Concentrator Photovoltaic System and its Advantages for Saudi Arabia: A Simulation Study

Reem Altuwirqi*‡, M.A. Gondal**, Hala Al-Jawhari*, A. K, Sheikh***

* Physics Department, Faculty of Science, King Abdulaziz University, Jeddah, Saudi Arabia

** Physics Department, Faculty of Science, King Fahd University of Petroleum & Minerals, Dhahran, Saudi Arabia

*** Mechanical Engineering Department, Faculty of Engineering, King Fahd University of Petroleum & Minerals, Dhahran, Saudi Arabia

‡ Corresponding Author; Tel: +966 12 695 2000 ext 26911, raltuwirqi@kau.edu.sa

Received: 11.04.2015 Accepted:24.05.2015

Abstract- The efficiency of the Photovoltaic (PV) system found to be boosted when mirrors and tracking devices are used. For this purpose reflective optical devises are usually mounted on a PV panel to form a V-trough that helps focusing the incident solar radiation flux onto the PV panel and, hence, increasing the total output power. The main objective of this work is to perform an optimization to achieve a reduction in the overall geometrical size of the system and a decrease in the step size of its tracking system while increasing its output power. A numerical simulation to achieve the optimum condition for a low Concentrated Photovoltaic (LCPV) systems located in Saudi Arabia was undertaken. Five cities were chosen as a case-study for our simulation, these cities are; Riyadh, Jeddah, Dhahran, Aljouf and Sharoora. Two models were proposed based on the geometry of the system. It was found that the first model (partial exposure) showed an efficiency of 165% whereas the efficiency of second model (double exposure) reached 230%. Furthermore, it was found that the efficiency of the models did not depend on the tracking step which makes LCPV low in cost and less complex. Nevertheless, increasing the tracking step size requires an increase in the width of the mirrors used which in turn affects the overall size of the system.

Keywords LCPV, Solar concentrators, Simulated PV, Solar tracking systems, Solar energy in Saudi Arabia.

1. Introduction

Saudi Arabia is one of the most intense sunlight regions in the world as it receives around 105 trillion kilowatt hours a day, which is equivalent to 10 billion barrels of raw oil in energy terms [1]. The large area of Saudi Arabia that spreads over 2,240,000 km^2 along with the high direct normal irradiation DNI which approximates 2200 $kWh/m^2/y$ sums up to tremendous power that Saudi Arabia can invest in [2]. According to King Abdullah City for Atomic and Renewable Energy (KACARE) report, electricity demand in Saudi Arabia is anticipated to raise from 51 GW in 2011 to 120 GW by the year 2030 [3], and 2.4 GW of this energy is expected to be covered by PV solar energy [4]. Nonetheless, there are different factors affecting the solar energy production such as spatial estimation of global solar radiation in the Kingdom and environmental factors affecting the performance of photovoltaic (PV) cells [5]. If the goal of producing electricity from solar energy conversion is achieved by means of a cost effective method, Saudi Arabia can take a leading role in exporting electricity [6].

One method of harnessing more sunlight is to use concentrators. The greatest advantage of these concentrators systems is its ability to obtain greater power from the same area of space occupied by the PV panel without concentrators. Concentrators can be classified, according to its concentrating ratio, into three main types; low (LCPV) for 20-40 fold concentration, medium (MCPV) for 40-350 fold concentration and high concentration (HCPV) for 350- 1000 fold concentration [7]. For both high and medium CPV, accurate tracking systems are required in order to maintain the focus of the sunlight onto the PV panel during the movement of the sun throughout the day. Although these systems can offer a high concentrating ratio, still, they are expensive and complex. On the contrary, low CPVs have simple linear geometry, can make use of diffuse sunlight and don’t require precision tracking systems. Using Low concentrated PV (LCPV), could save up to 50% of the crystalline silicon without facing a drop in efficiency [8]. Commercial flat rooftops, chalets, traffic lights and street lamps, are particularly suited for this application.

