Performance Evaluation for the Parabolic Photovoltaic/Thermal Hybrid Solar System

Heba A. Mosalam
Electro mechanics *Department*
Heliopolis University for Sustainable Development
Cairo, Egypt
Email:heba.mosalam@hu.edu.eg

*M. A. Moustafa Hassan**
Electro mechanics Department
Heliopolis University for Sustainable Development
Cairo, Egypt
Email: *mohamed.mustafa@hu.edu.eg*
ORCID:0000-0001-6116-6707
**On Sabbatical Leave from Cairo University*

Abstract— Concentrated PhotoVoltaic Thermal (CPVT) or as it known in markets as stand-alone unit for the remote areas to supply the area with electricity and thermal hot water which differ for many years with different applications. In Heliopolis University (HU) for Sustainable Development two modules have been tested, thermally and electrically. The module of triple junction photovoltaic is the one which has the ability to work under high temperature. When the concentrated heat was focused on the electric module, the cooling is must to drop the temperature from 120C to 45C. The production of the heat has directed to cool the cell plays important role to use the thermal heat in different applications. The performance of the two modules have been investigated and the whole system has been described in details. At the end the research proposed different types of the thermal modules when it was noted that the useful power produced by the thermal was much power than the electric power produced by the photovoltaic PV.

The system moves about two tracking axes and operated to test modules thermal PV. The receiving modules placed on the focus line displays with ten concave mirrors five up and five down. The triple junction photovoltaic cells technology has applied with water flow channels to cool the PV cells from back. The inlet water varied from 25C to 35C.

By sensing the module temperature by the thermocouple, a solar pump is operated for circulating water in the system cycle. Temperature limit is set to 72C, above which the pump operates. Within that time temperature goes below the limit and thus the operating temperature of PV can be maintained with in specified limits to secure the life time of the modules. The outlet electrical power has connected to the grid by single phase invertor. The direct normal irradiation (DNI) is measured by solar sensors mounted on a solar tracker. Experimental results are used to evaluate the optimum application in Egypt from the thermal and electrical power obtained from the system. Therefore, CPVT is a promising technology for smart Cities.

Keywords— Direct Normal Irradiation, Hybrid CPVT, PV, Thermal, Renewable Energy, Clean Energy, Smart Cities

I. *Introduction*

The researchers attempted to enhance the performance of the photovoltaic which started from 8% performance reached to 20% with different types and manufactures [1], the system of the photovoltaic usually affected by many parameters which reduce to power output and drop the current-volt (IV) curve of the maximum power point of the PV[2]. Dust, temperature, tilting angle and orientations are parameters have significant consequences on the performance of the PV [3]-[8].

