Journal of Sustainable Development of Energy, Water and Environment Systems

http://www.sdewes.org/jsdewes

Year 2020, Volume 8, Issue 4, pp 622-640

Review paper

Potential for Mitigation of Solar Collector Overheating Through Application of Phase Change Materials – A Review

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Cite as: Ranilović, B., Grozdek, M., Potential for Mitigation of Solar Collector Overheating Through Application of Phase Change Materials – A Review, J. sustain. dev. energy water environ. syst., 8(4), pp 622-640, 2020,
DOI: https://doi.org/10.13044/j.sdewes.d8.0324

ABSTRACT

Demand for domestic hot water and heating is rarely perfectly concurrent with solar irradiation, which means that collectors can overheat in periods of high incident radiation and low demand. Phase change materials have been used as energy storage in space heating applications to absorbs excess heat during low demand periods for use in peak demand periods. This paper reviews the current state of research on the possibility of application of such materials as energy storage for solar collectors, in order to avoid collector overheating. Finally, various materials were evaluated and ranked for this application based on required properties and price. An example model of such materials being applied in a typical family house domestic hot water solar system is also provided.

KEYWORDS

Phase change materials, Overheating, Temperature of stagnation, Flat plate solar collector.

INTRODUCTION

One of the major limiting factors in large scale application of solar thermal collectors is their price. In mass production conditions economies of scale minimize many production costs present in smaller production runs. This makes limitations of the production process itself and the price of raw materials the primary driving forces behind high production cost. Currently the selection of materials used in collector design is relatively limited due to strict and often conflicting demands of necessary material properties. This in turn also limits the production processes which can be used. In an average collector there are strict requirements for thermal, mechanical and optical properties of the material. A significant cause of this problem is collector overheating, i.e. a high temperature of stagnation.

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The temperature of stagnation is the highest temperature reached by the collector when exposed to maximum incident solar radiation and high ambient temperature at a time when no flow through the collector is present. This can happen due to flow problems in the system, but its most common cause in normal collector operation is that the set point temperature in the hot water tank is achieved and the pump is turned off in order to avoid overheating the water in the tank.

The temperature of stagnation of the most basic flat plate solar collector design is high and regularly exceeds 150 °C. This limits the selection of materials for collectors to materials with high thermal stability and appropriately high melting points. In industrial practice this has meant that metals have been the most common materials used to produce collector absorbers. The use of alternative and cheaper materials such as polymers has been very limited. The primary factor limiting the use of polymers is the fact that most polymers undergo glass transition at temperatures as low as 100 °C. That temperature is much lower than the temperatures a standard flat plate collector's absorber reaches during stagnation.

In spite of these limitations there have been attempts to make a polymer flat plat solar collector. An example is the research by de la Peña and Aguilar [1]. This solution doesn't reduce the high temperature of stagnation, but instead uses a special polymer that is stable at high temperatures. The price of this material is high, and the overall price of the collector is not reduced compared to collectors made with industry-standard materials.

Another option discussed is the use of channels for air-cooling behind the collector, as presented by Hengstberger *et al.* [2]. Kessentini *et al.* [3] used a polymeric transparent insulation material. Föste *et al.* [4] approached the problem from another angle, and use butane instead of water as a heat transfer medium. In addition to these, thermotropic and thermochromic materials have shown promise. Significant reduction of absorbed solar radiation has been noted by this method by Muehling *et al.* [5]. Similar results were obtained by Föste *et al.* [6] and Hussain *et al.* [7]. This reduction is still not sufficient to enable the use of commodity polymers in every part of the collector.

The methods listed above aim to reduce or increase heat transfer to or from the collector during stagnation. Another approach was considered in Hengstberger *et al*. [2], by examining the use of Phase Changing Materials (PCMs) as a form of overheating protection. This potential solution is positively reviewed and potential PCMs suitable for further study were suggested. Forzano *et al.* [8] and Dehgahn and Pfeiffer [9] discuss integration of PCMs as energy storage in buildings in a method that may be transferable for collector applications.

The possibility of application of PCMs as overheating protection in solar collectors is a topic which has not been extensively researched so far. This paper aims to provide an extensive overview of currently available materials. It also aims to provide an analysis of their potential applicability in this application. To show the potential of this technology, an example PCM protected system will be given for a typical family house solar domestic hot water system.

OVERVIEW OF PHASE CHANGE MATERIALS

PCM are materials which undergo phase transition at a technologically advantageous temperature and have a relatively high latent heat of fusion. While phase transition can occur in any material, only a limited number meet these specific requirements. There are usually additional requirements which include, but are not limited to: non-toxicity, low or high thermal resistance, small volume change after phase transition, inertness in contact with other materials, durability, and affordability. All of these requirements make PCM selection a complex task which requires an in-depth analysis.

Mao *et al.* [10] provided an overview of low-temperature PCMs and their latent heat properties. Palomba *et al.* [11] gave an overview of PCMs used in non-concentrating solar applications and identified paraffinic materials and hydrated salts as the most promising solutions. Kahwaji *et al.* [12] provided a through overview of the properties of paraffins within the temperature range for building and domestic solar applications, giving important input values for future analysis. A similar analysis of materials was given by Tao *et al.* [13]. Raud *et al.* [14] provided a cost-effectiveness analysis of PCMs for solar thermal power. The required temperature range for solar application is under 100 °C, which includes all paraffins, but only a smaller number of other materials. Based on this data, it is possible to exclude materials with phase transition temperatures outside the range of applicability in domestic hot water solar systems. A partial overview of materials selected for analysis is given in Table 1 and is adapted from the work of Pereira de Cunha and Eames [15] and Sharma *et al.* [16].