The main components of an LCPV system are a PV panel and two attached mirrors. The role of the mirrors is to help focus the incident radiation on the PV panel hence increase the conversion level of the absorber and in turn increase the output power. Mechanical tracking systems, when fitted, will enhance the rate of incident radiation falling on the PV panel thought the daylight [9]. In order to achieve a successful optimization for the operation of LCPV systems, it is crucial to identify all the parameters involved. These parameters are linked to the design of the model itself, its tracking system, the geographic location and pollution of the environment. Hermenean *et. al.*[10] developed a comprehensive numerical study of LCPV considering the equatorial tracking system for the geographical location of the Brasov - Romania area. Their simulation results for a V-trough geometric model showed that the best opening angle (θ) equals to 65° while the tracking step-size barely affect the efficiency. Recently Mroczka and Plachta [11] have simulated the efficiency of Λ-ridge and V-trough low concentrator systems. They found that Λ-ridge concentrator system is about 1.5% more efficient than the V-trough solution. According to their model, the most optimal and reasonable conditions to use Λ-ridge concentrator system, accompanying good efficiency and acknowledged total size, is with opening angle (θ) equal to 57°, the tracking step equal 15 minutes.

The aim of this work is to perform simulations to optimize the efficiency of a V-trough low CPV system located in different areas in Saudi Arabia. Five cities were chosen in this study, which are Riyadh, Jeddah, Dhahran, Aljouf and Sharoora. These cities where chosen as a representative sample of Saudi Arabia. Jeddah and Dhahran are two industrialized cities on the west and east coasts, respectively. Riyadh represents the middle desert yet an urban city. In addition, Aljouf and Sharoora are both rural areas in the north and south of Saudi Arabia, respectively. Hence, these five cities can help map the efficiency of any LCPV system in the different locations of Saudi Arabia.

2. Optimization of the Low CPV System

The geometrical model used in this work was based on the suggested model of Hermenean *et. al* [10]. This LCPV model consists of a PV panel with attached two mirrors to its sides that formulate specific angles with the PV surface (Fig. 1).

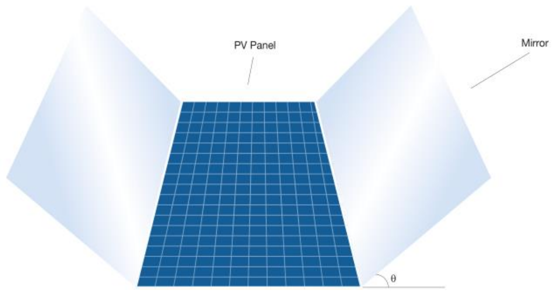
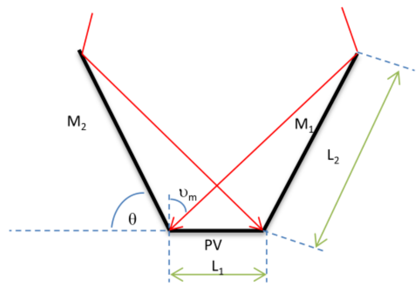


Fig. 1. Low solar concentrating system consisting of a photovoltaic panel and two attached mirrors.

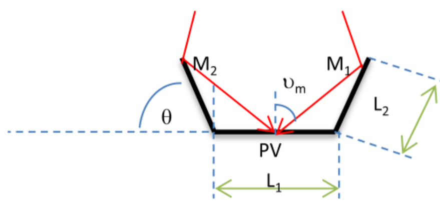
The design parameters within the simulation model can be narrowed down into a set of factors, classified into two main categories: inner parameters, and outer parameters. The inner parameters revolve around the *angle* between the PV module and the mirrors, and the *width* of the mirror, assuming that the width of the PV panel remains constant. The outer parameters, however, consist of the *geometric location* (latitude, longitude and altitude), the *clearness of the sky* (associated to the linked turbidity factor), and the *tracking system step-size*. The main objective of the optimization is to reduce the overall geometrical size of the system and decrease the step size of its tracking system while increasing the output power of the system.

In the work of Hermenean *et. al* [10] two cases were considered. The first case (A) is the double coverage case, where the light reflected from each mirror covers the whole area of the PV panel. While for the second case (B), only partial coverage of redirected radiation falls of the PV panel from each mirror. Schematic drawing of these two cases are shown in Figs. 2 (a) and (b), respectively.