The type of the thermal modules was playing an importing role to increase the performance of the thermal system which were either flat plate collectors or evacuated tube collectors [9], [10]. With reference to the previous work, the annual absorbed by our land approximated to be 3.85 million EJ [11], the collectors also were varied from parabolic trough (PTC), or linear Fresnel reflectors and concentrator of photovoltaic thermal CPVT. These types contributed to enhance the usage of the solar power into heat and electricity[12]. The beginning of the work for CPVT type of collectors started in Sandia the national Labs in 2007 [13]. Science that, several approaches and designs with number of experiments and investigations to improve the performance of the PV and thermal unit in the CPVT some of the experiments reached 66% of the system [14] and maximum media fluid to 200C [15]. The cost benefits in Egypt was not in the scope of research for small applications yet but it should be further work of our team and applied on the system exist in our university. Meanwhile cost of electricity in the application of the concentrated solar power was 2.37 $ per watt in [16] and the total production of thermal and electricity cost 8.7$ per watt in [17]. The thermal conductivity and the basics of the thermodynamics become the essential researches to enhance the performance of the CPVT. Also the concentration ratio is one of the main factors for the CPVT collectors. The PV for the system of CPVT is expected to reach 30% according to the experiments studies in that issue [18]-[20]. Among the alternatives of the CPVT units and collectors, Fresnel lens reflectors ranked as the most suitable type to be used in CPVT for advantages of the size, the weight and cost in the previous work [21]. It reaches 26% with production of 30KW. Hybrid the thermal and photovoltaic has overcome the challenge of expensive PV for high performance and the number of the cells has reduced. The previous work of the researchers, a dynamic simulation model for the performance of the heating and cooling of the solar power has studied applied on LiBr-HO absorption Chiller for both types of concentrated solar power and evacuated tubes and the results were simulated on Matlab and agreed with the pervious studied using Trasys software [22]. In Tunisian research team, the researchers tested two water mass flow rates and 3D CFD model interpreting and predicted the temperature for the different components in this hybrid system [23]. Much more studies of the different collectors and parameters with their effect of the coefficient of performance of the CPVT is discussed in details in [24]. Also in India, the researchers studied the performance of the fully use of the solar efficiency as heat and electricity and have concluded their work with using the water as the fluid to cool the PV cell[25]. Modeling of both the thermal and electrical modules has applied using COMSOL Multiphysics environmental software and PSIM environmental software to enhance the performance of the system[26]. Another modeling has presented in Tunisia for the texture application and improve the total efficiency including the losses of heat [27], and another application for supermarket [28]. Also for small scale as domestic use [29]. For the large scale systems, compound parabolic concentrated system has been used in steady and unsteady state conditions, the output were 55% and 1,730,039 KJ [30].

As compared to most existing low concentration systems with linear focus, which use silicon crystalline cells, as reported in the review paper [31]. In the present system, the module installed is called triple junction solar cells. This type is depended on efficiency on the operating temperature and can work with good efficiency even with high temperature which could reach 120°C, as shown for example by [32] . This allows heat production at medium temperature during the experiment with active cooling.

The experiment of a system of concentrated photovoltaic/thermal prototype has set at Heliopolis University (HU) for Sustainable Development in Egypt as hot arid region. The system has been tested and the results has recorded with its remarks and conclusion. Consequently, CPVT is a encouraging technology for future Smart Cities which is based on the clean renewable energies.

Nomenclature

CPVT	*Concentrated photovoltaic/thermal*
PV	*Photovoltaic*
A_m	*projected area of the mirrors* (m^2)
c_p	*specific heat of the water* ($J\ kg^{-1}\ K^{-1}$)
DNI	*Direct Normal Irradiance* ($W\ m^{-2}$)
$\dot{m}_W$	water mass flow rate ($kg\ s^{-1}$)
I	current generated by the photovoltaic cells (A)
HE	heat exchanger
I_L	light current (A)
E	voltage (V)
P_{el}	electrical power (W)
q_{th}	useful heat flow rate (W)
t	time (s)
I_0	diode reverse saturation current (A)
T	temperature (°C)
T_m^*	reduced temperature difference ($K\ m^2\ W^{-1}$)
$\dot{V}$	Volumetric flow (m^3)
Greek symbols	
η_{el}	electrical efficiency (-)
η	global efficiency (-)
ρ	density ($kg\ m^{-3}$)
η_{th}	thermal efficiency (-)

The rest of the Article is organized as follow: Section II discusses the Concentrated Photovoltaic Thermal Prototype. Whicle Section III presents Experimental set up. Meanwhile, Section IV explains Handling of Data. Additionally, Section V demonstrates Experimental Results. Furthermore, Section VI validates the Comparison of Thermal and Electrical Model. Finally; Section VII concludes the article.

