International Journal of Scientific & Engineering Research, Volume 7, Issue 6, June-2016
ISSN 2229-5518

Solar Thermal Steam Generation System at Domestic Level

Noman Ijaz, Jan Shair, Ehtesham Bokhari, Nasrullah Khan

Abstract— In recent years, power demand has been drastically increased whereas conventional energy resources are decreasing day by day. Most of the existing power generating stations in the world are based on fossil fuels, resulting in huge amount of CO_2 emissions that have harmful impacts on environment. In this work, a heater powered steam generation system is designed and optimized. A Linear Fresnel Reflector (LFR) and receiver may be used to collect heat from sun. The heat energy received from Concentrated Solar Power (CSP) may be utilized for steam generation using heat exchanger. Thermia-B oil, having high heat transfer coefficient, is used as Heat Transfer Fluid (HTF). In this work, different design parameters such as, the rate of oil flow, steam pressure and temperature, oil temperature, water flow and rate of steam generation are optimized on experimental basis. The designed steam generation system provides enough steam that can run a 1 KVA steam generator for power production. This provides green electricity at domestic level to cope with energy crisis, using sustainable energy source.

Index Terms— CSP receiver, Linear Frsenel reflector, Heat exchanger, Heat Storage, Heat transfer fluid, Renewable energy sources, Solar powered steam generation system, sustainable energy

---

1 Introduction

ENERGY demad is continuously increasing in the recent decades that reflects an alamrming future for the world [1]. On the other hand, fossil fule reserves are drastically decreasing while they are major energy sources for electricity production throughout the world. Fossil fuel based power generation results in CO_2 emission which pose a potential risk to the environment. The awareness of climate change and sustainable energy production has been increased since last decade [2]. For that reason, it is essential to find satisfactory alternatives and comprehensive strategies for a shift to other energy sources that deliver least environmental impact.

Sun is the permanent source of energy in direct (solar radiations) and indirect forms (wind, biogass, etc.). Numerious studies have been carried out in countries, such as Slovenia [4], India [5], Bangladesh [6], Ghana [7], Nepal [8], Malaysia [9] and Nigeria [10], where it was assessed that renewable energy sources are viable sustainable energy alternative to cope with problems like energy crisis and Green House Gass (GHG) emissions [11].

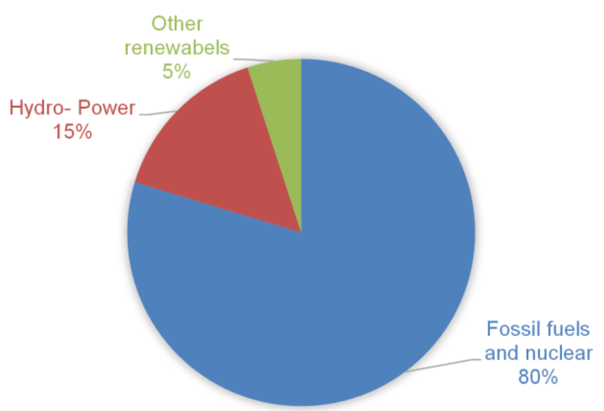

Fig. 1. Global share of power generation resources [3]

Sun gives 100,000 TW solar power on earth surface in one hour which is sufficient to meet world energy demand for one year. Solar energy can be directly harnessed by Photovoltaic (PV) and CSP plants. CSP is a low cost and CO_2 free technology that makes it a potential candidate to be a global green energy technology as compared with PV [12]. There are four main CSP systems reported in literature and are named as, 1) parabolic trough, 2) centeral receiver or solar tower, 3) parabolic dish, and 4) LFR. Direct solar radiation based solar thermal plants are non-dispatchable sources of energy. Heat storage system is necessary to make it dispatchable. CSP receivers must have good optical performance with ability of absorbing as much heat as possible [13] and heat storage system must have high heat storage density having good heat transfer rate [14]. Compact heat exchanger is used to exchange heat between HTF and water for steam generation.

In this research, LFR based aluminum duct type CSP reciver was designed to collect solar radiation from sun. LFR reflects the incoming solar radiations from sun and focuses on aluminum receiver. HTF collects the heat through reciver and stores in heat storage tank. A heat exchanger was designed to generate steam from hot oil.

