

A TWO-STAGE FEASIBILITY APPROACH
FOR SOLAR CHIMNEY POWER PLANT DESIGN

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ABSTRACT

A TWO-STAGE FEASIBILITY APPROACH FOR SOLAR CHIMNEY POWER PLANT DESIGN

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Diverse renewable energy systems accessible to technologically less developed countries are urgently needed to ensure energy security, enrich the generation portfolio, and tackle clean development issues. Solar chimney power plants (SCPP) offer this opportunity and have been accepted as one of the promising technologies for solar energy utilization. In this thesis, a two-stage feasibility approach for SCPP is proposed based on a new nonlinear programming model. In the first stage, we solve the proposed optimization model which determines the optimal SCPP dimensions that not only minimize the capital cost of building the plant and the present value of the periodic operation and maintenance costs but also satisfy the energy demand within a specified reliability. In the second stage, we compute the net present value (NPV) of building the SCPP by deducting the present value of life-cycle costs found in the first stage from the present value of revenues obtained due to selling the electricity generated by the SCPP. The novelty of the proposed model is due to the fact that it identifies whether building the plant is feasible or not by taking into account the site-specific data of solar radiation, ambient temperature, available land area, the price of electricity, electricity demand, discount rate, and cost of building and operating the plant. The proposed approach is tested on a case study in Potiskum, Nigeria, which

reveals that building a SCPP with a collector diameter of 1,128 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 7,500 people with a high level of reliability. Managerial insights on the impact of the efficiency of the collector, the efficiency of the turbine, electricity price, electricity demand, meteorological input variables, and discount rate on the size of the plant and the net present value are analyzed through a detailed sensitivity analysis. Moreover, the analysis suggests that the proposed SCPP would improve the social, economic and environmental development in the regions through the detail sustainable impact assessment. Overall, this study shows a new feasibility approach to find optimum SCPP dimensions by maximizing net present value.

Keywords: solar chimney power plant, electricity generation, optimal dimensions, nonlinear optimization, economic feasibility

ÖZ

GÜNEŞ BACASI SANTRAL TASARIMI İÇİN

İKİ AŞAMALI FİZİBİLİTE YAKLAŞIMI

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Teknolojik olarak az gelişmiş ülkelerde erişilebilir durumdaki çeşitli yenilenebilir enerji sistemleri; enerji güvenliğini sağlamak, üretim portföyünü zenginleştirmek ve temiz kalkınma konularını ele almak açılarından acilen gereklidir. Güneş bacası santralleri (SCPP) bu fırsatı sunan ve güneş enerjisi kullanımı için umut verici teknolojilerden biri olarak kabul edilmektedir. Bu tezde, SCPP için doğrusal olmayan yeni bir programlama modeli temel alınarak iki aşamalı bir fizibilite yaklaşımı önerilmektedir. İlk aşamada, sadece santral kurulum maliyeti ile periyodik işletme ve bakım maliyetlerinin bugünkü değerini en aza indiren değil, aynı zamanda enerji talebini belirli bir sistem güvenilirliği içerisinde karşılayan en uygun SCPP boyutları belirlenmektedir. İkinci aşamada, santralin kullanımda kaldığı süre boyunca SCPP tarafından üretilen elektrik satışından elde edilen gelirlerin bugünkü değerinin ilk aşamada bulunan yaşam döngüsü maliyetlerinin bugünkü değerinden düşülmesi suretiyle santralin net bugünkü değeri (NPV) hesaplanmaktadır. Önerilen modelin getirdiği yenilik, santralin kurulduğu yere özgü güneş ışıınımı, hava sıcaklığı, mevcut arazi alanı, elektrik fiyatını, elektrik talebini, faiz oranlarını ve bina inşaat ve işletim maliyetlerini göz önünde bulundurarak kurulması planlanan santralin ekonomik olarak uygulanabilir olup olmadığını belirleyebilmesidir. Önerilen yaklaşım, Nijerya'nın

Potiskum yöresi için örnek olarak uygulanmış ve %3'lük getiri oranına göre kolektör çapı 1128 m ve baca yüksekliği 715 m olan bir SCPP'nin yatırımcılar için karlı olacağı hesaplanmıştır. Bahsedilen test koşullarındaki bir SCPP'nin yüksek bir güvenilirlik düzeyinde yaklaşık 7500 kişiye elektrik sağlayacağı öngörülmüştür. Kolektör ve türbin verimleri ile elektrik birim fiyatı, elektrik ihtiyacı, meteorolojik girdi değişkenleri ve iskonto oranının santralin en uygun boyutları ve santralin net bugünkü değeri üzerindeki etkileri için detaylı bir hassasiyet analizi yapılmıştır. Ayrıca, detaylı sürdürülebilirlik etki değerlendirmesi yoluyla yapılan analizler, önerilen SCPP'nin yerel sosyal, ekonomik ve çevresel kalkınmayı geliştireceğini göstermektedir. Genel olarak, bu çalışma SCPP'nin net bugünkü değerini mümkün olan en yüksek değer çıkararak santralin boyutlarını bulan yeni bir fizibilite çalışması sunmaktadır.

Anahtar Kelimeler: Güneş bacası santrali, elektrik üretimi, optimum boyutlar, doğrusal olmayan optimizasyon, ekonomik fizibilite

DEDICATION

To the Almighty God for the strength and wisdom to actualize this work, my beautiful wife, and Parents for their unconditional love, prayers, support, trust, understanding and encouragement.

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LIST OF SYMBOLS AND ABBREVIATIONS

Acronyms

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

Indices

j	days of the year or service life of the plant
m	months of the service life of plant

Parameters

A_{coll}	area of the solar collector (m^2)
$C_{black,tube}$	specific 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}	specific cost of water ($€/m^3$)
CC_{sc}	specific capital cost of chimney due to material and construction cost ($€/m^3$)
C_p	specific heat capacity ($J/kg\cdot K$)
$C_{O\&M}$	cost of system operation and maintenance (€)
D_{ch}	diameter of the solar chimney (m)
D_h	hydraulic diameter (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)
h_1	heat transfer coefficients of collector cover ($\text{W/m}^2\cdot\text{K}$)
h_2	heat transfer coefficients of collector ground ($\text{W/m}^2\cdot\text{K}$)
h_{rs}	radiative heat transfer coefficient between collector cover and sky ($\text{W/m}^2\cdot\text{K}$)
h_{r21}	radiative heat transfer coefficient between the ground and the collector cover ($\text{W/m}^2\cdot\text{K}$)
h_w	convective heat transfer coefficient from the collector cover ($\text{W/m}^2\cdot\text{K}$)
H_{ch}	height of the chimney (m)
H_{coll}	height of the collector (m)
H_{sl}	height of the water storage layer (m)
i	monthly discount rate
I	solar radiation (W/m^2)
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)
η_{ch}	efficiency of chimney
η_{coll}	efficiency of the solar collector
$\bar{\eta}_{coll}$	average daily efficiency of the solar collector
η_{tur}	efficiency of the turbine
n_{hour}	number of sunshine hours
$\bar{n}_{hour}$	average daily sunshine hours
θ_{1-r}	value at which the probability of X being less than or equal to $\bar{E}/(A_{coll} \frac{g H_{ch}}{c_p} \bar{\eta}_{coll} \eta_{tur} \bar{n}_{hour})$ is equal to $1 - r$
ρ	air density (kg/m^3)

r	desired reliability
r_{real}	realized 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)
μ	dynamic viscosity (kg/m·s)
P_{ele}	power output from the solar chimney (kW)
Pt_{coll}	product of capital cost of the collector per square meter
Pt_{Hcoll}	percentage 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
S_1	solar radiation in the collector cover (W/m ²)
S_2	solar radiation in the ground absorber (W/m ²)
ΔT	temperature difference between the inlet and exit of the solar collector (K)
$\Delta P_{dynamic}$	change in dynamic pressure (Pa)
ΔP_{total}	change in total pressure (Pa)
v_{ch}	maximum flow speed (m/s)
X	continuous random variable denoting the ratio of solar radiation to ambient temperature (W/m ² ·K)
<i>Variables</i>	
D_{coll}	diameter of the solar collector (m)

H_{ch}	height of chimney (m)
Z	objective function value (€)

CHAPTER 1

INTRODUCTION

In recent years, the use of fossil fuels for electricity generation is being questioned due to its contributions to ozone depletion, acid rain and global warming [1]. In addition, these finite fossil fuels based energy sources are becoming scarce leading to an increased cost of electricity derived from them. For this reason, renewable resources and technologies are being promoted globally as sustainable alternatives to these fossil fuel based resources [2–4]. These renewable resources and technologies which include but are not limited to the wind, biomass, hydropower, geothermal and solar, have been utilized with proven results [4–9]. The advantages of these renewable energy options include the following: (i) guaranteeing energy security and promoting economic advancement [2]; (ii) reducing or eliminating fuel costs and conserving finite fossil fuel resources [3]; and (iii) environmental benefits and internalization of external costs [4]. In addition, Okoye and Atikol [10] mentioned that the inexhaustible nature of these resources makes them ideal alternatives to conventional fossil fuel resources.

Among all renewable energy alternatives, solar stands out as a promising and valuable source for future electricity generation in both urban and rural areas. Zhou *et al.* [11] state that solar together with the allied technologies are the most developed sources of renewable alternatives. The sun is one of the most well-known and widely studied alternative energy sources. Sungur [12] mentioned that the amount of energy which can be generated from solar technologies depends entirely on the available solar resources in a location and the conversion efficiency of the adopted system. Moreover, the problems of huge capital investment 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 [13,14]. On the other hand, after initial investment and installation cost of solar-to-electricity conversion technology and any necessary maintenance, the resulting energy may be considered free.

Schlaich *et al.* [15] mentioned that practical technology for wider utilization of solar resources must be simple, reliable and accessible to technologically less developed countries with a limited raw material. Solar Chimney Power Plant (SCPP) as a low-temperature thermal power plant meets the criteria described by Schlaich *et al.* [15]; thus, has been accepted as a promising approach for future large-scale electricity generation [16]. SCPP offers a unique opportunity to generate electricity by combining relatively simple and reliable old technologies of the solar thermal collector, chimney, and turbine with the ground working as a natural heat storage layer. The advantages of SCPP systems relative to other solar technologies include but not limited to [15,17,18]:

- i. The ability to utilize global solar radiation
- ii. The high reliability due to low rotating parts
- iii. Not using scarce water resources for heat rejection during operation
- iv. The ability to work during the night 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 longer lifecycle time

In order to predict the performance of SCPP technology for any location, experimentation is often required. This experimentation process involves building and

operating a small pilot plant. In addition to being expensive and time-consuming, it requires a specific skill set to realize and needs to be installed in the location of interest due to variable ambient conditions. Another method of understanding and predicting the overall performance of SCPP including the costs is through numerical modeling. However, many existing models available in the literature are simply devoted to studying the technical feasibility of SCPP. These models help to understand the working potential of SCPP system but tell little about the economic feasibility considering the huge capital investment required to realize it. Moreover, a potential investor (whether local or foreign) would be particularly interested in what would be the return on the capital considering other competing projects for the limited available resources. A limited number of models involving the cost analysis of the SCPP systems are available, and in those models, the economic feasibility of the systems are estimated after technical analysis using the obtained power output. In other words, the plant size is arbitrarily chosen in the estimation of the electricity which is generated from the proposed SCPP system.

For favorable deployment of SCPP technology, an integrated optimization model which not only predicts the optimal plant size but also answers the investors question on feasibility is imperative. Schlaich *et al.* [15] mentioned that there is no optimum SCPP plant configuration since the resulting power output increases with an increase in the dimensions. They emphasized that an SCPP can only be optimized considering local environmental conditions including the price of electricity and the costs of labor, land and concrete. With known local conditions, an optimization model can be used to increase the resulting power output and decrease the capital investment cost of SCPP simultaneously. In previous studies, an attempt has been made at obtaining the optimal

size of SCPP [19–21], but the solution methods even though serve as a building block in this present study are based on genetic algorithms (GAs); thus, they do not guarantee either local or global optimal solution. Perez *et al.* [22] stated, GAs as a heuristic algorithm focus on finding an acceptable solution in an attempt to capture the global optimum solution but they do not guarantee either local or global optimum. To claim optimality, Karush-Kuhn-Tucker (KKT) conditions must be satisfied (for KKT conditions see e.g. pp. 691–700 of Winston [23]).

1.1. Problem statement

To accurately inform potential investors on whether to or not invest their limited resources on SCPP, an appropriate economic optimization tool is imperative. This tool should be able to predict the optimal SCPP dimensions necessary to satisfy a given energy demand within a specified reliability while allowing comment on the economic feasibility. In other words, for any given location with known energy demand, ambient meteorological conditions, cost of electricity, service lifecycle time of SCPP plant, cost of reinforced concrete cement, discount rate, and cost of operation & maintenance, the problem consists of determining the optimal size of SCPP that minimizes the present value of total service life costs of building and operating the SCPP, and then to assess the feasibility of the obtained size of SCPP given the price of electricity, discount rate and the service life of the plant.

1.2. Objectives

To address the aforementioned problem statement, it is the intention of this present study to offer an integrated economic feasibility tool in order to foster the adoption of SCPP as a sustainable electricity generation alternative offer a new integrated design tool that would not only yield the global optimum SCPP dimensions but also at glance answer the potential investors' question on the economic feasibility of the proposed system. This type of design tool is necessary in order to promote the adoption of SCPP as sustainable electricity generation tool. The summary of the task undertaken is provided in Figure 1.

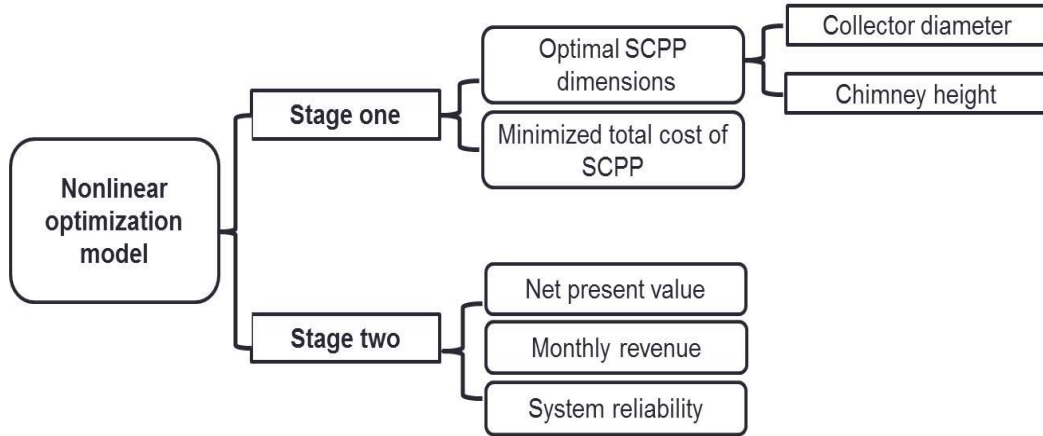


Figure 1. Thesis research framework.

The tasks are highlighted as:

- i. Propose a novel nonlinear optimization model based on two-stage feasibility approach to assess the performance of SCPP.
- ii. In stage one, the model determines the optimal SCPP dimensions (chimney height and collector diameter) while minimizing the total cost of the system.
- iii. In stage two, using the predicted optimal plant size, the net present value, monthly revenue and the system reliability is determined.

Additionally, the thesis:

- i. Offers the model for energy storage layer, thus, ensures continuous operation of the SCPP even in the period when there is no solar radiation.
- ii. Incorporates chance constraint into the model to account for randomness in the solar radiation and ambient temperature data.
- iii. Validates the developed model using a case study involving electrification of rural Nigeria.
- iv. Offers valuable managerial insight on the effect of some important parameters on both the optimal plant size and economic feasibility of the proposed SCPP.

1.3. Scope of the study and contribution to the body of knowledge

This study presents an optimization model which can be used for the design and feasibility assessment of optimal dimensions of SCPP so as to foster the adoption of the technology. The model yields the discounted revenue and reliability of the system in addition to answering the question of the feasibility of the proposed system. The reliability is defined as the percentage of the demand which can be satisfied by the proposed optimal SCPP design. The main contribution of this thesis to the body of knowledge is the development of an integrated optimization tool based on a formal mathematical programming model for the optimal design of SCPP and economic feasibility assessment. The developed is general, thus, can be utilized in any location of the world for SCPP design and assessment.

1.4. Limitation of the study

This study focuses on providing a model for optimal SCPP design assuming that the proposed plant would be constructed as the build-operate-transfer (BOT); however, fails to provide detailed insight into the complex mechanism of BOT including risk.

1.5. Organization of the thesis

The remainder of this thesis work consists of five chapters which are organized as follows:

Chapter 2 starts by reviewing the working principle of the SCPP technology. Previous works on the SCPP technology both experimental and theoretical analysis is presented together with relevant case study applications and results obtained. Economic feasibility approach adopted for SCPP technology. Additionally, the previous optimization attempts on the SCPP technology are reported which provided a milestone for establishing the proposed model. Finally, a discussion of input data of solar radiation, ambient temperature and wind velocity which are necessary for assessing the resulting power output from any proposed SCPP design is presented.

Chapter 3, at first, presents the mathematical model for the solar collector, chimney, and turbine including the assumption made. After words, the two-stage feasibility approach based on a new nonlinear programming model is presented. In the first stage, a non-linear optimization model which determines the optimal SCPP dimensions that minimize the NPV of the capital cost of building the plant and the periodic operation and maintenance costs are proposed. The second stage deducts the NPV of the lifecycle cost obtained in the first stage from the present value of revenues obtained due to selling the electricity generated by the SCPP, thus, it presents the feasibility of the proposed SCPP.

Chapter 4 starts with the general energy situation in the country of the case study, the available solar radiation and barriers to the solar energy development in the country. This is followed by the identification of the specific location in the country for the case application. Some features that would favor the development of SCPP in the case application location are highlighted. The parameters used and the results of the proposed model are presented and discussed for the case application. Finally, the sustainable impact of the proposed SCPP in the area is presented.

Chapter 5 shows the effect of some important parameters on both the optimal plant dimension and the economic feasibility of the proposed SCPP design through detailed sensitivity analysis. In this chapter, the impact of the discount rate, collector efficiency, turbine efficiency, electricity price, electricity demand, and meteorological conditions are examined on the model performance so as to offer managerial insights.

Chapter 6 summarizes the research findings, results, conclusion and offers recommendations for future work.

CHAPTER 2

LITERATURE REVIEW

The solar chimney power plant (SCPP), also known as solar updraft tower power plant is a device that produces buoyancy to drive air in order to generate electricity. The idea of producing electricity with the use of solar chimney was first conceived and proposed by a Spanish colonel named Isidoro Cabanyes in 1903 [24]. The proposition consists of an air heater attached to a house with a chimney as shown in Figure 2. A wind propeller was placed in the housing interior for the sole purpose of producing electricity. The concept was based on the fact that, if the speed of air flow is relatively high for a large scaled thermal collector, electricity can be generated by the turbine generator placed under the chimney.

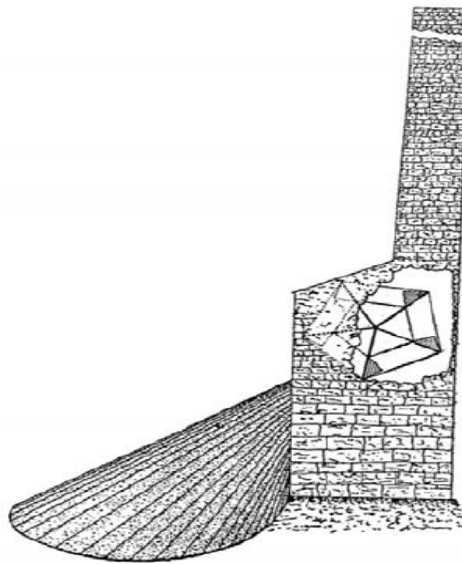


Figure 2. Solar engine proposed by Isidoro Cabanyes [24].

Subsequently, in 1926 Prof. Bernard Dubos proposed the construction of a long SCPP in North Africa with its tower on the slope of a high mountain as depicted in Figure 3.