II. Concentrated Photovoltaic Thermal Prototype

The total efficiency of the system will be calculated as the submission of the thermal and electrical efficiency separately as shown in Equation 1:

$$\eta_o = \eta_{th} + \eta_e \qquad (1)$$

During the experiment, the efficiency of the photovoltaic module has be tested according to the total power of the sun to the power produced by the cell and has reached to 0.14

The value of the electric power and thermal power is differs according to the form of energy. Since the electric energy is converted from thermal energy so in order to correct that value and the energy saving of the CPVT, it should define the term of the primary energy saving as the following order:

$$E_f = \frac{\eta_e}{\eta_{power}} + \eta_{th} \qquad (2)$$

When η_e the electric power generation efficiency for the photovoltaic ; and η_{power} is the electric power generation efficiency for the designed value and η_{th} is the heat collection efficiency of the CPVT and deferent shapes of modules has been investigated to reach the maximum thermal power [33]

The new prototype of linear photovoltaic concentrator is shown in Figure 1. Ten parabolic trough mirrors concentrate the solar radiation onto a linear receiver 6.2 m long, where a photovoltaic-thermal module is placed (at Heliopolis University (HU)). The aperture area of the present system is 17.5 m^2 and the geometrical concentration ratio is nearly 144. The system moves about two-axes (azimuthal and Elevation motions), to have the solar beam perpendicular to the surface plane. The tracking of the sun is governed by a solar algorithm and by a pyranometer sensor when achieving the best receiver alignment.

In Figure 2, the photovoltaic-thermal module is presented. A secondary optics device which is type of composed of flat aluminums mirrors, has been designed for reducing optical losses. The module is produced with GaInP/GaAs/Ge triple junction solar cells soldered on a ceramic substrate.by using active cooling system including an aluminum roll-bond in thermal contact heat exchanger and a closed loop for pumping water as the coolant. The roll-bond plate is applied to the back side and drowned into an elastomeric material. The PV cells have shape of square with side length equal to 10 mm and are electrically connected by number of 22 cells in package. The PV package has designed with high photovoltaic efficiency of 34.6% at 25°C cell temperature, 1000 W m^{-2} DNI, 1.5 air mass and 500X solar concentration ratio, as delivered by the manufacturer.

Figure 1: Concentrated Photovoltaic Thermal (CPVT) prototype during tests at HU, Egypt

III. Experimental set up

A scheme of the hydraulic loop built up at Heliopolis University for Sustainable Development to test the solar concentrator is reported in figure 3. The system is described as: the water coming from the active cooling system of the photovoltaic cells enters the storage 1, then passes through a plate of heat sink. Then the water enters the storage 2, which contains number of electrical heaters for the temperature control. The operating mass flow rate is between 720 and 660 lt/hr. hence, it is possible to set the electric power to obtain a desired and constant temperature of the liquid at the inlet of the test section. From storage 2, pump is used before entering the heat exchanger of the module. PT100 platinum resistance thermometers is used to measure inlet and outlet water temperatures in the test section and the ambient air temperature.

The electrical terminals of the module are connected to a rheostat and a power analyzer that measures the current of the circuit, the voltage across the resistive load and the electrical power supplied by the PV cells. The sliding contact of the rheostat is set in order to make the PV module work close to the maximum power point during run the experiment. The type of the two solar sensors are equipped with a measuring system of solar irradiance.

Figure 2: Photovoltaic Thermal module

The first is the standard pyranometer for the measurement of horizontal global irradiance, and the second is standard pyranometer shaded with a band for the measurement of the horizontal diffuse irradiance and a pyrheliometer mounted on a sun tracker for measuring the Direct Normal Irradiance (DNI).

