Available online at www.sciencedirect.com

ScienceDirect

Energy Procedia 91 (2016) 113 – 121

Energy Procedia

SHC 2015, International Conference on Solar Heating and Cooling for Buildings and Industry

Assessing the thermal performance of phase change material in a photovoltaic/thermal system

Maria C. Browne*, Declan Quigley, Hanna R. Hard, Sarah Gilligan, Nadja C. C. Ribeiro, Nicholas Almeida and Sarah J. McCormack

Trinity College, The University of Dublin, College Green, Dublin 2, Ireland

Abstract

Photovoltaic/ thermal (PV/T) systems refer to systems which integrate photovoltaic and solar thermal technologies and have the added advantage of producing both electrical and thermal energy. This study has been carried out to experimentally investigate the application of phase change material (PCM) in a thermal system under the climatic conditions of Ireland. In this system, a stainless steel container of PCM was integrated with a PV panel. PCM absorbs heat generated by the PV during daylight hours. Water is piped through the PCM and absorbs heat stored by the PCM. The application of the PCM alone was found to regulate the temperature of the PV panel by approximately 5ºC under climatic conditions of Ireland. This paper presents a method to assess the performance of a photovoltaic/thermal system with integrated PCM taking into account the useful heat energy gained by the water, stored by the PCM and the delay in available heat factor.

Peer-review by the scientific conference committee of SHC 2015 under responsibility of PSE AG

Keywords: Photovoltaic; thermal; phase change material

1. Introduction

The projected growth of the global energy consumption is 1.5 % per annum from 2010 to 2040 which corresponds to a 0.24 quadrillion kWh compared to 0.15 quadrillion kWh in 2010 [1]. Fossil fuels dominate global energy usage, accounting for 80 % in 2010, a figure which is not predicted change through to 2040 [1]. It is difficult

---

* Corresponding author. Tel.:+00353-1-896-4813.
E-mail address: brownema@tcd.ie

Peer-review by the scientific conference committee of SHC 2015 under responsibility of PSE AG
doi:10.1016/j.egypro.2016.06.184

to predict when fossil fuel reserves will be depleted, although it has been suggested oil, coal and gas will be depleted in 35, 107 and 37 years respectively [2]. Rapid deployment of renewable sources of energy must be made if global dependence on fossil fuels is to be reduced.

The EU's renewable energy directive sets a binding target of 20% final energy consumption from renewable sources by 2020 [3], an equivalent saving of 250 million toe (tonnes of oil equivalent) per year. Solar energy, wind power, hydropower and biomass are expected to play a major role in meeting these targets. The International Energy Agency (IEA) estimates approximately 885 million Terawatt hours [4] of energy reach the earth's surface from the Sun annually. Considerably larger than the global energy demand, predicted as 16,500 Mtoe (million tonnes of oil equivalent) for 2030 [5]. Solar energy is environmentally advantageous relative to any other energy source which does not compromise or add to global warming. Further benefits are an increase in national energy independence and security of energy supply due to consistent and abundant supply. However, the issue lies with how best to exploit solar energy and the most efficient and cost effective way to do so.

In order to decrease the global dependence on fossil fuels and also to play its part in global warming mitigation, renewable energy technologies must be developed further to become sustainable in the long term. Solar energy based technologies have enormous potential in delivering clean and reliable energy compared to other forms of energy. The scope behind this research is to design a Photovoltaic (PV) system which integrates a thermal collector to take full advantage of solar radiation, to generate electricity and to provide heat for water or space heating.

Nomenclature

Q_u = Useful energy gain (W)
A_{PV} = Surface area of PV (m^2)
G_{Tot} = Intensity of solar radiation ($W.m^2$)
T_i = Inlet temperature (ºC)
T_o = Outlet temperature (ºC)
T_a = Ambient temperature (ºC)
T_{IC} = Inside container temperature (ºC)
m_w = Mass flow rate of fluid (kg/sec)
C_p = Specific heat capacity of fluid (kJ/kg.K)
t_{ext} = Time period for which water can be heated outside of sunrise and sun set
$t_{sunrise}$ = Time of sunrise
t_{sunset} = Time of sunset
α = Absorption coefficient of plate
τ = Transmittance coefficient of glazing
m= mass (kg)
m_w= mass flow of water (kg)

1.1. Background

Photovoltaic panels and solar thermal collectors are the most common devices used to trap the suns energy to convert it to electrical or thermal energy. Photovoltaic (PV) technologies produce electricity directly using solar radiation. Typically 15 – 18 % of solar radiation incident on a PV module is converted to electricity and 82 – 85 % is converted to heat [6]. Solar thermal collectors convert energy from a solar resource to thermal energy which is transferred to its working fluid in solar thermal applications, generally providing domestic hot water or heating. Hybrid PV systems can generate electricity and heat simultaneously as the heat generated at the PV in a PV/T system is captured using a confined water or air flow. Passive removal of heat is a naturally induced temperature difference and the use of an external mechanical system is known as active or forced.

