Hybrid concentrated photovoltaic thermal technology for domestic water heating

M.K.Panjwani[1], S.X.Yang[2], F.Xiao[3], K.H.Mangi[4], R.M.Larik[5], F.H.Mangi[6], M.Menghwar[7], J.Ansari[8], K.H.Ali[9]
[1,2,3,7]Renewable Energy School, North China Electric Power University Beijing China, China
[4]GEPEA-UMR 6144 CNRS, Laboratory Saint Nazaire, University of Nantes, France
[1,6,9]Department of Energy Systems Engineering, Sukkur IBA University Pakistan, Pakistan
[5]School of Electrical Engineering, Universiti Teknologi Malaysia Skudai, Malaysia
[8]School of Electrical and Electronic Engineering, North China Electric Power University Beijing China, China

Article Info

Article history:

Received Mar 1, 2019
Revised Jun 4, 2019
Accepted Jun 26, 2019

Keywords:

Energy efficiency
Hybrid thermal technologies
Photovoltaics
Solar concentrators
Water heating

ABSTRACT

There is an increasing reliance on renewable energy especially Solar Energy as the fossils are on the way to depletion. It offers an environmental friendly solution with an affordable comparative paradigm. Solar photovoltaic-thermal collectors have remained of the particular interest because of their higher overall efficiencies. Most of its applications related with solar hybrid PVT systems focuses more on electrical output rather than thermal output, and the contacting fluid is allowed to act as a coolant to assure that the solar cell operates in the ranges specified by the manufacturer to guarantee higher electrical efficiency. This ultimately allows fluid to retain higher temperature that could be utilized for meeting the heating demand of any residential household. First, the PVT analyses are performed over a system comprising of Fresnel-based Solar Module to allow higher irradiance to fall for relative higher conversion of efficiency and to achieve higher temperature ranges in the contacting fluid (water). The electrical parameters are compared, and a significant increase in the power ranges is concluded. Secondly, a simulated thermal structure of the heating tank is presented that utilises the heated water from the PVT system in meeting the heating demand of a residential household. When accounting all the electrical parameters, approximately 10% increase is noticed in power produced, and sufficient energy used for the traditional heating of water is retained.

Corresponding Author:

Manoj Kumar Panjwani,
Department of Energy Systems Engineering, Sukkur IBA University Pakistan
Renewable Energy School, North China Electric Power University Beijing China
Email: manoj.panjwani@iba-suk.edu.pk

1. INTRODUCTION

Solar energy is proving out to be a promising energy source which can be converted into heat and useful electricity in a reliable way. It possesses the considerable potential of replacing the fossils for the production of power and heat in the near future. The solar resource has a higher prediction as compared to other renewable energy sources, e.g. wind. One of the reasons for the fast penetration of this technology is because of their nonmoving parts, low maintenance and running cost as compared with other available resources. The daily varying energy demand for the heat and electricity for the purpose of electricity generation and thermal storage at particular lower irradiance is readily achievable. In addition to solar technology, the solar thermal technologies are currently offering significant fraction for the heating opportunities for residential and industrial activities. The Solar thermal technologies are offering aspects of heating and cooling that makes it a need for the developing countries in the coming future. It provides one of the leading solutions in aspects of its potential for a decrease in greenhouse gas emissions [1-4].

Approximately near 50% of the global energy consumption is used for the heating and the cooling purposes, allowing a higher zone for the solar thermal technologies over establishing clean and sustainable future technology for the energy consumers. Moreover, the hybrid solar photovoltaic and thermal (PVT) systems will enable in offering solutions for both, the heating and cooling, and simultaneously allowing the access to electricity generated through the Photovoltaic [5].

The overall mechanism stands with the total efficiency of the solar cell and incident irradiance. The conversion efficiency of the silicon-based systems ranges in between 5-20%. Additionally, the heat produced is found to constitute about 60-70% of the incident irradiance. This is because the minimum energy that is required by the photon to absorb and get converted to electricity corresponds to the threshold light wavelength of 1.1 µm for the Silicon solar cells [6]. The wavelengths of the light that appear to be in a visible region corresponds to 400-700nm. However, the bandwidth wavelength of the silicon lies in the near infrared region. With every radiation with a higher value of wavelengths such as microwaves or radio waves, will ultimately lack the required energy to produce energy and eventually lead to increasing the temperature of the system.