IV. Handling of Data

To characterize the thermal performance of the CPVT prototype, the inlet and outlet temperatures of the working fluid, the mass flow rate, and the ambient air temperature together with DNI, global and diffuse horizontal irradiance are measured. It was noticed that by taking the DNI's values every 10″ by a pyreliometer, the values were different than the data by JRC PVGIS by varieties from 40% to 8%. At the morning 08:00 am, the difference could reach 40% then decrease unregularly till reaches 8% at 01.00 pm

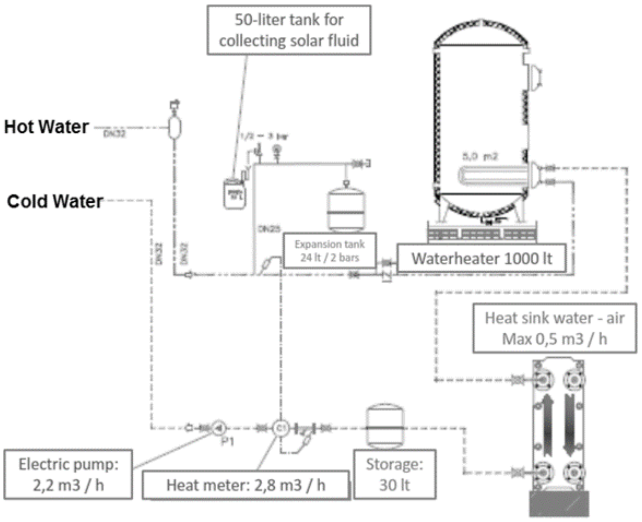

Figure 3, Schematic View Of The Auxiliary Hydraulic Components In-Out The Module.

It was noted that there are no appropriate standard procedures for testing and qualifying concentrated photovoltaic-thermal devices with active cooling system as reported by[34]. The steady-state method described in EN 12975-2:2006 for the present experimental tests.

Another assumption has been used during the experiment that the direct normal irradiance is considered instead of the global irradiance on the collector plane because it is the actual input energy flux of the studied solar concentrator.

The mass flow rate during the experiment was 260 kg/h, in compliance with the stated fluid flow rate of 0.02 kg/s per square meter of the aperture area. With repeating the measurements at varying inlet water temperature. And for the outlet temperature of each hydraulic circuit integrated in the heat exchanger and at the mixing point.

Test runs have been performed with two condition: in open electric circuit conditions and with electric load and connecting the rheostat and the power analyzer to the electrical terminals of the module. The output power of the single phase inverter has connected to the Egyptian local grid. The power analyzer measures the current generated by the photovoltaic cells and the voltage across the resistive load and the supplied power. To obtain the maximum power point for the electrical power output, the proper position is manually checked several times during each test run and during steady-state test conditions, measurements are collected to produce a set of thermal efficiency data points:

$$\eta_{th} = \frac{q_{th}}{DNI.A_m} = \frac{m_w.c_{p.w.}}{DNI.A_m}(T_{w,out} - T_{w,in}) \qquad (3)$$

For the thermal power performance of the concentrator is mainly depends of the heat transfer and the thermal conductivity of the material of each module. The Described of the thermal efficiency is plotted as a function of the reduced temperature difference. The electrical efficiency can be calculated according to Eq. (3) when the rheostat and the power analyzer are electrically connected to the module,:

$$\eta_{el} = \frac{p_{el}}{DNI.A_m} = \frac{E.I}{DNI.A_m} \qquad (4)$$

Where, the p_{el} is the power produced by the electrical module, and considering both thermal power presented in the useful heat flow rate and the electric power provided by the CPVT prototype, the general efficiency of the investigated system can be defined as follows:

$$\eta = \frac{q_{th} + p_{el}}{DNI.A_m} \qquad (5)$$

V. Experimental Results and Discussion

Two modules have been tested. The first one is the hybrid electrical thermal output, and the second is thermal only. Thermal insulation of both types of modules will stabilize the thermal power and in case of blackout the heat output will increase. During the test, the invertor switched off due to the local electrical grid instability in frequency. And this lead to increase the thermal power as shown in figure 4 in case of hybrid module.

For the experiment boundaries, *DNI* between 500 Wm^{-2} and 850 Wm^{-2}, ambient temperature between 15°C and 21°C. In open electric circuit conditions, the water inlet temperature is set at 20°C, 40°C and 45°C. With closed electric load, the simultaneous production of useful heat flow rate and electrical power is investigated by sending water to the test section at inlet temperature of 20°C, 70°C and 80°C. During the test it was noted that high umidity rate stops ultraviolet wavelength of light (< 400 nanometers) and decrease the pointing sensor efficiency.