This research focouses on following contributions;

- Optimization of different parameters such as oil temperature, steam pressure and temperature for steam generation.
- Designing a steam generation system which can run 1 KVA steam generator for electricity production.
- Designing a solar powered heat storage system which can be used for cooking meal, water heating purposes

- *Noman Ijaz is currently pursuing masters degree program in electrical engineering in COMSATS Institute of Information Technology Islamabad, Pakistan, PH-923316859190. E-mail: noman_khund@hotmail.com*
- *Jan Shair is currently pursuing masters degree program in electrical engineering in COMSATS Institute of Information Technology Islamabad, Pakistan, PH-923005388556. E-mail: janshair@outlook.com*

This research work is organized into four sections. Section 1 provides a brief introduction about renewable energy sources, CO_2 emmision and CSP systems. Section 2 describe the methodology of system design for CSP reciver, heat storage tank, heat exchanger and steam generation system. Experimental results and discussion for parameter optimization are presented in section 3 followed by coclusion in section 4. Section 5 indicates the future work on the designed system.

2 System Design

The detailed schematic diagram of the designed solar thermal steam generation system is given in Fig. 2. It consists of a CSP receiver, heat storage tank and a heat exchanger. Engine oil pumps are used to feed water to heat exchanger and for oil circulation. Temperature sensors are used to measure temperature of oil and steam. Data logger is used to record temperature data from all sensors. CSP receiver, heat storage tank and heat exchanger are discussed below.

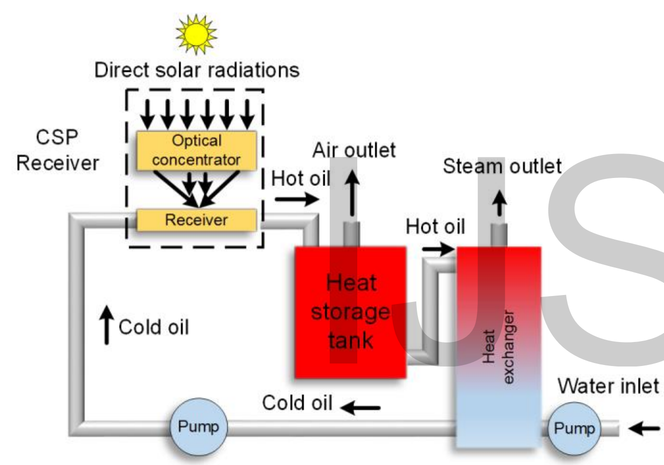

Fig. 2. Schematic of solar thermal steam generation system

2.1 CSP Receiver

The CSP receiver consists of an optical concentrator and a receiver. Optical concentrator uses LFR to reflect direct radiations from sun at different appropriate angles [15]. The angle of each mirror is manually adjusted such that the solar radiations are focused at the same line on receiver as shown in Fig. 3. The reflected radiations from sun are then focused on aluminum duct type receiver. The mirrors are placed horizontal on the ground. The design parameters of the LFR mirrors are given in Table 1.

The receiver uses a longitudinal aluminum duct as shown in Fig. 3. The three sides of the aluminum duct are covered with glass wool for insulation and ceramic wool for high temperature resistance, while bottom side is covered with 8 mm thick tempered crystal glass to trap infrared radiations and to provide insulation to the aluminum duct from bottom side.

Heat losses in CSP reciver can be calculated as;

TABLE 1
Design parameters of linear Fresnel mirror

Design parameters	Value
Total area of Fresnel mirrors	5.2 m^2
Total effective area of Fresnel mirrors	4.1 m^2
Transmissivity of Fresnel mirrors	< 95%
Heat conductivity of insulation	0.04 W/m.K
Thermal absorption of aluminum duct	75%
Thickness of the insulation	7.62 x 10^{-2} m
Effective area from each side	2.7871 x 10^{-1} m^2
Effective area from top	4.6452 x 10^{-1} m
Effective area from the bottom	2.7871 x 10^{-1} m^2
Air channel thickness from bottom	1.27 x 10^{-2} m

$$Q_R = \frac{KA\Delta t}{l} \quad (1)$$

Where, Q_R = Heat transfer, K = Thermal conductivity, A = Cross sectional area, Δt = Temperature difference and L = Thickness of insulation, which are given in Table 1.