Table 1. PCMs selected for evaluation (part of selection shown)

Material	Type	T_m [°C]	ΔH_d [kJ/kg]	$c_{p,s}$ [kJ/kgK]	$c_{p,l}$ [kJ/kgK]	ρ_s [kg/m^3]	Price [EUR/m^3]
Lauric acid	org.	44	212	2.02	2.15	1,007	319.66
Sodium sulph. decahydrate	inorg.	32	180	1.93	2.80	1,485	55.59
$CaCl_2$ $(H_2O)_6$ $MgCl_2$ $(H_2O)_6$	eut.	25	127	1.62	2.27	1,661	92.66
Stearic acid/palmitic acid	eut.	53	182	1.72	2.23	971	406.52
Paraffin 18	org.	28	244	3.00	2.00	894	486.44
Paraffin 22	org.	44	249	3.00	2.00	908	509.60
Paraffin 26	org.	56	256	3.00	2.00	922	532.77
Paraffin 30	org.	65	251	3.00	2.00	936	555.93

The table above is not exhaustive. Recent research methods for modifying PCM properties have been suggested which may add new materials for consideration. Xiao *et al.* [17] suggested employing copper foam as the supporting material in hydrated salt PCMs to enhance their thermal conductivity, which is a limiting factor in solar applications. Jin *et al.* [18] studied composite hydrated salt PCMs and reported an improvement in the solar thermal conversion efficiency, Rao *et al.* [19] reported good thermal properties for the same type of material.

Another suggested approach to modifying PCM materials is the use of micro and nano particles. Qiu *et al.* [20] gave a broader review of micro and nano PCMs in thermal solar applications focusing on thermal conductivity. Sivasamy *et al.* [21] investigated Ag-nanoparticles dispersed myristic acid. Sari *et al.* [22] investigated silica fume/myristic acid composite doped with carbon nanotubes. They found that with a melting temperature of around 54 °C it is a promising PCM for solar applications. Further investigation of fabrication of nano PCMs was given by Zhang *et al.* [23]. Chen *et al.* [24] proposed the addition of a small amount of CuO nano-powders to paraffins to increase light absorption. Hybrid nanofluids in solar systems are reviewed further by Shah and Ali [25]. They conclude that their use has economic and ecological benefits, but also acknowledge that there are drawbacks like instability, increased friction loses and rheological issues which prevent wider commercialization. Kumar *et al.* [26, 27] found that adding small amounts of silicon dioxide (SiO_2) nanoparticles increased the thermal conductivity of paraffin PCMs. Chen *et al.* [28] successfully used a composite carbon monolith with an organic PCM n-octadecane to achieve a high system efficiency. Li *et al.* [29] showed similar increases in thermal conductivity with the addition of graphite flakes to the PCM material.

Other researchers suggested a different approach with the use of micro or nano-encapsulated PCMs. Bao *et al.* [30] showed that the thermal conductivity of microencapsulated PCM cement composites decreases with the increase of nanosilica content, but improves with the presence of carbon fibers by up to 17.8%. This finding has implications for facade mounted solar collectors. Liu *et al.* [31] and Jian *et al.* [32] provided comparable results for other microencapsulated PCMs. Ma *et al.* [33] reported higher thermal conductivity and specific heat for another microencapsulated PCM.

Ma and Zhang [34] studied a nano-encapsulated phase change slurry used in a volumetric absorption solar collector, and found promising results.

While eutectic materials usually have transition temperatures outside the useful range for domestic solar, Dheep and Sreekumar [35] found promising results with long term thermal reliability, good heat storage properties and less corrosive nature with metallic components when using phenly acetic acid as a PCM in solar air heaters. Mawire *et al.* [36] compared a eutectic colder (Sn63/Pb37) with high density polyethylene inside similar spherical aluminum capsules. They found that Sn63/Pb37 shows potential for medium temperature applications. A new eutectic PCM with a melting temperature of 75.56 °C was described by Purohit *et al*. [37]. It was then tested experimentally in a solar thermal system with good results. A solar thermal storage system using stearic acid/palmitic acid eutectic PCM had a higher charging efficiency compared to paraffin and puretemp68, as reported by Prakash *et al.* [38]. The behavior of a stable-form PCM created by impregnating delignified wood with capric-palimitic acid eutectic mixture was investigated by Ma *et al.* [39] and showed promising results. However, with a transition temperature as low as 23.4 °C this material has to be excluded from the applications considered in this paper. Rea *et al.* [40] considered an aluminum-silicon eutectic as a PCM, but the phase change temperature is too high for domestic solar applications. Calabrese *et al.* [41] researched the corrosion behavior of three metal alloys when exposed to a salt hydrate PCM. Additional research is still necessary to explore the behavior of polymer tanks with PCMs.

PCM emulsions are another approach to this issue. This promising technology for increasing energy storage capacity of solar systems has so far been limited because emulsions can become unstable and lose their properties. Agresti *et al.* [42] described a new way of stabilizing PCM emulsions and their solution provided a gain of up to 40% in thermal capacity and long-term emulsion stability, but it had issues with undercooling.

Another proposed way of increasing effectiveness of PCM materials is by increasing heat transfer in the storage tank by employing a novel fin design. Singh *et al.* [43] found that a reduction of 43% in melting time can be obtained by the use of a novel configuration in combination with graphene nanoplates. Zhou *et al.* [44] studied the use of PCMs as anti-freeze protection with good success. A composite aerogel-paraffin PCM was investigated by Min *et al.* [45]. This material was found to have a high thermal conductivity and therefore fast charging. Xiao *et al.* [46] described a novel light-to-thermal phase change hydrogel, which can be integrated in a solar collector. Alva *et al.* [47] suggested the use of branched polyurethane copolymers as PCMs. It has to be noted that its charging and discharging temperatures are not ideal for the use discussed here.

Addition of graphite or graphene to PCMs is also suggested in literature. The review by Allahbakhsh and Arjmand [48] outlined the recent progress in employing graphene-based nanostructures for mitigation of problems with low thermal conductivity and shape-instability in PCMs. Gu *et al.* [49] described the experimental process used to obtain a form stable PCM from palmitic acid, mullite and graphite. They achieved improvements in thermal conductivity over pure palmitic acid. Han *et al.* [50] demonstrated that a form stable PCM can be achieved using composite expended graphite. No change was reported in thermal properties over as many as 500 cycles. This research has provided experimental data aimed to enable the use of such materials in engineering design.

