Research Article
Comparative Evaluation of Reflective and Refractive Optical Concentration Systems in Tropical Climate

[1,2]Abdulkarim Hamza El-Ladan, [1]M.H. Ruslan, [1]H.Y. Chan, [1]K. Sopian and [1]Saleem H. Zaidi
[1]Solar Energy Research Institute (SERI), Universiti Kebangsaan Malaysia (UKM), 43600 UKM Bangi,
Selangor, DarulEhsan, Malaysia
[2]Department of Physics, Umaru Musa Yaradua University, P.M.B. 2218, Katsina,
Katsina State, Nigeria

Abstract: Convergence of global economic inequalities and greenhouse emissions makes it imperative that fossil-fuel dependence be replaced by renewable energy revolution. Sunlight is the only truly free and abundant global energy resource capable of replacing fossil fuels. Historically, thermal and electrical forms of energy have been generated through Concentrated Solar Power (CSP) systems. A major disadvantage of existing CSP systems lies in their long lead times, large start-up costs and integration with an advanced electricity transmission grid. Research work reported here is focused on evaluation of reflective and refractive optical concentration systems in tropical climate with the aim of developing small scale distributed electricity generation systems linked to micro grids. Evaluation of seven optical concentrators in reflection and refraction modes in tropical Malaysian climate has been carried out. The experimental methodology was based on measurement of temperature at the focal point of the optical systems as a function of time and solar irradiance. Highest temperatures achieved with reflective systems were in 200-300°C range, in contrast, Fresnel-lens based refractive systems approached temperatures in excess of ~1300°C. For the Fresnel lenses investigated, an approximate logarithmic temperature dependence on lens diameter was determined. For the Malaysian climate, sunlight to thermal energy conversion of refractive systems was determined to be significantly superior to reflective systems.

Keywords: Concentration ratio, efficiency, figure of merit, fresnel lens, stagnation temperature, tropics

INTRODUCTION

With rapidly rising greenhouse emissions coupled with growing economic inequalities, the business as-usual model of fossil-fuel based electricity, Bazmi and Zahedi (2011) supplied through large scale transmission grids has become unsustainable (Levin and Thomas, 2012). The current world coal consumption is about 4.3 billion tons with china alone consuming 3.8 billion tons in 2011 (E.I.A., 2012). Such high levels of coal consumption have significantly degraded global environment. For example, in October, 2013, the visibility due to greenhouse gas emissions in industrial parts of china was reduced to 10 m due to an air pollution levels 30-45 times above recommended safety levels (http://rt.com/news/china-biggest-coal-consumption-086/, 2013). There is clear and compelling evidence for transition from fossil fuels to sustainable and renewable resources. The global distribution of primary energy generation resources by fuel reveals that almost 80% originated from fossil fuels with only about 1% originating from renewable resources (geothermal, solar, wind and heat) (I.E.A., 2013).

Almost 66.4% of global energy consumption is attributed to fossil fuels, biofuel waste accounted for about 12.5%; electricity accounted for 17.7% with 68% of it generated from fossil fuels. Similarly, almost 68% of global electricity generation is attributed to fossil fuels, 12% nuclear, 16% hydro; only 4% to renewable sources (I.E.A., 2013). Distribution of global green house gas emissions illustrates that carbon-based fossil fuels are the principal source of greenhouse gas emissions responsible for approximately 99% of the total global emission. The energy generation and consumption data unambiguously demonstrate the relationship between the dependence on consumption of carbon-based fossil fuels and their adverse impact on global environment; this is unsustainable for long-term human survival on Earth. Clearly, there is an urgent need for transition from carbon-based fuels to renewable resources. An energy source that meets such sustainability requirements is "solar thermal technology", which requires harnessing limitless solar energy for thermal and electrical energy generation (El-ladan *et al*., 2013).