PCM absorb thermal energy as latent heat at a constant phase change temperature. At initial heating, a PCM heats sensibly and when the PCM reaches the melting/solidification temperature, the material absorbs latent heat, progressively melting. Melted PCM continues to warm further as it melts. The duration and temperature range over which the phase change takes place depends on the mass of PCM and the thermal conductivity of PCM and any enhanced heat transfer elements therein [7].

PCM with a suitable phase transition temperature can be used to regulate the temperature of PV cells [8-10] thus maintaining high efficiency for an extended period of time. For insolation of 500 W/m^2, a small scale system with capric:lauric and capric:palmitic were shown to maintain a lower PV temperature for the longest period, (up to 2.5 hours at 10 ºC lower than the reference system) [9]. A two-axis concentrating photovoltaic system thermally regulated by PCM was fabricated and tested outdoors in Pakistan. Lauric acid was found to reduce the peak PV temperature by 22 ºC and palmitic acid found a maximum temperature difference of 19.5 ºC. However, palmitic has a higher heat of fusion and temperature regulation capabilities [11]. The corrosive nature of some PCM and material pairs has been previously investigated using the immersion corrosion method [11].

2. Experimental set-up

The use of PCM has the advantage of storing heat energy that can be used asynchronously in a PV/T/PCM system. The system presented involves using solar energy to generate electrical energy, store heat and pre-heat water.

A stepped approach was taken when designing the experiment, starting from the reference, System 1(PV panel only), and building on System 1 to produce System 2 with an added heat sink (PV with container) to building on this to produce System 3 which included a PV with an integrated pipe network (PV/T system) and finally System 4 which included all previous components along with PCM energy storage (PV/T/PCM system). System 1 is a PV panel only and System 2 builds on this with an attached container referred to act as a heat sink. System 3 and System 4 have their PV panel removed to differentiate between each system. System 3 includes a pipe network within an empty container (air filled) and a tank and System 4 includes the pipe network within a PCM filled container. These systems are presented in Figure 1.

