Design and Experimental Validation of a Photovoltaic-Thermal (PVT) Hybrid Collector

Nayeem Ur Rahman Chowdhury*‡

*Department of Energy System Engineering, Institute of Energy Studies, University of North Dakota, USA

‡ Corresponding Author: nayeem.chowdhury@und.edu, Upson II Room 366, 243 Centennial Drive, Grand Forks, ND 58202-8153

Received: 30.06.2016 -Accepted:23.07.2016

Abstract- In order to reduce carbon dioxide, the use of renewable energy is inevitable. Among the different renewable energies, solar is the most abundant and easily harness able. To convert solar energy to useful energy solar collectors are the bridge between them. Therefore designing an appropriate and efficient solar collector which is able to make solar energy feasible and useful. In this paper, a concentrated hybrid photovoltaic-thermal collector is developed and analyzed its electrical and thermal characteristics. The unique design has been developed under Solarus AB, Alvkerleby, Sweden. Also, it has been tested in Alvkerleby and at University of Dalarna, Sweden. The designed collector has been compared with another similar collector and also the thermal analysis has been compared between two regions. The novel collector constitutes a new technical approach to maximize the total efficiency compared to the traditional hybrid collector.

Keywords- Solar collector, PV/T (Photovoltaic thermal), Compound Parabolic Collector (CPC), Thermal and electrical energy, Incident angle

1. Introduction

A hybrid solar collector can be defined as a type of solar collector which has a capability of producing both heat and electricity without compromising either. It provides the same advantages of photovoltaic (PV) and thermal collector. In [1], it shows conventional PV system has an efficiency of 10-25%, it means it can convert 10-25% incident solar energy to electricity, the excess temperature decreases the cell efficiency [2]. Another undesirable consequence is permanent physical damage and shorter product life [1]. The hybrid photovoltaic-thermal (PVT) collector is able to introduce the solution if these undesirable problems. It can generate higher electricity output than a common PV system, maximizes available roof surfaces and minimizes installation cost. The concept of photovoltaic/thermal (PV/T) gives an opportunity to use the excessive heat and which will increase the overall efficiency of the system. Commonly, to increase the output voltage and decease the resistive loss of the system, the cells are connected in series. Although, by connecting the cells are in series, the least efficient solar cell will affect the current flow. This phenomenon has been defined as current matching problem [3]. Therefore, it is very important to keep a uniform temperature distribution throughout the PV array. In this concept, the water will flow through the channels and the solar cells are laminated on top of the channels. The water decreases the cell temperature by absorbing the heat and produce hot water.

The research has been going on in the field of hybrid photovoltaic thermal collector. The main concepts of this type of collectors has been introduced in [4], they used water and air as a fluid coolant. A non-empirical structure of the PVT system has been presented in [5] which also includes the usual solar thermal concept. In [6], a performance analysis has been done on hybrid collector.

The transfer of the energy between the different components of the hybrid PVT system by the use of liquid coolant has been analyzed [7]. The study on the PVT air heating system in simple and alternative glazing system has been discussed [8].

Various research work has been published such as the hybrid PVT collector integrated with the system in [9], [10], and [11].

The air cooled PV modules for the building integrated photovoltaic system has been proposed in [12-15]. In these research, the modelling of PV modules has been discussed. In [16], the building integrated air-cooled photovoltaic system include the multi-operational PV with solar air collectors and the ventilated building PV facades has been discussed in [17-19], also the design process for cooling air to reduce the efficiency loss has been proposed in [20].

Moreover, in [21], the reliability analysis has been done for a building integrated photovoltaic-thermal system, the TRANSYS software has been used to simulate the system for different latitude [22]. In [23], [24] the performance improvement of the PVT system has been discussed. The objective of this paper is to introduce a new PVT collector design, analyzing its thermal and electrical performance, and compare with an off-the-Shelf PVT collector.

2. A proposed design of Concentrating Asymmetric Photovoltaic/Thermal Collector (CPC-PV/T)

The modules manufactured and marketed by Solarus AB. This model has evolved from the MaReCo (Maximum Reflector Collector) design. This model came from Vattenfall's solar energy research program. It has an asymmetric concentrator which means the receiver located to the side of the concentration trough rather than in the center. This gives a Compound Parabolic Concentrator (CPC) shape to ensure that reflected light reaches the receiver.