There are various studies focused on utilizing the maximum out of the solar energy including one of utilizing the higher wavelength light for solar heating. However, there are various negative impacts that the heat casts on the overall power production of the solar panel. In regard to the above, various procedures were followed to ensure that the surface temperature of the Solar Panel is maintained as specified by the manufacturer (i.e. below or equals 25*C) [7-9].

The problem is associated with the portion of the heat that ultimately leads to an increase in the temperature of the PV system. Higher temperatures on the PV results in a reduction of the conversion efficiency mentioned by the manufacturer on the manufacturer sheet [10-11]. The additional heat is eventually lost in the form of heat and is wasted to the environment following radiation and the convection heat transfer [12]. Several sustainable technologies for the PVT (Photovoltaic Thermal) currently exists in the commercial market that can be coupled with other available systems for the provision of the domestic water heating and the space heating. Impact of the temperature was thoroughly studied, and the temperature of the panel was reduced by 40% using a DC brushless fan as a cooling device [13]. The effect of empowering air cooling mechanisms under indoor testing using halogen lamp was thoroughly investigated where the PV output power was carefully monitored with an increase in the amount of solar radiation [14].

For the PVT System, various aspects are to be considered to assure effective results that include the characteristics of the absorber and the collectors mainly consisting of the thermal collector parameters, photovoltaic laminations, thermal and electrical yield ratio etc. These parameters high influence the temperature on the panel and the comparative output power from the system. Various studies are carried on PVT collectors which major include bases on air, water, air to water heating, and nanofluids flow as a major heat carrier [15-20].

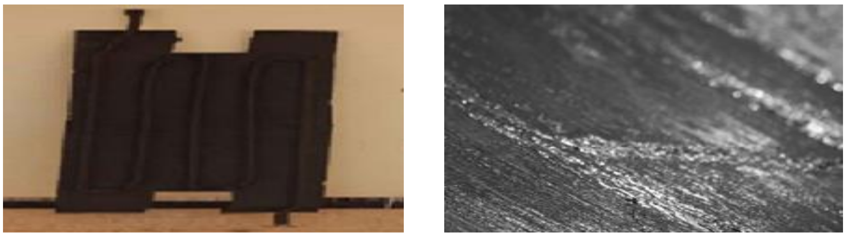
The focus of this research was to study the technical feasibility of the Hybrid PVT system by considering the affordability and small modular unit that can be scaled for meeting the varying energy demand levels. This paper studies the technical and practical issues by carefully monitoring the parameters responsible for effective energy generation that includes irradiance, heat transfer at the PV cell to fluid and the integration of the fluid for incorporating the domestic water heating for residential consumers to meet their electrical and thermal demands. This research focuses on meeting the electrical and the thermal demand of a residential household. This study presents a smart solution for using a small space for generating electricity and heat for meeting the energy demand. A brief analysis of the electrical parameters of PV-T system is carried, and a significant increase in the power production from the Photovoltaic (10% approximately) is achieved.

2. MATERIALS AND METHODS

The system aimed at monitoring the electrical parameters and the uniform distribution of the temperature across the panel and the fluid. For this purpose, we used the Fresnel lens based Module which comprises of 24 TSEC (Taiwan's) Solar Cells (Polycrystalline) attached in series. Two modules were designed so as to meet the considerable electrical demand of a household as in Figure 1. The size of the solar cell is 156x156mm±0.25mm and has certification from ISO9001/14001 and OHSAS18001 with a cell efficiency of 16.4-17%. Fresnel lens with a length of 0.1 m and a width of 0.3 m was designed. The focal length was maintained at 0.3 m. Another Fresnel Lens HW-F1000-5 having a size of 1000*1000mm was utilised for the purpose of tank heating to heat the water to a level that can be used for meeting domestic heating demand.