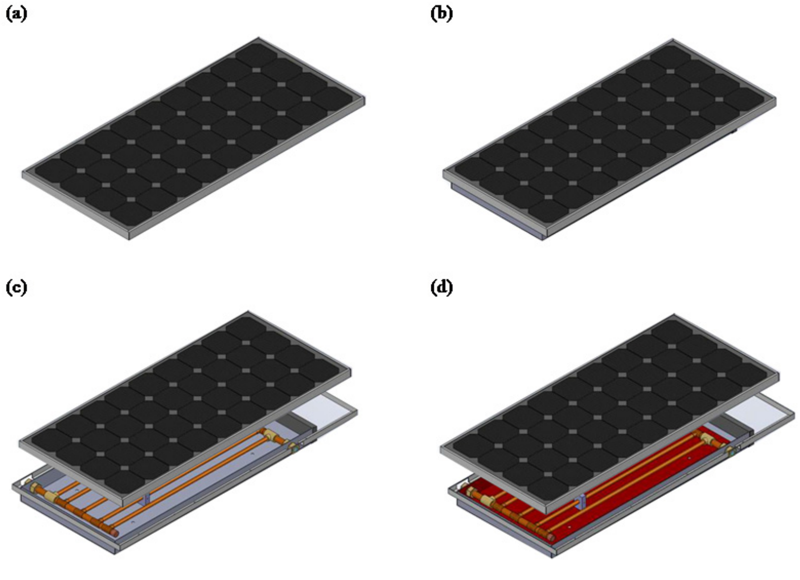
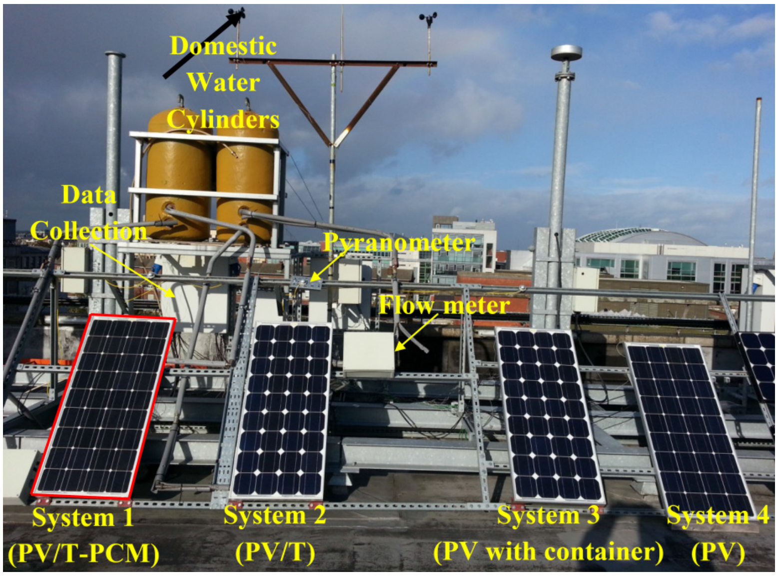
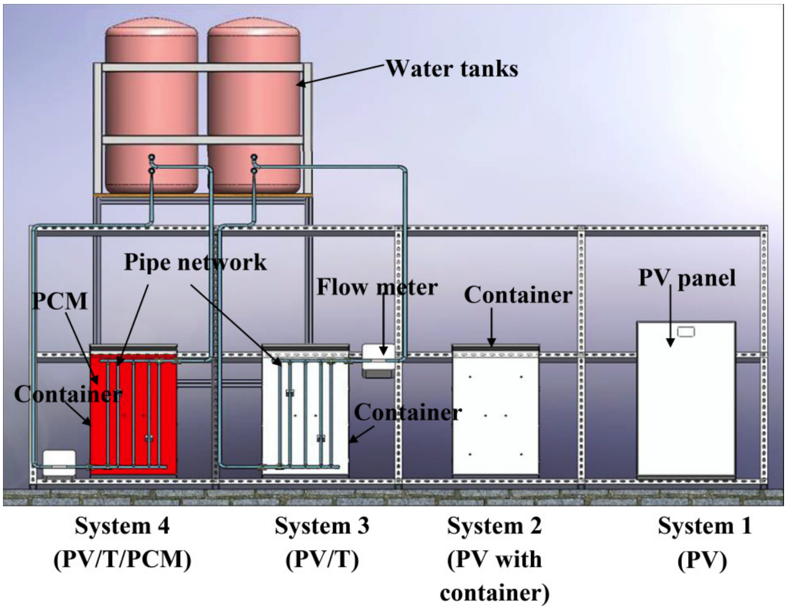


Fig. 1. (a) System 1 (PV System); (b) System 2 (PV with container) (c) System 3 (PV/T) (d) System 4 (PV/T/PCM)



(a)



(b)

Fig. 2. (a) Photograph of completed experimental set-up (b) cross–section drawing of experimental set-up

The objective of System 4 is to use the PCM as a method of storing heat during the day. As the temperature of the PV rises due to the increased solar radiation and ambient temperature during daylight hours, the PCM will charge using the heat transferred from the PV. At night when ambient temperatures decrease, the PCM discharges the stored heat to the water, pre-heating the water. The completed experimental set-up is shown in Figure 2.

The PCM used in the experiment was a fatty acid eutectic of capric:palmitic. The properties of which are presented in Table 1 which were found using Differential Scanning Calorimetry and were also reported in literature [12]. The PCM. There was approximately 20 kg of PCM integrated into the collector with a maximum latent heat storage capacity of 4590 kJ when fully charged.