METHODS OF INTEGRATION OF PCMs AND NUMERICAL ANALYSIS

PCMs need to be integrated into a solar system to be an effective overheating protection. This section of the paper gives an overview of possible methods of integration of PCMs and their feasibility for domestic solar collector application.

Building integration is one possible method of solar collector installation. Zhou *et al.* [51] gave an overview of PCM integration into a building's envelope. This may serve as a basis for research focusing in façade-mounted collector integration. A similar approach was outlined by Saxena *et al.* [52]. They found a temperature reduction of 5-6 degrees in comparison with conventional solutions. Garnier *et al.* [53] discussed a novel building integrated solar water heater and showed good results with limited stratification. A similar example is given by Vanaga *et al.* [54]. Vasquez *et al.* [55] used a solar accumulator detached from the collector. Muhumuza *et al.* [56] described the use of small volumes of PCMs as a heat transfer fluid to create thermal diodes which increased collection efficiency. The optimization of the amount of PCMs in traditional building materials was studied by Ryms and Klugmann-Radziemska [57]. This approach could potentially be expanded to other materials, such as collector frames. Another example of integration of a PCM into a building's structure in parallel to a solar system was shown by Dehghan and Pfeiffer [58]. In this case the two are not directly connected in a single system. A similar study was done by Zhou *et al.* [59] and Bouhal *et al.* [60]. An analysis of PCMs used in concentrating solar plants was given by Tehrani *et al.* [61]. Shafieian *et al.* [62] considered the same problem in relation to heat pipe solar collectors. Asgharian and Baniasadi [63] reviewed the use of PCMs in general applications. They found that PCM integration decreases average photovoltaic panel temperature by 9.7%. In a part of their review, Fertahi *et al.* [64] presented results of different studies covering the problem of integrating PCMs in stratified storage tanks. Yuan *et al.* [65] explored the use of PCM to delay overheating of a PV cell during the day and increase its temperature overnight. The operational principle is the same as the one discussed in this paper, though with a different intended application. A similar study was performed by Ma *et al.* [66].

It is important to consider the optical system of a solar collector when discussing the issue of overheating. This section gives a brief overview of the optical properties of PCMs which can be applied in solar collectors. Zhu *et al.* [67] described a composite window which uses a highly selective coating of cesium tungsten bronze in combination with a paraffinic PCM. This combination protects the window from overheating. An overview of the behavior of the collector's optical system when a PCM is integrated in the glazing was given by Liu *et al.* [68]. Abuska *et al.* [69] investigated the use of a honeycomb core for a flat plate solar air collector with a PCM-Rubitherm. They found that the heat conductivity was increased. This increase was particularly significant during the discharge period, but it also slightly reduced efficiency. Similar findings were reported by Egolf *et al.* [70] and again by Abuska *et al.* [71]. Wang *et al.* [72] suggested integration of PCM with the buildings and active management on a day-ahead scheduling basis. This could also be applied in principle to mitigate overheating.

PCMs can also be integrated within the tank of the solar system. A number of papers covering this scenario are presented here. Mousa *et al.* [73] studied the behavior of a water tank with integrated PCM pipes, both theoretically and experimentally. Zhou *et al.* [74] investigated a solar system with a PCM in the storage tank and found an improvement in the solar fraction of the system. A numerical comparative approach towards the same problem was provided by Bouhal *et al.* [75]. Mahdi *et al.* [76] used numerical simulations to study the behavior of paraffin wax in a shell and tube latent heat thermal storage unit and found that the addition of fins enhanced the melting process by an average of 50%. A similar analysis of a finned absorber plate was given in by Josyula *et al.* [77]. Reyes *et al.* [78] described the use of a combination of two different paraffins with different melting temperatures to enhance the discharge efficiency of a solar thermal system. They found that a combination of two materials is beneficial if the lower melting temperature material is placed first.

Experimental verification is expensive and time consuming, so numerical simulations can provide a cost-effective method for testing new PCMs and methods of their application. The following section presents an overview of latest research and work in this field.

Al-Musawi *et al.* [79] developed a numerical model to investigate the use of a PCM as coolant in a photovoltaic thermal system. They found an increase of 8% in electrical and

25% in thermal efficiency in the case where a PCM is used. PCM integration in a photovoltaic thermal system was also experimentally tested by Choubineh *et al.* [80]. A similar model was developed by Rabie *et al.* [81] for a concentrator photovoltaic system. Motte *et al.* [82] presented a mathematical model of a PCM thermal process in a solar collector system. They focused primarily on heat loss reduction and overall performance improvement. The behavior of PCM in a solar chimney system was simulated numerically by Xaman *et al.* [83]. A similar model was developed by Fadaei *et al.* [84]. This is conceptually similar to a PCM integrated in a ventilated collector, and as such may be of interest for further research. A theoretical model for a solar desalinator with a PCM was given by Abu-Arabi *et al.* [85]. It showed good agreement with experimental results. Swami *et al.* [86] used a similar approach for solar dryer with PCM. Yadav *et al.* [87] provided a CFD simulation of the drying process in a system with a PCM. Amirifard *et al*. [88] suggested the use of PCMs for solar ponds. They found a 6.1% increase in charging time. Plytaria *et al.* [89] discussed the use of PCMs in solar cooling. They reported that the use of PCMs provided an up to 30% reduction in auxiliary energy. Wei *et al.* [90] presented a novel PCM based thermal energy storage system. The thermal performance of this system was evaluated with a detailed analytic thermodynamic model. The results showed that such a system is feasible. Mao *et al.* [91] developed a similar model in MATLAB. An experimentally validated model of an integral solar collector which has a PCM storage section integrated into a flat-plate collector was developed by Bilardo *et al.* [92]. This model uses an electrical analogy scheme to model the behavior of the collector. Zhao *et al*. [93] provided a detailed overview of the practical application of PCM integrated solar heating in Tibet.