It was reported that besides the enormous amount of energy extracted from the wind turbines, the system can attain an air flow speed up to 50 m/s [25].

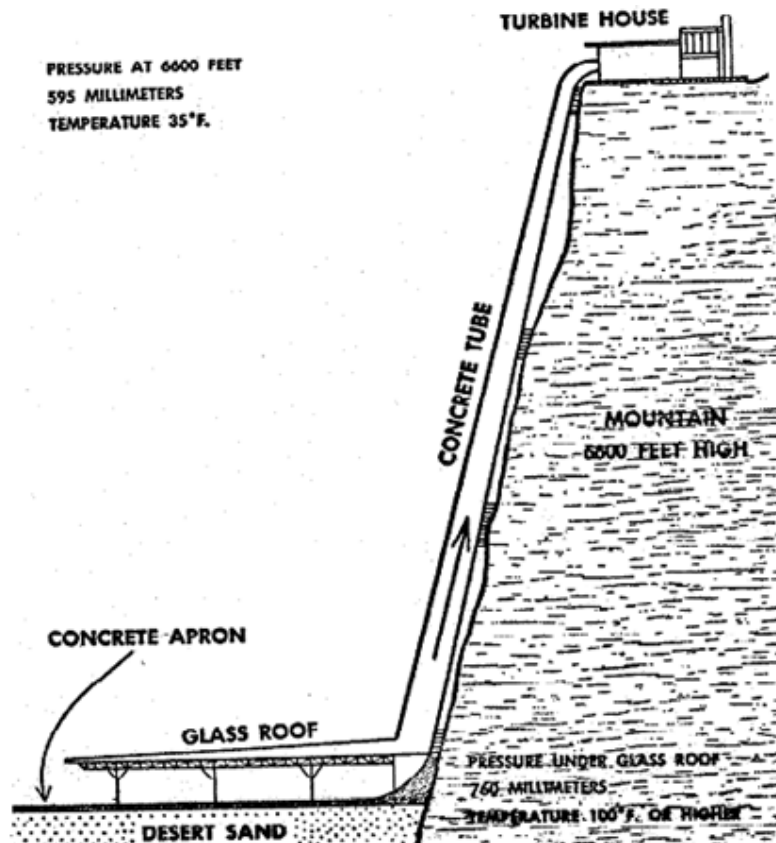


Figure 3. Solar Aero-Electric power plant proposed by Prof. Dubos [25].

However, the first practical action on the development of SCPP was the design and construction of the prototype in Manzanares, Spain by the Prof. Schlaich and his team in 1982. The prototype which consists of collector diameter of 244 m, chimney height and diameter of 194.6 m and 10 m, respectively produced peak power output of 50 kW. The construction of the pilot prototype was commissioned by the Minister of Research and Technology of the Federal Republic of Germany [26]. The prototype which was connected to the utility network produced power continuously throughout the eight years of operation. The constructional features, the principle of operation, the

technical feasibility and the result of the pilot SCPP was presented by Haaf *et al.* [26] and Haaf [27], where brief discussions of the energy balance and cost analysis were presented. The authors mentioned that SCPP systems would be economically feasible for large-scale power design. For this reason, extrapolation of the pilot plant experimental results to the large scale power plant was presented by Schlaich *et al.* [15].

2.1. The working principle of SCPP system

The SCPP combines three known reliable technology of solar collector, solar chimney situated in the center of the collector, and power conditioning unit (turbine) as shown in Figure 4 to produce electricity during operation. The description of the working is presented here by considering what is happening in each of the technology.

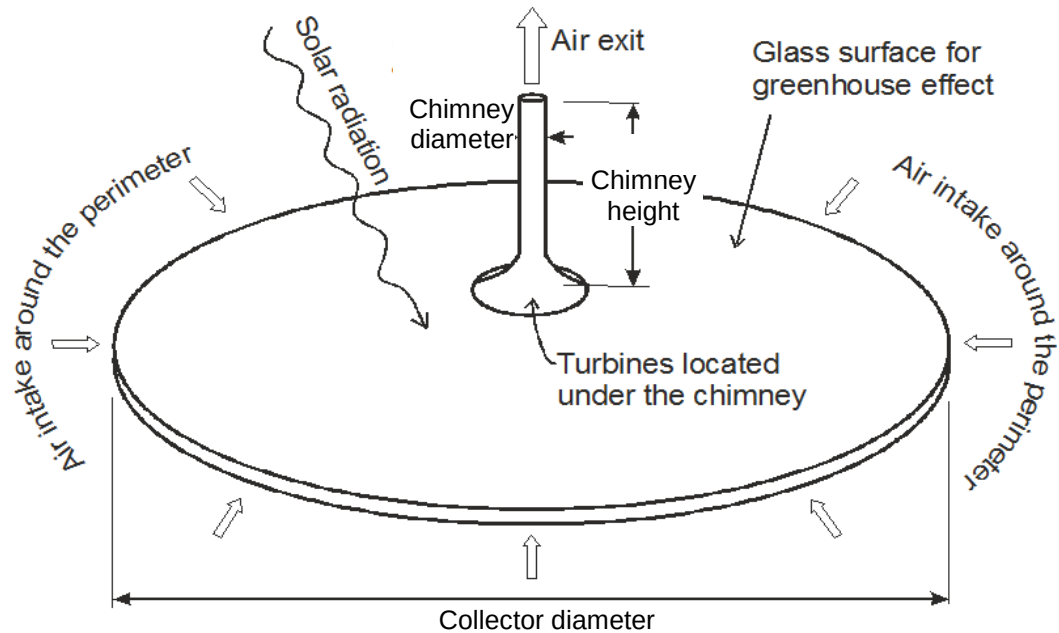


Figure 4. Schematic of a solar chimney power plant [10].

2.1.1. Solar collector

A solar air collector is formed when a large transparent glass or plastic roof is supported above the ground by a column and support matrix. The placing of the transparent glass or plastic roof above the ground is to allow air intake around the perimeter as shown in Figure 4. Moreover, the ground serves as a natural heat storage layer. Thus, the solar collector essentially consists of a column support, a transparent roof and a support matrix. Incident solar radiation which comprises of both direct and diffuse component strikes the collector. Some fraction of the radiation is transmitted while other are either absorbed or reflected by the glass collector. The amount absorbed, reflected or transmitted depends on the solar incidence angle and optical characteristic of the adopted glass collector which includes extinction coefficient, thickness, and the refractive index. The schematic diagram presented by Cao *et al.* [28] captures the absorbed, transmitted, reflected and series of multiple reflection between the transparent collector and the ground as shown in Figure 5.

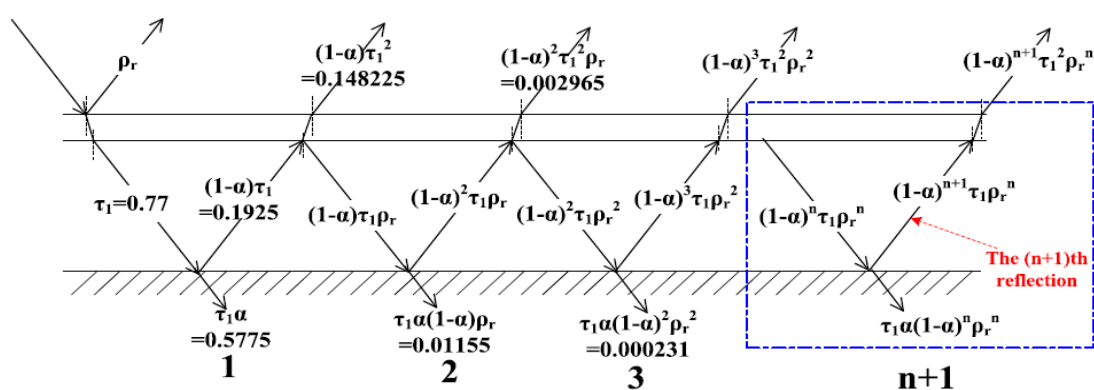


Figure 5. Multiple reflections between the transparent collector and the ground [28].

For this reason, it is important to choose a collector with good thermal and optical properties (high transmittivity) in order to reduce energy losses due to glass absorptivity and reflectivity. The collector admits the transmitted radiation and retains the long-

wave from the heated ground thus producing a greenhouse effect. The ground beneath the collector heats up and transfers its heat through natural convection mechanism to the air above it. This radially flowing air enters from the collector peripheral and is driven by buoyancy towards the center where the chimney is located. It is important to note that some of the heat energy absorbed by the ground are lost to the earth beneath it.

2.1.2. Chimney

The chimney is located at the center of the transparent collector and as such act as the thermal engine of the SCPP that channels the heated air flowing from the collector to the chimney base using temperature difference effect. Zhou *et al.* [29] describe the chimney as a pressure tube with low friction due to its favorable surface-volume ratio. They mentioned that the mass flow of the updraft air is approximately proportional to the collector air temperature rise and the height of the chimney. Different materials have been proposed for chimney design such as metal sheet, reinforced concrete, floating chimney using inflated structures. Moreover, Schlaich [30] recommends the use of reinforced concrete in the construction of the commercial chimney due to its long lifespan even though guyed corrugated metal sheet flue was used in the Manzanares prototype. At the exit of the collector (inlet of the chimney), the heat energy of the flowing air is converted into kinetic energy at the chimney and a pressure difference (which can be estimated from the density difference) is produced between the chimney base and ambient pressure at the outlet.

2.1.3. The power conditioning unit (PCU)

The PCU of an SCPP consists of one or several turbine generator, power electronics, a grid interface and a horizontal-to-vertical transition section (HTVTS) [29]. The HTVTS house the inlet guide vanes (IGV) which function as converting the horizontal flow at the exit of the collector into a vertical flow at the inlet of the chimney. The air flow is then channeled through the turbine that powers a generator. The air flow kinetic energy turns the blades of the turbine to drive the generator in order to produce electricity. The different geometric configuration of HTVTS such as a straight junction, curve junction, slanted junction, conic, and the curved junction with guiding cone were presented and compared in terms of mass flow rate by Bernardes *et al.* [31].

2.2. Other experimental studies on SCPP

SCPP has attracted much attention for electricity generation due to its numerous advantages as previously stated. As a result, experimental studies involving SCPP are now well-established for different locations, as various research sought to assess the performance of SCPP under given environmental conditions after the construction of the Manzanares pilot plant prototype. The experimental studies on the basic SCPP performance provide a solid foundation for the development and establishment of a mathematical model that would be useful in studying the performance of commercial SCPP before deployment. Examples of these studies can be found [32–42] for different locations and the detail of the structural dimensions are presented in Table 1. For a more comprehensive report on the experimental setup of SCPP please see the recent comprehensive review of Zhou *et al.* [43].

Table 1. Structural dimensions of some of SCPP experimental setup.

N/S	Location	Collector	Chimney	Chimney	Collector	Temp.	Vel.	Ref.
		Diameter	Diameter	Height	Material	Rise	(m/s)	
		(m)	(m)	(m)		(°C)		
1	Wuhan, China	10	0.3	8.8	Glass	24.1	2.81	[36]
2	Izmir, Turkey	3.4	0.07	2	-	-	-	[37]
3	Florida, USA	18.3	2.44	7.92	Plastic	27.8	-	[42]
4	Damascus, Syria	3.99	0.3	9	Glass	19	2.9	[35]
5	Texas, USA	11.58	0.19	4.88	Plastic	-	2	[32]
6	Tehran, Iran	3	0.2	2	Glass	11.05	1.3	[34]
7	Nakhon Ratchasima, Thailand	8.2	2	8	Plastic	-	-	[38]
8	Zanjan, Iran	10	0.25	12	Plastic	25	3	[33]
9	Kerman, Iran	45.15	3	60	Glass	-	-	[40]
10	Karak, Jordan	6.8	0.58	4	Plastic			[39]
11	Nanjing, China	-	0.08	2.5	Glass	14	-	[41]

2.3. SCPP models

The solar collector, chimney, and turbine are very important in estimating the resulting power output from an SCPP system. For this reason, the available literature on SCPP is extensive employing both analytical and numerical models for better understanding and improvement. The detailed mode of applicable heat transfer, temperature distribution along the collector and various operational strategies of SCPP have been addressed by Bernardes *et al.* [44–46]. Backstrom and Gannon [47] developed a one-dimensional compressible flow equation to estimate all the thermodynamic variables which are dependent on the chimney height, wall friction, additional losses, internal drag and area change. They conclude that the vertical acceleration pressure drop can be eliminated by flaring the chimney by 14% to keep the through-flow mach number constant. In addition, a simplified analytical model for determining the optimum ratio of pressure drop was presented by Nizetic and Klarin [48]. The obtained turbine pressure drop for SCPP is in the range of 0.8 – 0.9, which is consistent with other studies. Pasumarthi and Sherif [49] presented two enhancements which include extending the collector base and introducing an intermediate absorber in the collector in an attempt to increase the power output from SCPP. Zhou *et al.* [50] provided a mathematical model for estimating the power output from SCPP, the model result was verified and validated with the calculations from the experimental measurement in HUST, China. Guo *et al.* [51] presented a numerical model for the SCPP collector and compared the result of collector performance with and without radiation model. They claimed that studies which did not incorporate radiation models tend to overestimate not only the temperature rise but also the efficiency of the collector. Moreover, Ming *et al.* [52] studied the power output smoothing methods for solar chimney power generation system. They found that hybrid energy storage of water and sandstone

could effectively decrease the fluctuations in solar chimney power output for smooth operation during the period when there is no solar radiation.

For the operation of SCPP during the night time when there is no solar insolation, Ming *et al.* [53] presented conjugate simulations of energy storage layer, the collector and the chimney in the power output estimation of the system. Additionally, Pretorius and Kroger [54] compared the performance of different ground storage layers such as sandstone, granite, and limestone on the power output. The study showed an insignificant annual power output decrease of about 0.3% for granite relative to sandstone and limestone. Furthermore, Bernardes [55] investigated the influence of thermal diffusivity and effusivity for some ground thermal properties. He found that ground materials with lower thermal diffusivity and effusivity substantially reduce power output peaks for periods with greater heat gain. Bilgen and Rheault [56] studied the performance of SCPP for high latitudes. Subsequently, Cao *et al.* [16] compared conventional and sloped SCPP using detailed heat transfer model for Lanzhou, China. They found that larger solar collector angle results in improved performance during the winter relative to the summer, and subsequently concluded that the sloped SCPP is more suitable for areas of high latitude. Koonsrisuk and Chitsomboon [57] compared some of the available simple theoretical models for the SCPP power output performance using carefully calibrated numerical computational fluid dynamics. They rated the performance of the analytical models in terms of their ability to reproduce the experimental results and found that the best analytical model was the one proposed by Schlaich [15]. Gannon and von Backstrom [58] presented an experimental investigation involving the performance of solar chimney turbine. Over the measured operating range of the turbine, the reported efficiency values are between 77 and 90%.

2.4. Case studies of SCPP

In addition to the collector diameter, and chimney height, the main factors affecting the system performance of an SCPP are the solar radiation, ambient temperature and wind speed. Some other studies have established the importance of environmental conditions on the resulting power output from the system; thus, emphasizing that case studies involving SCPP are very valuable [16,59]. The SCPP is presently competitive in areas in which global radiation is greater than 1950 kWh/m². These areas include but not limited to the larger part of Africa, North and South America, the greater part of Australia, the Near East, and the western part of Asia [60]. Some of the case study results evaluated under different meteorological conditions are presented in Table 2. Moreover, a comprehensive review by Zhou *et al.* [43] reported different unit costs of electricity produced from SCPP under different operating conditions and plant capacities.

From Table 2, it is apparent that there is no specified plant configuration available in the literature, as a result, different dimensions of chimney height, chimney diameter, and collector diameter have been chosen in these studies. Schlaich *et al.* [15] mentioned that there is no optimum SCPP plant configuration since the resulting power output increases with an increase in the dimensions. They emphasized that an SCPP can only be optimized considering local environmental conditions including the price of electricity, and the costs of labor, land, and concrete. To increase the resulting power output and decrease the capital investment cost of SCPP, an optimization model can be used.

Table 2. Modeling case studies of SCPP at different locations.

N/S	Location	Collector Diameter (m)	Chimney Diameter (m)	Chimney Height (m)	Power Output (MW)	Reference
1	Croatia	1250	82	550	2.8 – 6.2	Nizetic <i>et al.</i> [61]
2	United Arab Emirates	2000	50	500	> 8	Hamdan [62]
3	Iran	1000	-	350	1 – 2	Sangi [63]
4	Yinchuan, China	400	10	200	0.11 – 0.19	Dai <i>et al.</i> [17]
5	Adrar, Algeria	500	5	200	0.14 – 0.20	Larbi <i>et al.</i> [64]
6	Girne, Cyprus	2900	70	750	28.8	Okoye and Atikol [10]
7	Thailand	400	-	400	0.20	Koonsrisuk and Chitsomboon [65]
8	Qinghai-Tibet Plateau, China	5650	80	1000	100	Zhou <i>et al.</i> [66]
9	Sinkiang, China	5500	60	1000	100	Guo <i>et al.</i> [67]
10	Manzanares, Spain	1250	45	550	5	Schlaich <i>et al.</i> [15]
		2900	70	750	30	
		4300	110	1000	100	
		7000	120	1000	200	

2.5. Economic feasibility of SCPP

To assess the economic feasibility of any project, economic metric indicator tools are normally employed. These tools include net present value (NPV), save to investment ratio (SIR), internal rate of return (IRR), simple payback period (SPP), and levelized cost of the electricity (LCOE). Among these metric tools, NPV and LCOE are widely utilized in SCPP studies.

2.5.1. Net present value (NPV)

Capital cost and maintenance expenses may be compensated by benefits such as fuel saving and environmental improvement generated from the SCPP. It is often believed that a project is viable if the NPV achieved after a number of years of the system operation is positive [10]. The discount rate is usually fixed and assumed to be equivalent to the interest rate. However, provided that SCPP generates positive environmental and social benefits [10,68], the application of the interest rate is questioned by ecological economists due to the fact that it underestimates the benefit of technology.

Okoye and Atikol [10] performed economic feasibility analysis adopting metric indicators of NPV, SIR, IRR and SPP for using an SCPP to replace an equivalently sized fossil fuel powered thermal plant in Northern Cyprus. To account for the environmental benefit, the authors computed the carbon mitigated from the proposed SCPP design and included the carbon trading benefit in the economic feasibility assessment. The study concluded that the SCPP technology is feasible but could be more viable if the price of the technology decreases due further research and development. Similarly, in another study Li *et al.* [68] developed a different model to analyze the cost and benefit of reinforced concrete solar chimney power plant built in

northwest China. The authors divided the life cycle time of the proposed system into four phases, after which the total net present value (TNPV) and minimum electricity price at each phase were estimated. The proposed system was compared with coal-fired power plants and the conclusion is made that huge advantages of RCSCPP over coal-fired power plant can be embodied in phase 2-4.

2.5.2. Levelized cost of electricity (LCOE)

The tipping point for the adoption of most solar-to-electricity conversion technologies is considered to be when systems achieve grid parity. Considering that the cost of electricity generated by the widely utilized conventional alternatives is rising due to their finite nature and the cost of energy from renewable alternatives are falling as a result of research and development. Grid parity refers to a situation whereby the price of electricity from a renewable system is comparable with the conventional sources on the grid. To access grid parity and economic feasibility of an energy generation project, LCOE is widely utilized. The LCOE method is straightforward and according to Branker *et al.* [69] lacks clarity of reporting assumptions and degree of completeness thus producing widely varying results. For SCPP, Fluri *et al.* [70] noted the significant differences in the LCOE calculated from different researchers even in cases where the input parameters are relatively the same and presented a more detail cost analysis based on LCOE for SCPP. The authors concluded that the previous research may have underestimated the initial cost and LCOE from the system.

Schlaich [30] presented cost values for all SCPP components for different plant sizes and a procedure for estimating the LCOE. The author investigates the sensitivity of the LCOE to interest rate and length of depreciation period. In another study, Schlaich *et*

al. [15] presented the component cost of different SCPP plant capacity for fixed economic parameters. The reported plant capacity and LCOE ranged from 5 – 200 MW and 0.21 – 0.74 €/kW h, respectively. In another study, Nizetic and Klarin [61] assessed the feasibility of SCPP under Mediterranean climate conditions and concluded that the unit cost of the energy generated from the system was higher than the cost of other energy generation technologies. Moreover, Zhou *et al.* [43] utilized the LCOE method to calculate the unit cost of electricity generated from different SCPP proposed in the literature in their comprehensive literature review.