This asymmetric design is basically suited for thermal applications in northern and southern climates, and was designed to provide maximum thermal heat in the winter. This is achieved because of the unique acceptance angle of the modules.

The collector has an aluminum plate, inside that plate it has hollows to flow liquid. The solar cells are laminate on the aluminum plate. The backside of the plate also has PV cells and to concentrate solar radiation, a parabolic concentrator has been used in the design.

The concentration factor of the parabolic concentrator is around 1.5, which is low. Though, the concentrator is able to affect the cell efficiency of the PV cells by increasing its temperature.

To reduce the temperature, the water has been flown into the hollows. Therefore, it increases the electricity generation and also hot water by absorbing the heat. The parabolic reflector which has been used in this system is made of anodized aluminum and the reflection coefficient of around 95% [25]. As it is depicted in the figure 1, the optical axis of the concentrator is 90 degrees to the covering glass of the collector. The glass cover of the collector made of low iron glass with solar transmittance of 0.9 at normal incidence angle.

This asymmetric design is basically suited for thermal applications in northern and southern climates, and was designed to provide maximum thermal heat in the winter. This is achieved because of the unique acceptance angle of the modules.

There are four PV strings in the receiver, two of them are at the font side and other are on the backside. Each string consists of 38 PV cells. The total number of PV cells per receiver is thus 152 cells. The total area of PV cells on a receiver was approximately 0.58 m². The system has been made in such a way that the active glazed area is maximum, in this case it is 0.87 m². In [26], the active glazed area has been defined as the area of the both cells but avoiding the area of the edges and spaces between cells [26].

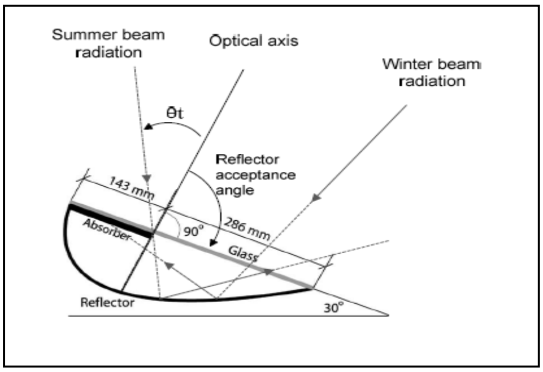

Fig. 1: Basic Geometry of Solarus PVT collector

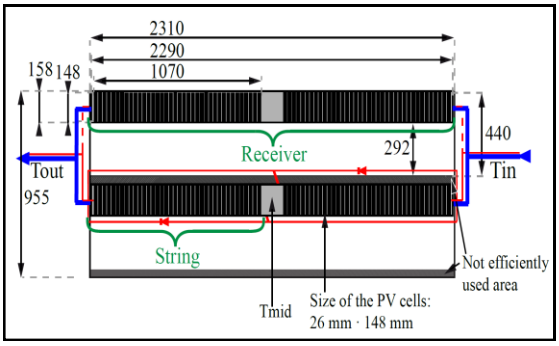

Fig. 2: Cell configuration of Solarus PV/T collector

The total area of the PVT system is 2.21 m². The height of the reflector which contributed to the electricity generation is 0.292 m. The height of the parabolic trough is 0.44m. This height includes the effective height of the concentrator and also, the height of the PV cells.

3. Thermal Analysis

The collector has a unique frame where the two collectors are placed. The two absorber plates were painted by the two selective surfaces (paints).

The collectors were facing the south during the measurements with a fix tilt of 45° as shown in Figure 3. Global and diffuse irradiation were measured by the two pyranometers, they were mounted on the collector plane, with a static shading ring was mounted in front of the pyranometer which was measuring the diffuse irradiation, as shown in Figure 4.

Fig. 3: Picture shows how the Thermal collectors were installed

The inlet and outlet temperatures of the collector were measured with temperature sensors (Pt 100) as shown in Fig. 5. Flow rates have been measured by the two inductive flow meters, a data logger stores data every 10 seconds during the evaluation period.