Figure 1. Fresnel lens based photovoltaic module

Black thermal grease made up of silicon adhesives (black colour) was empowered between the rare face of the module and the prototype absorber which is made of the aluminium because of its better heat conductivity, and it's commercially cheap as in Figure 2. The role of the thermal grease was to ensure higher efficiency for the heat transfer and the aluminium pipes roles in the hybrid collector was to ensure adequate transmission of heat to the internal fluid.



(a) (b)

Figure 2. (a) Aluminum sheet with pipes (b) Black thermal paste on the Module's back

Two Thermocouples were deployed in the collector's areas which produces a potential difference with exposure of variation in the temperature. Laser Infrared Thermometer was also used to reverify the temperature ranges of the system to assure a double check on the system. Four Heat exchange sensors were also deployed to notice the surface temperature of the solar chip/cell, Fresnel lens, Aluminum sheet as represented in Figure 2(a) and thermal paste on Module's back as represented by Figure 2(b). The temperature ranges were monitored carefully that includes a temperature of water inlet, water outlet, PVT cells, absorption tank. Later on, a tank was used to store the heated water that can be utilized for the residential purpose. The system also included six tungsten filament bulbs and 12 multimeters for continuously monitoring the electrical parameters including voltages and the currents. DiLog SL102 Advanced Irradiance Meter was utilized to monitor the solar irradiance. The system was later on accompanied by an insulator so that the heat inside can be preserved and can be utilized for the water heating.

3. RESULTS AND DISCUSSION

Concerning Figure 3, it can be noticed that due to the concentration of the light that was achieved by using the Fresnel lens, the temperature of the Solar Chip/cell was seen increased due to the fact that highly concentrated light was projected on the solar chip/cell. This corresponds to the fact that the light wavelengths that would have exceeded the threshold value of the energy band gap might possibility have contributed towards increasing the on surface temperature of the Solar Chip, thus allowing Solar Chip to operate in higher temperature ranges. Similar results are also dicussed in the study of (Wu, Yupeng. et al., 2012) [21]. Besided a thermal regulation technique is also coupled with the module to control the over heating of solar cell and operate is optimum temperature range for maximum energy output. The coupled thermal regulation is receiving the access heat and utilize it for pre-heating of water.

Figure 4 depicts the irradiance that was measured on the surface of the Fresnel lens and after the concentration by the Fresnel lens. The significant increment was found which appears to produce extra power out of the solar cell and results are quite comparable with the study of (Jing et al., 2014) [22] and (Panjwani et al., 2018) [23], where he got an increase of solar cell efficiency up to 9 % by unsig optimized Fresnel lens. However, due to the concentration, the light wavelength that falls exceeding the threshold, the concentration of the solar irradiance on the solar chip/cell directly results in increasing the solar chip/cell's temperature, thus raising the issue of the power decrement and durability of the solar cell.

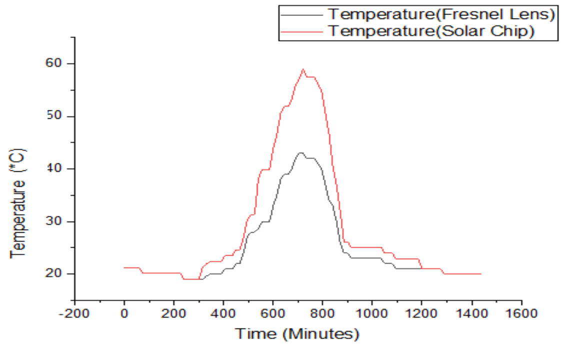


Figure 3. Temperature difference calculated at the Fresnel lens and the Solar Chip/cell

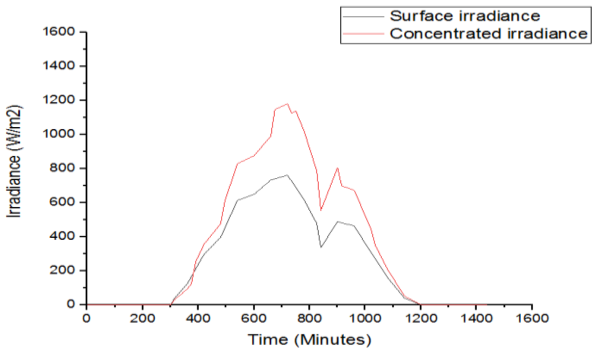


Figure 4. Irradiance measures on the surface of the Fresnel lens and after the concentration on Solar Chip/cell