2.6. Optimization of SCPP

An attempt on optimization of SCPP has been made by Pretorius and Kroger [19] by means of thermo-economic analysis in which an approximated cost model was developed and presented. Similarly, Kasaeian *et al.* [34] presented an analytical and numerical study of geometric optimization of SCPP prototype in University of Tehran, Iran. The constructional features of the prototype are 2 m chimney height and 6 m collector diameter and by varying parameters, the authors concluded that collector inlet of 0.06 m, chimney height of 3 m and chimney diameter of 10 m were the best alternative for the constructed prototype. Dehghani and Mohammadi [21] and Gholamalizadeh and Kim [20] developed genetic algorithms (GAs) to provide near-optimal solutions for the SCPP design. In these studies, Pareto front which represents the set of non-dominated solutions based on the specified objective functions were presented. The multi-objective optimization model presented by Dehghani and Mohammadi [21] simultaneously considers power output maximization and capital cost minimization of SCPP, whereas the optimization model of Gholamalizadeh and

Kim [20] attempts to maximize both the total efficiency and power output and at the same time minimize the capital investment cost.

In a more recent study, Shariatzadeh *et al.* [71] presented an optimization model for floating SCPP combined with a solid oxides fuel cell. The idea is that the floating SCPP will produce electricity by sunlight to supply part of the demand while additional electricity is generated through the high-temperature electrolysis that produces hydrogen which is stored and converted into electricity by the solid oxide fuel cell. The model was solved using GAs. To our knowledge, all optimization algorithms proposed thus far for the SCPP are based on heuristic procedures using GAs (see [20,21]). However, as Perez *et al.* [22] stated, GAs focus on finding an acceptable solution in an attempt to capture the global optimum solution, but they guarantee neither local nor global optimum.

2.7. Meteorological data for technical and economic assessment of SCPP

Site-specific meteorological data are essential inputs in assessing both the technical and economic feasibility of SCPP. Quality meteorological data includes but not limited to solar radiation, ambient temperature, and wind speed [72]. These data are often obtained from a local meteorological station if available. Because the cost of running and setting up these stations are high these data are often not available for some location of interest. In other words, access to quality data is limited, and even when available may not be in a standardized format to enable easy long-term system performance predictions. Standardized meteorological data are reported in various studies in the following forms: Test Reference Year (TRY); Typical Meteorological Year (TMY); Example Weather Year (EWY); Weather Year for Energy Calculations

(WYEC); and Typical Principal Component Year (TPCY) [11,73,74]. Although TRY and TMY are widely utilized, proponents of TMY recommended its usage because of its ability to give a fairly reliable result over a long term condition. Skeiker [73] applied several methods for generating TMY data using 10 years hourly measured meteorological data in Damascus, Syria. The obtained TMY's were evaluated based on their impact on typical building thermal systems and the author concluded that TMY data generated using the modified Sandia method gives the closest result to the average performance of the building's thermal system relative to other methods such as Crows, Danish, Festa-Ratto, Miquel-Bilbao, Gazela-Mathioulakis and average meteorological year.

Similarly, Chow *et al.* [75] emphasized the superiority of TMY over TRY data sets based on over a century of data for the cities of Hong Kong and Macau. Moreover, Zhou *et al.* [11] pointed out that TMY is one of the most common synthetic weather data formats used in a solar energy assessment, where synthetic means that an hourly meteorological data set is synthetically generated from a more limited meteorological data set. TMY2 data contains parameters such as extra and terrestrial hourly insolation (direct normal insolation, diffuse horizontal insolation, and global horizontal insolation), ambient conditions (dry bulb temperature, dew point temperature, and relative humidity), wind speed, and direction. Hourly Typical Meteorological Year 2 (TMY 2) data set is utilized in the simulation of the SCPP performance. The importance of using TMY data in assessing the long-term performance of the solar system was emphasized in the work of Ohunakin *et al.* [76], where the authors presented the method for converting measured solar radiation data into TMY.

CHAPTER 3

NUMERICAL MODEL OF SOLAR CHIMNEY POWER PLANT

The mathematical model of the SCPP is divided into the subsystem components for brevity. Power output from SCPP depends on geometric parameters of the plant (the collector and the chimney), and the environmental conditions (ambient temperature, and solar insolation).

3.1. Assumptions of the study

For the proposed optimization model, the following assumptions are made in this study:

- I. Steady state operation is assumed considering that solar radiation and the ambient temperature is transient in real conditions.
- II. The collector is placed on the horizontal surface and flow in the collector is considered as uniform flow between two parallel plates.
- III. Air is an ideal gas and evaporation does not take place inside the collector.
- IV. The proposed SCPP would be build-operate-transfer (BOT) by the investors thus the cost of land and transmission will be catered by the government.
- V. No salvation value after the service life of the SCPP for the investors.
- VI. The electricity demand is constant.

3.2. Solar collector model

The solar chimney collector utilizes solar radiation as fuel to heat a working fluid. The collector comprises a large plate (collector cover) placed at a height above the ground to create an airflow channel. The collector cover function is to transmit the radiant

energy received to heat both the ground and flowing ambient air in-between. The heated ground reflects the energy received to increase the radiant of the flowing air. Several formulations are available in the literature for the estimation of the collector efficiency [10,17,61,63]. These formulations define the collector efficiency as a function of the available solar radiation and the temperature difference between the surroundings and the inlet of the chimney. In reality, the associated heat losses via convection and radiation affect the air temperature and, thus, the efficiency of the collector. A recent study by Guo *et al.* [51] revealed that the efficiency of the solar chimney collectors is overestimated when radiation model is not taken into consideration. This overestimation can introduce errors in the economic feasibility of SCPP and ultimately lead to the wrong conclusion. Figure 6 shows the flow of energy and the thermal network of the flat plate collector.

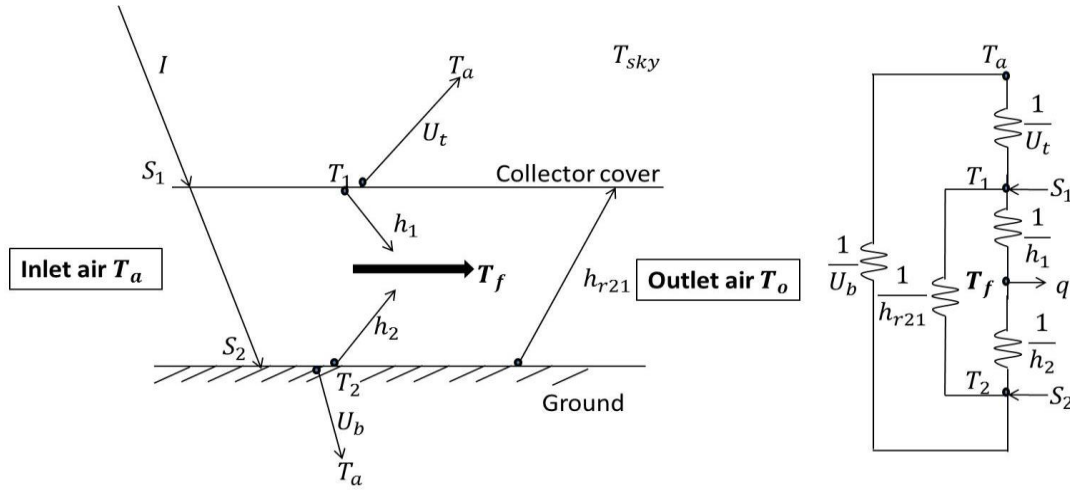


Figure 6. Air flow, energy interactions and thermal resistances in the collector.

The energy balances in the collector are outlined at the collector cover, for the air flow, and ground absorber, respectively, as:

$$S_1 + h_{r21}(T_2 - T_1) + h_1(T_f - T_1) = U_t(T_1 - T_a) \quad (1)$$

$$h_1(T_1 - T_f) + h_2(T_2 - T_f) = q \quad (2)$$

$$S_2 + h_2(T_f - T_2) + h_{r21}(T_1 - T_2) = U_b(T_2 - T_a) \quad (3)$$

where S_1 is the incident solar radiation in the collector cover, T_2 is the ground temperature, T_1 is the collector cover temperature, T_f is the air flow temperature, S_2 is the solar radiation absorbed by the ground, U_t is the overall heat loss coefficient in the top of the collector cover, U_b is the ground loss coefficient, h_{r21} , h_1 and h_2 are the heat transfer coefficients between the ground and the collector cover, the collector cover and air flowing inside the collector, and the collector cover and air flowing inside the collector, respectively.

The complication arising from the heat balance equation presented above is that there is no straight-forward analytical solution for solving the temperatures T_1 , T_2 and T_f since the heat transfer coefficients h_{r21} , h_1 , h_2 , U_t and U_b are dependent on them. For this reason numerical iteration solution is imperative, in which guess temperature values are initially utilized.

The equations for calculating the variables which appear in equation are outlined as follows,

Incident solar radiation on the collector cover S_1 and the ground absorber S_2 is given as;

$$S_1 = \alpha_1 I \quad (4)$$

$$S_2 = \alpha_2 \tau_1 I \quad (5)$$

where α_1 is the absorptivity of the collector cover, I is the available solar radiation, and α_2 and τ_1 are the corresponding absorptivity of the ground and transmissivity of the collector cover, respectively. The formulation and procedure for calculating the absorbed and transmitted incident solar radiation are obtained from Duffie and Beckman [77]. Additionally, the overall heat loss coefficient in the top of the collector cover U_t is obtained as,

$$U_t = h_w + h_{rs} \quad (6)$$

where the wind convective heat transfer, h_w , [64] and the radiation heat transfer coefficient between the collector cover and the sky, h_{rs} , [42] are, respectively, as follows,

$$h_w = 5.67 + 3.86 (V) \quad (7)$$

$$h_{rs} = \sigma \varepsilon_1 (T_{sky} + T_1) (T_{sky}^2 + T_1^2) \left(\frac{T_1 - T_{sky}}{T_1 - T_a} \right) \quad (8)$$

where V is site location wind speed, and ε_1 is the emissivity of the collector cover, T_{sky} is the sky temperature expressed as $T_{sky} = 0.0552(T_a)^{1.5}$ [78].

The radiation heat transfer coefficient between the cover and the ground absorber can be estimated by,

$$h_{r21} = \frac{\sigma(T_2 + T_1)(T_2^2 + T_1^2)}{\frac{1}{\varepsilon_2} + \frac{1}{\varepsilon_1} - 1} \quad (9)$$

The free convection heat transfer coefficient between the collector cover and the air flow, h_1 and that between the absorber plate and the air flow, h_2 are found using,

$$h_k = Nu \frac{k_{air}}{D_h} \quad \text{for } k = 1, 2 \quad (10)$$

In the equation, Nu is Nusselt number, k_{air} is thermal conductivity of the air. For the circular shaped collector with diameter D_{coll} and height H_{coll} , the hydraulic diameter D_h is calculated as,

$$D_h = \frac{4(\pi D_{coll} \times H_{coll})}{2(\pi D_{coll} + H_{coll})} \quad (11)$$

For solar chimney power plants where $H_{coll} \ll D_{coll}/2$, Bernardes *et al.* [45,79] and Larbi *et al.* [64] used the approximation $D_h \approx 2H_{coll}$.

Bernardes *et al.* [45] performed detail analysis of heat transfer coefficients for SSCP collector thus the dimensionless Nusselt number is obtained from the correlations of Petukhov and Popov (1963), Lloyd and Moran (1974), and Baehr and Stephan (1996) following their study.

Bernardes *et al.* [79], and Bilgen and Rheault [56] presented the following expression for evaluating the useful heat transferred to the moving air stream q and ground loss coefficient U_b ,

$$q = \tau (T_f - T_a) \quad (12)$$

$$U_b = 2 \left(\frac{k \rho C_p}{\pi t} \right)^{0.5} \quad (13)$$

where $\tau = \dot{m}C_p / \pi r H_{coll}$, t is the hour from midnight and $r = D_{ch}/2$

The properties of air are functions of the temperature, thus the following empirical equation can be used to estimate air density ρ , thermal conductivity k , specific heat capacity C_p and dynamic viscosity μ , for temperature range from 280 K to 470 K [80] as:

$$\rho = 3.9147 - 0.016082T + 2.9013 \times 10^{-5}T^2 - 1.9407 \times 10^{-8}T^3 \quad (14)$$

$$k = (0.0015215 + 0.097459T - 3.3322 \times 10^{-5}T^2)T^{-6} \quad (15)$$

$$C_p = 1002.5 + 275 \times 10^{-6}(T - 200)^2 \quad (16)$$

$$\mu = 1.458 \times 10^{-6} \frac{T^{1.5}}{T+110.4} \quad (17)$$

Finally, the air flow temperature and the collector efficiency are given, respectively, as:

$$T_f = \frac{T_o + T_{fi}}{2} \quad (18)$$

$$\eta_{coll} = \frac{h_1(T_1 - T_f) + h_2(T_2 - T_f)}{I} \quad (19)$$

Rather than resolving the energy balance equations presented in Eq. (1) - (3) by performing complex algebraic manipulation, they are rearranged in terms of temperature and subsequently absorbed into 3×3 matrix form displayed as:

$$\begin{bmatrix} (h_1 + h_{r21} + U_t) & -h_1 & -h_{r21} \\ h_1 & -(h_1 + h_2 + \text{r}) & h_2 \\ -h_{r21} & -h_2 & (h_2 + h_{r21} + U_b) \end{bmatrix} \begin{bmatrix} T_1 \\ T_f \\ T_2 \end{bmatrix} = \begin{bmatrix} S_1 + U_t T_a \\ -\text{r} T_{fi} \\ S_2 + U_b T_a \end{bmatrix} \quad (20)$$

The temperatures are determined by matrix inversion. The resulting matrix is solved iteratively, and the newly calculated temperatures are compared to the previous values until they converge. The convergence tolerance is set in such a way that the difference between the new temperature and guessed temperature is less than 0.01 K.

3.3. Chimney model

In the chimney, the heated air (thermal energy) from the collector is converted into kinetic energy. Heat transfer in the chimney section is negligible [79]. The pressure difference is produced between the chimney base and the surroundings due to change in the frontal area as the heated air enters the chimney. From Bernoulli's equation, the pressure drop ΔP_{turb} across the turbine can be expressed as a function of the total pressure difference as:

$$\Delta P_{turb} = \Delta P_{tot} - \frac{\rho_2 V_{ch}^2}{2} \quad (21)$$

The resulting total pressure ΔP_{tot} is the sum of both the dynamic $\Delta P_{dynamic}$ and static pressure ΔP_{static} [15],

The static pressure is equal to zero [15], hence,

$$\Delta P_{tot} = \Delta P_{dynamic} = \rho_2 g H_{ch} \frac{\Delta T}{T_a} \quad (22)$$

Nizetic and Klarin [48] mentioned that at the inlet of the chimney; the optimal air flow velocity has a square root dependence on air temperature increase in the collector for any given solar chimney height. They estimated V_{ch} as follows:

$$V_{ch} = \sqrt{\frac{2 g H_{ch} \Delta T}{3 T_a}} \quad (23)$$

The efficiency of the chimney η_{ch} which is directly proportional to its height is estimated as [61],

$$\eta_{ch} = \frac{g H_{ch}}{c_p T_a} \quad (24)$$

3.4. Turbine model

The turbine is the main power generating device in SCPP, thus, converts the kinetic and potential energies into mechanical energy. The shrouded wind turbine in the SCPP is different from the wind turbine used in a conventional wind farm. There is a significant change in pressure at the inlet and outlet of the turbine even though the air velocities are relatively the same. For this reason, Betz limit is not obeyed in the pressure stage wind turbine. Nizetic and Klarin [48] concluded that the turbine pressure drop factors are in the range of 0.8 – 0.9 while emphasizing that it is not a function of temperature rise in the collector as it is influenced by the air flow velocity. Detailed investigation of wind turbines has been carried out [43,58,81,82]. From the recent review work of Zhou and Xu [43], the selected values for turbine efficiency widely adopted in SCPP studies ranges between 50 and 90%. The turbine converts the resulting heat energy of the airflow emanating from the collector into electricity. For this reason, the efficiency being less than 100% accounts for the conversion losses in turning the shaft. Nizetic and Klarin [61] showed that for different SCPP capacities, the efficiency of the turbine remains approximately the same at 80%.

Schlaich *et al.* [15] mentioned that the resulting power output from SCPP is directly proportional to the collector area and chimney height. Following Schlaich *et al.* [15], the electrical power output P_{ele} from the SCPP is calculated as:

$$P_{ele} = I A_{coll} \eta_{ch} \eta_{coll} \eta_{tur} \quad (25)$$

where I is the available solar radiation, A_{coll} is the area of the solar collector, and η_{ch} , η_{coll} , and η_{tur} are the chimney, collector, and turbine efficiencies, respectively. Note that $A_{coll} = \pi D_{coll}^2/4$ where D_{coll} is the diameter of the collector.

On the other hand, Koonsrisuk and Chitsomboon [57] reported that the theoretical model by Schlaich *et al.* [15] for power output performance is the best even though the resulting system efficiency and power output from the model are independent of the chimney diameter. On the other hand, the simulation results of computational fluid dynamics in [57] for validation suggested that the efficiency and power output increases with the chimney diameter. Similarly, Hamdan [62] explained that this increase is only when the chimney diameter is below a critical value which depends on the Reynolds number and boundary layer thickness. The author reported that for commercial SCPP above the critical value, the effect of increasing the chimney diameter on the power output is very insignificant (i.e., the power variation of about 0.14% is found when the chimney diameter is increased from 60 m to 80 m).

3.5. Proposed optimization model

The addressed problem is to determine the optimal SCPP dimensions, such that the NPV of the total revenue obtained from the electricity produced less total costs of the system is maximized given the energy demand of an urban or rural area, the meteorological data of the area, the price of electricity, the capital cost of building an SCPP, the operation and maintenance costs, the discount rate and the service life of the plant.

The urban or rural area with a given population has an energy demand E_j in day j , which has to be met by the SCPP with a certain level of reliability. Reliability r is defined here as the percentage of days in a year that the amount of energy generated by the SCPP is sufficient to satisfy the demand. The amount of energy generated by

the SCPP during a time period is found by multiplying the power output in Eq. (1) with the duration of sunshine in that time period.

Based on the amount of energy demand satisfied and the unit price of electricity $C_{\text{electricity}}$, revenue is obtained every month throughout the service life S of the SCPP. The unit price of electricity is the amount determined either by the public utility for electricity or by the agreement with the government and the private sector that builds the SCPP in a build-operate-transfer (BOT) system.

Building a SCPP incurs some initial investment cost as well as periodic operation and maintenance costs. The approximate cost model proposed by Pretorius and Kroger [19] and subsequently utilized in Dehghani and Mohammadi [21] and Gholamalizadeh and Kim [20] is adopted for the capital cost of building the SCPP in this study. Accordingly, the capital cost of chimney C_{ch} , collector C_{coll} , and turbine C_{tur} are given, respectively, as:

$$C_{ch} = \frac{\pi}{4} ((D_{ch} + 0.001H_{ch})^2 - D_{ch}^2) H_{ch} CC_{sc} \quad (26)$$

$$C_{coll} = \frac{\pi D_{coll}^2}{4} (Pt_{coll} CC_{sc}) + \frac{\pi D_{coll}^2}{4} (Pt_{coll} CC_{sc}) Pt_{H_{coll}} H_{coll} \quad (27)$$

$$C_{tur} = Pt_{tg} (C_{ch} + C_{coll}) \quad (28)$$

where D_{ch} is the chimney diameter, CC_{sc} is the specific capital cost of chimney due to material and construction cost and Pt_{tg} is the specific percentage of the capital cost of collector and chimney. While the term in Eq. (26) assume that the average chimney thickness increases by one millimeter per one cubic meter increase in chimney height, the expression in Eq. (27) presumes that the base cost of the collector per m^2 will be

Pt_{coll} percent of the cost of CC_{sc} plus an additional $Pt_{H_{coll}}$ percent for every one meter height of the collector inlet.