Fig. 4: The two pyranometers for measuring the global and diffuse irradiation, mounted in the collector plane

Fig. 5: Collector inlet side with Pt 100 sensors inside

Before the two collector troughs with different selective surface coatings are compared, the trough which has to be compared originally it was planned to do measurements on a solar thermal low-concentrating collector to see if the two troughs identical in geometry and material properties, to show the same performance. Although identical, there is a risk that the heat losses from the lower trough will heat up the upper trough through convection, and therefore reducing the heat losses from the upper trough. There is no air exchange between the two troughs and therefore it is assumed that the heat losses from the front side will be equal. Eventually there will be an air movement from both sides of the lower trough by convection through the air to the upper trough, which will reduce the heat losses from the upper trough. Another phenomenon could be tested is the air between the trough on the back side of the collectors heated, which affects the heat losses from the two troughs differently.

Two thermometers were placed under each trough to see the difference in temperature, if really there are more losses in one trough comparing to the other. We measured the two temperatures of the both troughs, we found the same temperature, and therefore it can be assumed that any heat loss between the troughs mainly depends on the different absorber paints.

Fig. 6: It shows the temperature reading of the two trough

Calculation

Measurements of the temperature inlet and outlet of the liquid in the collector, the ambient temperature, hemispherical radiation in the collector plane and the flow rate, allow us to evaluate the thermal performance of solar collectors, The EN 12975 standard has been maintained during the thermal performance analysis of the collector. The overall efficiency is defined as in Equation 1, with C_p is the specific heat capacity, A_c is the aperture area of the collector and $\dot{m}$ is the mass flow rate. The specific heat capacity of the water varies with water temperature; therefore it should take into an account the mean temperature of the liquid in the collector.

$$\eta = C_p \dot{m} (T_{out} - T_{in}) / G_T A_C \quad (1)$$

The thermal performance measurements make the calculation of the optical efficiency η_0 of the solar collector possible, by rearranging the Equation 1 in Equation 2.

$$\eta_0 = qF'U_L(T_m - T_a)/G_T \quad (2)$$

Where, G_T= Global annual radiation on a tilted surface.

T_{out}=Outlet temperature of the fluid

T_{in}= Inlet temperature of the fluid

$F'U_L$= Heat loss.

This evaluation has been done to show the difference in performance between the two troughs, which belong to the same solar collector. The solar collector was mounted facing south. The first is painted with mate (Q Loss) and the second is painted with a glossy paint (Solkote), this evaluation will show which paint performs better, Therefore we had to vary the flow rate for different values, from 20 to 90 l/h with a step of 10, in order to have different DT/G with different efficiencies, for both troughs and plot the efficiency curve, as shown on the Figure 7, in order to define the optical efficiency and the heat losses.

The measurement devices which are used in the eperiemntal test have shown in the Table I.

The inlet and outlet water temperatures were measured using Pt 100, at an average hemispherical irradiance of 935 W/m^2 with varied water inlet temperature from 37°C to 25°C, which decreased with increasing the flow rate, the ambient temperature was almost constant at 16°C, with a variation of 1°C during the test and the hot water reached to a maximum temperature of 53°C.

Table 1.Measurement devices used during the experiment

Measurement Devices	**Specification**	**Model**
Pyranometers	Operational temperature range: -40 °C to +80 °C. Maximum solar irradiance:4000 W/m²	Kipp & Zonen CM22
Temperature Sensors(for inlet/outlet fluid)	Temperature range: –30 to +350 °C. Accuracy:±0.15 °C @ 0 °C Class A	Pico Technology, PT100
Temperature Sensors(ambient temperature)	Temperature range: -40 to 110 -55 to 150 0 to 100 0 to 70	Texas Instrument LM35

The standard efficiency curves of the two troughs and its results are shown in Figure 7 and in Table II.

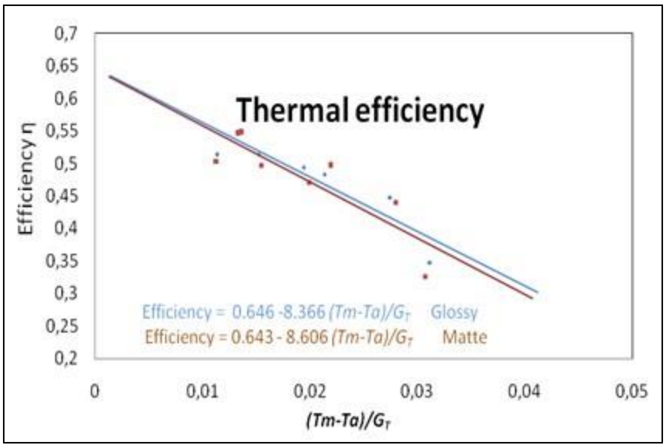

Fig. 7: The standard efficiency curves of the two troughs with different selective surfaces.