The graph in Figure 4a) refers to the collected data during a test run displaying an outlet water temperature of around 25°C, with the rheostat and the power analyzer connected to the electrical terminals of the module. The input power, given by the *DNI* multiplied by the projected area of the mirror, the useful heat flow rate and the electrical power gained from the module are plotted against the time of the test day. The outlet water temperature is also plotted. Figure 4b) reports the same graph referred to a test run with electrical production and useful heat recovery and water outlet temperature of around 86°C.

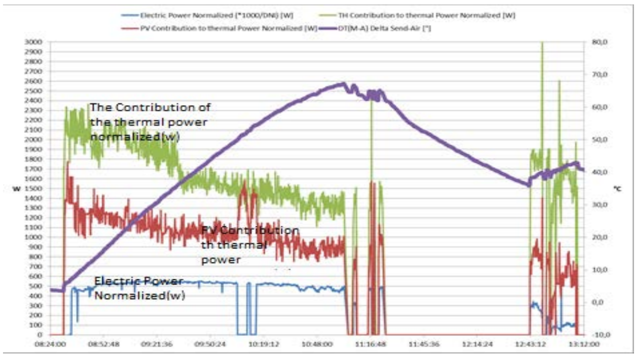

Figure 4: All Power Converted To Thermal Power while the invertor is switched off.

VI. Comparison of Thermal and Electrical Model

One PV-T module is modeled and combined with thermal module. The thermal module only produced 2.365 watt thermal. And the hybrid PV-T produced 604 watts Electrical + 1.622 watts thermal. With total power 4.591 watts total. With two different output temperatures modeled as two different applications. The system reading has plotted with respect to DNI in w/m2. Figure 5 is plotted at output temperature of 45ºC. This temperature has taken as hot water temperature in hotel. The DNI was 800w/m2 and produced 700 watt El.

Figures 5 and 6 explain the relation between the temperature and the output DC power in watt. When the temperature increases, the output DC power decrease. In order to describe the performance of the present linear concentrator, thermal efficiency, electrical efficiency and global efficiency, measured during test runs with electric load, have been reported in Figure 6 as a function of the reduced temperature difference , the thermal efficiency obtained in test runs without electrical load is plotted against $T\ m^*$.

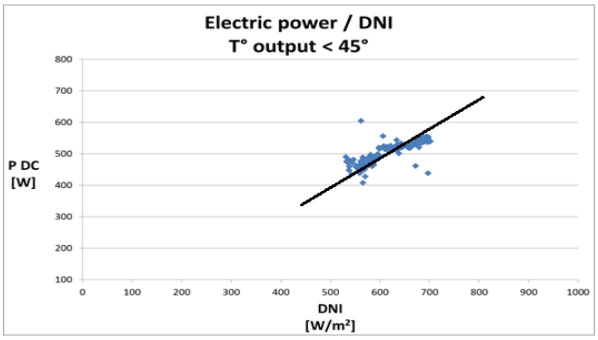

Figure 5: Output power with respect to DNI in w/m^{2}at 45^{o}C

Figure 6 illustrates the solar cooling in temperature 75^{0}C

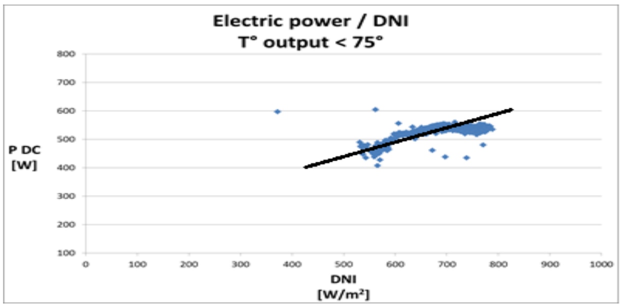

Figure 6: The Output Power With Respect to DNI in W/m^{2}at 75^{o}C

In agreement with the previous considerations, the thermal and electrical efficiency decrease when increasing the reduced temperature difference. This means that for a given DNI and ambient air temperature, the thermal and electrical performance of the investigated device decreases when increasing the mean temperature of the working fluid. On the whole, the global efficiency ranges between 0.7 and 0.55 when the reduced temperature difference Tm* varies between 0 and 0.082 Km2/W-1