Hirmiz *et al.* [94] proposed a reduced analytical methodology for sizing PCM storage tanks based on a comparison of numerical and analytical methods. Gulfam *et al.* [95] provided an overview of the selection process for a paraffinic PCM. Numerical parametric analysis was conducted by Kazemian *et al.* [96]. It was found that an increase in the melting temperature of PCM employed in a photovoltaic thermal system increased the surface temperature and decreased the percentage of PCM melted. A review was given by Jimenez-Xaman *et al.* [97] on the current state of research in PCMs for solar chimneys. It had a particular focus on computational fluid dynamics and global energy balance models. Based on this, a new model was formulated by Vargas-Lopez *et al.* [98]. Reyes *et al.* [99] showed that by using a fuzzy logic control system the period of energy retention of the PCM could be extended. In principle, the same should be true for the discharge from a PCM.

Elbahjaoui and El Qarnia [100] developed a model based on the finite volume method for a flat-plate collector with latent heat storage units composed of rectangular slabs. This model was later used by Elbahjaoui and El Qarnia [101] to perform an optimization study for a solar system in Marrakesh. A similar analysis was given by Allouhi *et al.* [102]. Sarbu and Dorca [103] provided a review of PCM materials followed by a two-dimensional heat transfer simulation model using a control volume technique. Forzano *et al.* [104] gave a model for energy savings per m^3 of PCM integrated into a building's envelope. This is similar in its approach to the evaluation presented in this paper. A model for encapsulated PCMs was given by Raul *et al.* [105]. Augspurger *et al.* [106] provided a model for solar salts.

EVALUATION OF PHASE CHANGE MATERIALS

To determine the usefulness of individual PCMs it is necessary to compare them to a standard solution. In this paper that solution is taken to be a larger water tank. The first step in this evaluation process is to calculate the effective heat capacity (c_{ef}) [Wh/kg] for all considered materials. This is done using equation:

$$c_{\mathrm{ef}} = \left[(T_{\mathrm{m}} - T_{\mathrm{low}}) c_{p,\mathrm{s}} + \left(T_{\mathrm{high}} - T_{\mathrm{m}} \right) c_{p,\mathrm{l}} + \Delta H_{\mathrm{m}} \right] \times 0.27778 \tag{1}$$

It includes both sensible and latent components. T_{m} is the transition temperature of the PCM. The variables $c_{p,\mathrm{s}}$ and $c_{p,\mathrm{l}}$ are the heat capacities of the solid and liquid states of the PCM. ΔH_{m} is the latent heat of fusion. These values are given for individual PCM in literature as stated in the previous section. The value of 0.27778 is used to convert the kJ/kg heat capacities found in literature into the desired Wh/kg unit. Before calculation it is necessary to check that the temperature of fusion falls between T_{low} and T_{high}. If not, then the appropriate term is removed from the equation, and in the other term T_{m} is replaced by T_{high} or T_{low}, respectively. ΔH_{m} also needs to be disregarded in the case where T_{high} is lower than T_{m}.

For this analysis T_{low}, the temperature the PCM tank reaches after overnight cooling is taken to be 20 °C. T_{high} is the highest allowed temperature in the solar system and therefore the tank. In this case it is set at 70 °C. This is well below the glass transition temperature of most commodity plastics which is between 90 and 120 °C. While it is true that heat transfer to and from PCMs is limited by their high thermal resistance, i.e. low thermal conductivity, the focus of this paper is on PCMs and tank design is beyond its scope. It should be noted that specific solutions were discussed by Faegh and Shafii [107], Khan *et al.* [108], Silva *et al.* [109], Liu *et al.* [110] and Kapsalis and Karamanis [111]. Guidelines outlined in these reviews are considered in this evaluation, but are not included in the calculation process.

Using eq. (1) the baseline value for c_{ef} for water ($c_{\mathrm{ef,w}}$) can be calculated as 58.1 Wh/kg. The density of water is taken from the literature for T_{high}. The values obtained for other materials are then compared with water using equation:

$$r_{\mathrm{ef}} = \frac{c_{\mathrm{ef,PCM}} \times \rho_{\mathrm{s}}}{c_{\mathrm{ef,w}} \times \rho_{\mathrm{w}}} \times 100 \tag{2}$$

The values of heat capacity and density are taken for each PCM that is considered, based on eq. (1) and data from literature. Based on r_{ef} [%] another selection can be made. All PCMs which have a r_{ef} smaller than 100% can be discarded, since using water is more volumetrically favorable than using such materials. As water is significantly cheaper than all considered PCMs, there is little reason to use PCMs instead of water if there is no decrease in tank volume.

To determine the economic viability of the remaining PCMs, the required capacity of the PCM tank needs to be determined based on the installed area of collectors of a domestic hot water solar system. The simulation model includes a flat plate collector array. To be applicable for polymer solar collectors the outlet temperature of water in the collector array (T_{w}) was set to 70 °C. This temperature is high enough to allow the water in the tank to be heated to a temperature above 60 °C and low enough to be below the glass transition temperature of most commodity plastics. The efficiency of the solar collector was calculated using equation, taken from Rodriguez-Hidalgo *et al.* [112]:

$$\eta_{\mathrm{NC}} = 0.85 - 4.07 \left(\frac{T_{\mathrm{w}} - T_{\mathrm{a}}}{G_{\mathrm{T}}} \right) - 0.007\, G_{\mathrm{T}} \left(\frac{T_{\mathrm{w}} - T_{\mathrm{a}}}{G_{\mathrm{T}}} \right)^2 \tag{3}$$

Collector inclination was set at an angle which ensures perpendicular incidence of solar radiation at noon and an intensity and temporal distribution for the summer solstice at a latitude of 45° North. This determines the incident angle (θ_{inc}) on the collector. The ambient temperature was set to 35 °C to simulate high temperatures in the summer. These inputs are shown in Table 2.