The operation and maintenance cost $C_{O\&M}$ that is incurred monthly is a percentage $Pt_{O\&M}$ of the total capital costs of the chimney, collector and turbine, and can be expressed as,

$$C_{O\&M} = Pt_{O\&M}(C_{ch} + C_{coll} + C_{tur}) \quad (29)$$

In addition, several studies mentioned that the use of water storage layer does not contribute significantly to the power output but helps to smooth the power output over time for continuous operation after the sunset and before the sunrise [15,52,55]. Thus, the water storage layer provides continuous availability of energy, which is an important advantage of SCPPs. However, this advantage comes with the capital cost of storage layer $C_{storage}$, which can be estimated as:

$$C_{storage} = A_{coll} H_{sl} (C_{water} + C_{black,tube}) \quad (30)$$

where H_{sl} is the thickness of water filled black tube, and C_{water} and $C_{black,tube}$ are the unit cost of water and black tube per volume, respectively.

The costs of land, transmission lines and connection to the network are not included. After the service life, the ownership of the SCPP is transferred to the government. Thus, the salvage value of the plant at the end of the contract period is assumed to be zero for the investors. In addition, all revenues and operation and maintenance costs are discounted to their present values using a monthly discount rate i .

The size of the SCPP to be constructed is limited. The minimum L_{coll} (L_{ch}) and maximum U_{coll} (U_{ch}) sizes of the collector diameter (chimney height) of the plant are defined due to the limited available area and construction specific restrictions. For instance, such minimum and maximum sizes are provided in Dehghani and Mohammadi [21].

3.5.1. The two-stage feasibility approach

In this section, we present our two-stage feasibility approach. In the first stage, we propose a nonlinear programming model to determine the optimal dimensions of the SCPP taking into account the present value of the total life-cycle cost of the system. Given the optimal dimensions of the SCPP and its total cost, we compute the present value of the revenues throughout the service life of the SCPP using a daily analysis and determine the feasibility of the system in the second stage.

The nonlinear programming model to be used in the first stage is presented first. The decision variables used in the model are as follows:

- D_{coll} : diameter of the solar collector.
- H_{ch} : height of chimney.

The objective function in the optimization model is to minimize Z which is defined as the sum of capital costs of building the SCPP and the discounted operation and maintenance costs over the service life of the SCPP as:

$$Z = C_{ch} + C_{coll} + C_{tur} + C_{storage} + \sum_{m=1}^S (Pt_{O\&M}(C_{ch} + C_{coll} + C_{tur})) / (1 + i)^m \quad (31)$$

The collector diameter and the chimney height of the SCPP have to be within the predetermined minimum and maximum sizes. These are ensured by the following constraints:

$$L_{coll} \leq D_{coll} \leq U_{coll} \quad (32)$$

$$L_{ch} \leq H_{ch} \leq U_{ch} \quad (33)$$

In order to ensure that the amount of energy generated by the SCPP is sufficient to satisfy the energy demand with a given level of reliability, we develop constraint (34) below in which we use average daily values of energy demand $\bar{E}$, collector efficiency $\bar{\eta}_{coll}$, and number of sunshine hours $\bar{n}_{hour}$, and define $X = I/T_a$ as a continuous random variable to incorporate the uncertainty in daily solar radiation and daily ambient temperature. The aim in using average daily values $\bar{E}$, $\bar{\eta}_{coll}$, and $\bar{n}_{hour}$ instead of their values for each day is to simplify the analysis. Thus, the probability of meeting average daily energy demand by the SCPP with a given level of reliability, r , can mathematically be expressed as:

$$P(X A_{coll} \frac{g H_{ch}}{C_p} \bar{\eta}_{coll} \eta_{tur} \bar{n}_{hour} \geq \bar{E}) \geq r \quad (34)$$

Note that Eq. (34) is regarded as a chance constraint ensuring the probability that energy generated by the plant being not less than the average daily energy demand is at least r . Using the daily values of I and T_a from the typical meteorological year (TMY 2) data, the best fitting probability distribution for X can be found by statistical goodness of fit tests. Defining θ_{1-r} as the value at which the probability of X being less than or equal to $(\bar{E} C_p) / (A_{coll} g H_{ch} \bar{\eta}_{coll} \eta_{tur} \bar{n}_{hour})$ is equal to $1 - r$ Eq. (34) can be transformed into the following deterministic constraint:

$$\theta_{1-r} A_{coll} \frac{g H_{ch}}{C_p} \bar{\eta}_{coll} \eta_{tur} \bar{n}_{hour} \geq \bar{E} \quad (35)$$

Thus, we solve the following optimization model in the first stage: $\min Z$ in Eq. (31) subject to constraints in (32), (33) and (35).

The proposed optimization problem is a nonlinear programming (NLP) model due to the nonlinearities in Eqs. (31) and (35). We easily solve this optimization problem to optimality using a commercial nonlinear programming solver.

In the second stage, we determine the feasibility of the system by calculating the NPV of the system given the optimal values of the collector diameter D_{coll}^* , chimney height H_{ch}^* and total cost Z^* . In order to find the NPV of the system, we calculate the revenue obtained from the energy produced in each month m as follows:

$$Rev_m = \sum_{j \in J_m} \min(EP_j, E_j) C_{electricity} \quad 1 \leq m \leq S \quad (36)$$

where J_m is the set containing all days of month m , EP_j denotes the amount of energy produced in day j (i.e., $EP_j = I \pi (D_{coll}^*/2)^2 ((gH_{ch}^*)/(C_p T_a)) \eta_{coll} \eta_{tur} n_{hour}$ with I , T_a , η_{coll} , and n_{hour} being the corresponding values in day j).

Note that we calculate monthly revenues because the consumers pay their electricity bills monthly. Thus, the NPV of the system can be found as follows:

$$NPV = \sum_{m=1}^S Rev_m / (1+i)^m - Z^* \quad (37)$$

Because of the uncertainty in daily solar radiation and ambient temperature, the realized reliability of the system r_{real} can be different from the desired reliability r . The realized reliability is obtained by considering the daily energy balance as follows:

$$r_{real} = \sum_{j=1}^{365} ES_j / 365 \quad (38)$$

where $ES_j = 1$ if $EP_j \geq E_j$, and $ES_j = 0$ otherwise.

Similarly, considering the daily energy balance, we can derive the loss of load probability (LLP) of the system, which is a widely used performance measure for the renewable energy systems [83]. The LLP of the system as a probability of insufficient power supply to the load demand can be expressed as:

$$LLP = \sum_{j=1}^{365} ED_j / \sum_{j=1}^{365} E_j \quad (39)$$

where the energy deficit ED_j in day j is equal to $\max(E_j - EP_j, 0)$.

CHAPTER 4

CASE APPLICATION

4.1 Current energy situation in Nigeria

As a developing country, Nigeria is one of the most populous nations in Africa with an estimated population of 170 million growing at 2.3% annually [84]. The country is located at latitude 4° - 14° N and longitude 2° - 15° E between the Equator and the Tropic of Cancer, and covers a total surface area of 923,768 km². In 2012, Nigeria's gross domestic product (GDP) per capital was 1557 USD with estimated annual growth of 5.8% [85]. Nigeria has features characteristic of a tropical climate and suffers from an austere energy crisis. Soneye and Daramola [86] state that energy is an important stimulant for social and economic growth. The energy crisis affects both rural and urban populations. Adaramola and Oyewola [87] state that the energy challenge is more pronounced among rural dwellers as approximately 70 million people in the rural communities does not have access to grid electricity. Consequently, diesel generating sets are widely utilized in these urban areas and the associated environmental and social impact of fumes and noise in those cities is significant. Moreover, the recent upsurge in the price of diesel with the removal of the federal government subsidy on petroleum products has compounded the situation. A recent study of Ohijeagbon and Ajayi, [88] showed that the unit cost of electricity from diesel standalone systems is relatively high at 0.62 USD/kWh thus beyond the reach of an average both in the rural and urban areas.

The reported peak electricity generation capacity of Nigeria as of February 2015 is 3,342.3 MW against an estimated peak demand of 12,800 MW representing a power

deficit of 74% [89]. This is in contrast to 2013 when the reported peak generation was 4,362 MW and estimated demand was 10,144 MW [76], which indicates that the peak generation is decreasing while the demand is rapidly increasing. As expected from a country with low generating capacity relative to demand such as Nigeria, some residents have access to electricity for only a limited number of hours in a week. In Table 3, the Nigerian power generating capacity is presented. The total installed electricity generation capacity consists of 22% from hydropower plants and 78% from thermal power plants utilizing fossil fuels.

Table 3. Power generation capacity of Nigeria [91].

Power plant	Installed Capacity (MW)	Average Availability (%)
Hydro Power Plants		
Kainji	760	54.3
Shiroro	600	65.0
Jebba	578	74.7
Thermal Power Plants		
Egbin	1320	62.1
Afam II, IV, V, VI	1166	39.2
Delta II-IV	900	38.1
Sapele	720	17.4
Olorunshogo I, II	710	45.6
Okpai	480	92.0
Geregu	414	50.4
Omosho	335	35.2
AES	302	68.9
Ibom G. S	155	53.5
Omoku	150	53.5
Ajaokuta G. S	110	0.0
Trans-Amadi	100	32.6
	8800	49.1

The hydro and thermal power plants have a weighted average availability of 49.1%. Ibitoye and Adenikinji [90] state that the low availability of the installed capacity is due to old infrastructure, lack of funds and poor maintenance.

As seen in Table 3, the energy generation mix in Nigeria is not very diverse and is completely dependent on fossil fuel and hydropower resources. The implication is that the reliability of the country's generating capacity can easily be affected by volatile fossil fuel prices for thermal power plants and climatic events such as droughts for hydropower plants.

4.2. Solar radiation in Nigeria

Abundant renewable energy resources of solar are reported for Nigeria [90], and solar resource potentials have been widely reported between 3.5 and 7.0 kWh/m² day in Nigeria [90,92,93]. Additionally, Fadare [94] reports an average solar irradiation of 5.25 kWh/ m² day and sunshine duration of 6.25 h/ day. Despite these large resources, Nigeria is yet to fully integrate solar energy into its energy generation mix. Table 4, a series of completed and ongoing solar renewable energy projects in Nigeria as reported by Awogbemi and Komolafe [95] and Nwofe [96] is presented. In Table 4, a series of completed and ongoing solar renewable energy projects in Nigeria as reported by Awogbemi and Komolafe [95] and Nwofe [96] is presented. In Table 4, it is evident that most of the completed and ongoing projects are located in the northern part of the country where there is abundant solar insolation, with most being in rural areas with low economic activities. This may be due to the fact that most studies on the solar resources and technology feasibility in Nigeria are more concentrated in the north where there is proven documented potentials [97–99].

Table 4. Completed and ongoing solar projects in Nigeria.

N/S	Project	Location	Capacity	Reference
1	Solar street lights	Ado Ekiti, South-West	-	[26]
2	Kwalkwalana Village Electrification	Sokoto, North	7.2 kW _p	
3	Nangere Water Pumping Scheme	Sokoto, North	1.5 kW _p	
4	Solar Rice Dryer	Adani, Enugu, South-East	2 tonne	
5	Iheakpu-Awka Village Electrification	Enugu, South-East	1.9 kW _p	
6	Solar Forage Dryer	Yauri, Kebbi, North	1.5 tonne	
7	Solar Energy Plant	Katsina, North	20 MW _p	[96]
8	Solar Farm (synergent Group)	Kaduna, North	50 MW _p	
9	Solar Power Plant (Nigeria-German Energy Partnership)	Katsina, North	60 MW _p	
10	Solar Farm (Nigeria Solar Capital Project and Gigawatt Solar)	Bauchi, North	100 MW _p	

Mohammed *et al.* [100] stressed that the intensity of solar radiation is highly variable from one location to another but is consistently higher in the north-east part of Nigeria. Additionally, the adoption of solar renewable technology in the country is low compared to the large potentials widely reported. Nwofe [96] mentioned the high initial capital cost of solar technologies, low levels of education and awareness about the social and economic benefits associated with solar technologies, and a lack of access to solar radiation data recording stations as several of the factors limiting the utilization of solar energy in Nigeria.

On the other hand, solar energy applications in Nigeria are faced with numerous barriers, some of which were reported in the recent study by Ohunakin *et al.* [101]. Figure 7 highlights the barriers to solar energy development and application in Nigeria which based on Painuly [102] can be categorized as follows: technical; social, cultural and behavioral; economic and financial; institutional; and political and market

distortion. Steps to overcome these barriers are provided in more detail by Soneye and Daramola [86] and Ohunakin *et al.* [101].

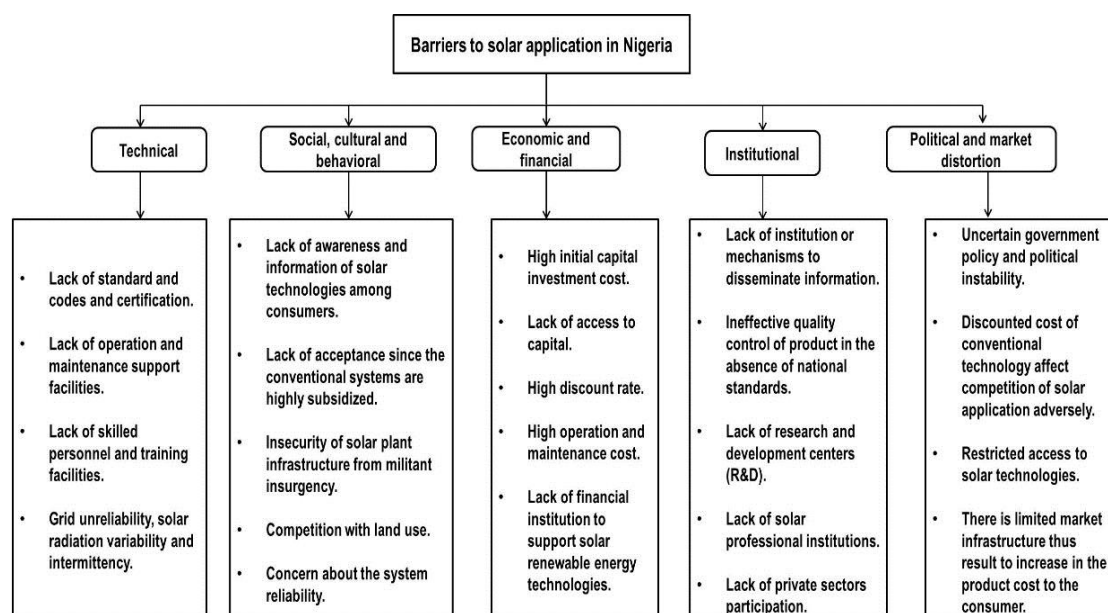


Figure 7. Barriers to solar applications in Nigeria [72].

4.3. Case study analysis of SCPP

The proposed model is tested on a case study in Nigeria. Nigeria is selected because of the widely reported high solar insolation and continuous chronic energy shortage. The SCPP advantages of low maintenance requirement, high durability, and high reliability are urgently needed to tackle the issue of unavailability of installed capacity in the country. In this study, the rural area of Potiskum in Yobe State is adopted due to (i) favorable meteorological conditions, (ii) the lack of grid connectivity, (iii) abundant land resources, and (iv) being predominantly occupied by farmers. The lack of access to grid implies the need for electrification. The available huge land resource is important for large scale SCPP development Potiskum, located in the arid zone of the northeastern part of Nigeria in the latitude 11° 25 'N and longitude 11° 10 'E has

a population of 205,876. The typical meteorological year (TMY 2) data of the location obtained from Meteonorm software [103], which contain the daily data of solar radiation and ambient temperature, are used in this case study. The importance of using TMY data set in the long term solar system performance assessment was mentioned in the study of Ohunakin *et al.* [104], where they provided a detailed method for converting historical measured solar radiation into TMY format. The daily average solar radiation, ambient temperature, and sunshine hours of Potiskum are 5.94 kWh/m², 28.88 °C and 9.5 hours, respectively. The variation in the solar radiation and temperature distribution for a typical day and average day of the month for Potiskum are depicted in Figure 8 and Figure 9.

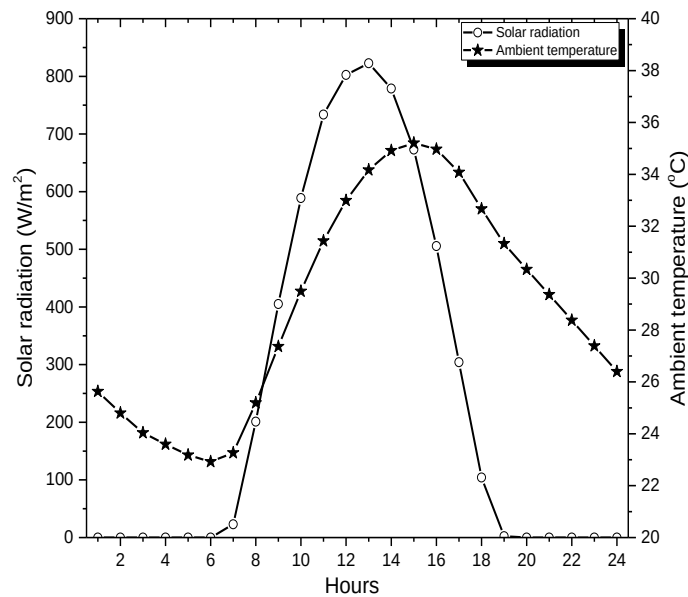


Figure 8. The variation in the solar radiation and temperature for a typical day in Potiskum.

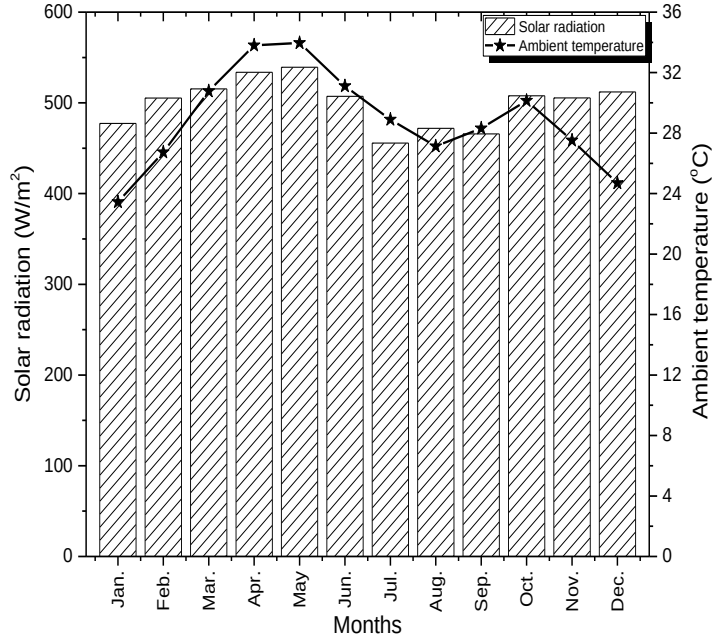


Figure 9. The variation in the monthly solar radiation and temperature of Potiskum.

The recent study of Okoye *et al.* [72] adopted 3% as the discount rate ($i = 0.25\%$ per month), thus, the same value is used in this study. The efficiency of the turbine is taken as 80% based on the experimental study by Gannon and von Backstrom [58]. Even though the unit electricity price of diesel generators in Nigeria is 0.563 €/kWh [88], 0.25 €/kWh is assumed to be the price negotiated with the government for the sale of electricity produced by the SCPP which is built as a BOT project. Although von Backstrom *et al.* [105] mentioned that the intended design service life of a commercial SCPP ranges from 80 to 120 years, the service life of SCPP is taken as 40 years (i.e., $S = 480$ months) following the study of Nizetic and Klarin [61]. Pt_{Hcoll} , Pt_{coll} and Pt_{tg} are assumed to be 8%, 8%, and 10%, respectively, following Dehghani and Mohammadi [21]. The annual operation and maintenance cost, $Pt_{O\&M}$, is assumed as 0.5% of the capital cost which was also utilized by Schlaich *et al.* [15]. The lower and upper bounds for the collector diameter and chimney are $100 \leq D_{coll} \leq 1500$ m, and

$60 \leq H_{ch} \leq 800$ m, respectively, based on the study by Dehghani and Mohammadi [21]. The chimney diameter is taken as 60 m to be above the critical value. Water storage height of 20 cm is assumed, and the cost of water and black tube are obtained from the utility and manufacturers as 0.142 €/m³ and 2 €/m³, respectively. The estimated cost of reinforced cement concrete (1:1:2) per cubic meter is 250 €/m³ which includes the costs of materials (cement, aggregate, sand and steel reinforcement), labor with mechanical mixers and vibrator, water, transportation and miscellaneous. The total daily electrical energy demand from 1500 households in Potiskum is calculated as 22,500 kWh assuming a 15 kWh daily consumption for a household of five residents (i.e., 3 kWh daily consumption per capita is assumed according to Ibitoye and Adenikinju [90]). Table 2 summarizes all the input parameters used in the proposed SCPP system analysis.