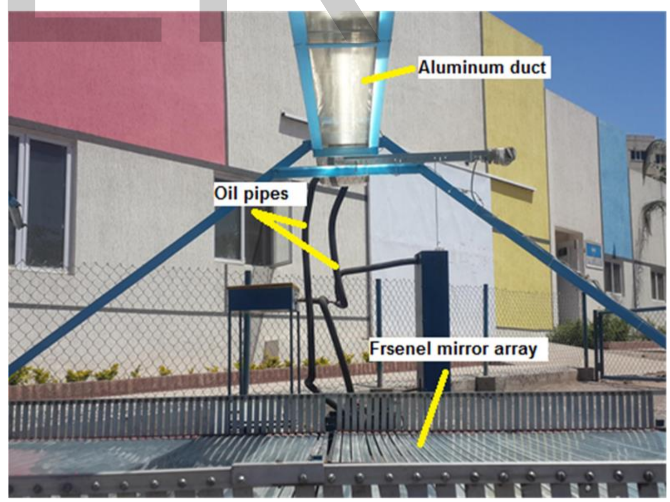

Fig. 3. CSP receiver

2.2 Heat Storage Tank

A cylindrical steel tank of 14 inch diameter and 13 inch height, is used for heat storage. The tank is filled with Shell Thermia-B oil as HTF that has low viscosity and high boiling temperature. Thermia-B oil can withstand temperatures as high as 340°C before boiling. The storage tank has been insulated from all sides with multiple layers of ceramic wool (thermal conductivity 0.12 k -W/ m.K) and glass wool (thermal conductivity 0.04 k W/ m.K)[16]. The ceramic wool layers have been used to withstand high temperatures in the closed vicinity of the storage tank. Fig. 4 shows a heat storage tank coverd with fiber tape.

2.3 Heat Exchanger and Steam Generation

The aluminum duct is enclosed with a heat exchanger as shown in Fig 3. Heat exchanger takes hot oil from heat storage tank and cold oil is pumped to CSP receiver via heat exchanger tubes. Two holes were placed at one side of the heat exchanger with connector for oil in and out. The cold water pumped to heat exchanger is converted into steam by exchanging the heat of hot oil from heat exchanger. The water flows in opposite direction of hot oil flow. A nozzle has been placed on the top of the heat exchanger to increase the pressure of steam. The design parameters of heat exchanger are given in Table 2.

Fig. 4. Heat storage tank

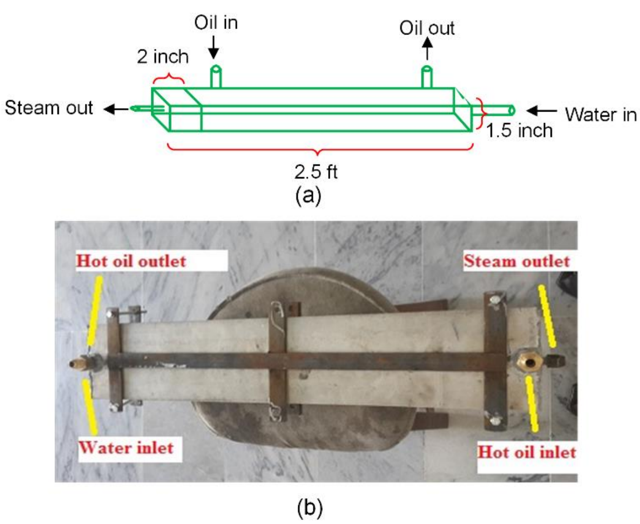

Fig. 5. Heat exchanger (a) HE with dimensions (b) HE eonclosed in aluminum sheet

TABLE 2
DESIGN PARAMETERS OF HEAT EXCHANGER

Design parameters	Value
Thickness of aluminum duct	1.5 mm
Length of aluminum duct	2.5 feet
Width of aluminum duct	3 inch
Height of aluminum duct	1.5 inch

Heat exchanger is insulated with three layers of fiber wool to reduce heat loses. Heat losses in heat exchanger can be calculated as follows;

$$\frac{Q_{HE}}{l} = \frac{2 \times Pl \times Km \times \Delta t}{\ln\left({D_o}/{D_i} \right)} \qquad (2)$$

Where, Q_{HE} = loss due to surrounding, l = length of shell in meter, Δt = change in temperature, D_o = outer shell diameter, D_i = internal temperature of shell, Km= thermal conductivity of shell.