Table 2. Maximum incident solar radiation per hour

Time [h]	6	7	8	9	10	11	12	13	14	15	16	17	18
θ_{inc} [°]	−90	−75	−60	−45	−30	−15	0	15	30	45	60	75	90
Q_{diff} [Wh/m^2]	43	55	126	140	159	162	153	179	178	101	89	56	27
Q_{beam} [Wh/m^2]	239	395	481	600	684	747	777	729	665	640	518	394	255

Values in the table above were obtained from the Photovoltaic Geographical Information System (PVGIS) of the European Institute for Energy and Transport. The values are given for a location with longitude 16°E and latitude 45°N, during the summer solstice. Q_{diff} is the diffuse component of incident solar radiation. Q_{beam} is the direct (beam) component of incident solar radiation. Reflected incident radiation from surrounding surfaces has to be disregarded to generalize the case considered, since reflected radiation entirely depends on the local conditions on site. The total incident radiation on the collector surface is given by the following equation:

$$G_{\mathrm{T}} = Q_{\mathrm{beam}} \times \cos(\theta_{\mathrm{inc}}) + Q_{\mathrm{diff}} \tag{4}$$

This is the maximum hourly value that can be transferred into the PCM tank by a collector array with ideal efficiency. From this the minimum (theoretical) volume of the PCM tank that needs to be included in the system to prevent collector overheating can be calculated, considering a collector with real efficiency obtained from eq. (3). This is given by equation:

$$V_{\mathrm{min}} = \frac{\sum G_{\mathrm{T}} \times \eta_{\mathrm{NC}}}{c_{\mathrm{ef}} \times \rho_{\mathrm{s}}} \tag{5}$$

Minimum tank capacity required and price of the required PCM for each case are given in Table 3. The prices for PCMs are wholesale prices of the material, and do not include transport and installation costs, as that is beyond the scope of this analysis. Both the price and the volume are given per m^2 of flat plate collector surface. In real world applications they need to be multiplied by the actual installed area of the collectors. Values presented per m^2 of collector surface are more versatile as they enable easy calculation for different commercial collector setups.

Table 3. Evaluation of PCMs (part of selection shown)

Material	Type	T_m [°C]	ΔH_d [kJ/kg]	c_{ef} [Wh/kg]	r_{ef} [%]	V_{min} [m^3/m^2]	Price [EUR/m^2]
Lauric acid	org.	44	212	87.9	151.4	0.039	12.62
Sodium sulph. decahydrate	inorg.	32	180	86.0	148.1	0.027	1.52
$CaCl_2 (H_2O)_6 MgCl_2 (H_2O)_6$	eut.	25	127	65.9	113.5	0.032	2.96
Stearic acid/palmitic acid	eut.	53	182	76.9	132.4	0.047	19.03
Stearic acid – acetamide	eut.	65	213	85.0	146.4	0.042	23.75
Paraffin 18	org.	28	244	97.8	168.4	0.040	19.44
Paraffin 22	org.	44	249	103.6	178.5	0.037	18.92
Paraffin 26	org.	56	256	109.0	187.7	0.035	18.52
Paraffin 30	org.	65	251	110.1	189.7	0.034	18.84

DISCUSSION

Prices given in Table 3 provide a minimum cost of the necessary PCM, as the method outlined in the previous section does not take into account heat transfer efficiency or rate in the PCM tank. In practice an increase in PCM volume would be necessary depending on the exact configuration of the tank and its heat transfer system. However, since most listed materials can be used in a number of configurations then a comprehensive comparison would only be possible if all such configurations were compared. This is not feasible because of the wide scope and because data is not available for a wide variety of configurations. Therefore, most configurations would need to be either experimentally or numerically tested.

Further consideration needs to be given to health concerns for any solution with PCMs. Domestic hot water applications require a medium that is non-toxic to humans as there is a risk of contamination of hot water. This water may be ingested by humans in case of tank or heat exchanger failure. Paraffins are the safest PCM option in this respect as they are safe for human consumption. While some inorganic and eutectic PCMs have significantly lower cost per m^2 of collector the added cost of additional heat exchangers needed to separate them entirely from the domestic hot water circuit, and the potential danger in case of human ingestion may render them inapplicable.

Compared with water, PCMs are not as sensitive to low temperatures and are at no risk of damage if the PCM is cooled to lower temperatures during winter months since the phase change behavior is already accounted for in tank design. Such tanks are therefore suitable for external installation. This is also favorable for overnight heat dissipation. If the tank can be placed outside it can cool using outside air without affecting the heat balance of the building. The cooling will also be at a much higher rate than would be possible in a boiler room setup.

Finally, the applicability of PCM tanks as passive method of overheating protection needs to be further examined. This is due to the fact that they need to be in reserve during normal operation. Furthermore, they need a more complex regulation system to ensure that flow through their heat exchanger only occurs during collector stagnation. To achieve this, a separate pump or an automatic valve would need to be used. Both of these components are susceptible to various modes of failure. Failure of these components could then cause the collector to be left without overheating protection. Therefore, such a solution can’t be considered truly passive. In order to achieve a fully passive solution the PCM would need to be integrated in the collector, as suggested in Hengstberger *et al*. [2].

CONCLUSIONS

From the above analysis it can be concluded that PCMs have potential as overheating protection in solar collectors. Many of the materials reviewed offer advantages in terms of volumetric savings compared to using larger water tanks. The downside of such a system is cost as PCMs are significantly more expensive than water. Yet, the possibility of integration of PCMs directly into collectors or in tanks which can be left outside during the whole year, may justify their use regardless of cost.

Of the materials analyzed, two salt hydrates (sodium sulphate decahydrate and sodium thiosulfate pentahydrate) and two eutectic PCMs [$CaCl_2$ $(H_2O)_6$ $MgCl_2$ $(H_2O)_6$ and $Mg(NO_3)_2$ $(H_2O)_6$ $MgCl_2$ $(H_2O)_6$] proved the most cost-effective. These two salt hydrates also have the highest r_{ef} out of the materials that were analyzed. While paraffins take all top ten spots in terms of c_{ef}, their relatively low density means that they are not able to achieve as high a value of r_{ef} as these other materials. It should be noted, however, that paraffins still do achieve relatively high values of r_{ef} and Paraffin 30 ranks among the top ten materials considered here. Paraffins are very interesting materials as they offer significant advantages in terms of safety, given that they are safe for human ingestion.