Although the main advantage of case A is the increase of incident radiation on the panel, which is to a lesser extent in case B, the disadvantage is the need to increase the size of the system to achieve the double coverage. Hence, optimization between size and amount of incident radiation is needed. The angle of inclination of the mirrors with respect to the PV panel plays a crucial role in the optimization process. This factor affects both the overall size of the system and the amount of incident radiation falling on the PV panel. The optimum angle of inclination can be deduced by plotting the relation between the percentage of PV exposure and the angle of inclination. According to Hermenean *et. al* [10] calculations, this angel was θ = 65°. In this work, and throughout our simulation process, the inclination angle of the mirrors was kept at this value.



(a)



(b)

Fig. 2. The two cases for irradiating the PV panel. (a) Case A: double exposure and (b) Case B: Partial exposure.

To calculate the direct solar radiation falling on the system, B_s , the following equations were used [12]:

$$B_s = B_o \exp\left[-\frac{T_r}{(0.9+9.4\ Sin\ \alpha)}\right] \qquad (1)$$

and

$$B_o = 1367\,[1 + 0.334\,Cos(0.9856\,\cdot N - 2.27)] \quad (2)$$

where T_r is the turbidity factor and N is the day number of the year, i.e. N=1 is the 1st of January. Moreover, α is the altitude angle and is given by:

$$\alpha = sin^{-1}(\sin\delta\cdot\sin\varphi + \cos\delta\cdot\cos\varphi\cdot\cos\omega) \quad (3)$$

where δ is the solar declination, φ the location latitude and ω the solar hour angle. The relation between the local solar time and the solar hour angle is given by the following equation:

$$\omega = 15^{o}(12 - T) \quad (4)$$

A FORTRAN program was written to simulate the geometric model of the low CPV system. A flowchart of the program is shown in Fig. 3. The required input parameters for the program are divided into three categories based on their relation with: (1) geometric model of LCPV, (2) tracking system and (3) geographic location and sky condition. Table (1) lists the parameter used in the program.

The first set of parameters, which are related to the geometric model of the LCPV, include the width of the PV panel L_1, width of the mirrors L_2, the inclination angle of the mirrors with respect to the PV panel θ and lastly the current value of the solar incidence angle φ. The value of L_1 was fixed at 0.5 m and θ at 65^{o} as indicated above. The value of L_2 was left to be deduced to give the optimal mirror length in the different cases.

The second category of parameters are those related to the tracking system, mainly φ_M the maximum incidence angle. The tracking step is linked to φ_M when φ_M = 15°, 7.5°, 3.75°, 1,875° it corresponds to a tracking time step of 2 hr, 1 hr, 30 min and 15 min, respectively.

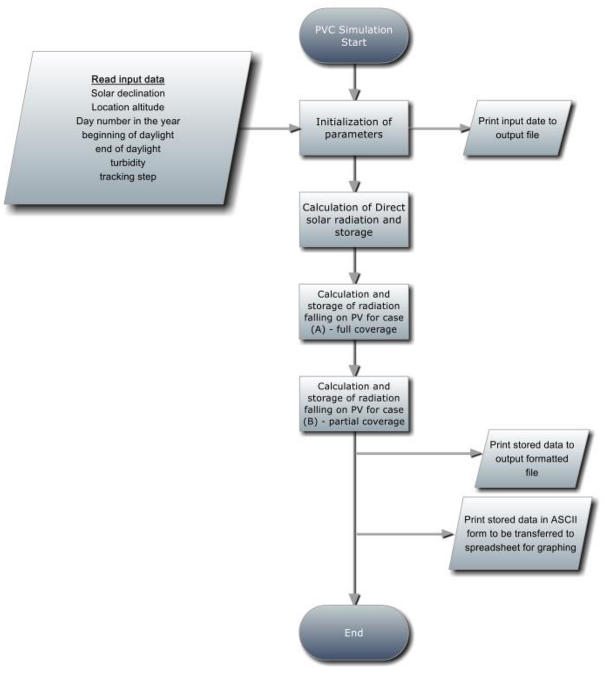


Fig. 3. Flowchart of the simulation program.