From Figure 5, various ranges of the temperature in the system could be noticed. (a) The temperature at the Fresnel lens (b) Refers to the temperature that was noticed without any PVT system. It can be seen that high ranges of the temperature were calculated and the highest touching approximately 59*C. Concerning the Manufacturers sheet, the standard temperature on which the solar cell is allowed to operate is 25*C. The temperature noticed was more than the double of the temperature listed on the manufacturer sheet. (C) Refers to the temperature that was achieved after the water heat transfer. It can be noticed that a sufficient decrease was seen which would allow Solar cell to operate on less temperature despite various wavelength of the light exceeding the threshold value. (d) Refers to the temperature of the water that was noticed at the outlet after exposing it to the system. The tap water was utilized for the system. The high-temperature water was later used for excess heating to be useful for meeting the residential water heating. The results are also quite comparable with the study of (Moharram et al., 2013) [24].

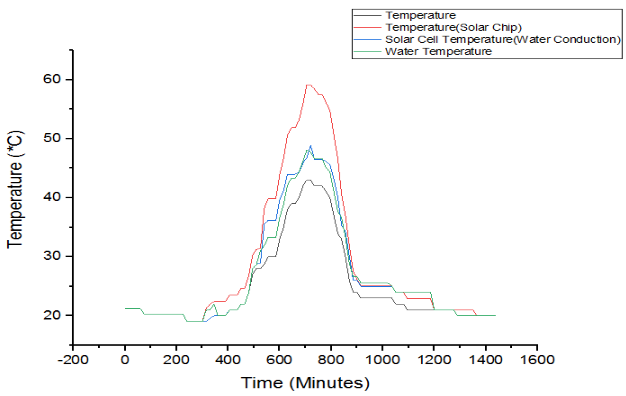


Figure 5. Temperature from the top (a) refers to Temperature of the water after heat transfer (b) Temperature of Solar Chip/cell/cell without water heat transfer (c) Solar Chip/cell temperature after the water heat transfer (d) Overall water temperature resulting from the heat transfer of solar chip/cell

From Figure 6, shows the variation in the power produced from the Solar Module before and after deployment of the PVT system. This is important to notice here that the power that is produced follows an average increase in the odd hours however there is a significant increase in the energy produced in the peak hour, thus enabling the system to utilise the peak hours for the power production. This is in response to the fact that the solar module experiences losses because of the temperature increase and thus enabling the system to deviate from the standard working of the Solar Panel. With the advancement of the system, the highest Percent Power increment was achieved to be approximately 10%, which is even highe in efficiency from (Sornek, Filipowicz and Jasek, 2018) [25] who got about 7% power increase while using Fresnel lens on photovaltic module installed directly on façade.

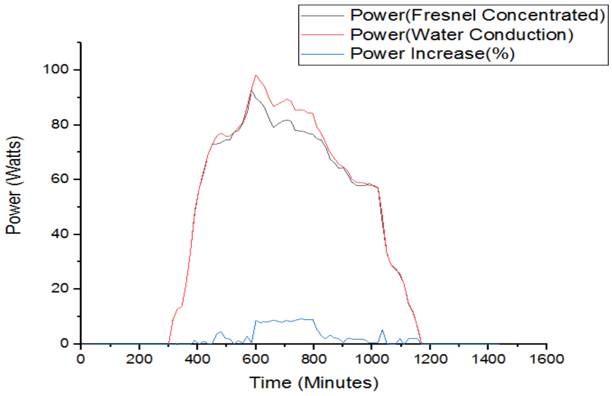


Figure 6. Power produced before and after the PVT System and Power Percent increase

Solidworks that are most widely used as a simulation software for thermodynamics was used to carefully simulate the parameters and the heat transfer that was taking place as can be seen from Figure 7. The results were also verified with ANSYS to assure if there was a mismatch in the results. Most parameters were calculated from the aspect of Fresnel lens and were incorporated to ensure that the simulation worked fine enough to ponder and accumulate the results as the part of water heating for the domestic heat application. From Figure 8, it states the geometrical dimensions of the water tank that is under investigation. A schematic diagram of the experimental setup as shown in Figure 9.