Table 1: Thermophysical properties of capric:palmitic acid

Properties	Melting range (°C)	17.72 – 22.76
	Solidification range (°C)	12.33 – 15.55
	Heat of fusion (kJ/kg)	191.24
	Thermal conductivity (W/m.K)	0.143
	Specific heat capacity (kJ/kg.K)	2.3

3. Methodology

The thermal investigation compares the absorption of energy by each system and quantifies the amount of useful heat gain, heat stored, and the level of potential each system has to heat water if material conductivities were improved. It was necessary to consider the efficiency on a daily basis rather than an instantaneous efficiency as the pre-heated water was available at night.
Three terms were used to assess the heat energy distributed throughout the PV/T/PCM system are:

(i) Useful heat in the water flow, as shown in equation 1, calculates the useful heat output achieved:

$$\eta_u = \frac{Q_u}{A_{PV} * \ \alpha\tau * G_{Tot}} \tag{1}$$

Where,

$$Q_u = m_w C_{p,w} (T_o - T_i)$$

(ii) Stored heat in the container (equation 2) calculates the efficiency of the PCM to store thermal energy:

$$\eta_s = \frac{Q_s}{A_{PV} * \ \alpha\tau * G_{Tot}} \tag{2}$$

Where,

$$Q_s = m C_{p,IC} (T_{IC} - T_i)$$

In the case of System 4, the stored heat inside the container (Q_s) takes into account the latent heat stored by the PCM by changing the specific heat capacity according to the temperature.

(iii) Percentage of time for which the heat in the container is available to the water flow (equation 3) outside the hours of sunrise and sunset:

$$\left(\frac{t_{ext}}{24}\right) * 100 \tag{3}$$

Where,

$$t_{ext} = t_{T_{IC}>T_i} \qquad \text{When, } t < t_{sunrise} \text{ or } t > t_{sunset}$$

The term t_{ext} (Equation 3) was used to represent the time for which the heat was available in a PV/T/PCM system compared to a PV/T system. This equation is applied only to the hours outside of sunrise and sunset in order to assess the advantage of the integration of the PCM and its ability to store energy when the energy input, the sun, has gone down thereby, shifting the time of availability.

4. Results and Discussion

Investigation of the thermal performance of the novel PV/T/PCM system in real outdoor operating conditions was carried out in Dublin, Ireland to quantify the thermal performance of the system in comparison to three other reference systems using the equations presented in Section 3. The weather conditions for these days are presented in Figure 3.

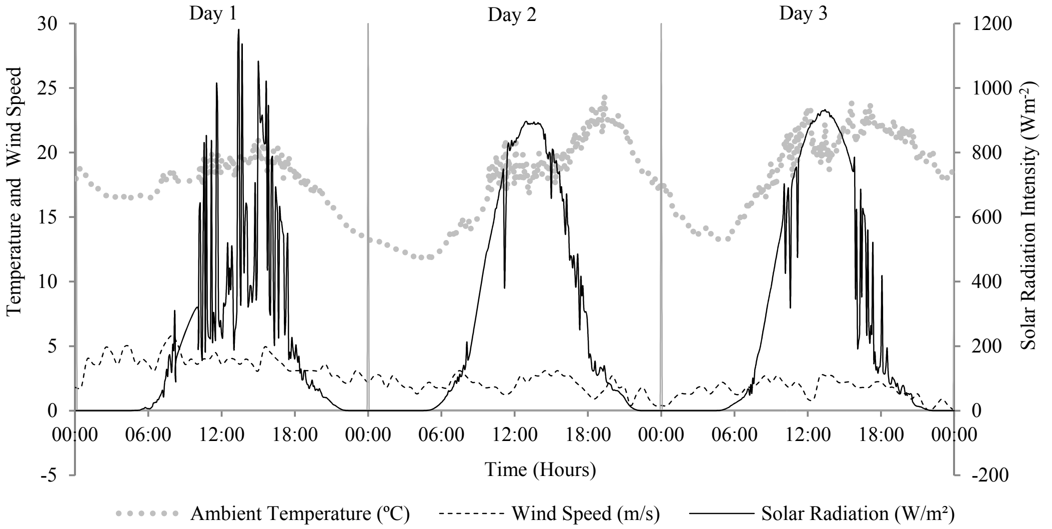


Fig. 3. Ambient temperature, wind speed measured and solar radiation measured in Dublin (53.33 N, 6.25 W) on the 4th - 6th of July 2013

The thermal investigation of a PV/T/PCM system compares the absorption of energy by each system and quantifies the amount of useful heat gain, heat stored, and the level of potential each system has to heat water if material conductivities were improved.