The third and last set of parameters represent the geographical location. The altitude angle α incorporates the latitude, longitude and solar declination angles. N is the day number of the year where simulation is to be measured. N was chosen to be day 172 which corresponds to the summer solstice; the day of the year with the longest period of daylight In addition, the turbidity T_r which reflects the condition of the sky which takes the values $T_r \geq 1$, where T_r =2 indicates a very clean cold air, T_r =3 clean warm air and T_r =6 polluted air [13].

Five different locations in Saudi Arabia were chosen for this simulation. These areas are Riyadh, Jeddah, Dhahran, Aljouf and Sharoorah. The turbidity factors for these cities were obtained from the work of Diabaté *et. al* [14]. The simulation results are discussed in the next section.

3. Results and Discussion

The simulation program was used to calculate the radiation that falls on the LCPV system in the two cases, A (double coverage of solar radiation on the PV panel) and B (partial coverage on the PV panel) as explained above and illustrated in Fig. 2. Moreover, the angle of inclination of the mirrors, with respect to the PV panel, was kept constant at the value of θ = 65^{o} which is the optimum angle based on the analysis of Hermenean *et al.*[10]. In addition, the summer solstice (N=172) was chosen for the simulation because it has the longest period of daylight. The width of the PV panel was fixed at a value of 0.5 m. The results depict the situation if the system, with the mentioned conditions, was installed in five cities in Saudi Arabia, namely: Riyadh, Jeddah, Dhahran, Aljouf, and Sharoora.

Figure 4 shows the results of the simulation for (a) Jeddah, (b) Dhahran, (c) Aljouf and (d) Sharoorah. Two tracking steps were chosen in generating the results depicted in Fig. 4. These steps are 2 hr and 15 min. The solid brown line illustrates the amount of solar radiation falling directly on the system for a certain value of turbidity which is indicated in the corresponding legend. By investigating Fig. 4, we can analyze the effect of double coverage vs. partial coverage and the tracking system step size on the output power of the LCPV. Moreover, the optimization of the output power with the overall size of the LCPV system.

It can be seen from Fig.4 that all simulation results follow the same pattern for the cities indicated. The variance is mainly due to the different turbidity values which affects the maximum amount of solar radiation reaching the location. Another common feature is that the double coverage of solar radiation (case A) on the PV panel give approximately double the output power when compared with the partial coverage case (case B).

By analyzing the effect of the tracking step size on the overall performance of the LCPV, we can see that the average output power falling on the PV from the two mirrors is the same for any instant of time throughout the day. Hence, this gives the conclusion that the total radiation falling on the system at a specific time does not depend on the tracking step of the system. Total radiation falling on the system only depends on the type of radiation coverage on the LCPV, whether double or partial, in addition to the turbidity.