Corresponding Author: Abdulkarim Hamza El-Ladan, Solar Energy Research Institute (SERI), Universiti Kebangsaan Malaysia (UKM), 43600 UKM Bangi, Selangor, DarulEhsan, Malaysia
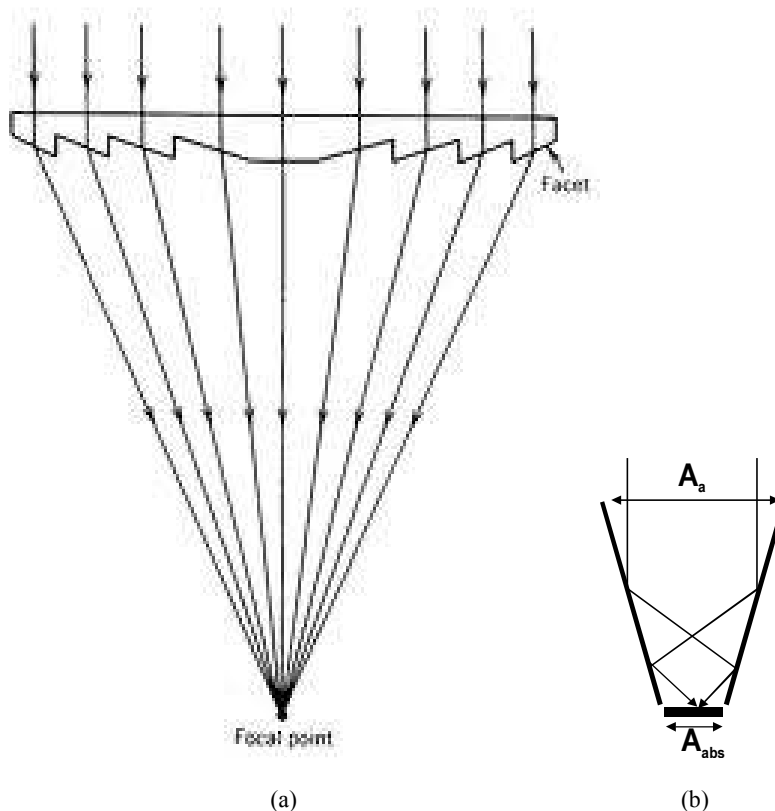
Fig. 1: Schematic diagram of (a) refractive and (b) reflective optical concentrators

Sunlight is the only free, global renewable energy resource. Sunlight has been harnessed for thermal, thermal electricity and direct electricity generation using photovoltaic effect (Bassam *et al*., 2013). Work reported here has focused on harnessing of sunlight directly for thermal and electricity generation. Historically, sunlight concentration methods have been used for a wide range of applications, a typical example being irrigation in Maadi, Egypt (Butti and Perlin, 1980). As early as 1695 in Florence, melting of diamond by solar energy had been demonstrated (Levin and Thomas, 2012). In the mid 1770's, the renowned chemist Antoine Lavoisier, considered as the father of modern chemistry, demonstrated spontaneous combustion by focusing sunlight over flammable materials, LLC (http://www.solarpoweredthermal. com/historical.shtml). A century later in 1878, the first solar power generation system based on focusing of sunlight with parabolic reflectors was developed LLC (http://www.solarpoweredthermal.com/historical.shtml) . It is likely that continued scientific developments in this field were delayed due to discovery of carbon-based fossil fuels far more efficient than steam LLC (http://www.solarpoweredthermal.com/historical.shtml. Almost a century later in 1968, Francia (1968) commissioned the first large scale Concentrated Solar Plant (CSP) in which the focused sunlight receivers were placed at the centre of an array of sunlight

reflectors (or collectors). This CSP plant was able to generate 1 MW using superheated steam at temperature of 500°C and pressure of 100 bar (~1459 lbs/inch) (Butti and Perlin, 1980).

Charles *et al*. have investigated parabolic trough for reflective optical concentration in order to determine thermal efficiency at indoor conditions where wind, ambient and sky temperatures were controlled; collector efficiency of 0.773 was demonstrated (Kutscher *et al*., 2010). However for refractive Fresnel lens collector optical concentrators, a higher value for efficiency was demonstrated in comparison with the evacuated CPC with the same type of receiver (Sorigal and Neaga, 2012).