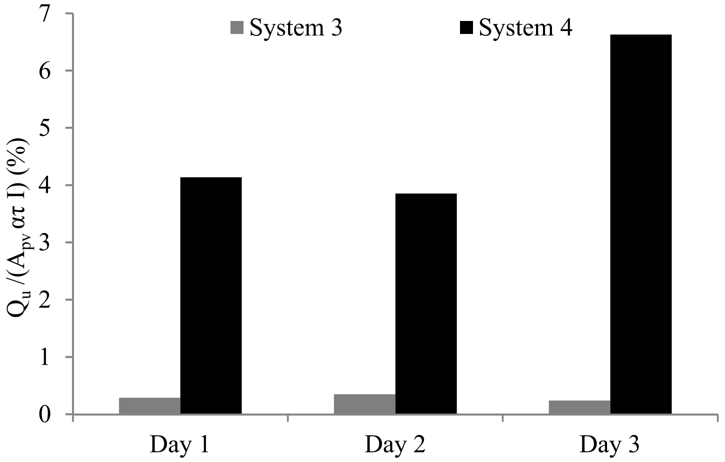


Fig. 4. Useful heat efficiency, η_u, of each system on Day 1, Day 2 and Day 3

The useful heat (Qu), which is the heat transferred to the water can only be compared between System 3 (PV/T) and System 4 (PV/T/PCM) as these systems contain a pipe network and tank. As a result, System 1 (PV) and System 2 (PV with container) have been removed from the graph as thermal efficiency is 0 %. As illustrated in Figure 4, System 3 (PV/T) can be seen to have a much lower efficiency of useful heat than that of System 4 (PV/T/PCM). The loss from the thermal collector is much larger in the PV/T system due to the absence of PCM. The PCM in System 4 can slowly release the heat to the water compared to System 3 where the heat is immediately available to the water which, if not transferred to the water, is lost to surrounding environment.

The stored heat efficiency, Q_s, is the amount of heat energy stored by the system compared to the amount energy made available by the income heat flux on a daily basis. System 4 (PV/T/PCM) was the only system to store the energy made available as shown in Figure 5, where the efficiency of System 4 (PV/T/PCM) reached values of up to 3.9 % (average 3.2 %).

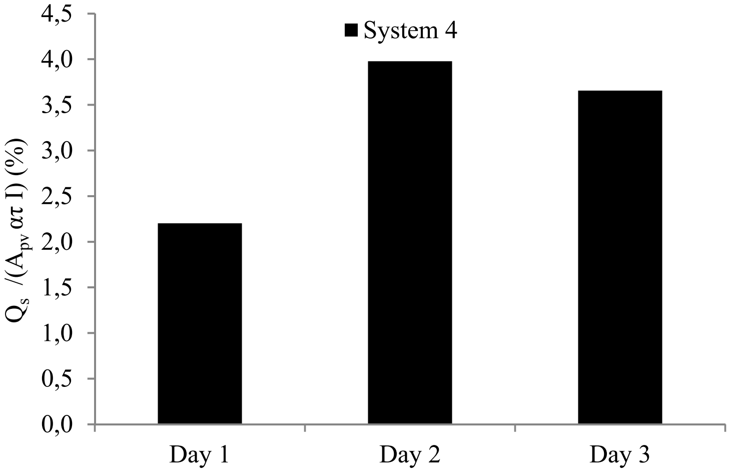


Fig. 5: Stored heat efficiency of System 4 on Day 1, Day 2 and Day 3

The PCM can be seen to be more efficient at storing the energy compared to other systems in the experiment. However, one issue is that a large quantity of the heat stored in the PCM is failing to reach the water. Methods to increase the heat transfer from the PCM to the water might include the installation of fins (metal conductors) around the pipe to increase the surface area for greater heat transfer.

The extended time of heat availability (t_{ext}) efficiency is the amount of time for which there is an opportunity to transfer heat from the inside of the container to the water, over a daily period. The added advantage of storage in System 4 (PV/T/PCM) is evident (from Figure 6) as the system can transfer heat for up to 28 % longer than that of the PV/T system.

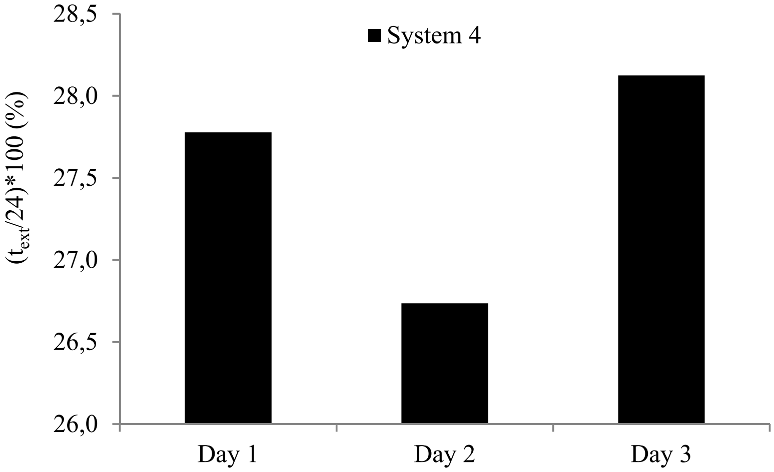


Fig. 6: Percentage of time for which the PCM extended heat availability each system on Day 1, Day 2 and Day 3