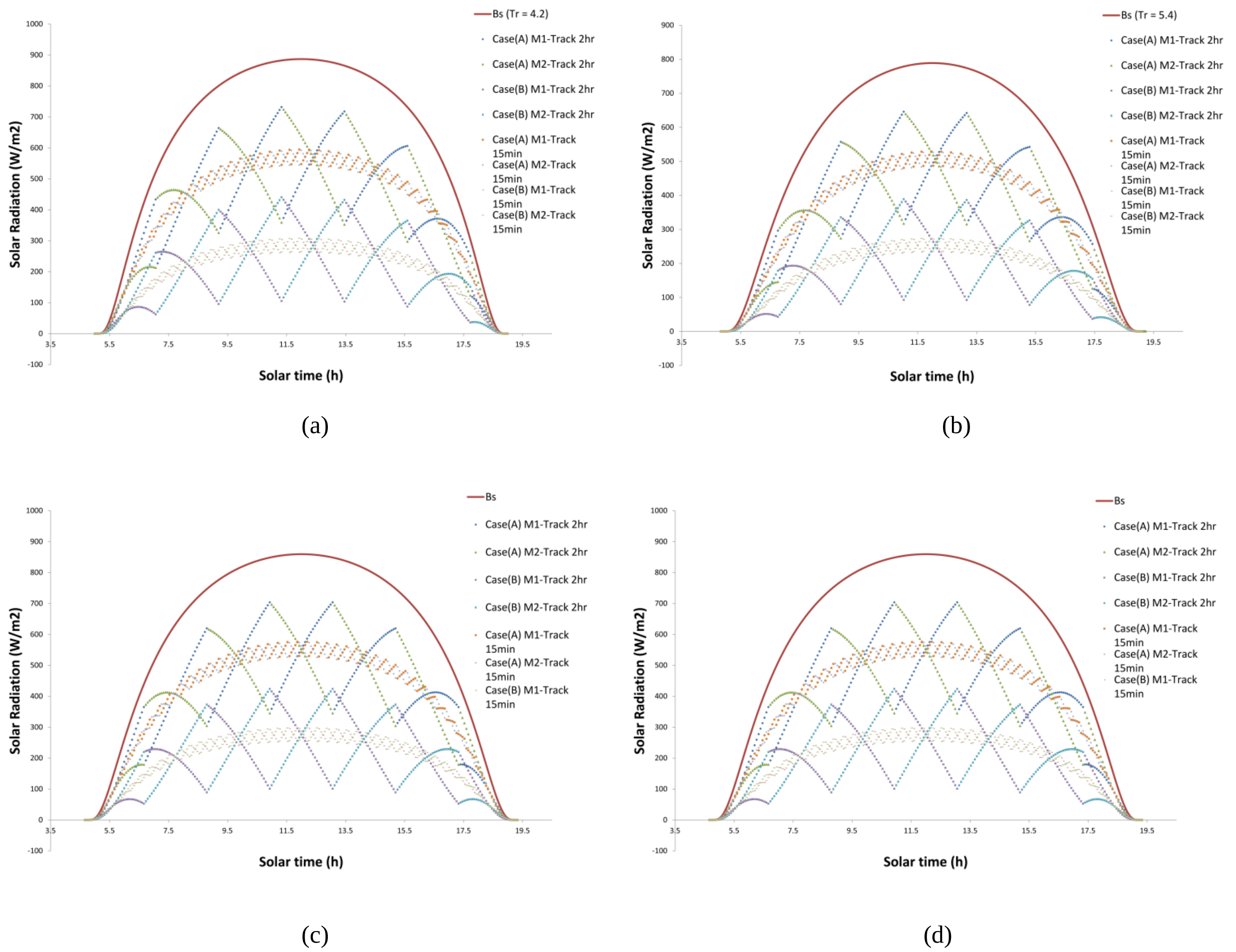


Fig 4. Simulation results for direct solar radiation normal to PV panel from both mirrors for (a) Jeddah, (b) Dhahran, (c) Aljouf and (d) Sharoorah.

Table 1. Parameters used in simulation program.

Category	Parameter	Cities				
		Riyadh	Jeddah	Dhahran	Aljouf	Sharoura
Geographic location and sky condition	δ (degree)	23.5	23.5	23.5	23.5	23.5
	φ (degree)	24.64	21.51	26.3	29.79	17.47
	N	172	172	172	172	172
	T_r	5.3	4.2	5.4	4.5	6
Geometric model of PVC	L_1	0.5 m				
	θ	65°				
Tracking system	φ_M	15°(2 hr), 7.5° (1 hr), 3.75°(30 min), 1,875°(15 min)				

Nonetheless, it is apparent that the tracking step size greatly affects the overall size of the system. For example with a tracking step of 2 hr, the minimum width of the mirrors for case A should be 2.36 m whereas for case B only mirrors of width 0.38 m are required. Changing the tracking step to 15 min gives the advantage to reduce the width of the mirrors to 0.85 m for case A while no reduction in mirrors size for case B occurs. Table 2 lists the geometrical size of the system in the different cases and step sizes.

Table 2. Geometrical size of the CPV for the different cases and step sizes.