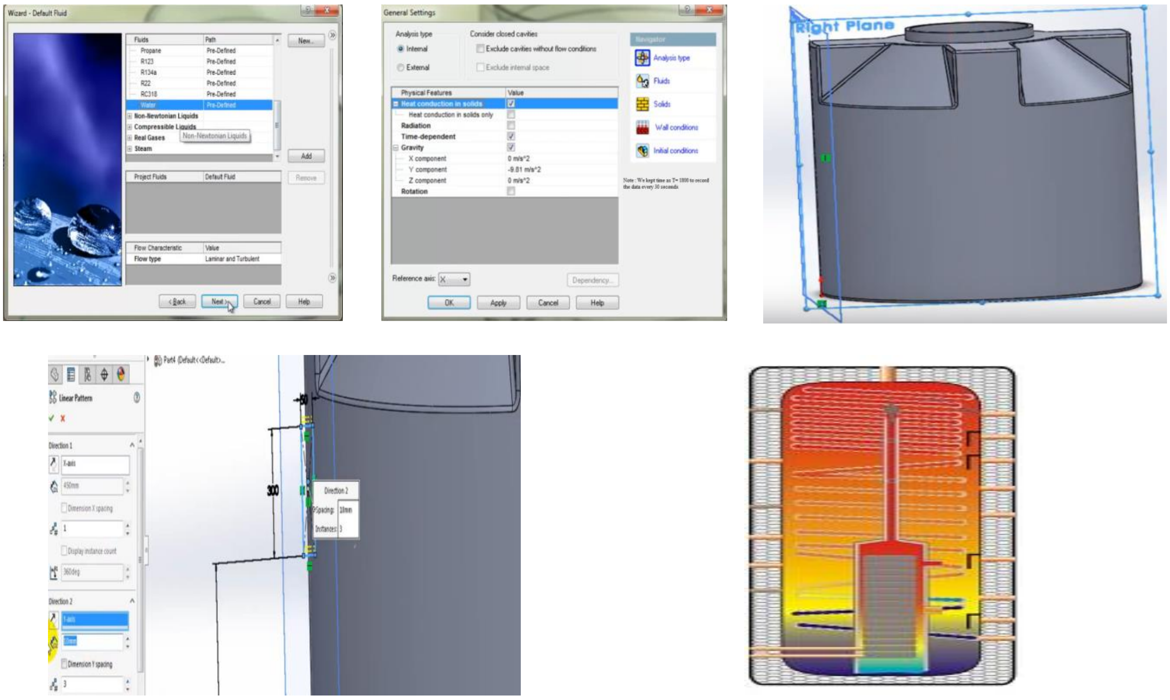


Figure 7. Simulating the thermal-stratified water tank on SolidWorks and ANSYS

Diameter, d (m)	0.210
Height, h (m)	0.500
Area, a (m^2)	0.035
Volume, V (m^3)	0.0173
Aspect Ratio, AR (h/d)	2.381