This study reports on an investigation of reflective and refractive optical concentration systems in tropical climates typical of equatorial-belt countries such as Malaysia. Figure 1a schematically describes an example of refractive optical concentrator such as a Fresnel lens. Incident light enters the lens through the aperture area A_a and is focused onto a small area A_{abs} at its focal point. Figure 1b is an example of the reflective optical concentrator in which incident light is multiply-reflected from the highly reflective sidewalls onto a smaller absorber area at the focal point. Principal objective of this study is to evaluate reflective and refractive optical concentration systems operating in tropical environment. The long-term goal of this

research effort is to develop small scale CSP systems to form an integral component of the distributed energy resource matrix connected to micro-grids. Such an approach to energy generation and distribution eliminates costly and wasteful large scale power plants and transmission grids (Henri *et al.*, 2012). This study reports on seven optical concentrators in reflection and refraction modes. Dimensions of optical components have been kept comparable for ease of performance evaluation (Fig. 1).

MATERIALS AND METHODS

Figure 2 describes the experimental methodology employed for the work presented here. Experimental work was based on automated measurements of temperature at the focal point of the optical system and solar irradiance as a function of time. Reflective systems studied included parabolic trough, cone frustum and hexagonal frustum configurations. Refractive-based optical systems were based on spherical and linear Fresnel lenses. Fresnel lens is a flat optical component made from (PMMA Polymethylmethacrylate) with its surface made up of many small concentric grooves with each groove behaves like an individual prism. There are several advantages of Fresnel lenses over other concentrators

including lightweight, lower cost compared to highly reflective mirror surfaces, mechanical strength, high temperature resistance, ability to generate higher temperatures and scalable to very large (tens of meters) areas.

For comparative analysis, dimensions of reflective and refractive systems were kept comparable in order to achieve objective comparison. Figure 3 shows pictures of the optical concentration systems setup on the 7th floor rooftop of the Solar Energy Research Institute (SERI) laboratory; seven different concentrators of the approximately comparable dimensions are shown. During data acquisition, all the concentrators were arranged in a row to avoid shading. Manual adjustments after every 5 min were carried out in order to maintain direct sunlight tracking. A Lab VIEW-based automated data acquisition computer program was used to acquire temperature and irradiance data using type K thermocouple and apogee Silicon cell Pyranometer (SP110), respectively. Some error in temperature measurement is introduced in the maximum stagnation temperature due to high convection losses of the receiver since it was not protected from exposure to the wind. However, this measurement uncertainty is cancelled out since the same procedure is employed for all optical concentrators.
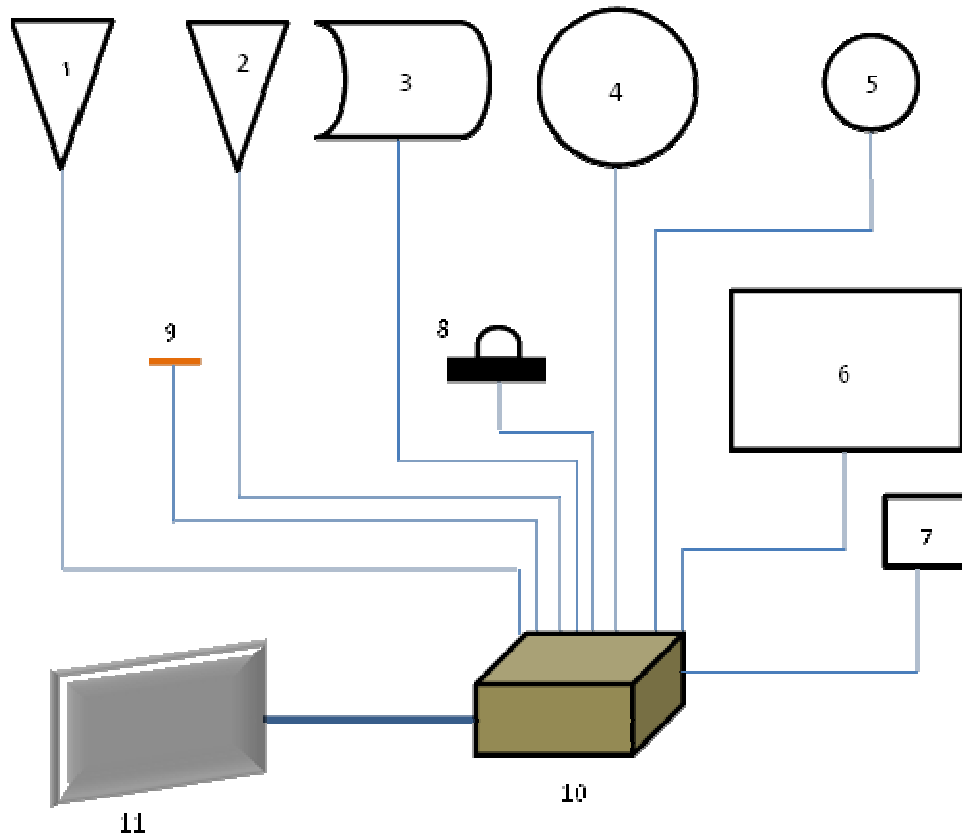