5. Conclusion

A novel PV/T/PCM system was installed and the investigation of the thermal performance of the system was carried out in Dublin, Ireland to quantify the performance of the system in comparison to three other reference systems over a three day period.

The equation took three terms into account: the gain in useful energy by the working fluid (water in this case), the heat stored by the system, and the time for which the heat is available to the working fluid. The thermal efficiency and the electrical efficiency were summed to give the cumulative efficiency of a system. The thermal efficiency of the novel PV/T/PCM system presented was found to range between 20 % - 25 %. However, it was noted that the release of heat from the PCM to the water needs to be improved by the increasing the thermal conductivity of the PCM or adding heat transfer enhancement techniques such as fins to the pipe network or within the container.

The thermal performance method presented applied could be used to assess the annual performance of the system, however, further data would have to be collected in order to assess this experimentally.

Acknowledgements

The authors would like to acknowledge the Higher Education Authority through GREP funding, Science Foundation Ireland through their Research Frontiers Program, COST Action TU0802 Next generation cost effective phase change materials for increased energy efficiency in renewable energy systems in buildings (NeCoEPCM) and European Union’s Horizon 2020 research and innovation programme under grant agreement No. 657466 (INPATH-TES).

References

[1] IEA, "International Energy Outlook 2013," Washington D.C.(25 July 2013).

[2] Shahriar Shafiee and Erkan Topal, "When will fossil fuel reserves be diminished?," *Energy Policy,* vol. 37, (2009), pp. 181-189.

[3] *Directive 2009/28/EC on the promotion of the use of energy from renewable sources and amending and subsequently repealing Directives 2001/77/EC and 2003/30/EC,* E. P. a. o. t. C. o. A. 2009,(2009).

[4] C. Philibert, "Solar Energy Perspectives - International Energy Acency Publication," (2011).

[5] K. H. Solangi, M. R. Islam, R. Saidur, N. A. Rahim, and H. Fayaz, "A review on global solar energy policy," *Renewable and Sustainable Energy Reviews,* vol. 15, (2011), pp. 2149-2163.

[6] H. G. Teo, P. S. Lee, and M. N. A. Hawlader, "An active cooling system for photovoltaic modules," *Applied Energy,* vol. 90, (2012), pp. 309-315.

[7] M. C. Browne, B. Norton, and S. J. Mc Cormack, "Phase change materials for photovoltaic thermal management," *Renewable and Sustainable Energy Reviews,* vol. 47, (2015), pp. 762-782.

[8] M. J. Huang, P. C. Eames, and B. Norton, "Phase change materials for limiting temperature rise in building integrated photovoltaics," *Solar Energy,* vol. 80, (2006), pp. 1121-1130.

[9] A. Hasan, McCormack, S. J., Huang, M. J., Norton, B., "Evaluation of phase change materials for thermal regulation enhancement of building integrated photovoltaics," *Solar Energy,* vol. 84, (2010), pp. 1601-1612.

[10] Ahmad Hasan, Sarah McCormack, Ming Huang, and Brian Norton, "Energy and Cost Saving of a Photovoltaic-Phase Change Materials (PV-PCM) System through Temperature Regulation and Performance Enhancement of Photovoltaics," *Energies,* vol. 7, (2014), pp. 1318-1331.

[11] Jawad Sarwar, "Experimental and Numerical Investigation of Thermal Regulation of Photovoltaic and Concentrated Photovoltaic using Phase Change Materials," PhD Thesis, Dublin Energy Lab, Dublin Institute of Technology, Dublin, Ireland, (2013).

[12] A. Hasan, S. J. McCormack, M. J. Huang, and B. Norton, "Characterization of phase change materials for thermal control of photovoltaics using Differential Scanning Calorimetry and Temperature History Method," *Energy Conversion and Management,* vol. 81, (2014), pp. 322-329.