Another assumption put one PV-T and four thermal as the focal line of the system is for number of five modules with each length of 0.95 meter. The main application was the hot water with total thermal power of 9460.00 watts in addition to hybrid PV-T with 604 watts electrical. The overall system produced 11886 watts which meets with the system peak power of 15000 watts total.

VII. **Concluding Remarks**

Heat transfer fluid (usually thermal oil) runs through the tube to absorb the concentrated sunlight. This increases the temperature of the fluid to some the heat transfer fluid is then used to heat steam in a standard turbine generator. The process is economical and, for heating the pipe, thermal efficiency ranges from 60-80%. The overall efficiency from collector to grid, i.e. (Electrical Output Power)/(Total Impinging Solar Power) is about 15%, similar to PV (Photovoltaic Cells). For the system dual axis tracking, the system has installed to track east-west direction which reduce the overall efficiency of the modules than the north-south axis. However the tracking here approaches the theoretical efficiency during fall equinoxes and spring but less accurate of light at other periods during the year. Some errors have noted due to the daily sky tracking greater at sunshine and sunset and less in noon. That was required to calibrate the solar sensors from time to time. In general the whole CPVT system introduced 1/3 of the theoretical efficiency due to the errors which mentioned above and the efficiency of the modules. The input power is slightly high during the test and the temperature of the outlet water around 86°C. The heat exchange was a parameter for the heat losses towards the external environment increase with the fluid working temperature and the electrical efficiency diminishes due to the higher working temperature of the photovoltaic cells. The peculiar properties of the triple junction photovoltaic cells employed in the present concentrator allow the electrical power to remain around 500 W per module even at the higher temperature and that make the electrical efficiency didn't exceed 14% comparing to 34% as manufactured. With regard to the thermal performance, the small area of the module limits the heat losses and that was advantages because free convection and radiation was ignored during the test calculations.

This trend in thermal performance has been observed also in the test in open electrical circuit conditions. The input power and the useful heat flow rate are reported against the time of the day for two different test in which the water inlet temperature was set equal to 20°C and 40°C, respectively. For the total efficiency of the system, it can be noted that when running the CPVT system without electrical load and water inlet temperature of 20°C, the thermal production increases by the amount of 50% which led to extend the experiment in the future with only thermal modules. Two modules has been developed to predict the electric and thermal production. The electric efficiency displays a minor penalization with increasing temperature difference. And that will give the possibility to increase the operating temperature (80-90°C) to produce more heat. The measured global efficiency reaches 65%.

Acknowledgements

The authors acknowledge the financial support of Heliopolis University as well as Regione del Veneto, through the project SMUPR No. 4148 "Polo di Ricerca nel Settore Fotovoltaico". The present authors want also to thank the company Greeneticasrl, Pordenone, Italy for their cooperation and technical support within the present project.

References

[1] S. Ghazi, A. Sayigh, and K. Ip, "Dust effect on flat surfaces - A review paper," *Renew. Sustain. Energy Rev.*, Vol. 33, 2014.

[2] W. Javed, Y. Wubulikasimu, B. Figgis, and B. Guo, "Characterization of dust accumulated on photovoltaic panels in Doha, Qatar," *Sol. Energy*, Vol. 142, 2017.