Fig. 2: Schematic diagram for the experimental data acquisition configuration

Fig. 3: Concentrators lined up for experiment and data collection

Theoretical considerations: To access the performance of the optical concentrator in the context of work reported here, thermal efficiency of the collector is a better indicator of its thermal performance and is defined as the ratio of the thermal energy delivered to the collector by the solar flux incident at it.

Using "Carnot limit" the Maximum conversion efficiency for thermal systems has been mathematically determined as:

$$E = 1 - T_\infty/T_P \tag{1}$$

where,
E   = The efficiency of the concentrator
T_∞ = Ambient temperature
T_P = Plate temperature, S.T.G

The optical concentration ratio, C, is defined as the ratio of the collecting lens area (A_a) to the receiver area (A_{abs}). The absorber concentration ratio determines the stagnation temperature, where stagnation temperature refers to the absorber temperature, efficiency and performance of all concentrators, its value varies from unity (flat plate collector) to several thousand such as for parabolic dish or a large Fresnel lens with small focusing spot:

$$C = A_a/A_{abs} = \pi R_1^2/\pi R_2^2 = R_1^2/R_2^2 \tag{2}$$

where, R_1 is the radius of the optical element and R_2 is the absorber radius. In the case of truncated frustum the following mathematical expression was used to calculate C (Emam, 2012):

$$C = (2\cos\theta + 1)^2 \tag{3}$$

where, θ is the acceptance angle.

In the experimental configuration described in Fig. 2, concentrators have been identified by numbers 1 through 7 with (1) for 50-cm diameter conical frustum,
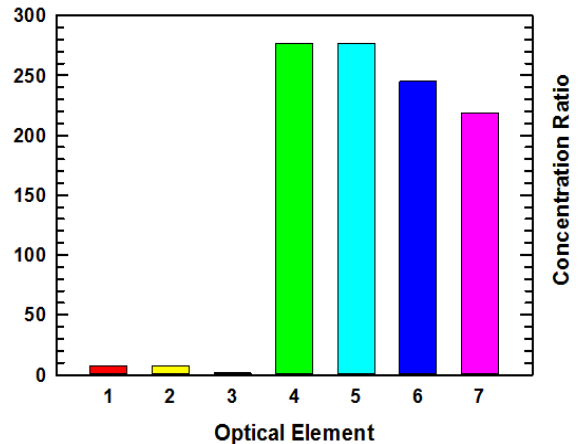

Fig. 4: Optical concentration ratios for the seven optical elements measured

(2) for 50-cm diameter hexagonal frustum, (3) for 50-cm diameter parabolic trough reflector, (4) for 100-cm diameter spherical Fresnel lens, (5) for 50-cm diameter spherical Fresnel lens, (6) for 130×80 cm^2 linear Fresnel lens and (7) for 25×25 cm^2 spherical Fresnel lens; the remaining three components are for data acquisition (8) pyranometer for solar insolation (W/m^2) measurement, (9) K type thermocouple for temperature (°C) measurements, (10) Lab View-based data logger and (11) the personal computer.