Further research is recommended towards more practical applications of this technology and the design of a practical system which would employ PCMs as overheating protection in solar collectors. Future research should expand this model to take into account the heat transfer in the PCM itself, as that can be a bottleneck for the operation of the system and may influence material choice in the end.

NOMENCLATURE

c	specific heat capacity	[kJ/kgK]

G_{T}	insolation	[Wh/m^2]
r	ratio of volumetric heat capacities of Phase Change Material and water	[%]
Q	incident radiation per hour per unit of collector area	[Wh/m^2]
T	temperature	[°C]
V_{min}	minimal required volume of Phase Change Material	[$\mathrm{m^3_{PCM}/m^2_{coll}}$]

Greek letters

ρ	density	[kg/m^3]
η_{NC}	efficiency of a flat plate solar collector	[%]
θ_{inc}	angle of incidence of solar radiation	[°]
ΔH_{m}	latent heat of fusion	[kJ/kg]

Subscripts and superscripts

a	ambient
beam	beam component of solar radiation
diff	diffuse component of solar radiation
eff	effective
high	maximum temperature in the tank
low	temperature after overnight cooling
m	phase transition
p,l	heat capacity in liquid state of Phase Change Material
p,s	heat capacity in solid state of Phase Change Material
PCM	phase change material
s	density in solid state of Phase Change Material
w	average for water at collector inlet and outlet

Abbreviations

eut.	Eutectic
inorg.	Inorganic
org.	Organic
PCM	Phase Change Material
sulph.	Sulphur

REFERENCES

1. de la Peña, J. L. and Aguilar, R., Polymer Solar Collectors. A Better Alternative to Heat Water in Mexican Homes, *Energy Procedia*, Vol. 57, pp 2205-2210, 2014, https://doi.org/10.1016/j.egypro.2014.10.187
2. Hengstberger, F., Zauner, C., Resch, K., Holper, S. and Grobbauer, M., High Temperature Phase Change Meterials for the Overheating Protection of Facade Integrated Solar Thermal Collectors, *Energy and Buildings*, Vol. 124, pp 1-6, 2016, https://doi.org/10.1016/j.enbuild.2016.04.020
3. Kessentini, H., Castro, J., Capdevila, R. and Oliva, A., Development of Flat Plate Collector with Plastic Transparent Insulation and Low Cost Overheating Protection System, *Applied Energy*, Vol. 133, pp 206-223, 2014, https://doi.org/10.1016/j.apenergy.2014.07.093
4. Föste, S., Schiebler, B., Giovanneti, F., Rockendorf, G. and Jack, S., Butane Heat Pipes for Stagnation Temperature Reduction of Solar Thermal Collectors, *Energy Procedia*, Vol. 91, pp 35-41, 2016, https://doi.org/10.1016/j.egypro.2016.06.168
5. Muehling, O., Seeboth, A., Eberhardt, V., Byker, H., Anderson, C. D. and De Jong, S., Solar Collector Cover with Temperature-Controlled Solar Light Transmittance,

Energy Procedia, Vol. 48, pp 163-171, 2014, https://doi.org/10.1016/j.egypro.2014.02.021

6. Föste, S., Pazidis, A., Reineke-Koch, R., Hafner, B., Mercs, D. and Delord, C., Flat Plate Collectors with Thermochromic Absorber Coatings to Reduce Loads During Stagnation, *Energy Procedia*, Vol. 91, pp 42-48, 2016, https://doi.org/10.1016/j.egypro.2016.06.169
7. Hussain, S. and Harrison, S. J., Experimental and Numerical Investigations of Passive Air Cooling of a Residential Flat-Plate Solar Collector Under Stagnation Conditions, *Solar Energy*, Vol. 122, pp 1023-1036, 2015, https://doi.org/10.1016/j.solener.2015.10.029
8. Forzano, C., Baggio, P., Buonomano, A. and Palombo, A., Building Integrating Phase Change Materials: A Dynamic Hygrothermal Simulation Model for System Analysis, *Journal of Sustainable Development of Energy Water and Environment Systems*, Vol. 7, No. 2, pp 325-342, 2019, https://doi.org/10.13044/j.sdewes.d6.0255
9. Dehghan, M. and Pfeiffer, C., Modelling and Control of Collecting Solar Energy for Heating Houses in Norway, *Journal of Sustainable Development of Energy Water and Environment Systems*, Vol. 5, No. 3, pp 359-376, 2017, https://doi.org/10.13044/j.sdewes.d5.0147
10. Mao, Q. J., Liu, N. and Peng, L., Recent Investigations of Phase Change Materials Use in Solar Thermal Energy Storage System, *Advances in Materials Science and Engineering*, Article ID: 9410560, pp 13, 2018, https://doi.org/10.1155/2018/9410560
11. Palomba, V., Brancato, V., Palomba, G., Borsacchi, S., Forte, C., Freni, A. and Frazzica, A., Latent Thermal Storage for Solar Cooling Applications: Materials Characterization and Numerical Optimization of Finned Storage Configurations, *Heat Transfer Engineering*, Vol. 40, No. 12, pp 1033-1048, 2019, https://doi.org/10.1080/01457632.2018.1451236
12. Kahwaji, S., Johnson, M. B., Kheirabadi, A. C., Groulx, D. and White, M. A., A Comprehensive Study of Properties of Paraffin Phase Change Materials for Solar Thermal Energy Storage and Thermal Management Applications, *Energy*, Vol. 162, pp 1169-1182, 2018, https://doi.org/10.1016/j.energy.2018.08.068
13. Tao, Y. B. and He, Y. L., A Review of Phase Change Material and Performance Enhancement Method for Latent Heat Storage System, *Renewable & Sustainable Energy Reviews*, Vol. 93, pp 245-259, 2018, https://doi.org/10.1016/j.rser.2018.05.028
14. Raud, R., Bell, S., Ong, T. C., Will, G. and Steinberg, T. A., Optimized Salt Selection for Solar Thermal Latent Heat Energy Storage, *Advanced Sustainable Systems*, Vol. 2, No. 11, Article ID: 1800074, 2018, https://doi.org/10.1002/adsu.201800074
15. Pereira de Cunha, J. and Eames, P., Thermal Energy Storage for Low and Medium Temperature Applications Using Phase Change Materials – A Review, *Applied Energy*, Vol. 177, pp 227-238, 2016, https://doi.org/10.1016/j.apenergy.2016.05.097
16. Sharma, A., Tyagi, V. V., Chen, C. R. and Buddhi, D., Review on Thermal Energy Storage With Phase Change Materials and Applications, *Renewable and Sustainable Energy Reviews*, Vol. 13, No. 2, pp 318-345, 2009, https://doi.org/10.1016/j.rser.2007.10.005
17. Xiao, Q. Q., Zhang, M. D., Fan, J. X., Li, L., Xu, T. and Yuan, W. H., Thermal Conductivity Enhancement of Hydrated Salt Phase Change Materials Employing Copper Foam as the Supporting Material, *Solar Energy Materials and Solar Cells*, Vol. 199, pp 91-98, 2019, https://doi.org/10.1016/j.solmat.2019.04.020
18. Jin, H., Liu, J., Zheng, M., Teng, H. P. and Wei, L. P., Application of Phase-Change Material in Solar Hot-Water System, *Proceedings of the Institution of Civil Engineers-Energy*, Vol. 172, No. 1, pp 12-18, 2019, https://doi.org/10.1680/jener.18.00010