Cases	Tracking step	Minimum width of mirrors	Average output power
Case A (double exposure)	2 hr	2.36 m	The same for all cases for any instant of time
	15 min	0.85 m	
Case B (partial exposure)	2 hr	0.38 m	The same for all cases for any instant of time
	15 min	0.38 m	

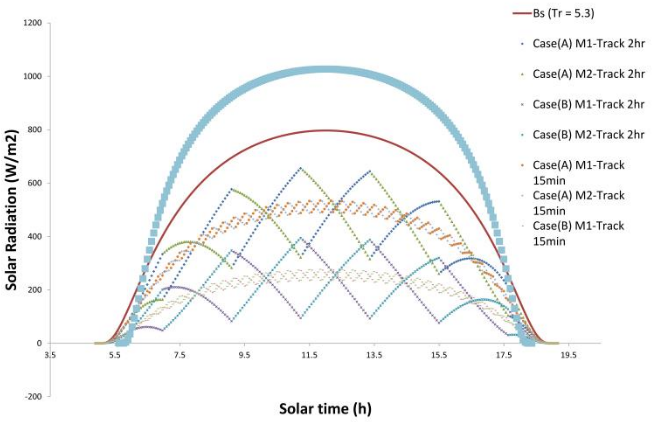


Fig 5. Simulation results for direct solar radiation normal to PV panel from both mirrors for Riyadh.

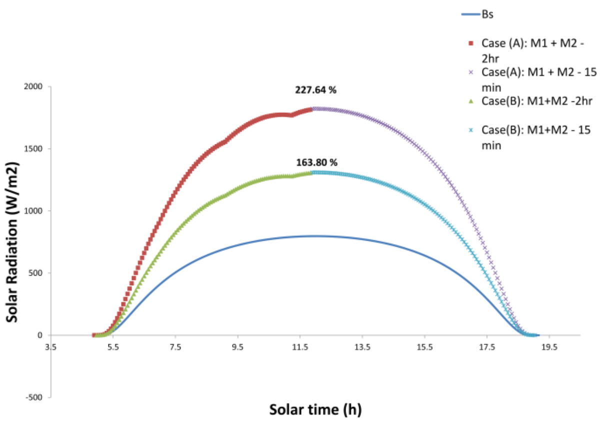


Fig 6. Absolute tracking efficiency from both mirrors compared to the direct available radiation.

Hence, it can be seen how the different factors affect the overall radiation falling on the LCPV system. As double coverage (Case A) increases the amount of radiation falling on the system, it will require large size mirrors compared to the partial coverage (Case B) setup, hence increasing the size of the system. In addition, while increasing the step size of the tracking system help in reducing the amount of energy it consumes doing its movement, it will require an increase in the size of the overall system with double coverage.

The results for the city of Riyadh are depicted in Fig. 5. This figure shows the effect of the turbidity factor on the LCPV system. The solid brown line indicates the amount of direct solar radiation on the system for T_r = 5.3, which is the value reported in ref [14]. At this value of turbidity, the amount of direct sunlight reaching the system at noon is approximately 800 W/m^2. With a lower turbidity factor, for example T_r = 3 which is presented by the solid sky blue line, the amount of solar radiation falling on the system increases to more than 1000 W/m^2. Hence, the degree of clearness of the sky, measured by the turbidity factor T_r, plays an important factor in the success or failure of any LCPV systems.

The absolute efficiency of the system can be determined by measuring the amount of radiation falling on the PV panel from both mirrors compared to the direct available radiation for both cases A and B and at different tracking steps. Figure 6 illustrates the absolute efficiency of the system as calculated in the Riyadh region. It can be seen that the efficiency is approximately 230% for case A whereas it is only 165 % for case B. In accordance with the results mentioned above, the absolute efficiency does not depend on the tracking step size.