3 Results and Discussion

Five experiments were perfomed on the solar thermal steam generation system for the purpose of finding best paramters. For the purpose of experiment only half litter water is taken as input to the heat exchanger for steam generation. The time taken to convert water into steam is observed for each experiment at different values of temperature and pressure.

First experiment was performed at 2 bar steam pressure.

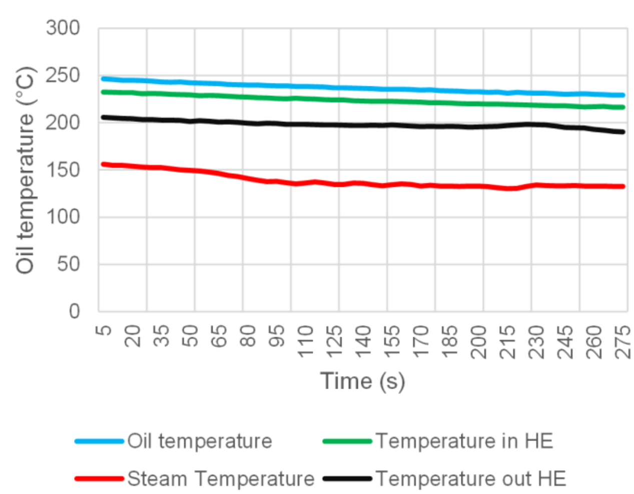

Fig. 6. Oil temperature at 2 bar steam pressure (Experiment 1)

The average value of steam temperature is found to be 138° C. Fig. 6 shows that temperature of oil is decreasing gradually with time due to low steam pressure. Steam temperature is also decreasing because rate of steam generation is high. At 2 bar steam pressure, half liter water is converted into steam in 4 minute and 40 seconds. After conversion of water into steam, initial oil temperature decreases from 246° C to 229° C. Average difference of entrance and exit temperature of heat exchanger comes out to be 25° C in 275s. This shows that oil temperature rapidly decreases at low steam pressure making the system inappropriate for storing heat for long run.

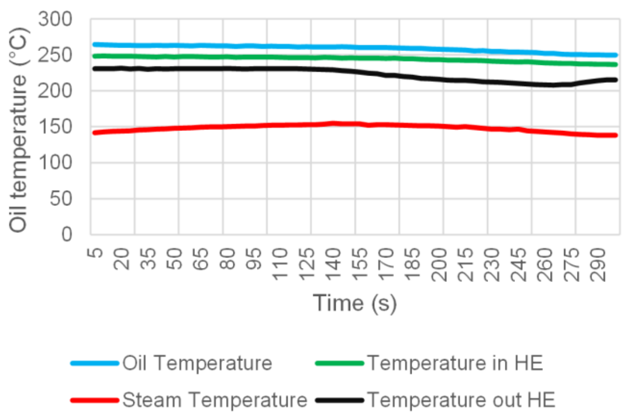

Fig. 7. Oil temperature at 3 bar steam pressure (Experiment 2)

The steam pressure is increased to 3 bar in the second experiment. The average value of steam temperature for this experiment is 148° C. Fig. 7 shows that temperature of oil and steam is decreasing gradually because the pressure of steam is still low. The steam temperature shows an increasing behavior at start but it decreases with time. The deviation of heat exchanger in and out temperature with time is also observed from the graphs. At 2 bar steam pressure, half liter water is converted into steam in 5 minute and 30 seconds. After conversion of water into steam, oil temperature decreases from initial temperature of 264° C to 248° C. Average difference of entrance and exit temperature of heat exchanger comes out to be 22° C. The results show that parameters in this experiments are not best for long term dispatching of solar thermal steam generation system.