RESULTS AND DISCUSSION

Optical concentration ratios as well as the measured receiver temperature for both reflective and refractive optical elements as a function of time and solar insolation have been plotted in Fig. 4 to 8. The bar graph in Fig. 4 plots the calculated concentration ratios of all optical elements. Highest concentration ratios in ~200-300 range are achieved with Fresnel lenses; reflective concentrators were defined by much lower (~10) ratios. Figure 5 plots measured stagnation temperature for the three spherical and one line linear Fresnel lens refractive concentrators. Largest diameter spherical Fresnel lens was (4) 100-cm diameter, followed by (5) 50-cm diameter, (6) 130×80 cm^2 linear Fresnel lens and (7) 25×25 cm^2 spherical Fresnel lens. The temperature measurements follow the solar insolation and exhibit rapid increase in temperature as a function of lens diameter. This is clearly seen in Fig. 6 which plots the highest temperature (black line) for each refractor diameter for spherical Fresnel lenses only. The red line represents a logarithmic fit to the measured temperature variation as a function of diameter x given by:
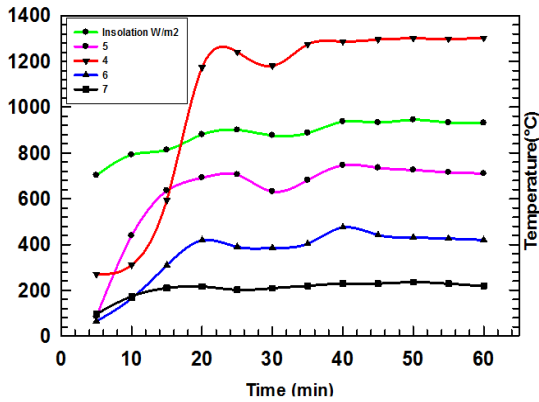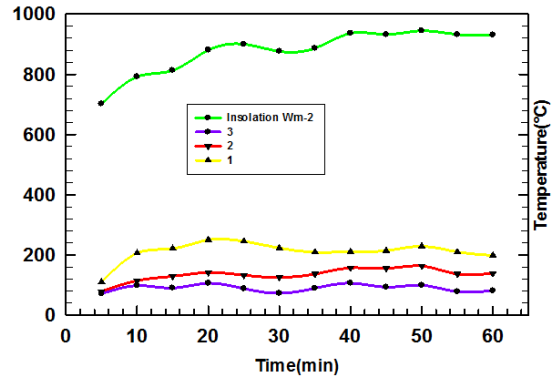
$$T(x) = T_0 + T_1 \ast \ln(x) \tag{4}$$

Fig. 5: Stagnation temperature (°C) as a function of time for refractive concentrators at fixed solar insolation (W/m²)
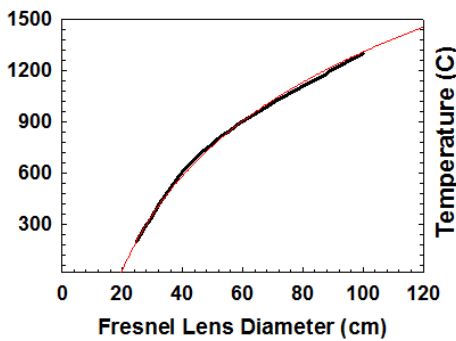

Fig. 6: Highest stagnation temperature (°C) variation as a function of spherical Fresnel lens diameter (black line); and logarithmic fit to temperature variation (red line)

where, $T_0 = -2345.78$, $T_1 = 793.48$ and x represents lens diameter in centimetres. Comparison of concentration ratios and temperatures achieved reveals that larger lens diameters are able to achieve much higher temperatures probably due to their large areas which is explains why the concentration ratios are comparable for all Fresnel lenses.

Figure 7 plots measured temperature variation for the four reflective concentrators. For these reflective optical elements, the highest temperature is achieved by the (1) conical frustum followed by (2) hexagonal frustum concentrator and (3) parabolic trough; all are of approximately comparable geometrical configuration in terms of the 50-cm diameter of the aperture. Comparison of the temperature data in Fig. 5 and 7 reveals that higher concentration ratios lead to higher stagnation temperatures. Nonetheless, the refractive Fresnel lens is able to achieve a stagnation temperature that is approximately three times higher than the reflective concentrator.