To find the best fitting probability distribution for X (i.e., the ratio of daily solar radiation to daily ambient temperature), the available data are fitted to several probability distributions. This is imperative to account for uncertainty and randomness (incorporating chance constraint). For this reason, the continuous random variable X is fitted into different probability distribution (PD). The selection of the appropriate probability distribution function is the most important step in frequency analysis as it affects not only the optimal SCPP dimensions but also the reliability of the proposed system. Due to existence of several PDF such as beta, burr, burr (4P), normal, chi-square, dagum, dagum (4P), Cauchy, gamma, gamma (3P), gumbel max, gumbel min, Kumaraswamy and log-logistic (3P), general extreme value, log-normal, log-Pearson III and Johnson SB etc., thus three known statistical measure of goodness-of-fit (GoF) was adopted in the ranking and selection of the best fit.

Table 2. Summary of the SCPP system design parameters.

Parameter	Unit	Value
Chimney height	m	$60 \leq H_{ch} \leq 800$
Collector diameter	m	$100 \leq D_{coll} \leq 1500$
Chimney diameter	m	60
Annual discount rate	%	3
Cost of water	€/m ³	0.142
Service life	year	40
Operation and maintenance	€	0.5% of total cost
Cost of black tube	€/m ³	2
Cost of reinforce concrete	€/m ³	250
Water storage height	m	0.2
Price of electricity	€/kWh	0.25
Pt _{Hcoll}	%	8
Pt _{coll}	%	8
Pt _{tg}	%	10
No of household	-	1500
Daily energy per capita	kWh	3
Desired system reliability	%	95

Moreover, the comparison is necessary since there is a tendency for one GoF to select a particular PD even though the other GoF's are strongly rejecting it. The widely utilized GoF statistics are the Kolmogorov-Smirnov (K-S), the Anderson-Darling (A-D) and the Chi-squared tests. These tests are performed by means of the Easyfit software [106], which not only provide fits for over 60 different probability distributions but also rank their performance according to the test statistics. The details of the GoF statistics test considered are provided in Appendix A.

4.3.1. Case study results

For Potiskum, in the three GoF test performed, dagum (4P) provided the best rank thus is used in this presented case analysis. The GoF statistics are 0.08899, 0.88706, and 12.715 for Kolmogorov-Smirnov (K-S), the Anderson-Darling (A-D) and the Chi-squared tests, respectively. The fitting parameters are as follows; shape ($k = 0.15689$), shape ($\alpha = 1502.6$), scale ($\beta = 71.729$), and location ($\gamma = -69.758$). The formula for calculating the probability density function (PDF) and cumulative distribution function (CDF) together with the associated ranking of the other PD considered are presented in Appendix B. The probability density function and probability-probability (P-P) plots are presented in Figure 10 and Figure 11 to show how well the distribution fits the observed meteorological data.

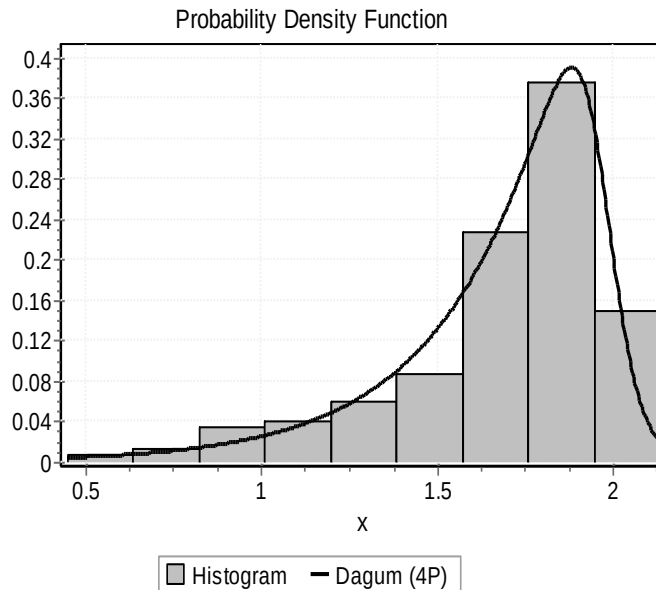


Figure 10. Probability density function of the Dagum (4P) distribution for Potiskum.

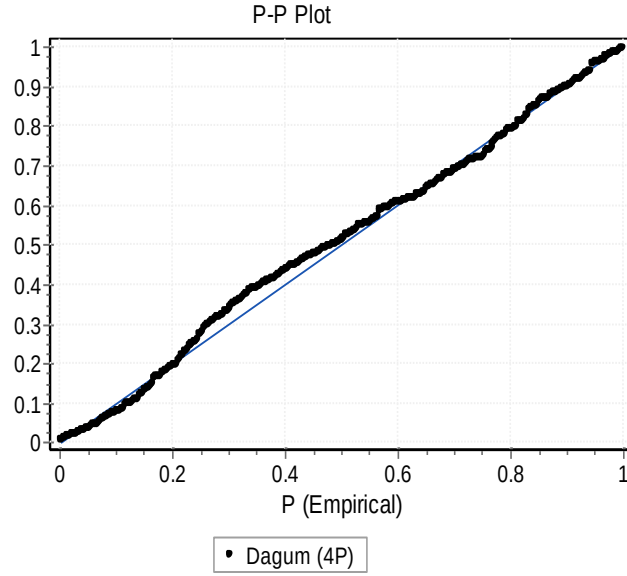


Figure 11. Probability-probability (P-P) plot of the Dagum (4P) distribution for Potiskum.

We solved the nonlinear programming model presented in chapter 3 to global optimality using the Excel add-in optimization solver, *What'sBest!* 13.0 (see www.lindo.com), and then implemented the second stage of our approach to find the NPV of the proposed SCPP. The results show that the proposed SCPP is feasible with a positive NPV of approximately 2.37 million € which indicates a marginal economic return on the invested capital. Note that negative NPV would imply that the system is not feasible.

In other words, the present value of the revenue from the proposed SCPP is more than the present value of the cost of building and operating the plant over the considered service lifetime. The obtained global optimal plant dimensions and other feasibility parameters are presented in Table 5. From Table 5, the realized reliability of the designed SCPP system is 93.2% at the target reliability value of 95%, which implies that the energy demand can fully be met in 340 days of a year. Note that the realized reliability obtained from the proposed SCPP is 1.8% less than what is desired. This is

mainly due to the approximation of using average daily value for the collector efficiency which actually depends on the uncertainty of solar radiation and ambient temperature. We also observe from Table 5 that the LLP of the designed SCPP system is 0.014 at 95% desired system reliability. The observed LLP of 0.014 implies that on an annual basis, about 8.1 GWh energy demand out of 8.21 GWh can be satisfied with the proposed SCPP system. Indeed, the LLP value of 0.014 without battery storage is very satisfactory.

Table 5. Summary of the proposed SCPP in Potiskum.

Parameter	Unit	Value
Collector diameter	m	1127.5
Chimney height	m	715.1
Net present value	million €	2.37
Total cost	million €	44.74
Realized system reliability	%	93.2
Loss of load probability	%	0.014
Annual revenue generated	million €	1.997
Simple payback period	year	22.4

The daily LLP and monthly generated revenue of the proposed SCPP are presented in Figure 12 and Figure 13, respectively. Figure 12 reveals that the days of low LLP coincides with the rainy season period in Nigeria which generally starts from April to September depicting that the effect of seasonality may be pronounced in the region. As expected, weather conditions, such as clouds, can be experienced in some days during this period. Figure 13 presents the monthly generated revenue considering the fact that the consumers pay their utility bills monthly.

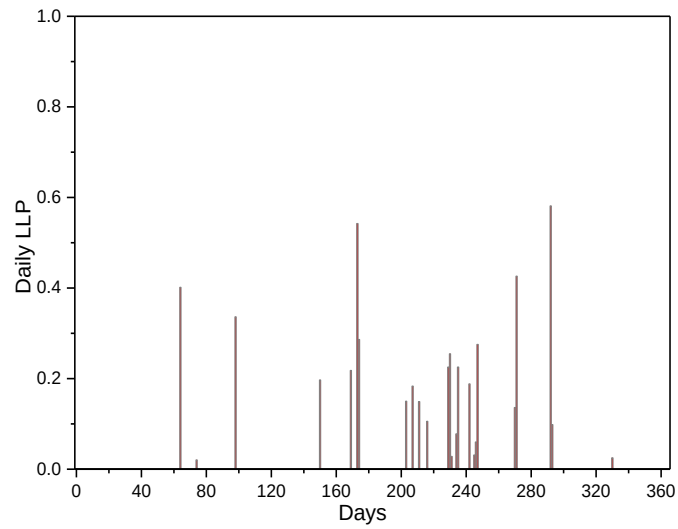


Figure 12. Daily percentage reliability of the SCPP design in Potiskum.

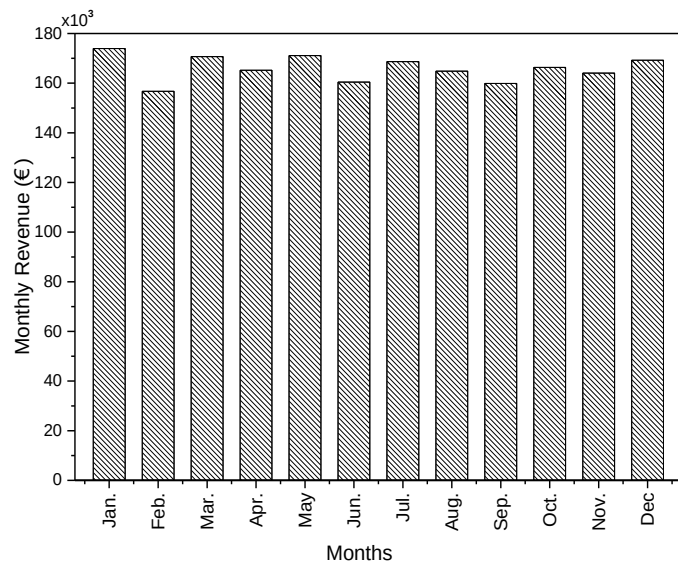


Figure 13. Monthly generated revenue from the proposed SCPP design in Potiskum.

CHAPTER 5

SENSITIVITY ANALYSIS

5.1. Parametric study

In order to examine the impact of various parameters affecting the performance of the proposed SCPP, different scenarios are identified and marked as A, B, C, D, and E. In each of these scenarios, the effect of varying a parameter is evaluated on the optimal SCPP dimensions, discounted total cost (TC), and the proposed net present value (NPV), while the other parameters are as previously defined in Chapter 4. The range used are based on results of different SCPP studies found in the literature for, collector [51,66], turbine [43], and discount rate [72].

5.1.1. Scenario A: Effects of the collector and turbine efficiencies

In Scenario A, the collector and turbine efficiency are varied between 20 - 60% and 50 - 90% respectively, each with increments of 5%. The results of the effect are presented in Figure 14, Figure 15, Figure 16 and Figure 17, respectively.

In Figure 14, it is found that increasing the collector efficiency leads to the corresponding decrease in TC and increase in NPV as expected. The implication is that for increasing collector efficiency, the marginal economic return on the SCPP investment over the service life of the SCPP is enhanced. In addition, the optimal SCPP collector diameter and chimney height decrease as more energy is produced with more efficient collectors considering that the electricity demand to be satisfied is constant as depicted in Figure 15. This result emphasizes the importance of the collector in the feasibility of SCPP and as such, adequate care should be taken in the collector design to avoid either overestimation or underestimation of the efficiency which obviously

affects investment decision. Ideally, the associated heat losses via convection and radiation should be considered in the collector design as recommended by Guo *et al.* [51].

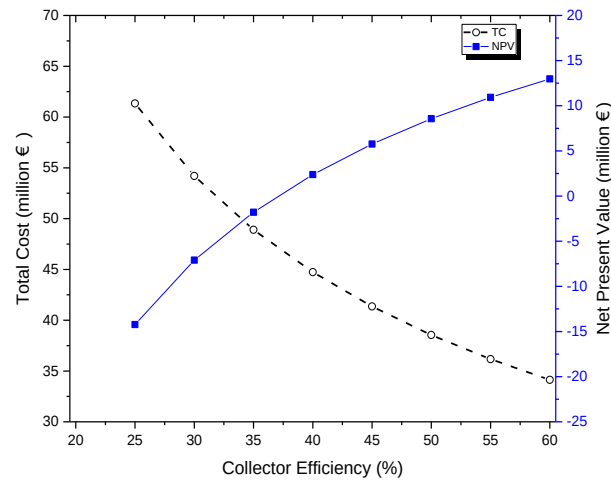


Figure 14. Effect of collector on the total cost and NPV of the proposed system.

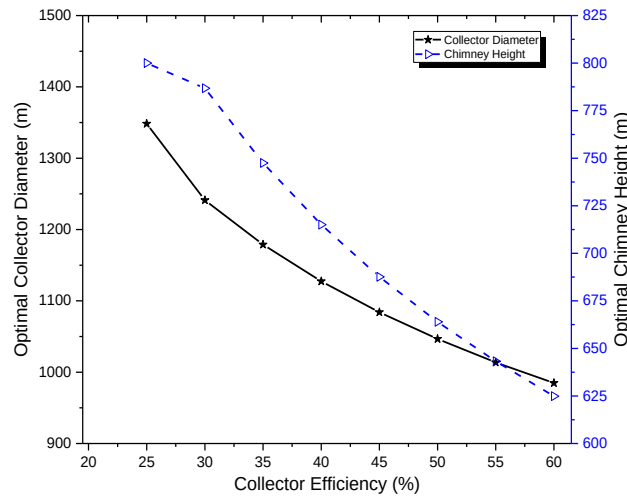


Figure 15. Effect of collector efficiency on the optimal SCPP dimension in Potiskum.

Note that for a collector efficiency of less than 35%, the proposed SCPP system design is not feasible as negative NPV values are obtained at the electricity price of 0.25 €/kWh. The optimal chimney height is equal to its upper limit for 25% collector

efficiency, whereas when the collector efficiency is 20%, the model does not give any feasible solution as the optimal SCPP is beyond the defined limits (i.e., $100 \leq D_{\text{coll}} \leq 1500$ m and $60 \leq H_{\text{ch}} \leq 800$ m).

For increasing turbine efficiency in Figure 16 and Figure 17, a similar trend with respect to the collector efficiency is observed. With increasing turbine efficiency, besides TC, the optimal dimensions of the proposed SCPP decrease whereas NPV increases accordingly. As an example, changing the turbine efficiency from 80 to 85% results in a 4% decrease in TC and 64% increase in NPV. Moreover, for turbine efficiency of less than 70%, the proposed SCPP is considered to be economically infeasible due to the negative NPV values. Additionally, the chimney height is the same for turbine efficiency of 50% and 55% due to the upper bound on chimney height ($60 \leq H_{\text{ch}} \leq 800$ m). Thus, to satisfy the desired demand within the specified reliability, the optimal collector diameter increases accordingly.

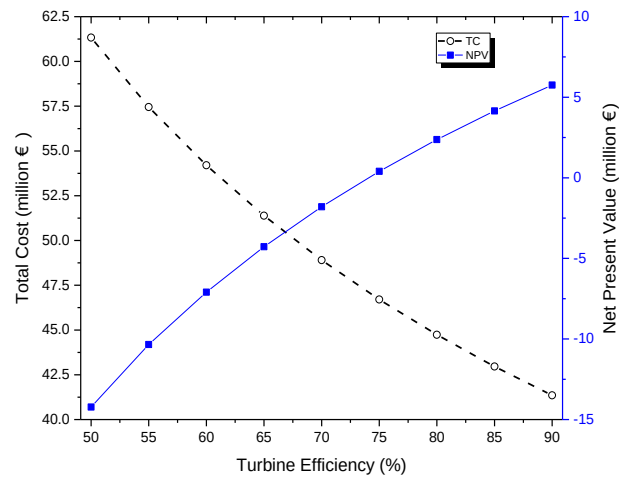


Figure 16. Effect of turbine efficiency on the total cost and NPV on the proposed system.

As per negative NPV obtained for the collector efficiencies less than 35% and turbine efficiencies less than 70%, the SCPP company or investor can either ask for

higher electricity price from the government or increase the BOT contract period to have a return on their investment.

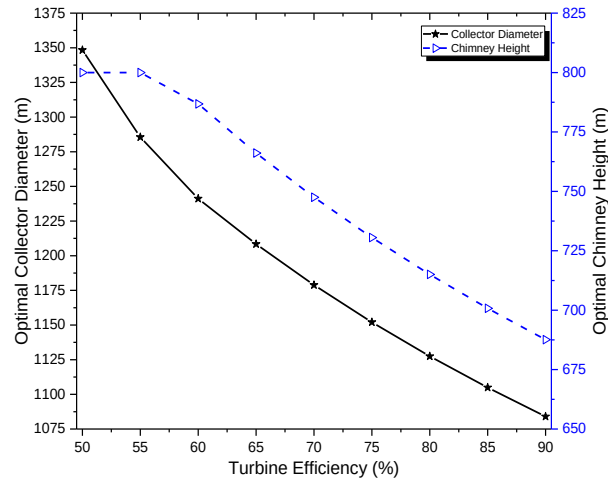


Figure 17. Effect of turbine efficiency on the optimal SSCP dimensions in Potiskum.

5.1.2. Scenario B: Effects of the electricity price and discount rate

In this Scenario, the electricity price is increased by 0.025 from 0.15 to 0.35 €/kWh and the annual discount rate is varied from 2 to 6% in increments of 0.5%. These parameters are varied both at the same time, in addition to varying them once at a time as previously stated, and the results are depicted in Figure 18, Figure 19, **Error! Reference source not found.** and **Error! Reference source not found.**

In Figure 18, it is clear that the increase in the unit price of electricity favors the economic feasibility of the plant as the NPV of the proposed plant linearly increases. On the other hand, increasing the discount rate decreases the NPV as expected. From Figure 18, it is possible to estimate the critical electricity price and discount rate value that makes the NPV be equal to zero. This information is precious to investors as it at a glance offers the margin to which to start negotiation for the proposed project. For instance, it is found that for varying discount rate (from 2% to 6%) at the electricity

price of 0.25 €/kWh, the critical discount rate for NPV to be zero is 3.37%. Similarly, for electricity price range (from 0.15 to 0.35 €/kWh) at a discount rate of 3%, the electricity price should be set at 0.237 €/kWh to make the NPV zero. In other words, positive NPV, thus, the feasible system is obtained for higher electricity prices and lower discount rates than their corresponding critical values. As a commitment to rural electrification program which, in turn, enhances the socio-economic development of the region, the government can offer to buy the electrical energy produced from the SCPP at a higher price in order to attract the BOT investments. In addition, note that the cost of electricity from the widely utilized diesel power generator in Nigeria is 0.563 €/kWh [88], excluding the externality (i.e., environmental cost), thus, much greater than the values considered in this study. For changing electricity price, the optimal SCPP size ($D_{coll} = 1128$ m, $H_{ch} = 715$ m) in Figure 19 and the TC (44.74 million €) remain constant since the proposed objective function is independent of the electricity price.