In third experiment, the steam pressure is now further increased to 4 bar with 147° C as an average value of steam temperature. Fig. 8 represents that oil temperature is decreasing normally because the steam pressure is now increased enough. It can be clearly seen that the temperature of steam is almost constant with a very slight deviation after some time. It takes 6 minutes and 3 seconds to convert half liter of water into steam in this experiment. The initial oil temperature was 207° C which decreases to 197° C. The average difference of entrance and exit temperature of heat exchanger comes out to be 18° C.

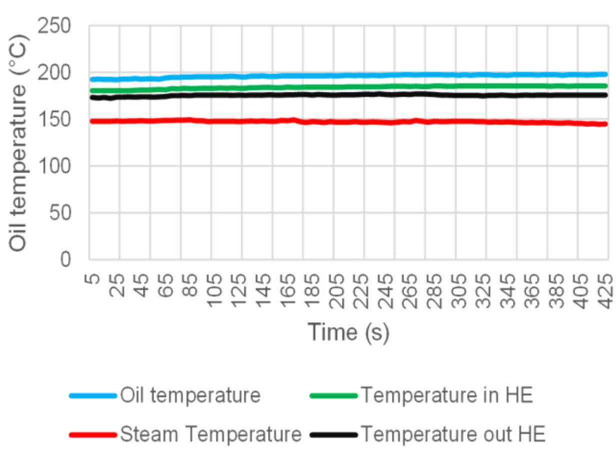

Fig. 8. Oil temperature at 4 bar steam pressure (Experiment 3)

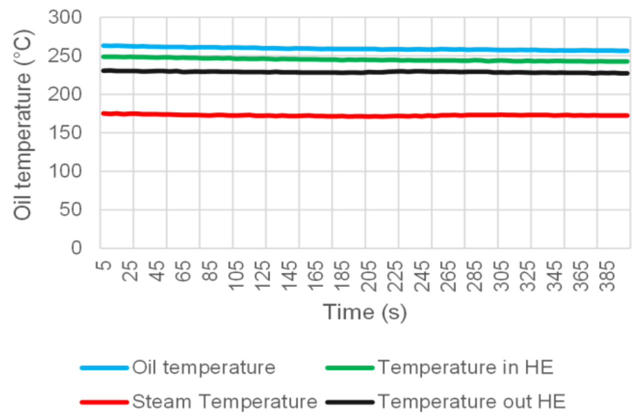

Fig. 9. Oil temperature at 5 bar steam pressure (Experiment 4)

Experiment four was performed at 5 bar steam pressure while the average value of steam temperature is 172° C. Fig. 9 shows that oil temperature is decreasing very slowly because the pressure of steam is high. In this graph, steam temperature, and in and out temperatures of heat exchanger remains almost constant. From Fig. 9, the heat exchanger in and out temperature alos remains constant during this time. At 5 bar pressure, half liter water is converted into steam in 6 minute and 45 seconds.

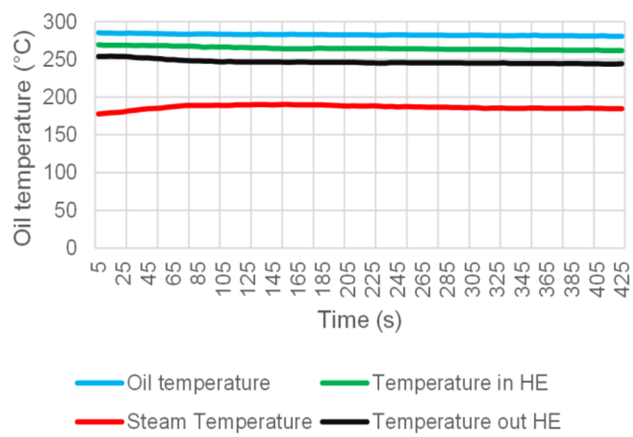

Fig. 10. Oil temperature at 6 bar steam pressure (Experiment 5)

Experiment 5 was performed at very high steam pressure of about 6 bar. In this experiment, the average value of steam temperature is 177° C. Fig. 10 shows that temperature of oil is decreasing very slowly because the pressure of steam is high.