Figure 8 plots the temperature data from all seven optical concentrator in three-dimensional contour
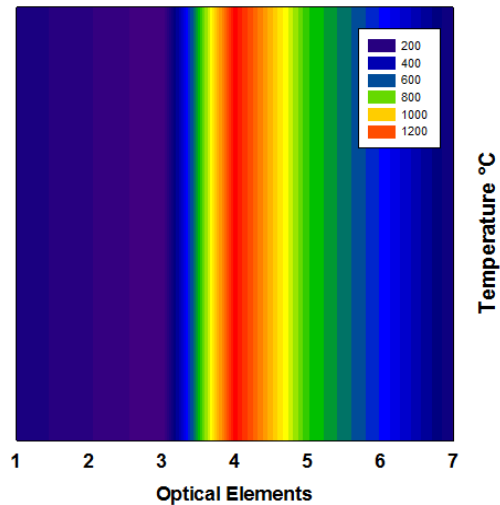

Fig. 7: Stagnation temperature (°C) as a function of time for the reflective concentrators at fixed solar insolation (W/m²)

Fig. 8: Three-dimensional contour plot of stagnation temperatures for seven optical concentrators at fixed solar insolation of 945 W/m²
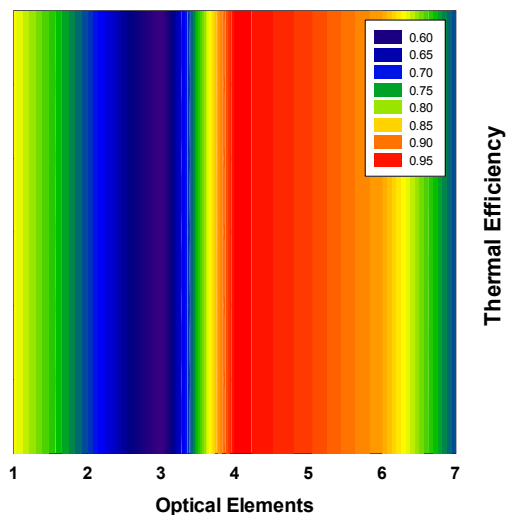

Fig. 9: Three-dimensional contour plot of average thermal efficiency for seven optical concentrators

format with vertical axis representing temperature and horizontal axis individual optical elements 1 through 7 according to the description given earlier. This kind of data presentation is visually easy to understand. It is observed that the 100-cm diameter spherical Fresnel lens (4) generates the highest stagnation temperature of 1300°C followed by a 50-cm diameter spherical lens (5) with 746°C, however the linear lens 130×80 cm (6) larger than the 50-cm diameter generates lower stagnation temperature 517°C with respect to its size and 25×25 cm lens (7) generates the lowest temperature at 236°C. In contrast, for the reflective concentrators, the conical concentrator (1) generates the highest temperature 250°C, followed by the hexagonal concentrator (2) at 165°C; the lowest is generated by the parabolic trough (3) at 130°C. Therefore, refractive concentrators have been demonstrated to be far more efficient in converting sunlight into heat.

Figure 9 plots thermal efficiencies for all seven optical concentrators. The highest efficiency is demonstrated by the 100-cm lens (4) followed by 50-cm lens (5), linear lens (6), conical frustum (1), hexagonal frustum (2), 25-cm lens (7) and lastly the parabolic trough (3). However the 25-cm lens efficiency was determined to be low in comparison with its concentration ratio that might be attributed to logarithmic dependence of temperature on lens diameter Eq. (4).