19. Rao, Z. H., Xu, T. T., Liu, C. Z., Zheng, Z. J., Liang, L. and Hong, K., Experimental Study on Thermal Properties and Thermal Performance of Eutectic Hydrated Salts/Expanded Perlite Form-Stable Phase Change Materials for Passive Solar Energy Utilization, *Solar Energy Materials and Solar Cells*, Vol. 188, pp 6-17, 2018, https://doi.org/10.1016/j.solmat.2018.08.012
20. Qiu, L., Ouyang, Y. X., Feng, Y. H. and Zhang, X. X., Review on Micro/Nano Phase Change Materials for Solar Thermal Applications, *Renewable Energy*, Vol. 140, pp 513-538, 2019, https://doi.org/10.1016/j.renene.2019.03.088
21. Sivasamy, P., Harikrishnan, S., Hussain, S. I., Kalaiselvam, S. and Babu, L. G., Improved Thermal Characteristics of Ag Nanoparticles Dispersed Myristic Acid as Composite for Low Temperature Thermal Energy Storage, *Materials Research Express*, Vol. 6, No. 8, Article ID: 085066, 2019, https://doi.org/10.1088/2053-1591/ab20ba
22. Sari, A., Al-Ahmed, A., Bicer, A., Al-Sulaiman, F. A. and Hekimoglu, G., Investigation of Thermal Properties and Enhanced Energy Storage/Release Performance of Silica Fume/Myristic Acid Composite Doped with Carbon Nanotubes, *Renewable Energy*, Vol. 140, pp 779-788, 2019, https://doi.org/10.1016/j.renene.2019.03.102
23. Zhang, J., Yu, J., Cai, Y. B., Lv, P. F., Zhou, H. M. and Wei, Q. F., Fabrication of Form-Stable Phase Change Materials Based on Mechanically Flexible SiO2 Nanofibrous Mats for Thermal Energy Storage/Retrieval, *Journal of Nanoscience and Nanotechnology*, Vol. 19, No. 9, pp 5562-5571, 2019, https://doi.org/10.1166/jnn.2019.16524
24. Chen, M. J., He, Y. R., Ye, Q., Zhang, Z. D. and Hu, Y. W., Solar Thermal Conversion and Thermal Energy Storage of Cuo/Paraffin Phase Change Composites, *International Journal of Heat and Mass Transfer*, Vol. 130, pp 1133-1140, 2019, https://doi.org/10.1016/j.ijheatmasstransfer.2018.11.026
25. Shah, T. R. and Ali, H. M., Applications of Hybrid Nanofluids in Solar Energy, Practical Limitations and Challenges: A Critical Review, *Solar Energy*, Vol. 183, pp 173-203, 2019, https://doi.org/10.1016/j.solener.2019.03.012
26. Kumar, P. M., Mylsamy, K. and Saravanakumar, P. T., Experimental Investigations on Thermal Properties of Nano-SiO_2/Paraffin Phase Change Material (PCM) for Solar Thermal Energy Storage Applications, *Energy Sources Part A: Recovery Utilization and Environmental Effects*, Early Access, 2019, https://doi.org/10.1080/15567036.2019.1607942
27. Kumar, P. M. and Mylsamy, K., Experimental Investigation of Solar Water Heater Integrated with a Nanocomposite Phase Change Material, *Journal of Thermal Analysis and Calorimetry*, Vol. 136, No. 1, pp 121-132, 2019, https://doi.org/10.1007/s10973-018-7937-9
28. Chen, B. L., Han, M., Zhang, B. W., Ouyang, G. Y., Shafei, B., Wang, X. W. and Hu, S., Efficient Solar-to-Thermal Energy Conversion and Storage with High-Thermal-Conductivity and Form-Stabilized Phase Change Composite Based on Wood-Derived Scaffolds, *Energies*, Vol. 12, No. 7, Article ID: 1283, 2019, https://doi.org/10.3390/en12071283
29. Li, C., Li, Q., Li, Y. L., She, X. H., Cao, H., Zhang, P. K., Wang, L. and Ding, Y., Heat Transfer of Composite Phase Change Material Modules Containing a Eutectic Carbonate Salt for Medium and High Temperature Thermal Energy Storage Applications, *Applied Energy*, Vol. 238, pp 1074-1083, 2019, https://doi.org/10.1016/j.apenergy.2019.01.184
30. Bao, X. H., Tian, Y. Y., Yuan, L., Cui, H. Z., Tang, W. C., Fung, W. H. and Qi, H., Development of High Performance PCM Cement Composites for Passive Solar Buildings, *Energy and Buildings*, Vol. 194, pp 33-45, 2019, https://doi.org/10.1016/j.enbuild.2019.04.011

