand in the world is in continuous increase [1] due to the population growth and higher rate of consumption per capita to face the improvement of the living standards. Utilization of sustainable and non-depleted sources of energy can face part of this increased demand for energy. The solar energy as a clean and renewable source of energy can play a major role in addressing these challenges. Intensive research efforts to improve the reliability and feasibility of the renewable energy systems can support the dissemination of these technologies.

To some extent, the fundamental, theoretical, and technical issues of solar energy were covered, but still, there are constraints in the practical application of the renewable energy systems. Pretorius and Kroger [2] evaluated technically the effect of design parameters and materials quality on the performance of solar chimney power plant (SCPP) and Tingzhen et al. [3] conducted heat transfer analysis of SCPP after divided the complete system into three regions of the collector, chimney, and turbine. Intermittency of solar and wind energy and high capital cost of renewable energy technologies are some of the challenges facing the dissemination of these clean technologies [4]. Solar photovoltaic (PV) technologies are obstacle by high cost, low financial ability, and limited application of the product [5]. Latent heat energy storage systems were proposed to face the intermittency in solar radiation. Aydin et al. [6] evaluated the impact of latent heat storage systems on the solar energy used for space heating in Istanbul, Turkey. Phase change materials used for latent heat storage systems are found suitable for domestic solar water heaters due to the high storage capacity and stable heat transfer temperature [7]. Heat generated by thermal conversion of solar energy is proposed to be injected into the ground to save energy [8].

Solar chimney used in natural ventilation of buildings by makes use of the difference in air density due to the temperatures difference, which is known as stack effect or buoyancy. Stackeffect increases the air flow rate to cool the building in warm humid

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**Nomenclature**

| | |
|---|---|
| $A_C$ | solar collector area |
| CFD | computational fluid dynamics |
| $CO_{CH}$ | chimney unit price of $(H * D)$ |
| $C_P$ | specific heat of air equal to 1005 J/kg K |
| $CP_{UAR}$ | cost per unit area of the collector including the land cost |
| CR | the ratio of annual running cost to the annual revenue |
| D | chimney diameter |
| design-C | solar power plant with reinforced concrete chimney |
| design-F | solar power plant with floating chimney |
| design-S | solar power plant with sloped collector |
| $EL_P$ | electricity price in USD/kWh |
| G | global solar radiation |
| g | gravitational acceleration equal to 9.81 $m^2$/sec |
| GTC | gas turbine cycle |
| $GY_{REV}$ | uniform annual revenue of the solar chimney power plant |
| H | chimney height |
| $H_{OPT}$ | optimum chimney height |
| $IN_{CH}$ | chimney initial cost |
| $IN_{CL}$ | collector initial cost |
| $IN_{CST}$ | the initial cost of the solar chimney power plant |
| $IN_{TG}$ | turbine and generator initial cost |
| $P_K$ | maximum power plant capacity at solar radiation 1000 W/$m^2$ |
| PV | solar photovoltaic |
| Q | air volume flow rate across the turbine |
| $R_{CST}$ | running cost of the solar chimney power plant |
| $RY_{CST}$ | the uniform annual running cost of the solar chimney power plant |
| SCPP | solar chimney power plant |
| $SP_{back}$ | simple payback period |
| $SP_{min}$ | simple minimum (optimum) payback period |
| T | the torque of the turbine shaft |
| $T_a$ | collector inlet temperature |
| $T_{CST}$ | the total cost of the solar chimney power plant |
| USD | United States Dollar adjusted for the value of the year 2014 |
| $\Delta P$ | the total pressure drop across the turbine |
| $\Delta T$ | the temperature difference between air inflow and outflow from the collector |
| $\alpha$ | effective absorption coefficient |
| $\beta$ | the factor of the convective energy loss (W/$m^2$ K) |
| $\omega$ | the rotational speed of the turbine shaft |
| $\eta_C$ | collector efficiency |
| $\eta_{CH}$ | chimney efficiency |
| $\eta_G$ | electric generator efficiency |
| $\eta_T$ | turbine efficiency |
| $\eta_{TOT}$ | the total efficiency of the solar chimney power plant |

climates [9]. Experimental investigations showed that airflow across a small chimney increases with the increase in each of solar radiation and the gap between absorber and glass cover [10]. A chimney is used for lifting air through the solar dryer to dry agricultural products [11]. Maia et al. [12] conducted an experimental study for the airflow inside a solar chimney used for drying of agricultural products and recommended to include the amount of water evaporated from the product into the performance evaluation of the dryer. A similar design consists of black tubes as a collector surrounding the chimney is proposed for nine cities in China with a different application to generate freshwater from the air [13].

Solar chimney power plant (SCPP) is proposed to be used for electricity generation and consists mainly of the solar collector, chimney, and turbine. Zou and He [14] evaluated a hybrid system integrating a solar chimney with a dry cooling tower and found that the output power can be increased up to 20 times compared to the conventional SCPP. An SCPP model of 2.5 m chimney height and 2 m collector diameter was constructed and tested with the application of corona wind to improve the airflow speed to 72% and the output power to about 5 times [15]. An SCPP was designed theoretically based on Jordanian weather conditions with 210 m chimney height and 40 m collector diameter to result in a maximum output power of 85 kW [16]. Electricity generation based on solar chimney technology is being proposed for Australia to generate 200 MW from a power plant with 1000 m chimney height and 5000 m collector diameter [17]. Optimization of the design parameters and geometry of the SCPP would contribute significantly into the feasibility of electricity generation based on this clean technology. The rotational speed of the turbine corresponding to the maximum turbine efficiency has to be slightly increased in order to achieve the maximum output power from an SCPP [18]. The solar collector as well known in other solar thermal applications is made in flat surface from transparent material either of glass panels or plastic film to harness the solar radiation through greenhouse effect and heat the air flowing through the chimney. The heated air flows through the solar chimney due to its density difference between inlet and outlet of the chimney. This heated air is forced the turbine to rotate and to generate electricity [19].

Compared to the electricity generation from conventional sources of energy, SCPPs are still constrained by huge initial cost and need long construction period [20], require large area of land for the collector, and the total system efficiency is very low [21]. The chimney associated with the SCPP is very tall compared to the conventional buildings which add a significant uncertainty with the construction and materials to be used. One of the challenges facing SCCP is the continuity of power generation during the night-time [22].

As SCPP is one of the renewable energy technologies, has the advantage of low environmental impact on air and water [23], unlike the conventional power plants based on fossil fuels. The solar energy source is freely available and storage systems can be added to the SCPPs to recover for the input energy when the solar radiation is unavailable. Black tubes filled with water located under the collector is one of the systems used for thermal energy storage and the amount of filled water depends mainly on the SCPP output power [24]. Al-Kayiem and Aja [25] concluded that SCPP performance can be improved considerably by adding another thermal energy source or by retrofitting a proper storage system. Flat mirrors to intensify the solar radiation on the solar chimney zone are also proposed to improve the SCPP performance [26].

The 50 kW SCPP prototype built and operated in Manzanares, Spain for seven years since 1982 [27] proved the reliability and assured the potential of the technology. The main objectives of Manzanares prototype were to verify the theoretical calculations of the design and to test the SCPP output power and the system efficiency under different weather conditions. The prototype was designed with 194.6 m chimney height, 10 m chimney diameter, and 122 m mean collector radius [28]. Manzanares prototype was operated for a total period of 8611 h at an average of 8.9 h