CONCLUSION AND RECOMMENDATIONS

Seven reflective and refractive optical concentrator systems were investigated. Highest temperatures achieved with reflective systems were in 200-300°C range while Fresnel lens based refractive systems approached temperatures in ~1000-1300°C range. For the spherical Fresnel lenses investigated, temperature increase followed logarithmic dependence on the diameter. In all cases concentration ratios have direct effect on the temperature generated at the focal point, which has a direct bearing on system efficiency. In a tropical climate typical of Malaysia, frequent cloud coverage results in large scattering and sky temperature fluctuations directly impacting optical response of the refractive and reflective systems. The experimental data reported here illustrates sunlight to thermal energy conversion for refractive optical systems as significantly superior to reflective systems. Concentration ratio, sunlight to thermal energy efficiency η (Carnot), figure of merit F and optical efficiency were determined for potential thermal and electricity generation applications. Parabolic concentrator, considered as the most matured concentrated solar power systems technology, exhibited the lowest conversion efficiency. In contrast, the Fresnel lens of similar dimension exhibited higher

conversion efficiency and figure of merit. For larger Fresnel lens, even higher respective conversion efficiency and figure of merit values were demonstrated.

Therefore, for tropical climatic conditions, refractive optical concentration systems based on Fresnel lenses were determined to be the most desirable candidates for thermal and electricity generation. Fresnel lenses are also attractive due to their favorable material properties including; low weight, mechanical strength, temperature resistance and inexpensive manufacturing (Newton, 2006). Though up till now no full-scale thermal systems using Fresnel lenses are known to be in operation as commercial power plant around the world, they are finding extensive applications for indoor cooking and extremely high concentration PV systems (E.I.A., 2012).

NOMENCLATURE

A_a : Collecting aperture area
A_{abs} : Absorber area
C : Concentration ratio
E : Concentrator efficiency
F_1 : First figure of merit
I_s : Solar insolation
R_2 : Absorber radius
T_P : Plate temperature
T_∞ : Ambient temperature
U_L : Heat lost factor
η_o : Optical efficiency
θ : Acceptance angle

ACKNOWLEDGMENT

REFERENCES

Bassam, N.E., P. Maegaard and M.L. Schlichting, 2013. Distributed Renewable Energies for Off-Grid Communities. Elsevier Science, New York, pp: 91-109.

Bazmi, A.A. and G. Zahedi, 2011. Sustainable energy systems: Role of optimization modeling techniques in power generation and supply-a review. Renew Sust. Energ. Rev., 15(8): 3480-3500.

Butti, K. and J. Perlin, 1980. A Golden Thread: 2500 Years of Solar Architecture and Technology. Cheshire Books, Palo Alto, pp: 66-100, ISBN: 0442240058.

E.I.A. (US Energy Information Administration), 2012. Retrieved from: http://en.wikipedia.org/wiki/Solar_thermal_energy#cite_note-51.

El-Ladan, A.H., C.H. Yen, M.H. Ruslan, K. Sopian and S.H. Zaidi, 2013. The Prospects of a promising solar thermal concentrator (Fresnel lens) for cooking, heating and electricity generation, latest trends in renewable energy and environmental informatics. Proceeding of the 7th International Conference on Renewable Energy Sources (RES'13).

Emam, S., 2012. A new design for an economical, highly efficient, conical solar cooker. Renew. Energ., 27: 599-619.

Francia, G., 1968. Pilot Plants of Solar Steam Generation Systems. Solar Energy, 12: 51-64.

Henri, R., J. Nildo and A. Cesar, 2012. The Brazilian experience of rural electrification in the Amazon with decentralized generation: The need to change the paradigm from electrification to development. Renew. Sust. Energ. Rev., 16(3): 1450-146.

I.E.A. (International Energy Agency), 2013. Key World Energy Statistics. Retrieved from: http://www.iea.org/publications/freepublications/publication/KeyWorld2013.pdf.

Kutscher, C., F. Burkholder and K. Stynes, 2010. Generation of a Parabolic Trough Efficiency Curve from Separate Measurements of Outdoor Optical Efficiency and Indoor Receiver Heat Loss. Proceeding of the SolarPACES 2010 Conference. Perpignan, France, Sep. 21-24, 2010.

Levin, T. and V.M. Thomas, 2012. Least-cost network evaluation of centralized and decentralized contributions to global electrification. Energ. Policy, 41: 286-302.

Newton, C.C., 2006. A concentrated solar thermal energy system. B.Sc. Thesis, Florida State University.

Sorigal, I. and C. Neaga, 2012. Thermal analysis of a linear Fresnel lens solar collector with black body cavity receiver. U.P.B. Sci. Bull., Series D, 74(4).