In the figure 7, the heat loss coefficient F'UL value is the slope of the graph and the intercept of the graph with the Y-axis is the optical efficiency, $\eta_{0.}$

The thermal efficiencies for both troughs with different painted absorber were found from the Equation 2 and based on the Gross area of each trough. Areas of both troughs are equal. The intercept of each line with the Y-axis defines the optical efficiency η_0 of each trough and the lines' slopes define their heat losses, these values are presented on the Table I.

The heat loss coefficient of the trough with Glossy[31] painted absorber as the slope of the line showed is $F'U_L$= 8.37 W/m$^{2°}$C. The intercept $F'U_L$ of the line with the Y-axis is 0.646, which represent an optical efficiency of about 65%. The trough with mate painted absorber has a slightly higher heat loss coefficient with $F'U_L$ = 8.61W/m^2°C, and slightly lower optical efficiency of 0.643 which represent almost 64%.

The two values of heat loss coefficient for the two troughs are quite high, if we compare them to the value which Solarus company report on their technical specification for this collector, because according to (Solarus AB, 2013) this collector has a heat loss coefficient of only 1.9 W/m^2°C, while the value which was found after the measurements is about 4 times higher. This could be happened due to the experimental environment and the company experiement condition is unknown.

There are some clear differences between the parameters, of both troughs, According to [27] only the operating conditions would decide which one should be used, and the range of values of DT/G_T that was expecting in an application, to heat a pool for example, no need for a high difference in temperature between the ambient and the absorber, in the other extreme case, when we make steam to turn a turbine we need a significant difference in the temperature at high efficiency for large values of DT/G_T.

Table 2. Heat Loss coefficient and Optical Efficiency

Trough	**Heat losses $F'U_L$ [W/m²°C]**	**Optical efficiency η_0**
Glossy	8.366	0.646
Matte	8.606	0.643

4. Electrical Analysis

4.1 Experimental Set up

The Solarus collector has been tested to analyze the electrical performance. The collector has been mounted at Alvkerleby Bruk, Gavle. The testing methodology was followed from L.R. Bernardo et al. (2011) [28] and Bernardo Ricardo et al. (2013) [20].

The solar irradiance was around 800W/m^2 and the average sunshine total hours of 1270 and an ambient temperature during operation of 13°C.

The collector was mounted in the outdoor testing laboratory at Solarus AB, Älvkarleby, Sweden (geo-coordinates: 60°33′58.9644'' North, 17°26′43.5984'' East), at an angle of 44° to the horizontal, facing due South. The laboratory was located in a section of the factory parking lot and due to the winter season the floor was covered with thick ice which has given a significant portion of the diffuse light, reflected from snow surface. So the collector's tilt has been chosen carefully to reduce the diffuse light.

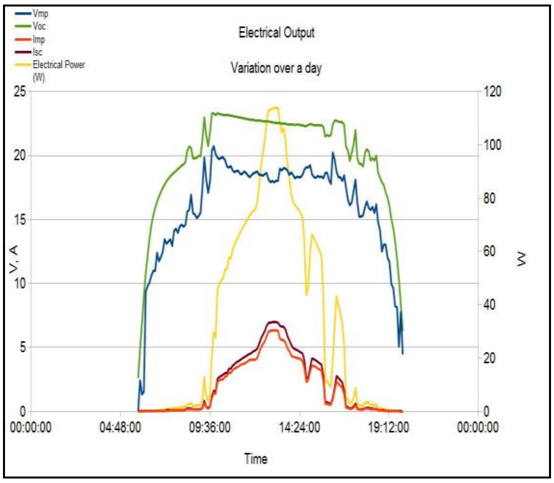

Fig. 8: Electrical output across a day

In figure 8, it illustrates that at the noon when the solar irradiation is high then we get higher electricity. It has some abrupt changes due to cloud and shading. The maximum electrical power was around 110W. It should be mentioned that here in this experiment only on trough has been tested. And one collector has two troughs.

4.2 Performance Analysis

4.2.1 Cell efficiency Vs Cell temperature

The changes in photovoltaic cell efficiency with cell temperature have been showing in figure 9. Cell electric efficiency is different from overall electric efficiency, as it is calculated based on the solar irradiance input to the cell area, whereas overall electric efficiency is based on the entire collector. The cell electric efficiency gives a better estimate of the operating conditions of the silicon cells in the receiver.