[3] H. A. Mosalam, "Evaluation Study Design and Operation

of a Building Integrated Photovoltaic System," in *https://ieeexplore.ieee.org/document/8634453. Conference prooceding: 2018 International Conference on Smart Grid (icSmartGrid) Nagasaki, Japan,IEEEXPOLR 2019*, 2018, p. 195–201, DOI: 10.1109/ISGWCP.2018.8634453.

[4] H. A. Mosalam, "Experimental Investigation of Temperature Effect on PV Monocrystalline Module," *Int. J. Renew. Energy Res. IJRER*, Vol. 8, No. 1, pp. 365–373, 2017.

[5] A. A. Serageldin, A. Ali, P. D. E. Ali Ahmed Hamza H., and S. Ookawara, *Effect of Dust Deposition on Performance of Thin Film Photovoltaic Module In Harsh Humid Climate*. 2013.

[6] S. A. Sulaiman, A. K. Singh, M. M. M. Mokhtar, and M. A. Bou-Rabee, "Influence of dirt accumulation on performance of PV panels," in *Energy Procedia*, 2014, Vol. 50, pp. 50–56.

[7] N. M. and F. K. K. Kajiwara, H. Tomura, "Performance-Improved Maximum Power Point Tracking Control for PV System," in *7th International Conference on Renewable Energy Research and Applications (ICRERA)*, 2018, pp. 1153–1156.

[8] C. Schill, S. Brachmann, and M. Koehl, "Impact of soiling on IV-curves and efficiency of PV-modules," *Sol. Energy*, Vol. 112, 2015.

[9] A. Buonomano, F. Calise, and A. Palombo, "Solar heating and cooling systems by CPVT and ET solar collectors: A novel transient simulation model," *Appl. Energy*, Vol. 103, pp. 588–606, Mar. 2013.

[10] A. N. Al-Shamani, K. Sopian, S. Mat, H. A. Hasan, A. M. Abed, and M. H. Ruslan, "Experimental studies of rectangular tube absorber photovoltaic thermal collector with various types of nanofluids under the tropical climate conditions," *Energy Convers. Manag.*, Vol. 124, 2016.

[11] T. B. Johansson, H. Kelly, A. K. N. Reddy, and R. H. Williams, "Renewable Fuels and Electricity for a Growing World Economy: Defining and Achieving the Potential," *Energy Stud. Rev.*, 1993.

[12] R. D. Azarian, E. Cuce, and P. M. Cuce, "An Overview of Concentrating Photovoltaic Thermal (CPVT) Collectors," *Energy Res. J.*, 2017.

[13] *Concentrator Photovoltaics*. 2007.

[14] J. Zhao, Y. Song, W.-H. Lam, W. Liu, Y. Liu, Y. Zhang, and D. Wang, "Solar radiation transfer and performance analysis of an optimum photovoltaic/thermal system," *Energy Convers. Manag.*, Vol. 52, No. 2, pp. 1343–1353, Feb. 2011.

[15] C. Kandilli, "Performance analysis of a novel concentrating photovoltaic combined system," *Energy Convers. Manag.*, Vol. 67, pp. 186–196, Mar. 2013.

[16] N. Xu, J. Ji, W. Sun, W. Huang, and Z. Jin, "Electrical and Thermal Performance Analysis for a Highly Concentrating Photovoltaic/Thermal System," *Int. J. Photoenergy*, Vol. 2015, pp. 1–10, 2015.

[17] S. Quaia, V. Lughi, M. Giacalone, and G. Vinzi, "Technical-economic evaluation of a Combined Heat and Power Solar (CHAPS) generator based on concentrated photovoltaics," in *SPEEDAM 2012 - 21st International Symposium on Power Electronics, Electrical Drives, Automation and Motion*, 2012.

[18] S. Van Riesen, A. Gombert, E. Gerster, T. Gerstmaier, J. Jaus, F. Eltermann, and A. W. Bett, "Concentrix solar's progress in developing highly efficient modules," in *AIP Conference Proceedings*, 2011.