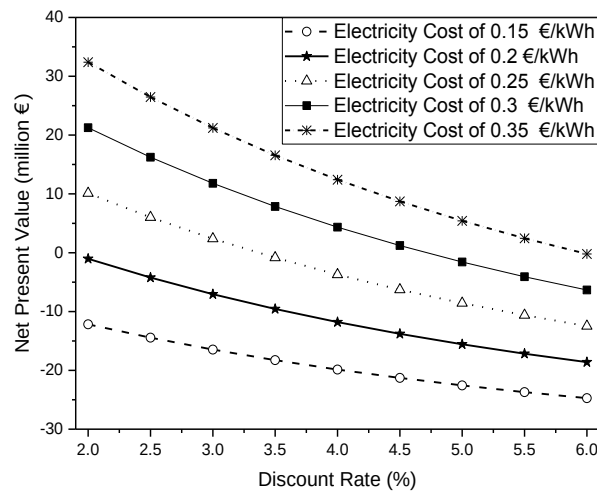


Figure 18. Effect of electricity price and discount rate on the NPV on the proposed SCPP design in Potiskum.

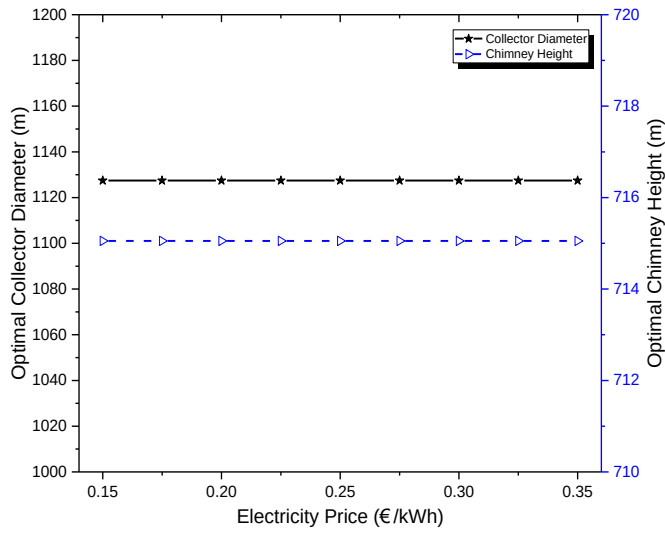


Figure 19. Effect of electricity price on the optimal SCPP dimensions in Potiskum.

Error! Reference source not found. and **Error! Reference source not found.** shows the effect of the annual discount rate on TC and optimal SCPP dimensions. For instance, increasing the discount rate from 2% and 6%, the TC decreased by 5.4% and optimal SCPP dimensions do not change. This is because only operation and maintenance cost constituting a small fraction of the total cost is discounted for TC.

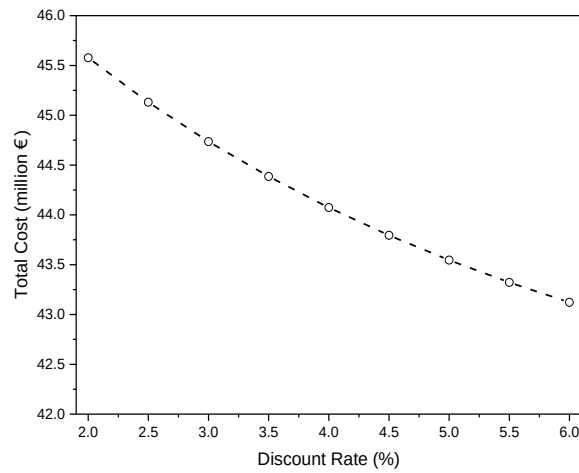


Figure 20. Effect of the discount rate on the total cost of the proposed system in Potiskum.

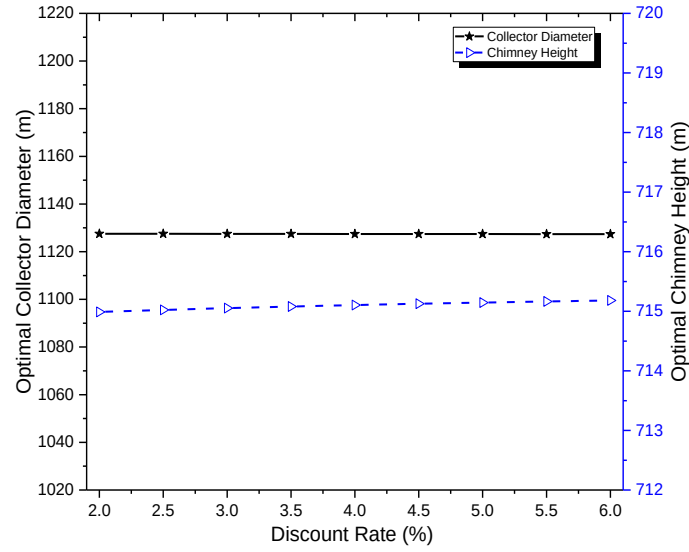


Figure 21. Effect of the discount rate on the optimal SCPP dimensions in Potiskum.

5.1.3. Scenario C: Effects of the energy demand per capita

The proposed plant is designed based on a 3 kWh daily consumption per capita as discussed in Chapter 4. The consumption pattern changes with location, awareness and attitude of individuals to energy conservation, the income of the individuals and characteristic of the house. For this reason, we study the effect of energy demand on the performance of the proposed SCPP design by varying the energy demand from 1 to 5 kWh per capita with steps of 0.5 kWh in this scenario. Note that the proposed plant is designed for 1500 households assuming an average of 5 residents in a house. The results presented in Figure 22 and Figure 23 indicate that increasing the energy demand increases not only the optimal plant dimensions but also TC and NPV. This trend is in agreement with the observations in previous studies [10,15] that the economic feasibility of SCPP improves with increasing plant dimensions.

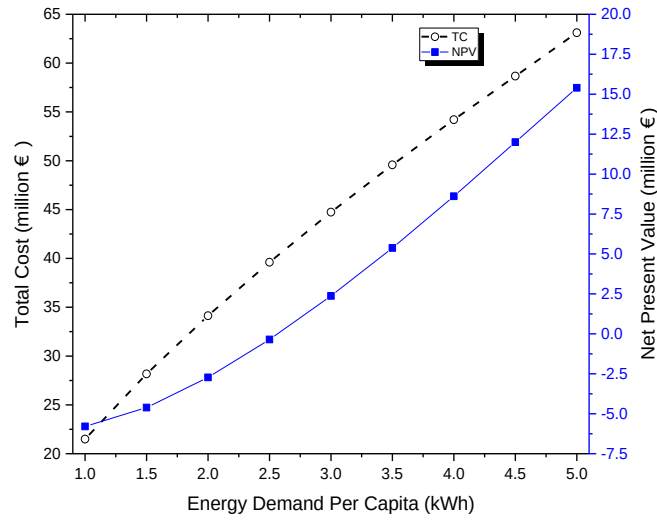


Figure 22. Effect of energy demand on the total cost and NPV on the proposed system.

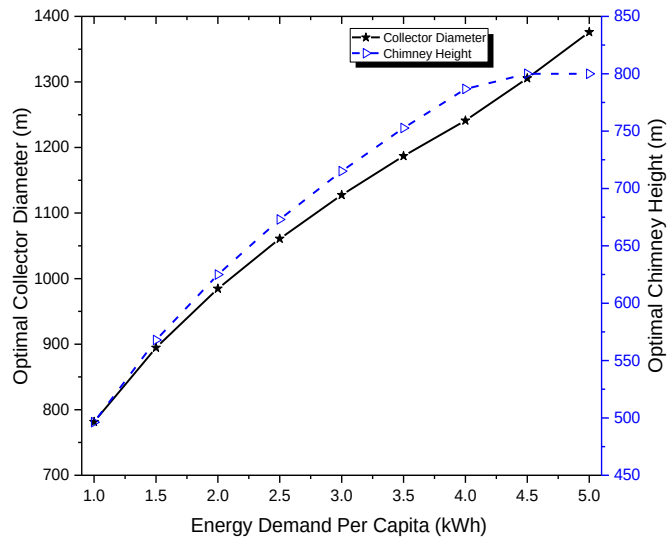


Figure 23. Effect of energy demands on the optimal SCPP dimensions in Potiskum.

As seen in Figure 22 and Figure 23, the proposed system at the electricity price of 0.25 €/kWh is feasible for more than 2.57 kWh per capita energy consumption. In addition, for energy demand higher than 4 kWh per capita, the chimney height reached the set upper bound (i.e., 800 m); therefore, collector diameter increased further to meet the target reliability.

5.1.4. Scenario D: Effects of the local meteorological conditions

This scenario considers the effect of meteorological input variables on the proposed optimal plant dimensions, TC, LLP, and NPV. Several studies have demonstrated that solar radiation and ambient temperature are very important in the SSCP design. Herein solar radiation and ambient temperature data from four different locations besides Potiskum are identified and utilized as an input in the proposed optimization model. The locations are selected in such a way not only to represent the two notable solar zones in Nigeria as reported by Ohunakin *et al.* [84], but also to depict areas with less population density due to land requirement. Table 6 shows the features of the location and the optimal SSCP design results.

Table 6. Typical features and results for different locations.

Parameter	Solar Zone I		Solar Zone II	
	Value			
Site	Kano	Katsina	Magama	Donga
Latitude (°N)/longitude (°E)	12.02/08.32	13.00/07.32	10.17/05.20	07.20/10.10
Elevation (m)	456	457	300	225
Daily solar radiation (kWh/m ²)	6.08	6.00	5.50	5.05
Ambient temperature (°C)	26.3	29.7	28.9	25.5
Best fitting probability distribution for X	Dagum 4P	Dagum 4P	Gen. extreme value	Johnson SB
Desired system reliability	95	95	95	95
Realized system reliability	94.8	94.2	94.8	95.3
Optimal solar collector (m)	1092.2	1095.5	1220.0	1326.2
Optimal chimney height (m)	692.8	694.9	773.4	800
NPV (million €)	5.28	5.00	-5.15	-12.48
Annual revenue (million €)	2.003	2.002	2.002	2.012
Simple payback period (year)	21.0	21.1	26.2	29.8
LLP (%)	0.011	0.012	0.012	0.007
Total cost (million €)	41.98	42.24	52.37	59.95

The results in Table 6 show that the meteorological conditions are very important in determining both the optimal SCPP dimensions and the feasibility of proposed SCPP. The location with the highest solar radiation yielded the smallest plant dimensions, simple payback period and the highest NPV as expected. The annual discounted revenue of all the location changes with the LLP since it is based on the demand satisfied, approximately 2 million € is obtain as shown in Table 6. In addition, the LLP of the system for the 95% desired reliability depends not only on the predicted optimal plant size but also on the distribution of the meteorological conditions as observed from the probability distribution fit. Thus, locations without uniformly distributed input solar radiation and temperature throughout the year may have better LLP due to larger optimal plant dimensions predicted and vice versa.

5.1.5. Scenario E: Effects of the desired reliability

This last but obviously not the least important scenario examines the reliability of the proposed SCPP at varying desired system reliability values. Here the reliability denotes the probability that the proposed SCPP plant dimensions would satisfy a given energy demand with a certain degree of assurance. Although 95% desired system reliability used in the original design seems reasonable for a solar system, changing this value highlights the possible tradeoff between the plant optimal dimensions, TC, NPV, LLP and real system reliability. Thus, this probability is varied from 50% to 99%, and the results are presented in Figure 24 and Figure 25. As depicted in Figure 24 and Figure 25, increasing the desired reliability increases TC and LLP. Hence, a higher desired reliability leads to greater optimal plant dimensions, higher total cost, and lower LLP. The variations of NPV based on the obtained system reliability are

depicted in in **Error! Reference source not found.** and **Error! Reference source not found.** for changing the price of electricity and discount rate.

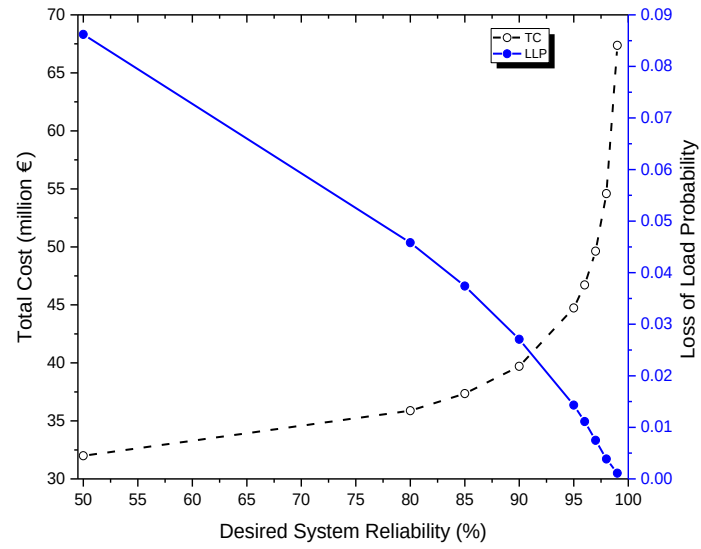


Figure 24. Effect of desired reliability on the total cost and loss of load probability.

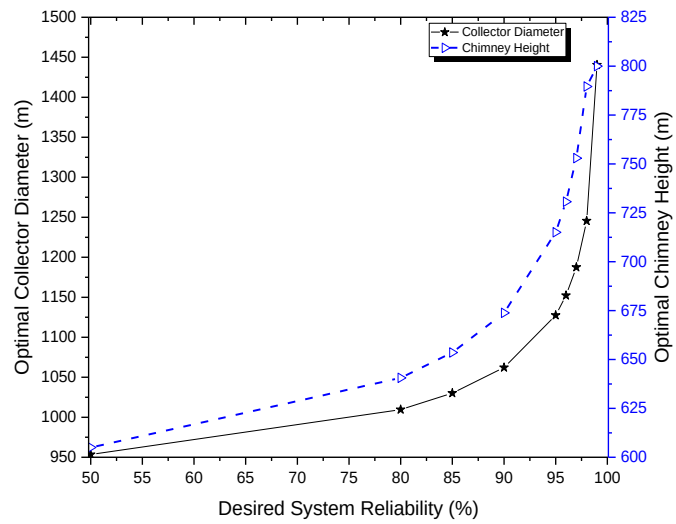


Figure 25. Effect of desired reliability on the optimal SCPP dimensions in Potiskum.

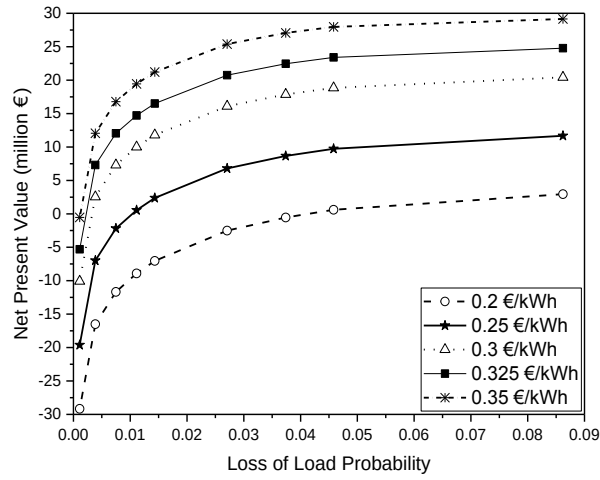


Figure 26. Economic NPV at different reliability for changing electricity price.

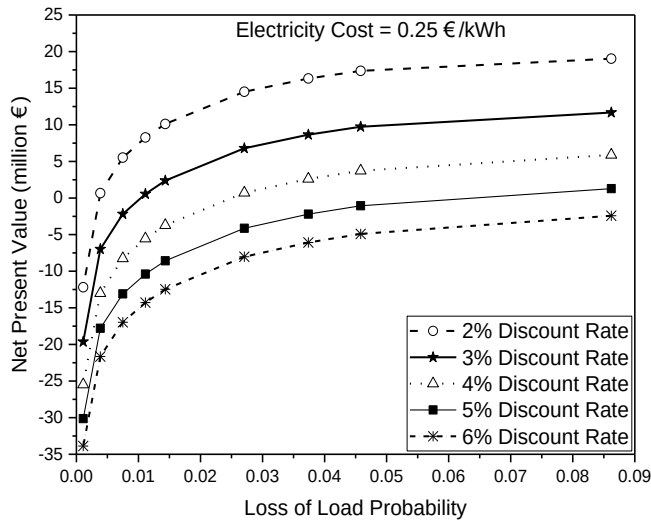


Figure 27. Economic NPV for the different discount rate value.

For instance, from in Figure 24, Figure 25, **Error! Reference source not found.** and **Error! Reference source not found.** at the electricity price of 0.25 €/kWh, increasing the desired system reliability from 50% to 99% increases the TC, D_{coll} H_{ch} and decreases the LPP approximately by 50.6%, 27.8% 11.9% and 92.3%, respectively at the expense of decreasing the economic feasibility (i.e., NPV) by about 102.5 %. For this reason, the tradeoff between enhancing the LLP by a fraction of 92.3% at the

economic expense of 102.5% cannot be over-emphasized. **Error! Reference source not found.** and **Error! Reference source not found.** shows that for the electricity prices considered, the proposed SCPP system is infeasible at LLP of 0.001. Additional information regarding the maximum rate of return and LLP, an investor can expect at different electricity price and discount rate values can be extracted from **Error! Reference source not found.** and **Error! Reference source not found.**. At electricity price and discount rate of 0.25 €/kWh and 3%, the investors cannot expect a return on the SCPP investment for LLP greater than 0.011. Similarly, when the electricity price is 0.25 €/kWh, the maximum rate of return investors can expect is 5% if a LPP value 0.086 is acceptable. Moreover, a comparison of the desired and realized reliability for the proposed SCPP system is presented in Table 7. In Table 7, the maximum difference of 2.3% occurred at 90% desired system reliability which represents 0.1 statistically level of significance.

Table 7. Comparison of desired and realized reliabilities at different level of significance.

Desired Reliability (%)	Realized Reliability (%)	Diff. (%)
50	51.8	1.8
80	79.2	-0.8
85	83.6	-1.4
90	87.7	-2.3
95	93.2	-1.8
96	94.5	-1.5
97	95.6	-1.4
98	98.1	0.1
99	99.5	0.5

5.2. Sustainable impact of the proposed SCPP on the rural areas of Nigeria

The conceptual framework of sustainable development employs substantive and procedural sustainability approach in assessing the impact of renewable energy projects on the local level [107]. Among the three major approaches to substantive sustainability identified by Delrio and Burguillo [107], the triangular method which considers interestingly the three interrelated dimensions of social, economic and environmental aspect is adopted herein. Poverty is the major obstacle to sustainable development in many developing countries such as Nigeria. A recent study of Olatomiwa *et al.* [108] revealed that poverty in Nigeria is more pronounced among rural dwellers where up to 80% survives on less than 1.14 €/day. As previously mentioned, diesel generating sets are widely utilized for electricity. However, the removal of fuel subsidy in Nigeria has compound the problem as the current price of diesel excluding transportation cost to the remote areas vary from 1.0 to 1.2 €/liter, thus, beyond the reach of an average rural dweller that lives below poverty line. The recent study of Ohijeagbon and Ajayi [88] puts the LCOE from diesel generators at 0.563 €/kWh. Following the dimensions of social, economic and environmental sustainability impact of the proposed SCPP, an endogenous development that is capable of supporting and improving not only the cultural but also the spiritual well-being of the rural areas of Nigeria can be achieved. The ideology of endogenous development is based on using local resources in achieving a localized change whose benefits are retained in the locality.

Based on the triangular approach to substantive sustainability, the impacts of the proposed SCPP installation in the rural areas of Nigeria can be categorized into social, economic, and environmental as shown in Figure 28. From Figure 28, the social impact is further sub-categorized into health, education, and technology.

On the other hand, it is imperative to mention that the sustainable impact presented in Figure 28 is independent of procedural sustainability approach which according to Delrio and Burguillo [107], takes into account the opinion and interest of stakeholders. However, for the fact the resources (solar radiation and ambient) for the operation of the proposed SCPP systems are locally available and considering the chronic lack of access to electricity in the regions. It is very likely that the proposed project would attract favorable opinion not only among the local population but also from other concern stakeholders.