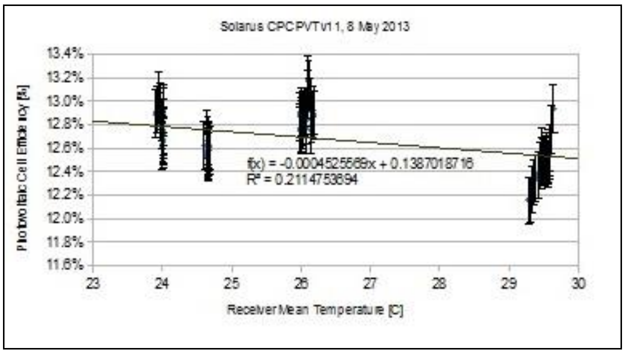

Fig. 9: Photovoltaic cell efficiency vs Receiver mean temperature

The collector was tracked to the sun in a vertical axis between each measurement, and the variation of the flow rate was between 15 l/h to 90 l/h in five even steps to control the mean cell temperature.

4.2.2 Electrical efficiency Vs Cell Temperature

The average electrical performance of a trough has been shown in the figure 10. It can be compared with other photovoltaic panels in order to observe the efficiency. At standard conditions (25 °C and 1000 W/m^2), the cells were operating at an efficiency of ~12.7 %. Though the manufacturer's datasheet states that the efficiency around 18.8% [29]. This is because of the glazing and reflection losses in the collector.

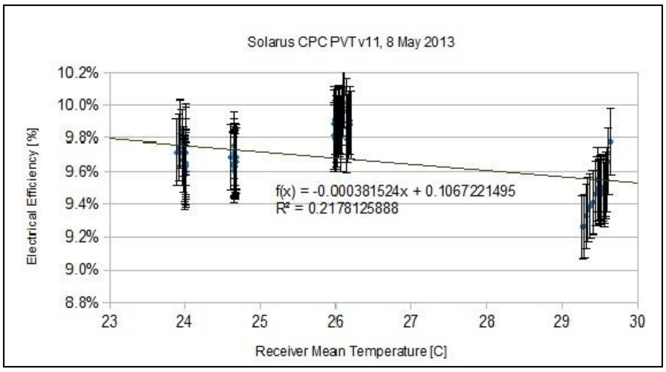

Fig. 10: Electrical efficiency (based on trough's aperture area) vs Cell temperature at University of Dalarna

4.2.3 Thermal efficiency Vs Reduced Temperature

The main cause of reducing efficiency in thermal collector is that the receiver loses heat by radiation. The reduced temperature is a proportional constant which in proportion to the collector heat loss. In figure 11, it shows how the receiver behaves as a thermal absorber.

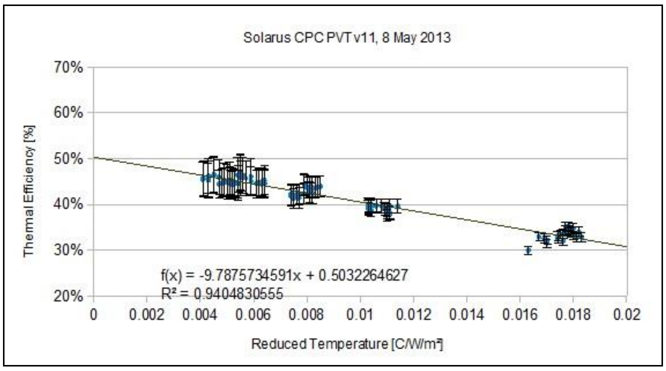

Fig. 11: Thermal efficiency vs reduced temperature

When the reduced temperature is zero (0), it means there is no loss. At higher temperature the losses from the collector increases significantly.

4.2.4 Thermal Vs Electrical Efficiency

The data of this analyzation have been gathered on 1st of April. This experiment gives an overall idea about the total efficient of the PVT collector.