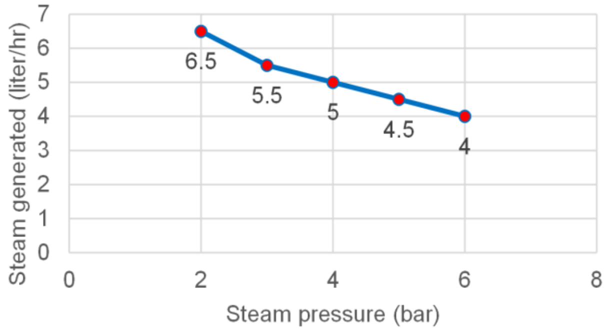

Fig. 11. Effect of pressure on rate of steam generation

In this graph, an increasing trend is observed for steam temperature at the beginning and becomes almost constant after a minute. At 6 bar pressure steam generation of half liter water is converted into steam in 7 minute and 25 seconds. The initial temperature of oil is 285° C, which decreases to 280° C after conversion of water into steam. Average difference of entrance and exit temperature of heat exchanger comes out to be 15° C.

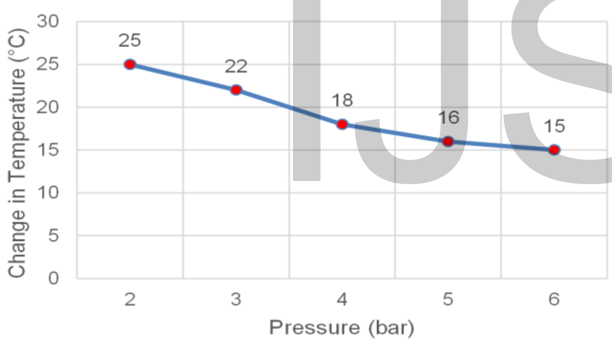

Fig. 12. Effect of pressure on difference in HE in and out temperature

Fig. 11 shows the relation between the rate lf steam generation and steam pressure based on five experiments. It is observed that rate of steam generation decreases as the steam pressure increases but the temperature becomes more stable at higher steam pressure.

The effect of pressure increase on heat exchanger in and out temperature is shown in Fig. 12. The graph shows that as the steam pressure increases the difference between heat exchanger in and out temperature decreases. Fig. 13 shows the effect of increase in pressure on half liter water to steam conversion time. It is clear from the line graph that at higher pressure the system takes longer time to convert water into steam which is undesirable. Steam pressure can be tradeoff for best performance of steam generation system.

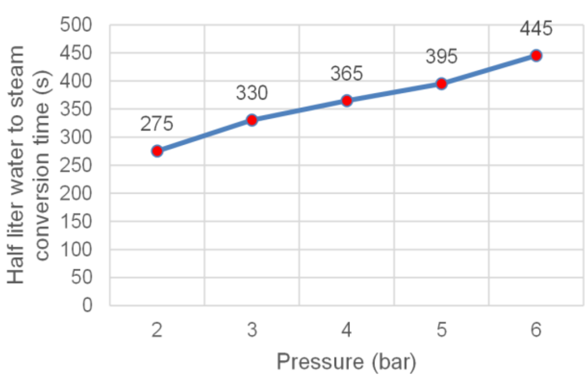

Fig. 13. Effect of pressure on half liter water to steam conversion time

4 Conclusion

The results presented in this work highlight the impact of different factors effecting the steam generation system. These parameters include oil temperature in the receiver, water pressure, oil flow, steam temperature, rate of steam generation, oil temperature in and out of heat exchanger. It has been observed that the steam generated at 5 bar pressure above 170° C system give best performance of solar thermal steam generation system. At this steam temperature and pressure, 4.5 liter of water is converted into steam in one hour. This system provides enough steam to run 1 KVA turbine for power generation. The steam generation system is also suitable for cooking meals, space and water heating applications.