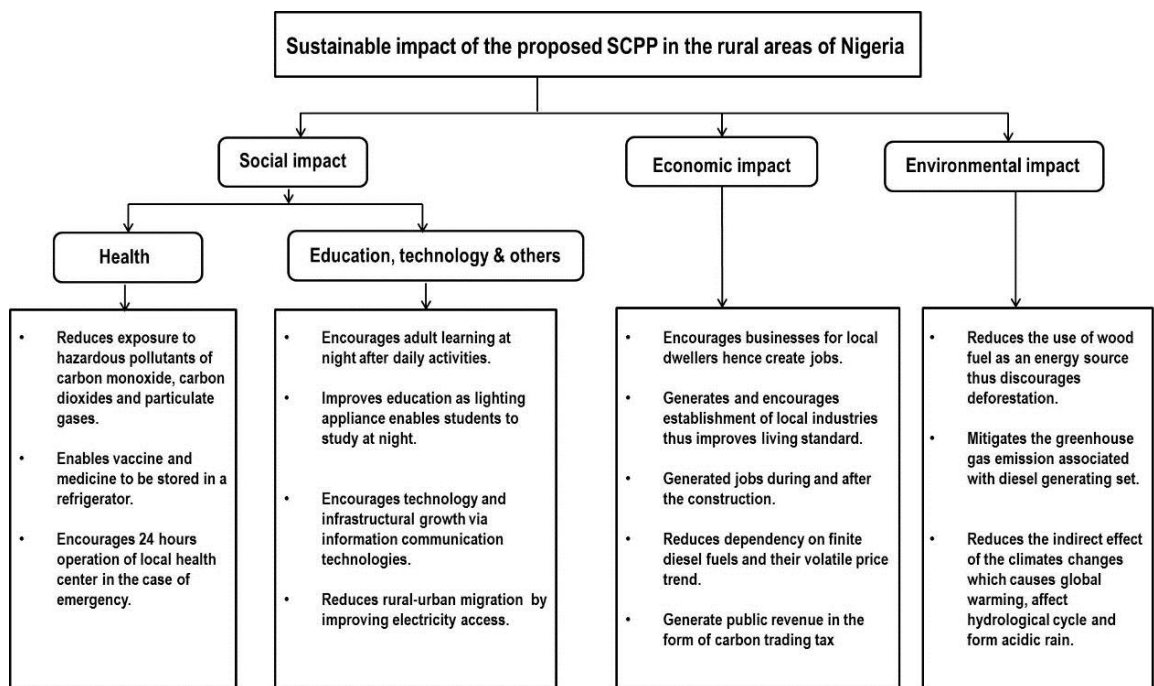


Figure 28. Sustainable impact of the proposed SCPP in the rural areas of Nigeria.

CHAPTER 6

CONCLUSIONS AND FUTURE WORK

6.1. Conclusions

Ensuring energy security especially in developing countries requires expanding yield and resilience of supply through source diversification. Solar chimney power plant (SCPP) offers an easy way to tap the freely available solar resources in the country with minimal maintenance and high reliability. This thesis presents a novel approach not only to predict the optimal SCPP dimensions (collector diameter and chimney height) but also to answer at a glance the investors' question on the economic feasibility (through NPV) of the proposed system. This type of model is important to inform potential investors on the feasibility of the environmentally friendly, highly reliable and durable SCPP technology as to foster adoption and deployment. The proposed model accounts for the capital costs associated with the solar collector, chimney, turbine, water storage layer, and monthly operation and maintenance costs in formulating the cost minimization problem.

The practicability of the model is demonstrated through the case of Potiskum in Nigeria where chronic energy shortage is prominent. In general, the current electricity generation in Nigeria is limited to hydro and fossil fuel based thermal power plants. This generation mix is highly unreliable due to volatile fossil fuel prices and climatic changes affecting the hydrological cycle. Solar energy is one of the most abundant

renewable energy resources in Nigeria and should be exploited using different technologies to improve energy access especially in the rural areas such as Potiskum.

The results emphasize the feasibility of the proposed SCPP as a sustainable alternative to diesel powered generators which are highly utilized in the region. Note that TC, NPV, generated revenue and optimal plant sizes obtained are location specific. Thus, it is important to assess the feasibility of SCPP before installation due to variable ambient conditions and material costs. In addition, this study produces precious managerial insight on the effect of some notable parameters on the optimal dimensions, TC and feasibility of the system through detailed sensitivity analyses. The obtained results reveal that for a constant energy demand at the desired system reliability; increasing the collector efficiency and turbine efficiency decreases the optimal SCPP dimensions and TC, but increases NPV. Moreover, the optimal SCPP dimensions do not depend on the electricity price and discount rate, but they increase with increasing demand and desired system reliability. Electricity prices increases the NPV but does not affect TC. Considering that the NPV and operation and maintenance cost of the proposed SCPP are discounted over the service life of SCPP, increasing discount rate decreases NPV and TC. As expected, the locations with better meteorological conditions are more economically feasible for SCPP installation since lower optimal plant dimensions can be used. Furthermore, the economic feasibility of the proposed system is enhanced when the energy demand is increased emphasizing that SCPP is truly a large-scale energy generation system. Moreover, larger power plants are needed to satisfy the more demand. Additionally, it can be deduced that increasing the reliability results to a corresponding increase in the optimal plant size and the overall system LLP at the expense of economic feasibility, NPV. In addition,

sustainable impact of proposed system is assessed and presented for the location of case study; similar impact would be obtained in other locations considering the current energy policy and infrastructure in Nigeria.

Overall, the proposed model is an effective tool that can be utilized by public authorities and investors not only to determine the optimal dimensions but also to assess the feasibility of SCPPs.

6.2. Future work

The model presented in this work considers constant electricity demand and assumes that the electricity generated (which is always equal or greater than the demand) is consumed by the household. If the generated electricity is greater than demand which is the most likely outcome considering the chance constraint imposed to ensure reliability; then, the excess energy is considered as dumped energy without any monetary value. In reality, this may not be true; thus, as future work we intend to do the following:

- Assess the actual household electricity demand considering daily and seasonal inter-variability using structured survey in the case study area.
- Assess willingness of the consumers to pay for the electricity produced from the SCPP (As some household might decide not to utilize the electricity from the SCPP and cannot be coerced).
- Consider detailed daily energy balance from the proposed system and also include the benefit of avoided carbon (environmental benefits) as a result of using the proposed system.

- Evaluate the detailed risk assessment in the SCPP BOT project proposal considering that the life-cycle time of the technology is long.

APPENDIX A

STATISTICAL TESTS

A.1. Goodness-of-fit (GoF) statistical test

These are important test statistics in which probabilistic values are employed to ascertain how well a set of data fit (or other not fit) a particular cumulative distribution function. In other words, the GoF test measures the compatibility of a random sample with theoretical probability distribution function.

A.2. Kolmogorov-Smirnov (K-S) test

K-S test is an empirical distribution function use to decide if a sample comes from a population with a specific distribution. As a nonparametric test, K-S does not depend on the continuous distribution function being tested for the GoF of the data set if the distribution function is fully specified. Accordingly, Okeniyi and Okeniyi [109] stated that “K-S GoF statistics gives an exact test at a limiting level of significance for the deviation between each of the observed values of the hypothesized continuous distribution and the expected value from the empirical distribution function used as the estimate of the population”.

Advantages of K-S test:

- It is considered to be an exact test
- The distribution of the statistic does not depend on the underlying cumulative distribution function being tested.

Disadvantages of K-S test:

- The test is only applicable to continuous distributions.
- The test is more sensitive at the center of the distribution relative to the tails.

The test statistic D is based on the largest vertical difference between the theoretical and the empirical cumulative distribution function and is given as:

$$D = \max_{1 \leq i \leq N} \left(F(x_i) - \frac{i-1}{N}, \frac{i}{N} - F(x_i) \right) \quad (40)$$

where F is the theoretical cumulative distribution of the data being tested. The cumulative distribution of the dataset must be continuous and fully specified such that the shape, scale and location parameters cannot be estimated from the data.

The K-S hypothesis testing is defined as,

H_0 : The data follow a specific distribution

H_1 : The data do not follow a specific distribution

The hypothesis regarding the distribution form is rejected at the chosen significance level (α) if the test statistic D is greater than the critical value obtained from the table. The fixed number of α (0.01, 0.05, 0.1, 0.2 etc.) are generally utilized to evaluate the null hypothesis.

The hypothesis of the test is rejected if D is greater than the critical value obtained from the table.

A.3. Anderson-Darling Test

The Anderson-Darling is a refinement of Kolmogorov-Smirnov test that gives more weight to the tail comparable to the K-S tests. The critical value of Anderson –Darling test statistic depends on the specific distribution being tested.

The Anderson-Darling statistics is defined as:

$$A^2 = -n - \frac{1}{n} \sum_{i=1}^n (2i - 1) [\ln F(X_i) + \ln(1 - F(X_{n-i+1}))] \quad (41)$$

The null and the alternative hypothesis are given as:

H_0 : The data follow a specific distribution

H_1 : The data do not follow a specific distribution

Here, the hypothesis regarding the distributional form is rejected at the chosen significance level (α) if the test statistic A^2 is greater than the critical value obtained from the table. The fixed number of α (0.01, 0.05, 0.1, 0.2 etc.) are generally utilized to evaluate the null hypothesis H_0 at various level of significance.

A.4. Chi-Squared test

Chi-Squared test is normally available for continuous sample data and is applied to binned data. Thus, the value of the test statistic depends on the way the data is binned as there is no optimal choice for the number of bins. Moreover, a sufficient sample size may be required in order for the Chi-Squared approximation to be valid. Several formulations are available for estimating the number of bins to be used based on the sample size.

$$k = 1 + \log_2 N \quad (42)$$

The Chi-Squared statistics is defined as:

$$X^2 = \sum_{i=1}^k \frac{(O_i - E_i)^2}{E_i} \quad (43)$$

where O_i is the observed frequency for bin i , and E_i is the expected frequency for bin i which can be estimated from:

$$E_i = F(X_2) - F(X_1) \quad (44)$$

where F is the cumulative distribution function of the probability distribution being tested, X_2 and X_1 are the upper and lower limits for the bin i

The null and the alternative hypothesis for Chi-Squared test are given as:

H_0 : The data follow a specific distribution

H_1 : The data do not follow a specific distribution

Here, the hypothesis regarding the distributional form is rejected at the chosen significance level (α) if the test statistic X^2 is greater than the critical value defined as:

$$\chi^2_{1-\alpha, k-1} \quad (45)$$

Which implies that Chi-Squared inverse CFD with $k - 1$ degree of freedom and a significance level of α . The fixed number of α (0.01, 0.05, 0.1, 0.2 etc.) are generally utilized to evaluate the null hypothesis H_0 at various level of significance

APPENDIX B

PROBABILITY DISTRIBUTION FITS RANKING FOR POTISKUM

The ranking of all the PD considered for Potiskum is presented in Table 8.

Table 8. Goodness-of-fit ranking for Potiskum.

N/S	Distribution	Kolmogorov-Smirnov		Anderson-Darling		Chi-Squared	
		Statistic	Rank	Statistic	Rank	Statistic	Rank
1	Dagum (4P)	0.05015	1	0.88706	1	12.715	1
2	Kumaraswamy	0.06711	2	2.2741	2	22.213	2
3	Gen. Extreme Value	0.06934	3	72.699	44	N/A	
4	Weibull (3P)	0.08307	4	4.2914	5	29.631	4
5	Johnson SB	0.0837	5	74.281	45	N/A	
6	Beta	0.08629	6	3.1094	4	34.724	6
7	Dagum	0.08899	7	2.8377	3	26.264	3
8	Burr (4P)	0.09514	8	4.6028	6	34.504	5
9	Gumbel Min	0.0987	9	5.3193	7	51.926	8
10	Log-Logistic (3P)	0.09882	10	11.043	10	89.63	12
11	Log-Pearson 3	0.10226	11	82.516	46	N/A	
12	Cauchy	0.12271	12	12.7	11	35.382	7
13	Burr	0.12379	13	9.7383	9	61.61	10
14	Pert	0.12524	14	7.7749	8	60.628	9
15	Power Function	0.1365	15	12.964	12	113.02	17
16	Gen. Pareto	0.14772	16	163.81	55	N/A	
17	Weibull	0.15283	17	17.372	21	160.87	34
18	Inv. Gaussian (3P)	0.16492	18	16.253	14	118.22	
19	Lognormal (3P)	0.16641	19	16.803	20	122.35	24
20	Fatigue Life (3P)	0.16713	20	16.425	16	113.55	18
21	Nakagami	0.16881	21	21.323	28	94.573	
22	Inv. Gaussian	0.16887	22	23.911	32	143.99	31
23	Normal	0.16888	23	16.553	17	115.3	19
24	Gen. Gamma (4P)	0.16893	24	16.642	18	116.11	
25	Logistic	0.16968	25	15.796	13	90.788	13
26	Pearson 6 (4P)	0.17053	26	16.766	19	115.34	20
27	Hypersecant	0.17062	27	16.378	15	84.922	11
28	Uniform	0.172	28	123.73	53	N/A	
29	Erlang (3P)	0.17487	29	18.311	23	132.9	27
30	Error	0.1769	30	17.507	22	91.939	
31	Gamma (3P)	0.18042	31	18.946	24	136.26	30
32	Pearson 5 (3P)	0.18122	32	19.23	25	135.45	29

33	Laplace	0.18785	33	19.424	26	106.99	16
34	Gamma	0.19396	34	23.273	29	130.78	26
35	Rice	0.19629	35	20.714	27	128.51	25
36	Erlang	0.1976	36	23.769	30	133.44	28
37	Gen. Gamma	0.19835	37	23.833	31	159.56	
38	Pearson 6	0.2016	38	23.926	33	148.47	32
39	Lognormal	0.20768	39	27.596	34	195.54	36
40	Log-Logistic	0.20777	40	27.661	35	215.19	38
41	Fatigue Life	0.21532	41	29.08	36	203.9	37
42	Pearson 5	0.22522	42	32.7	37	242.23	39
43	Gumbel Max	0.2394	43	47.21	39	177.12	35
44	Triangular	0.25727	44	37.156	38	119.86	23
45	Frechet (3P)	0.26141	45	58.254	42	N/A	
46	Frechet	0.28067	46	48.809	40	334.78	41
47	Rayleigh	0.2885	47	64.431	43	643.86	44
48	Rayleigh (2P)	0.30351	48	58.156	41	400.84	43
49	Exponential (2P)	0.38031	49	96.778	48	352.76	42
50	Exponential	0.41593	50	114.33	49	930.6	49
51	Chi-Squared (2P)	0.43126	51	84.712	47	817.36	47
52	Pareto 2	0.4371	52	122.91	52	873.76	48
53	Pareto	0.43746	53	122.41	51	283.61	40
54	Levy (2P)	0.56147	54	121.35	50	657.92	45
55	Reciprocal	0.57402	55	277.42	57	718.83	46
56	Levy	0.61113	56	148.09	54	1353.1	
57	Chi-Squared	0.63623	57	258.78	56	1018.5	50
58	Error Function	0.97807	58	4929.9	58	39742	52
59	Johnson SU			No fit			
60	Log-Gamma			No fit			
61	Student's t			No fit			

The formulas for estimating the probability density function and the cumulative distribution function for four-parameter Dagum distribution (Dagum 4P) obtained for Potiskum. The probability density function and cumulative distribution function are:

$$f(x) = \frac{\alpha k \left(\frac{x-\gamma}{\beta}\right)^{\alpha k-1}}{\beta \left(1 + \left(\frac{x-\gamma}{\beta}\right)^{\alpha}\right)^{k+1}} \quad (46)$$

$$F(x) = \left(1 + \left(\frac{x-\gamma}{\beta}\right)^{-\alpha}\right)^{-k} \quad (47)$$

where k is the continuous shape parameter ($k > 0$), α is the continuous shape parameter ($\alpha > 0$), β is the continuous scale parameter ($\beta > 0$), and γ is the continuous location parameter.

From Table 8, it can be observed that Dagum 4P was ranked the best irrespective of the chosen GoF test adopted. The details of the GoF are provided in Table 9.

Table 9. Dagum 4P hypothesis testing results for different significant level.

Kolmogorov-Smirnov					
Sample Size	365				
Statistic	0.05015				
P-Value	0.30727				
Rank	1				
α	0.2	0.1	0.05	0.02	0.01
Critical Value	0.05616	0.06401	0.07108	0.07946	0.08527
Reject?	No	No	No	No	No
Anderson-Darling					
Sample Size	365				
Statistic	0.88706				
Rank	1				
α	0.2	0.1	0.05	0.02	0.01
Critical Value	1.3749	1.9286	2.5018	3.2892	3.9074
Reject?	No	No	No	No	No
Chi-Squared					
Deg. of freedom	8				
Statistic	12.715				
P-Value	0.12204				
Rank	1				
α	0.2	0.1	0.05	0.02	0.01
Critical Value	11.03	13.362	15.507	18.168	20.09
Reject?	Yes	No	No	No	No

REFERENCES

- [1] Balta MT. Exergetic cost analysis and sustainability assessment of various low exergy heating systems. *Energy Build* 2012;55:721–7. doi:10.1016/j.enbuild.2012.09.030.
- [2] Zhao H, Guo S, Fu L. Review on the costs and benefits of renewable energy power subsidy in China. *Renew Sustain Energy Rev* 2014;37:538–49. doi:10.1016/j.rser.2014.05.061.
- [3] Li H, Jenkins-Smith HC, Silva CL, Berrens RP, Herron KG. Public support for reducing US reliance on fossil fuels: Investigating household willingness-to-pay for energy research and development. *Ecol Econ* 2009;68:731–42. doi:10.1016/j.ecolecon.2008.06.005.
- [4] Stigka EK, Paravantis JA, Mihalakakou GK. Social acceptance of renewable energy sources: A review of contingent valuation applications. *Renew Sustain Energy Rev* 2014;32:100–6. doi:10.1016/j.rser.2013.12.026.
- [5] McKendry P. Energy production from biomass (part 3): gasification technologies. *Bioresour Technol* 2002;83:55–63. doi:10.1016/S0960-8524(01)00120-1.
- [6] Tsoutsos T, Frantzeskaki N, Gekas V. Environmental impacts from the solar energy technologies. *Energy Policy* 2005;33:289–96. doi:10.1016/S0301-4215(03)00241-6.
- [7] Mosier N, Wyman C, Dale B, Elander R, Lee YY, Holtzapple M, et al. Features of promising technologies for pretreatment of lignocellulosic

- biomass. *Bioresour Technol* 2005;96:673–86.
doi:10.1016/j.biortech.2004.06.025.
- [8] Joselin Herbert GM, Iniyan S, Sreevalsan E, Rajapandian S. A review of wind energy technologies. *Renew Sustain Energy Rev* 2007;11:1117–45.
doi:10.1016/j.rser.2005.08.004.
- [9] Lesser J a., Su X. Design of an economically efficient feed-in tariff structure for renewable energy development. *Energy Policy* 2008;36:981–90.
doi:10.1016/j.enpol.2007.11.007.
- [10] Okoye CO, Atikol U. A parametric study on the feasibility of solar chimney power plants in North Cyprus conditions. *Energy Convers Manag* 2014;80:178–87. doi:10.1016/j.enconman.2014.01.009.
- [11] Zhou W, Lou C, Li Z, Lu L, Yang H. Current status of research on optimum sizing of stand-alone hybrid solar–wind power generation systems. *Appl Energy* 2010;87:380–9. doi:10.1016/j.apenergy.2009.08.012.
- [12] Sungur C. Multi-axes sun-tracking system with PLC control for photovoltaic panels in Turkey. *Renew Energy* 2009;34:1119–25.
doi:10.1016/j.renene.2008.06.020.
- [13] Thirugnanasambandam M, Iniyan S, Goic R. A review of solar thermal technologies. *Renew Sustain Energy Rev* 2010;14:312–22.
doi:10.1016/j.rser.2009.07.014.
- [14] Tester JW, Drake EM, Driscoll MJ, Golay MW, Peters WA. Sustainable Energy: Choosing Among Options. 2nd ed. The MIT Press Cambridge,

Massachusetts London, England; 2012.