Figure 8. Geometrical Dimensions of the investigated tank

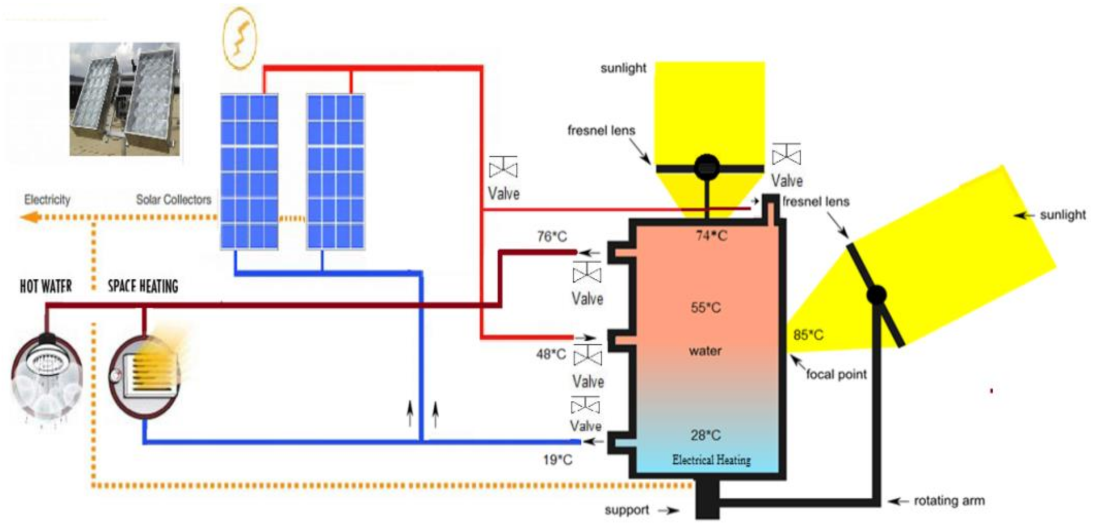


Figure 9. A schematic diagram of the experimental setup

The thermal analysis and calculations are calculated using SolidWorks and ANSYS-CFX. Electricity generated by the PV Modules is subjected to meet the household's electrical demands or in the case can be fed to the grid through net metering. A solar thermal system designed for space heating and hot water usually comprised of a solar array, circulation pumps and heat exchangers and a tank as storage. The tank is based on the stratified systems which help in maintaining the temperature differences inside the storage tank. The system that is considered in our experimental setup utilises the tap water at the initial stage and follows a closed loop circulation to meet our thermal demands. Generally, the systems that are used for domestic hot water are comparatively small as compared to space heating as the space heating requires continuous heating. The tap water was allowed to enter into the PVT system. The output water from the PVT system which was calculated to be at 48*C was allowed to enter from the middle inlet of the water tank where the thermocline zone is formed between the hot and the cold water. Two Fresnel lenses were used to assure falling of high-temperature irradiance on the water tank thus contributing towards the heating of the water inside the water tank. As per the fact that the density of the warm water is low, the warm water floats in the water tank. The density of the cold water is high, the cold water settles at the bottom and then is boosted to enter in the system. Moreover, the cold water coming out from the space heating is also utilized with the system and is then pumped to the PVT system for repeated cycles. The loop of the electrical heating can also be incorporated in the system so that the tank can be heated up in the days where there is no exposure of sun, especially in the rainy season to meet the thermal demand of the particular household. The values of the temperature are based on simulations and may vary a little when it's commercially implemented. In the absence of solar energy, the system can typically function as traditional and the electrical energy can be used to preheat the water and can utilize the water for the residential household.

4. CHALLENGES AND RECOMMENDATIONS

One of the main challenges in adoption of the solar thermal energy systems at the commercial level is their design concerns as it varies for each building, particular rooftop, climatic concerns, thus leading to variation and not having a standard design available in the commercial market. Other issues are related to their technical issues and their scaling which is limited by the space and the control concerns. The thermal and the electrical efficiencies are radically influenced by the collector design parameters such as the thermal contact between the panel/cell to the coolant fluid, their relative width of the pipe diameter. They are also influenced by the environmental parameters that seem to have an unpredictable concern on the power output of the systems. Following issues concerned with the pipe diameters and the channels/unit width, better convective heat transfer, especially in channels which has a consequent enhancement of the cooling, can be achieved with reducing the pipe diameter and increasing the number of the channels/unit width. Values of the W/D for a sheet-tube collector can be tried to reduce to unity using the corrugated panels. There are various issues related to the sensitivity of the thermal contact between the solar cell and the fluid.