[19] G. S. Kinsey, A. Nayak, M. Liu, and V. Garboushian, "Increasing power and energy in amonix CPV solar power plants," *IEEE J. Photovoltaics*, 2011.

[20] T. T. Chow, "A review on photovoltaic/thermal hybrid solar technology," *Appl. Energy*, vol. 87, No. 2, pp. 365–379, Feb. 2010.

[21] K. Araki, T. Yano, and Y. Kuroda, "30 kW Concentrator Photovoltaic System Using Dome-shaped Fresnel Lenses," *Opt. Express*, 2010.

[22] A. Buonomano, F. Calise, and A. Palombo, "Solar heating and cooling systems by CPVT and ET solar collectors: A novel transient simulation model," *Appl. Energy*, vol. 103, pp. 588–606, 2013.

[23] M. Chaabane, H. Mhiri, and P. Bournot, "Experimental validation of the thermal performance of a concentrating photovoltaic/thermal system," *IREC 2014 - 5th International Renewable Energy Congress*. 2014.

[24] R. Daneshazarian, E. Cuce, P. M. Cuce, and F. Sher, "Concentrating photovoltaic thermal (CPVT) collectors and systems: Theory, performance assessment and applications," *Renew. Sustain. Energy Rev.*, Vol. 81, pp. 473–492, Jan. 2018.

[25] A. M. Manokar, D. P. Winston, and M. Vimala, "Performance Analysis of Parabolic trough Concentrating Photovoltaic Thermal System," *Procedia Technol.*, Vol. 24, pp. 485–491, Jan. 2016.

[26] A. Elnozahy, A. K. A. Rahman, A. H. H. Ali, M. Abdel-Salam, and S. Ookawara, "Thermal/Electrical Modeling of a PV Module as Enhanced by Surface Cooling," *J. Clean Energy Technol.*, Vol. 4, No. 1, pp. 1–7, 2015.

[27] W. Ben Youssef, T. Maatallah, C. Menezo, and S. Ben Nasrallah, "Assessment viability of a concentrating photovoltaic/thermal-energy cogeneration system (CPV/T) with storage for a textile industry application," *Sol. Energy*, Vol. 159, pp. 841–851, 2018.

[28] C. Renno, D. D'Agostino, F. Minichiello, F. Petito, and I. Balen, "Performance analysis of a CPV/T-DC integrated system adopted for the energy requirements of a supermarket," *Appl. Therm. Eng.*, Vol. 149, pp. 231–248, 2019.

[29] M. Herrando and C. N. Markides, "Hybrid PV and solar-thermal systems for domestic heat and power provision in the UK: Techno-economic considerations," *Appl. Energy*, Vol. 161, 2016.

[30] Z. Wang, J. Wei, G. Zhang, H. Xie, and M. Khalid, "Design and performance study on a large-scale hybrid CPV/T system based on unsteady-state thermal model," *Sol. Energy*, Vol. 177, pp. 427–439, Jan. 2019.

[31] D. Chemisana, "Building Integrated Concentrating Photovoltaics: A review," *Renew. Sustain. Energy Rev.*, Vol. 15, No. 1, pp. 603–611, Jan. 2011.

[32] A. G. and V. P. Pérez-Higueras P, Muñoz E, "High Concentrator Photovoltaics efficiencies: Present status and forecast," *Renew. Sustain. Energy Rev.*, Vol. 15, pp. 1810–1815, 2011.

[33] N. A. R. and R. S. M. George, A. K. Pandey, "Recent studies in concentrated photovoltaic system (CPV): A review," in *5th IET International Conference on Clean Energy and Technology (CEAT2018)*, pp. 1–8.

[34] M. Vivar, M. Clarke, J. Pye, and V. Everett, "A review of standards for hybrid CPV-thermal systems," *Renew. Sustain. Energy Rev.*, Vol. 16, No. 1, pp. 443–448, Jan. 2012.