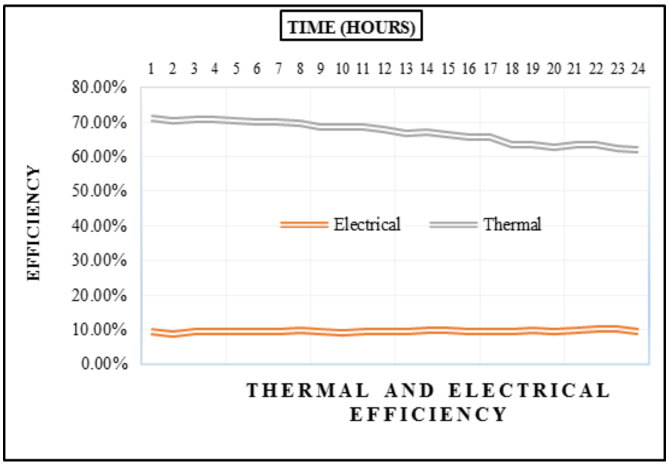

Fig. 12: Thermal vs Electrical Efficiency across a day

Discussion

A latest design [30] has been studied in order to compare the efficiency with the new collector discussed in this paper.

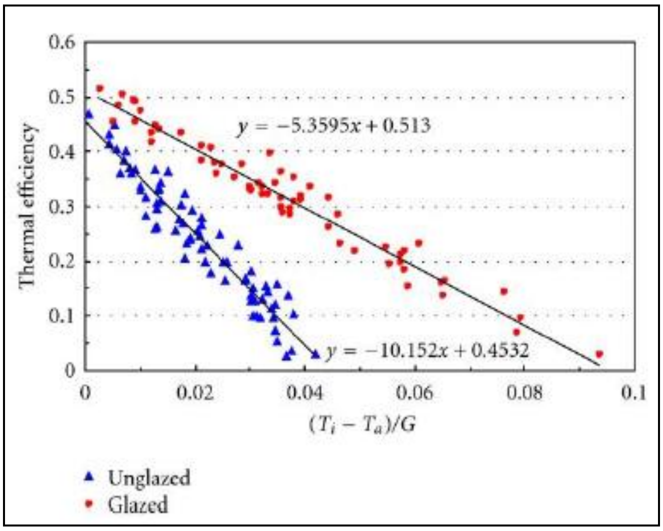

Fig. 13: Glazed and unglazed PVT collector thermal efficiency[30].

In figure 13, it is depicted that the thermal efficiency of the PVT collector is approximately 55%. Whereas in figure 12, the thermal efficiency of the proposed design is more than 60%.

Which concludes that from the literature review and the experiment data the new design able to show better performance.

5. Conclusion

In this paper, a novel PVT hybrid collector is proposed with a new design approach. The aim is to increase the total efficiency of the collector. The total efficiency of almost 80% is achieved.

The experimental results show that the experimented solar collector has higher efficiency than an off the shelf PVT collector.

The detailed discussion and thermal and electrical performance analysis of a PVT system have been determined in this paper.

The determined efficiency of this system is higher than combining the individual efficiency of solar and thermal collectors. This is because, the excessive heat has been converted to useful energy. Advantages of PV/T collectors include higher electricity output than a standard PV panel, Maximizes available roof space and Lower installation costs.

Acknowledgements

The author is thankful to Solarus AB and Joao Gomes for their support and advices during the research work.

References

[1] J Xu, Xinqiang, et al. "Performance and reliability analysis of hybrid concentrating photovoltaic/thermal collectors with tree-shaped channel nets' cooling system." IEEE Transactions on Components, Packaging and Manufacturing Technology 3.6 (2013): 967-977.

[2] Radziemska, E. "The effect of temperature on the power drop in crystalline silicon solar cells." Renewable Energy 28.1 (2003): 1-12.

[3] Royne, Anja, Christopher J. Dey, and David R. Mills. "Cooling of photovoltaic cells under concentrated illumination: a critical review." *Solar energy materials and solar cells* 86.4 (2005): 451-483.

[4] Kern Jr, E. C., and M. C. Russell. *Combined photovoltaic and thermal hybrid collector systems*. No. COO-4577-3; CONF-780619-24. Massachusetts Inst. of Tech., Lexington (USA). Lincoln Lab., 1978.

[5] Hendrie, Susan D. "Evaluation of combined photovoltaic/thermal collectors."*Presented at Intern. Solar Energy Soc. Meeting, Atlanta, 28 May 1979*. Vol. 1. 1979.

[6] Sopian, Kamaruzzaman, et al. "Investigation into the performance of a double pass photovoltaic thermal solar collector." *ASME*. 1995.