5. CONCLUSION

Hybrid Photovoltaic Thermal system application was used in the system to assure that the available solar energy can be wisely utilized to produce higher electrical and thermal energy for meeting residential household's electrical and thermal demand. The results of the study are very encouraging. The Fresnel lens helped in concentrating the irradiations falling thus allowing a higher range of irradiance on the solar module to convert to the Electrical energy. Moreover, it will enable the solar cell to achieve higher temperatures because of the light falling in the wavelength above the threshold and not resulting in the absorption by the solar cell, to be used by the contacting fluid for water heating. During its exploitation, the cell efficiency was improved because of lowering its temperature using a fluid to assure a smooth heat transfer from the cell to the connected fluid thus allowing the solar module to work in the standard ranges and producing higher power outputs in peak hours. Approximately 10% increase in the power output was achieved. The heated fluid was utilized in the water tank to assure that the tank can be heated by a Fresnel lens in comparatively less time than that of ordinary to ensure slight higher efficiency in domestic water heating application. The system can be used ahead in the future for the water treatment to assure that the water from the water tank can be chemically treated and can fulfil the drinking water requirement of a household.

ACKNOWLEDGEMENTS

The authors would like to acknowledge the facilities provided by North China Electric Power University and Sukkur IBA University Pakistan for the accomplishment of this work, and China Scholarship Council for their financial support.

REFERENCES

[1] Energy Technology Perspectives 2012. Technical report, International Energy Agency (IEA), 2012. URL https://www.iea.org/publications/freepublications/publication/ETP2012_free.pdf. Accessed April 2017

[2] M. Tripathy, P.K. Sadhu. "Building Integrated Photovoltaic is a Cost Effective and Environmental Friendly Solution." *TELKOMNIKA Indonesian Journal of Electrical Engineering*. 2015; 14 (1): 49-54.

[3] Guarracino, I. (2017)."Hybrid photovoltaic and solar thermal (PVT) systems for solar combined heat and power" (Doctoral dissertation, Imperial College London).

[4] M rwanto, YM Irwan, I Safwati, Wai-ZheLeow, N Gomesh. "*Analysis Simulation of the Photovoltaic Output Performance*." IEEE 8th International Power Engineering and optimization Conference (PEOCO). 2014.

[5] R. Santbergen and R.J.C. van Zolingen. "The absorption factor of crystalline silicon PV cells: A numerical and experimental study". *Solar Energy Materials and Solar Cells*, 92(4):432-444, 2008.

[6] A.R. Amelia, Y.M. Irwan, M. Irwanto, W.Z. Leow, N. Gomesh, I. Safwati, M.A.M. Anuar. "Cooling on Photovoltaic Panel Using Forced Air Convection Induced by DC Fan". *International Journal of Electrical and Computer Engineering (IJECE)*. 2016, 6(2): 526-534.

[7] Leow, W. Z., Y. M. Irwan, M. Asri, M. Irwanto, A. R. Amelia, Z. Syafiqah, and I. Safwati. "Investigation of solar panel performance based on different wind velocity using ANSYS." *Indonesian Journal of Electrical Engineering and Computer Science (IJEECS)*, 1, no. 3 (2016): 456-463.

[8] Panjwani, Manoj Kumar, Li Meicheng, Danish Khan, Idris Khan, and Mohan Menghwar. "*Effect of solar concentrators on the efficiency of solar panels*." In 2018 International Conference on Computing, Mathematics and Engineering Technologies (iCoMET), pp. 1-7. IEEE, 2018.

[9] Shvarts, M. Z., V. M. Andreev, V. S. Gorohov, V. A. Grilikhes, A. E. Petrenko, A. A. Soluyanov, N. H. Timoshina, E. V. Vlasova, and E. M. Zaharevich. "*Flat-plate Fresnel lenses with improved concentrating capabilities: designing, manufacturing and testing*." In 2008 33rd IEEE Photovoltaic Specialists Conference, pp. 1-6. IEEE, 2008.

[10] Perraki, V., and G. Tsolkas. "Temperature dependence on the photovoltaic properties of selected thin-film modules." *International Journal of Renewable and Sustainable Energy* 2, no. 4 (2013): 140-146.