5 Future Work

The design of solar powered steam generation system can extended to;

- Design a 1 KVA steam turbine for power generation at domestic level.
- Design cooking appliances such as pressure cookers.
- design a water heating applications at domestic level

Acknowledgment

The authors appreciate the support from COMSATS IIT Islamabad, Pakistan. The authors would like to thanks Mr. Waqar Haider Bokhari for his great support and guidance during experiments.

References

[1] Şen Zekai, "Solar energy in progress and future research trends," Progress in Energy and Combustion Science, vol. 30, no. 4, pp. 367-416, 2004.

[2] Everett, Robert and Boyle, Godfrey and Peake, Stephen and Ramage, Janet, *Energy Systems and Sustainablity: Power for Sustaniable Future.* Oxford Univerity Press, 2012.

[3] Awan, Ahmad Bilal and Khan, Zeeshan Ali, "Recent progress in renewable energy - Remedy of energy crisis in Pakistan,"Renewable and Sustainable Energy Reviews, vol. 33, no. 4, pp. 236-253, 2014.

[4] Ahmed, Shamsuddin and Islam, Md Tasbirul and Karim, Mohd Aminul and Karim, Nissar Mohammad, "Review of green electricity production in Slovenia,"Renewable Energy, vol. 11, no. 9, pp. 2201-

ISSN 2229-5518

[5] 2208, 2007.

[6] Khare Vikas, Nema Savita, and Baredar Prashant, "Status of solar wind renewable energy in India,"Renewable and Sustainable Energy Reviews, vol. 27, pp. 1-10, 2013.

[7] Ahmed, Shamsuddin and Islam, Md Tasbirul and Karim, Mohd Aminul and Karim, Nissar Mohammad, "Exploitation of renewable energy for sustainable development and overcoming power crisis in Bangladesh,"Renewable Energy, vol. 27, no. 2, pp. 223-235, 2014.

[8] Gyamfi, Samuel and Modjinou, Mawufemo and Djordjevic, Sinisa, "Improving electricity supply security in Ghana—the potential of renewable energy,"Renewable and Sustainable Energy Reviews, vol. 43, pp. 1035-1045, 2015.

[9] Gurung, Anup and Karki, Rahul and Cho, Ju Sik and Park, Kyung Won and Oh, Sang-Eun, "Roles of renewable energy technologies in improving the rural energy situation in Nepal: Gaps and opportunities,"Energy Policy, vol. 62, pp. 1104-1109, 2013.

[10] Ahmad, Salsabila and Ab Kadir, Mohd Zainal Abidin and Shafie, Suhaidi, "Current perspective of the renewable energy development in Malaysia,"Renewable and Sustainable Energy Reviews, vol. 15, no. 2, pp. 897-904, 2011.

[11] Aliyu, Abubakar Sadiq and Dada, Joseph O and Adam, Ibrahim Khalil, "Current status and future prospects of renewable energy in Nigeria,"Renewable and Sustainable Energy Reviews, vol. 48, pp. 336-348, 2015.

[12] Muhammad Asif, "Sustainable energy options for Pakistan,"Renewable and Sustainable Energy Reviews, vol. 13, no. 4, pp. 903-909, 2009.

[13] Behar, Omar and Khellaf, Abdallah and Mohammedi, Kamal, "A review of studies on central receiver solar thermal power plants,"Renewable and Sustainable Energy Reviews, vol. 23, pp. 12-39, 2013.

[14] Steinhagen, Hans and Trieb, Franz, "Concentrating solar power," A review of the technology. Ingenia Inform QR Acad Eng, vol. 18, pp. 43-50, 2004.

[15] Dincer, Ibrahim and Dost, Sadik and Li, Xianguo, "Performance analyses of sensible heat storage systems for thermal applications," International Journal of Energy Research, vol. 22, no. 12, pp. 1157-1171, 1997.

[16] Abbas, R and Montes, MJ and Piera, M and Mart, "Solar radiation concentration features in Linear Fresnel Reflector arrays," Energy Conversion and Management, vol. 54, no. 11, pp. 133-144, 2012.

[17] Che, Jianwei and Cagin, Tahir and Goddard III, William A, "Thermal conductivity of carbon nanotubes," Nanotechnology, vol. 11, no. 2, pp. 65, 2000.