[7] Bergene, Trond, and Ole Martin Løvvik. "Model calculations on a flat-plate solar heat collector with integrated solar cells." *Solar energy* 55.6 (1995): 453-462.

[8] Garg, H. P., and R. S. Adhikari. "Performance analysis of a hybrid photovoltaic/thermal (PV/T) collector with integrated CPC troughs."*International journal of energy research* 23.15 (1999): 1295-1304.

[9] Huang, B. J., et al. "Performance evaluation of solar photovoltaic/thermal systems." Solar energy 70.5 (2001): 443-448.

[10] Zondag, Herman A., et al. "The thermal and electrical yield of a PV-thermal collector." Solar energy 72.2 (2002): 113-128.

[11] Zondag, H. A., et al. "The yield of different combined PV-thermal collector designs." Solar energy 74.3 (2003): 253-269.

[12] Hegazy, Adel A. "Comparative study of the performances of four photovoltaic/thermal solar air collectors." *Energy Conversion and Management* 41.8 (2000): 861-881.

[13] Lee, W. M., D. G. Infield, and R. Gottschalg. "Thermal modelling of building integrated PV systems." *INTERNATIONAL SOLAR ENERGY SOCIETY UK SECTION-CONFERENCE-C*. 2001.

[14] Chow, T. T. "Performance analysis of photovoltaic-thermal collector by explicit dynamic model." Solar Energy 75.2 (2003): 143-152.

[15] Ito, Sadasuke, and Naokatsu Miura. "Usage of a DC fan together with photovoltaic modules in a solar air heating system." Proc. of ISES World Congress. 2003.

[16] Cartmell, B. P., et al. "A multi-operational ventilated photovoltaic and solar air collector: application, simulation and initial monitoring feedback." *Solar Energy* 76.1 (2004): 45-53.

[17] Infield, David, Li Mei, and Ursula Eicker. "Thermal performance estimation for ventilated PV facades." Solar Energy 76.1 (2004): 93-98.

[18] Guiavarch, Alain, and Bruno Peuportier. "Photovoltaic collectors efficiency according to their integration in buildings." *Solar Energy* 80.1 (2006): 65-77.

[19] Charron, Remi, and Andreas K. Athienitis. "Optimization of the performance of double-facades with integrated photovoltaic panels and motorized blinds."*Solar Energy* 80.5 (2006): 482-491.

[20] Brinkworth, B. J., and Mats Sandberg. "Design procedure for cooling ducts to minimise efficiency loss due to temperature rise in PV arrays." *Solar energy* 80.1 (2006): 89-103.

[21] Battisti, R., and Y. Tripanagnostopoulos. "PV/T systems for industrial applications." *Proc. 20th European PV Solar Energy Conf*. 2005.

[22] Kalogirou, Soteris A., and Y. Tripanagnostopoulos. "Hybrid PV/T solar systems for domestic hot water and electricity production." *Energy Conversion and Management* 47.18 (2006): 3368-3382.

[23] Tonui, J. K., and Y. Tripanagnostopoulos. "Improved PV/T solar collectors with heat extraction by forced or natural air circulation." *Renewable energy*32.4 (2007): 623-637.

[24] Tonui, J. K., and Y. Tripanagnostopoulos. "Air-cooled PV/T solar collectors with low cost performance improvements." *Solar energy* 81.4 (2007): 498-511.

[25] Energies Renouvelables; Energies Renouvelables. [ONLINE], Available at: http://www.energies-renouvelables.org; 2013.

[26] Duffie, John A., and William A. Beckman. "Solar engineering of thermal processes." (1980).

[27] McCrone, Angus, et al. "Global trends in renewable energy investment 2012." *Frankfurt School UNEP Collaborating Centre for Climate and Sustainable Energy Finance* (2012).

[28] Bernardo, Luís Ricardo, et al. "Performance evaluation of low concentrating photovoltaic/thermal systems: A case study from Sweden." *Solar Energy*85.7 (2011): 1499-1510.

[29] Chowdhury, Md. "Technical and economic analysis of a novel asymmetric PVT hybrid solar collector." (2013).

[30] Kim, Jin-Hee, and Jun-Tae Kim. "Comparison of electrical and thermal performances of glazed and unglazed PVT collectors." *International Journal of Photoenergy* 2012 (2012).

[31] http://www.solec.org/solkote/solkote-technical-specifications/