4. Conclusion

A simple geometrical model of LCPV was used to maximize harnessing of the sun's radiation in an innovative way by optimizing the parameters involved to make it cost effective. These parameters include the size of the mirrors, inclination angle of the mirrors and step size of the tracking system. Simulation of this model was carried out for five cities in Saudi Arabia to give a reasonable representation of the different geographical areas of the county. These cities are; Riyadh, Jeddah, Dhahran, Aljouf and Sharoorah. The model showed an efficiency that ranged from 165% (partial exposure) to 230% (double exposure). The overall efficiency of the model did not depend on the tracking step which makes this system low in cost and less in complexity. Nevertheless, turbidity plays a significant role on the efficiency of the system. Therefore, keeping our skies clean will enhance the benefit of utilizing the solar radiation in addition to overall global health.

Although the LCPVs promise an increase in output power for any specific area of PV panel, there still remain great challenges for these systems which have to be investigated further. One of which is the increased temperature of the PV panel due to the enhancement of solar radiation falling on it. Increased temperatures could deteriorate the overall performance of the system and reduce its efficiency and life span. Therefore, new and innovative designs are required to include suitable heat sinks in order to reduce the temperature of the system. Simulation results obtained in this work will help in designing LCPV systems with optimal conditions prior to manufacturing. As future work, LCPV system will be built based on the values reported here. This will aid in performing a comparison study between experimental results and simulated data. Moreover, an investigation of the effect of temperature on the deterioration of the efficiency will be undertaken to explore different designs to reduce the increased temperatures as a results of the increased concentration of solar radiation.

Acknowledgements

The authors would like to acknowledge the support of King Fahd University of Petroleum and Minerals through the Center for Clean Water and Clean Energy at KFUPM and MIT (R6-DMN-08- Design and Manufacturing of Solar Power Systems and Devices for Challenging Environments).

References

[1] H. Baig , N. Sellami, H. Bahaidarah and T. Mallick, "Optical analysis of a CPC based CPV/T system for application in the kingdom of Saudi Arabia", 28th EU PVSEC2013, Paris. pp. 653-657, 30 Sep - 4 Oct 2013.

[2] A. Baras, W.B., Y. AlKhoshi, M. Alodan and J. Engel-Cox, "Opportunities and challenges of solar energy in Saudi Arabia", World Renewable Energy Forum, Denver. pp. 4721, 13-17 May 2012.

[3] R. Shamseddine, "Saudi Signs Deal to Build 4-GW Gas Power Plant", Reuters, 21 Sep. 2011.

[4] A. McDowall, "Saudi sets out roadmap for major renewable energy programme", Reuters, 23 Feb. 2013.

[5] M. Green, K..Emery, Y. Hishikawa and W. Warta, "Solar cell efficiency tables (version 42)", Prog. Photovolt: Res. Appl, DOI: 10.1002/pip.2404, vol. 21, pp. 827-837.

[6] S. Alawaji, "Evaluation of solar energy research and its applications in Saudi Arabia", Renewable and Sustainable Energy Reviews, DOI:10.1016/S1364-0321(00)00006-X, Vol. 5, pp. 59-77.

[7] M. Meyer, "Sunny prospects for concentrated PV". Living Energy, No.7, Nov. 2012.

[8] (KICP), KICP Saudi Arabia Solar Energy: Manufacturing and Technology Assessment. KICP Annual Strategic Study , King Abdullah University of Science and Technology, 2009.

[9] Y. Goswami, F. Kreith and J. Kreder, Principles of solar engineering. 2nd ed., Philadelphia: Taylor & Francis, 2000.

[10] I.Hermenean, I. Visa, A. Duta and D. Diaconescu, "Modelling and Optimization of a Concentrating PV-Mirror System", ICREPQ'10, Granada, 23-25 March 2010.

[11] J. Mroczka and K. Plachta, "Modelling and simulation of Λ-ridge concentrator system using commercial PV modules", ICREPQ'14, Cordoba, 8-10 April 2014.

[12] M. Meliss, Regenerative energiequellen: Praktikum, Berlin: Springer–Verlag,, 1997.

[13] "Linke turbidity factor". A. Clima. Solar Radiation. JRC-IPSC and CRA-CIN. Web. 21 May 2015.

[14] L.Diabaté, J. Remund and L. Wald, "Linke turbidity factors for several sites in Africa", Solar Energy, vol. 75, No. 2, pp. 111-119, 2003.