- [15] Schlaich J, Bergermann R, Schiel W, Weinrebe G. Design of commercial solar updraft tower systems—utilization of solar induced convective flows for Power generation. *J Sol Energy Eng* 2005;127:117. doi:10.1115/1.1823493.
- [16] Cao F, Zhao L, Li H, Guo L. Performance analysis of conventional and sloped solar chimney power plants in China. *Appl Therm Eng* 2013;50:582–92. doi:10.1016/j.applthermaleng.2012.06.038.
- [17] Dai Y, Huang H, Wang R. Case study of solar chimney power plants in Northwestern regions of China. *Renew Energy* 2003;28:1295–304. doi:10.1016/S0960-1481(02)00227-6.
- [18] Ferreira AG, Maia CB, Cortez MFB, Valle RM. Technical feasibility assessment of a solar chimney for food drying. *Sol Energy* 2008;82:198–205. doi:10.1016/j.solener.2007.08.002.
- [19] Pretorius JP, Kröger DG. Thermoeconomic Optimization of a Solar Chimney Power Plant. *J Sol Energy Eng* 2008;130:021015. doi:10.1115/1.2840571.
- [20] Gholamalizadeh E, Kim M-H. Thermo-economic triple-objective optimization of a solar chimney power plant using genetic algorithms. *Energy* 2014;70:204–11. doi:10.1016/j.energy.2014.03.115.
- [21] Dehghani S, Mohammadi AH. Optimum dimension of geometric parameters of solar chimney power plants – A multi-objective optimization approach. *Sol Energy* 2014;105:603–12. doi:10.1016/j.solener.2014.04.006.

- [22] Pérez B, Mínguez R, Guanche R. Offshore wind farm layout optimization using mathematical programming techniques. *Renew Energy* 2013;53:389–99. doi:10.1016/j.renene.2012.12.007.
- [23] Winston WL. *Operations research: Applications and algorithms*. 3rd ed. 1993.
- [24] dos Santos Bernardes MA. Solar Chimney Power Plants–Developments and Advancements. In: Rugescu RD (Ed. ., editor. *Sol. Energy*, INTECH, Croatia; 2010, p. 953–78.
- [25] Dhahri A, Omri A. A review of solar chimney power generation technology. *Int J Eng Adv Technol* 2013;2:1–17.
- [26] Haaf W, Friedrich K, Mayr G, Schlaich J. Solar chimneys Part I: Principle and construction of the pilot plant in Manzanares. *Int J Sol Energy* 1983;2:3–20.
- [27] Haaf W. Solar chimneys Part I: Preliminary test results from the Manzanares pilot plant. *Int J Sol Energy* 1984;2:141–61.
- [28] Cao F, Li H, Zhao L, Bao T, Guo L. Design and simulation of the solar chimney power plants with TRNSYS. *Sol Energy* 2013;98:23–33. doi:10.1016/j.solener.2013.05.022.
- [29] Zhou X, Wang F, Ochieng RM. A review of solar chimney power technology. *Renew Sustain Energy Rev* 2010;14:2315–38. doi:10.1016/j.rser.2010.04.018.
- [30] Schlaich J. *The solar chimney: electricity from the sun*. C. Maurer, Geislingen, Germany; 1995.

- [31] dos Santos Bernardes MA, Molina Valle R, Cortez MF-B. Numerical analysis of natural laminar convection in a radial solar heater. *Int J Therm Sci* 1999;38:42–50. doi:10.1016/S0035-3159(99)80015-4.
- [32] Raney SM, Brooks JR, Schaffer JP, French JJ. Experimental validation of solar chimney performance models and operational characteristics for small scale remote applications. 6th Int. Conf. Energy Sustain., San Diego, California: ASME; 2012, p. 27–32.
- [33] Kasaeian AB, Heidari E, Vatan SN. Experimental investigation of climatic effects on the efficiency of a solar chimney pilot power plant. *Renew Sustain Energy Rev* 2011;15:5202–6. doi:10.1016/j.rser.2011.04.019.
- [34] Kasaeian A, Ghalamchi M, Ghalamchi M. Simulation and optimization of geometric parameters of a solar chimney in Tehran. *Energy Convers Manag* 2014;83:28–34. doi:10.1016/j.enconman.2014.03.042.
- [35] Kalash S, Naimeh W, Ajib S. Experimental investigation of the solar collector temperature field of a sloped solar updraft power plant prototype. *Sol Energy* 2013;98:70–7. doi:10.1016/j.solener.2013.05.025.
- [36] Zhou X, Yang J, Xiao B, Hou G. Experimental study of temperature field in a solar chimney power setup. *Appl Therm Eng* 2007;27:2044–50. doi:10.1016/j.applthermaleng.2006.12.007.
- [37] Kulunk H. A prototype solar convection chimney operated under Izmit conditions. In: Veriroglu T, editor. *Proceeding 7th Miami Int. Conf.*, 1985, p. 162. doi:10.1287/mnsc.48.2.241.255.

- [38] Koonsrisuk A. Analysis of flow in solar chimney for an optimal design purpose. Ph.D. thesis, Suranaree University of Technology, Nakhon Ratchasima, Thailand, 2009.
- [39] Al-Dabbas M. The first pilot demonstration: solar updraft tower power plant in Jordan. *Int J Sustain Energy* 2012;31:399–410.
doi:10.1080/1478646X.2011.589516.
- [40] Najmi M, Nazari A, Mansouri H, Zahedi G. Feasibility study of a solar chimney power plant in Jordan. *Heat Mass Transf* 2012;48:475–85.
doi:10.1007/s00231-011-0894-5.
- [41] Zuo L, Yuan Y, Li Z, Zheng Y. Experimental research on solar chimneys integrated with seawater desalination under practical weather condition. *Desalination* 2012;298:22–33. doi:10.1016/j.desal.2012.05.001.
- [42] Pasumarthi N, Sherif SA. Experimental and theoretical performance of a demonstration solar chimney model—part II: experimental and theoretical results and economic analysis. *Int J Energy Res* 1998:443–61.
doi:10.1016/S0140-6701(98)93929-7.
- [43] Zhou X, Xu Y. Solar updraft tower power generation. *Sol Energy* 2014.
doi:10.1016/j.solener.2014.06.029.
- [44] Bernardes MA dos S, Voß A, Weinrebe G. Thermal and technical analyses of solar chimneys. *Sol Energy* 2003;75:511–24.
doi:10.1016/j.solener.2003.09.012.
- [45] Aurélio dos Santos Bernardes M, Von Backström TW, Kröger DG. Analysis

- of some available heat transfer coefficients applicable to solar chimney power plant collectors. *Sol Energy* 2009;83:264–75.
doi:10.1016/j.solener.2008.07.019.
- [46] Bernardes MA dos S, von Backström TW. Evaluation of operational control strategies applicable to solar chimney power plants. *Sol Energy* 2010;84:277–88. doi:10.1016/j.solener.2009.11.009.
- [47] von Backström TW, Gannon AJ. Compressible Flow Through Solar Power Plant Chimneys. *J Sol Energy Eng* 2000;122:138. doi:10.1115/1.1313528.
- [48] Nizetic S, Klarin B. A simplified analytical approach for evaluation of the optimal ratio of pressure drop across the turbine in solar chimney power plants. *Appl Energy* 2010;87:587–91. doi:10.1016/j.apenergy.2009.05.019.
- [49] Pasumarthi N, Sherif SA. Experimental and theoretical performance of a demonstration solar chimney model-part I: mathematical model development. *Int J Energy Res* 1998;277–88. doi:10.1016/S0140-6701(98)96631-0.
- [50] Zhou X, Yang J, Xiao B, Hou G. Simulation of a pilot solar chimney thermal power generating equipment. *Renew Energy* 2007;32:1637–44.
doi:10.1016/j.renene.2006.07.008.
- [51] Guo P, Li J, Wang Y. Numerical simulations of solar chimney power plant with radiation model. *Renew Energy* 2014;62:24–30.
doi:10.1016/j.renene.2013.06.039.
- [52] Ming T, Meng F, Liu W, Pan Y, de Richter RK. Analysis of Output power smoothing method of solar chimney power generating system. *Int J Energy*

Res 2013;37:1657–68. doi:10.1002/er.2986.

- [53] Ming T, Liu W, Pan Y, Xu G. Numerical analysis of flow and heat transfer characteristics in solar chimney power plants with energy storage layer. *Energy Convers Manag* 2008;49:2872–9. doi:10.1016/j.enconman.2008.03.004.
- [54] Pretorius JP, Kröger DG. Critical evaluation of solar chimney power plant performance. *Sol Energy* 2006;80:535–44. doi:10.1016/j.solener.2005.04.001.
- [55] Bernardes MA dos S. On the heat storage in solar updraft tower collectors – influence of soil thermal properties. *Sol Energy* 2013;98:49–57. doi:10.1016/j.solener.2013.07.014.
- [56] Bilgen E, Rheault J. Solar chimney power plants for high latitudes. *Sol Energy* 2005;79:449–58. doi:10.1016/j.solener.2005.01.003.
- [57] Koonsrisuk A, Chitsomboon T. Accuracy of theoretical models in the prediction of solar chimney performance. *Sol Energy* 2009;83:1764–71. doi:10.1016/j.solener.2009.05.012.
- [58] Gannon AJ, von Backström TW. Solar Chimney Turbine Performance. *J Sol Energy Eng* 2003;125:101. doi:10.1115/1.1530195.
- [59] Cao F, Zhao L, Guo L. Simulation of a sloped solar chimney power plant in Lanzhou. *Energy Convers Manag* 2011;52:2360–6. doi:10.1016/j.enconman.2010.12.035.
- [60] Ninic N. Available energy of the air in solar chimneys and the possibility of

- its ground-level concentration. *Sol Energy* 2006;80:804–11.
doi:10.1016/j.solener.2005.05.010.
- [61] Nizetic S, Ninic N, Klarin B. Analysis and feasibility of implementing solar chimney power plants in the Mediterranean region. *Energy* 2008;33:1680–90.
doi:10.1016/j.energy.2008.05.012.
- [62] Hamdan MO. Analysis of a solar chimney power plant in the Arabian Gulf region. *Renew Energy* 2011;36:2593–8. doi:10.1016/j.renene.2010.05.002.
- [63] Sangi R. Performance evaluation of solar chimney power plants in Iran. *Renew Sustain Energy Rev* 2012;16:704–10. doi:10.1016/j.rser.2011.08.035.
- [64] Larbi S, Bouhdjar A, Chergui T. Performance analysis of a solar chimney power plant in the southwestern region of Algeria. *Renew Sustain Energy Rev* 2010;14:470–7. doi:10.1016/j.rser.2009.07.031.
- [65] Koonsrisuk A, Chitsomboon T. Mathematical modeling of solar chimney power plants. *Energy* 2013;51:314–22. doi:10.1016/j.energy.2012.10.038.
- [66] Zhou X, Wang F, Fan J, Ochieng RM. Performance of solar chimney power plant in Qinghai-Tibet Plateau. *Renew Sustain Energy Rev* 2010;14:2249–55. doi:10.1016/j.rser.2010.04.017.
- [67] Guo P, Li J, Wang Y. Annual performance analysis of the solar chimney power plant in Sinkiang, China. *Energy Convers Manag* 2014;87:392–9. doi:10.1016/j.enconman.2014.07.046.
- [68] Li W, Wei P, Zhou X. A cost-benefit analysis of power generation from

- commercial reinforced concrete solar chimney power plant. *Energy Convers Manag* 2014;79:104–13. doi:10.1016/j.enconman.2013.11.046.
- [69] Branker K, Pathak MJM, Pearce JM. A review of solar photovoltaic levelized cost of electricity. *Renew Sustain Energy Rev* 2011;15:4470–82. doi:10.1016/j.rser.2011.07.104.
- [70] Fluri TP, Pretorius JP, Dyk C Van, Backström TW Von, Kröger DG, Zijl GPAG Van. Cost analysis of solar chimney power plants. *Sol Energy* 2009;83:246–56. doi:10.1016/j.solener.2008.07.020.
- [71] Joneydi Shariatzadeh O, Refahi AH, Abolhassani SS, Rahmani M. Modeling and optimization of a novel solar chimney cogeneration power plant combined with solid oxide electrolysis/fuel cell. *Energy Convers Manag* 2015;105:423–32. doi:10.1016/j.enconman.2015.07.054.
- [72] Okoye OC, Taylan O, Baker DK. Solar energy potentials in strategically located cities in Nigeria : Review, resource assessment and PV system design. *Renew Sustain Energy Rev* 2016;55:550–66. doi:10.1016/j.rser.2015.10.154.
- [73] Skeiker K. Comparison of methodologies for TMY generation using 10 years data for Damascus, Syria. *Energy Convers Manag* 2007;48:2090–102. doi:10.1016/j.enconman.2006.12.014.
- [74] Chow T, Chan A, Fong K, Lin Z. Some perceptions on typical weather year—from the observations of Hong Kong and Macau. *Sol Energy* 2006;80:459–67. doi:10.1016/j.solener.2005.04.017.
- [75] Chow TT, Chan a. LS, Fong KF, Lin Z. Some perceptions on typical weather

- year—from the observations of Hong Kong and Macau. *Sol Energy* 2006;80:459–67. doi:10.1016/j.solener.2005.04.017.
- [76] Ohunakin OS, Adaramola MS, Oyewola OM, Fagbenle RO. Generation of a typical meteorological year for north – east, Nigeria. *Appl Energy* 2013;112:152–9. doi:10.1016/j.apenergy.2013.05.072.
- [77] Duffie JA, Beckman WA. *Solar engineering of thermal processes*. Third Edit. John Wiley & Sons, INC; 2006.
- [78] Ong KS. A mathematical model of a solar chimney. *Renew Energy* 2003;28:1047–60. doi:10.1016/S0960-1481(02)00057-5.
- [79] Dos S. Bernardes MA, Voß A, Weinrebe G. Thermal and technical analyses of solar chimneys. *Sol Energy* 2003;75:511–24. doi:10.1016/j.solener.2003.09.012.
- [80] Dixon J. *The shock absorber handbook*. 2nd ed. West Wussex, England: Professional Engineering Publishing Ltd., and John Wiley and Sons Ltd.; 2007.
- [81] von Backström TW, Gannon AJ. Solar chimney turbine characteristics. *Sol Energy* 2004;76:235–41. doi:10.1016/j.solener.2003.08.009.
- [82] Fluri TP, von Backström TW. Comparison of modelling approaches and layouts for solar chimney turbines. *Sol Energy* 2008;82:239–46. doi:10.1016/j.solener.2007.07.006.
- [83] Sinha S, Chandel SS. Review of recent trends in optimization techniques for

- solar photovoltaic–wind based hybrid energy systems. *Renew Sustain Energy Rev* 2015;50:755–69. doi:10.1016/j.rser.2015.05.040.
- [84] Ohunakin OS, Adaramola MS, Oyewola OM, Fagbenle RO. Solar energy applications and development in Nigeria: Drivers and barriers. *Renew Sustain Energy Rev* 2014;32:294–301. doi:10.1016/j.rser.2014.01.014.
- [85] Oseni MO. Improving households ' access to electricity and energy consumption pattern in Nigeria : Renewable energy alternative. *Renew Sustain Energy Rev* 2012;16:3967–74. doi:10.1016/j.rser.2012.03.010.
- [86] Soneye A, Daramola A. Energy access in Nigeria: An assessment of solar utilization in Ibadan. *Int J Renew Energy Resour* 2012;2:6–12.
- [87] Adaramola MS, Oyewola OM. Evaluating the performance of wind turbines in selected locations in Oyo state, Nigeria. *Renew Energy* 2011;36:3297–304. doi:10.1016/j.renene.2011.04.029.
- [88] Ohijeagbon OD, Ajayi OO. Potential and economic viability of standalone hybrid systems for a rural community of Sokoto, North-west Nigeria. *Front Energy* 2014;8:145–59. doi:10.1007/s11708-014-0304-z.
- [89] Presidential Task Force on Power 2015. <http://www.nigeriapowerreform.org/> (accessed November 19, 2015).
- [90] Ibitoye F, Adenikinju A. Future demand for electricity in Nigeria. *Appl Energy* 2007;84:492–504. doi:10.1016/j.apenergy.2006.09.011.
- [91] Faleye OO. Modelling demand uncertainties in generation-transmission

- expansion planning: A case study of the Nigerian power system. Royal Institute of Technology (KTH), 2012.
- [92] Oyedepo SO. Towards achieving energy for sustainable development in Nigeria. *Renew Sustain Energy Rev* 2014;34:255–72.
doi:10.1016/j.rser.2014.03.019.
- [93] Mohammed YS, Mustafa MW, Bashir N, Mokhtar AS. Renewable energy resources for distributed power generation in Nigeria: A review of the potential. *Renew Sustain Energy Rev* 2013;22:257–68.
doi:10.1016/j.rser.2013.01.020.
- [94] Fadare D. Modelling of solar energy potential in Nigeria using an artificial neural network model. *Appl Energy* 2009;86:1410–22.
doi:10.1016/j.apenergy.2008.12.005.
- [95] Awogbemi O, Komolafe CA. Potential for sustainable renewable energy development in Nigeria. *Pacific J Sci Technol* 2011;12:161–9.
- [96] Nwofe PA. Utilization of solar and biomass energy-A panacea to energy sustainability in a developing economy. *Int J Energy Environ Res* 2014;2:10–9.
- [97] Adaramola MS. Viability of grid-connected solar PV energy system in Jos, Nigeria. *Int J Electr Power Energy Syst* 2014;61:64–9.
doi:10.1016/j.ijepes.2014.03.015.
- [98] Adaramola MS, Paul SS, Oyewola OM. Assessment of decentralized hybrid PV solar-diesel power system for applications in Northern part of Nigeria.

- Energy Sustain Dev 2014;19:72–82. doi:10.1016/j.esd.2013.12.007.
- [99] Oyedepo SO, Adaramola MS, Paul SS. Analysis of wind speed data and wind energy potential in three selected locations in south-east Nigeria. *Int J Energy Environ Eng* 2012;3:7. doi:10.1186/2251-6832-3-7.
- [100] Mohammed YS, Mustafa MW, Bashir N, Mokhtar AS. Renewable energy resources for distributed power generation in Nigeria : A review of the potential. *Renew Sustain Energy Rev* 2013;22:257–68. doi:10.1016/j.rser.2013.01.020.
- [101] Ohunakin OS, Adaramola MS, Oyewola OM, Fagbenle RO. Solar energy applications and development in Nigeria: Drivers and barriers. *Renew Sustain Energy Rev* 2014;32:294–301. doi:10.1016/j.rser.2014.01.014.
- [102] Painuly J. Barriers to renewable energy penetration; a framework for analysis. *Renew Energy* 2001;24:73–89. doi:10.1016/S0960-1481(00)00186-5.
- [103] Meteonorm n.d. www.meteonorm.com.
- [104] Ohunakin OS, Adaramola MS, Oyewola OM, Fagbenle RO. Generation of a typical meteorological year for north–east, Nigeria. *Appl Energy* 2013;112:152–9. doi:10.1016/j.apenergy.2013.05.072.
- [105] Von Backström TW, Harte R, Höffer R, Kratzig WB, Kröger DG, Niemann H-J, et al. State and Recent Advances in Research and Design of Solar Chimney Power Plant Technology. *VGB Powertech* 2008;88:64–71.
- [106] Easyfit n.d. <http://www.mathwave.com/easyfitxl-distribution-fitting->

excel.html.

- [107] Delrio P, Burguillo M. Assessing the impact of renewable energy deployment on local sustainability: Towards a theoretical framework. *Renew Sustain Energy Rev* 2008;12:1325–44. doi:10.1016/j.rser.2007.03.004.
- [108] Olatomiwa L, Mekhilef S, Huda ASN, Ohunakin OS. Economic evaluation of hybrid energy systems for rural electrification in six geo-political zones of Nigeria. *Renew Energy* 2015;83:435–46. doi:10.1016/j.renene.2015.04.057.
- [109] Okeniyi JO, Okeniyi ET. Implementation of Kolmogorov–Smirnov P -value computation in Visual Basic®: implication for Microsoft Excel® library function. *J Stat Comput Simul* 2012;82:1727–41. doi:10.1080/00949655.2011.593035.