[11] Hossein Shahinzadeh, Mohammad Moien Najaf Abadi, Mohammad Hajahmadi, Ali Paknejad. "Design and Economic Study for Use the Photovoltaic Systems for Electricity Supply in Isfahan Museum Park." *International Journal of Power Electronics and Drive System (IJPEDS)*. 2013; 3 (1): 83-94.

[12] Z. Farhana, Y.M. Irwan, R.M.N. Azimmi, A.R.N. Razliana, N.Gomesh. "Experimental investigation of photovoltaic modules cooling system." *IEEE Symposium on Computers & Informatics*; 2012

[13] Y.M. Irwan, W.Z. Leow, M. Irwanto, Fareq. M, A.R. Amelia, N. Gomesh, I. Safwati. "Analysis Air Cooling Mechanism for Photovoltaic Panel by Solar Simulator." *International Journal of Electrical and Computer Engineering (IJECE)*. 2015; 5 (4): 636-643.

[14] Fudholi A, Sopian K (2018), "R&D of Photovoltaic Thermal (PVT) Systems: an overview". *International Journal of Power Electronics and Drive Systems (IJPEDS)*, 9 (2), 803-10.

[15] Fudholi A, Sopian K (2018), "Review on exergy and energy analysis of solar air heater". *International Journal of Power Electronics and Drive Systems (IJPEDS)*, 9 (1), 420-26.

[16] Zohri M, Nurato N, Fudholi A (2017), "Photovoltaic thermal (PVT) system with and without fins Collector: Theoretical Approach". *International Journal of Power Electronics and Drive System (IJPEDS)* 8(4), 1756-63.

[17] Sarhaddi, F., S. Farahat, Hossein Ajam, A. M. I. N. Behzadmehr, and M. Mahdavi Adeli. "An improved thermal and electrical model for a solar photovoltaic thermal (PV/T) air collector." *Applied Energy* 87, no. 7 (2010): 2328-2339.

[18] Razali, Nur Farhana Mohd, Ahmad Fudholi, Mohd Hafidz Ruslan, and Kamaruzzaman Sopian. "Electrical characteristic of photovoltaic thermal collector with water-multiwalled carbon nanotube nanofluid flow." *Indonesian Journal of Electrical Engineering and Computer Science (IJEECS)*, 13, no. 1 (2019): 324-330.

[19] Zohri, Muhammad, Lalu Darmawan Bakti, and Ahmad Fudholi. "Exergy Assessment of Photovoltaic Thermal with V-groove Collector Using Theoretical study." *TELKOMNIKA (Telecommunication, Computing, Electronics and Control)*, 16, no. 2 (2018): 550-557.

[20] Solanki, S. C., Swapnil Dubey, and Arvind Tiwari. "Indoor simulation and testing of photovoltaic thermal (PV/T) air collectors." *Applied energy* 86, no. 11 (2009): 2421-2428.

[21] Wu, Yupeng, Philip Eames, Tapas Mallick, and Mohamed Sabry. "Experimental characterisation of a Fresnel lens photovoltaic concentrating system." *Solar Energy* 86, no. 1 (2012): 430-440.

[22] Jing, Lei, Hua Liu, Yao Wang, Wenbin Xu, Hongxin Zhang, and Zhenwu Lu. "Design and optimization of Fresnel lens for high concentration photovoltaic system." *International Journal of Photoenergy* 2014 (2014).

[23] Panjwani, Manoj Kumar. "Solar Concentrator's Effect on Solar Panel Efficiency." *Sukkur IBA Journal of Emerging Technologies* 1, no. 1 (2018): 15-27.

[24] Moharram, Khaled A., M. S. Abd-Elhady, H. A. Kandil, and H. El-Sherif. "Enhancing the performance of photovoltaic panels by water cooling." *Ain Shams Engineering Journal*, 4, no. 4 (2013): 869-877.

[25] Sornek, Krzysztof, Mariusz Filipowicz, and Jakub Jasek. "The Use of Fresnel Lenses to Improve the Efficiency of Photovoltaic Modules for Building-integrated Concentrating Photovoltaic Systems." *Journal of Sustainable Development of Energy, Water and Environment Systems*, 6, no. 3 (2018): 415-426.