31. Liu, H., Wang, X. D., Wu, D. Z. and Ji, S. F., Fabrication and Applications of Dual-Responsive Microencapsulated Phase Change Material with Enhanced Solar Energy-Storage and Solar Photocatalytic Effectiveness, *Solar Energy Materials and Solar Cells*, Vol. 193, pp 184-197, 2019, https://doi.org/10.1016/j.solmat.2019.01.012
32. Jiang, Z. N., Yang, W. B., He, F. F., Xie, C. Q., Fan, J. H., Wu, J. Y. and Zhang, K., Microencapsulated Paraffin Phase-Change Material with Calcium Carbonate Shell for Thermal Energy Storage and Solar-Thermal Conversion, *Langmuir*, Vol. 34, No. 47, pp 14254-14264, 2018, https://doi.org/10.1021/acs.langmuic.8b03084
33. Ma, X. C., Liu, Y. J., Liu, H., Zhang, L., Xu, B. and Xiao, F., Fabrication of Novel Slurry Containing Graphene Oxide-Modified Microencapsulated Phase Change Material for Direct Absorption Solar Collector, *Solar Energy Materials and Solar Cells*, Vol. 188, pp 73-80, 2018, https://doi.org/10.1016/j.solmat.2018.08.021
34. Ma, F. and Zhang, P., Heat Transfer Characteristics of a Volumetric Absorption Solar Collector using Nano-Encapsulated Phase Change Slurry, *Heat Transfer Engineering*, Vol. 39, No. 17-18, pp 1487-1497, 2018, https://doi.org/10.1080/01457632.2017.1369827
35. Dheep, G. R. and Sreekumar, A., Thermal Reliability and Corrosion Characteristics of an Organic Phase Change Materials for Solar Space Heating Applications, *Journal of Energy Storage*, Vol. 23, pp 98-105, 2019, https://doi.org/10.1016/j.est.2019.03.009
36. Mawire, A., Lentswe, K. A. and Shobo, A., Performance Comparison of Four Spherically Encapsulated Phase Change Materials for Medium Temperature Domestic Applications, *Journal of Energy Storage*, Vol. 23, pp 469-479, 2019, https://doi.org/10.1016/j.est.2019.04.007
37. Purohit, K., Murty, V. V. S., Dixit, R. C. and Sharma, A., Development of an Acetanilide/Benzoic Acid Eutectic Phase Change Material Based Thermal Energy Storage Unit for a Passive Water Heating System, *Bulletin of Materials Science*, Vol. 42, No. 3, Article ID: UNSP 119, 2019, https://doi.org/10.1007/s12034-019-1731-6
38. Prakash, J., Roan, D., Tauqir, W., Nazir, H., Ali, M. and Kannan, A., Off-Grid Solar Thermal Water Heating System Using Phase-Change Materials: Design, Integration and Real Environment Investigation, *Applied Energy*, Vol. 240, pp 73-83, 2019, https://doi.org/ 10.1016/j.apenergy.2019.02.058
39. Ma, L. Y., Wang, Q. W. and Li, L. P., Delignified Wood/Capric Acid-Palmitic Acid Mixture Stable-Form Phase Change Material for Thermal Storage, *Solar Energy Materials and Solar Cells*, Vol. 194, pp 215-221, 2019, https://doi.org/10.1016/j.solmat.2019.02.026
40. Rea, J. E., Oshman, C. J., Singh, A., Alleman, J., Parilla, P. A., Hardin, C. L., Olsen, M. L., Siegel, N. P., Ginley, D. S. and Toberer, E. S., Experimental Demonstration of a Dispatchable Latent Heat Storage System with Aluminum-Silicon as a Phase Change Material, *Applied Energy*, Vol. 230, pp 1218-1229, 2018, https://doi.org/10.1016/j.apenergy.2018.09.017
41. Calabrese, L., Brancato, V., Paolomba, V. and Proverbio, E., An Experimental Study on the Corrosion Sensitivity of Metal Alloys for Usage in PCM Thermal Energy Storages, *Renewable Energy*, Vol. 138, pp 1018-1027, 2019, https://doi.org/10.1016/j.renene.2019.02.013
42. Agresti, F., Fedele, L., Rossi, S., Cabaleiro, D., Bobbo, S., Ischia, G. and Barison, S., Nano-Encapsulated PCM Emulsions Prepared by a Solvent-Assisted Method for Solar Applications, *Solar Energy Materials and Solar Cells*, Vol. 194, pp 268-275, 2019, https://doi.org/10.1016/j.solmat.2019.02.021
43. Singh, R. P., Xu, H. X., Kaushik, S. C., Rakshit, D. and Romagnoli, A., Effective Utilization of Natural Convection Via Novel Fin Design & Influence of Enhanced Viscosity Due to Carbon Nano-Particles in a Solar Cooling Thermal Storage System, *Solar Energy*, Vol. 183, pp 105-119, 2019, https://doi.org/10.1016/j.solener.2019.03.005

44. Zhou, F., Ji, J., Yuan, W. Q., Modjinou, M., Zhao, X. D. and Huang, S. J., Experimental Study and Performance Prediction of the PCM-Antifreeze Solar Thermal System Under Cold Weather Conditions, *Applied Thermal Engineering*, Vol. 146, pp 526-539, 2019, https://doi.org/10.1016/j.applthermaleng.2018.10.038
45. Min, P., Liu, J., Li, X. F., An, F., Liu, P. F., Shen, Y. X., Koratkar, N. and Yu, Z. Z., Thermally Conductive Phase Change Composites Featuring Anisotropic Graphene Aerogels for Real-Time and Fast-Charging Solar-Thermal Energy Conversion, *Advanced Functional Materials*, Vol. 28, No. 51, Article ID: 1805365, 2018, https://doi.org/10.1002/adfm.201805365
46. Xiao, Q. Q., Fan, J. X., Li, L., Xu, T. and Yuan, W. H., Solar Thermal Energy Storage Based on Sodium Acetate Trihydrate Phase Change Hydrogels with Excellent Light-To-Thermal Conversion Performance, *Energy*, Vol. 165, Part B, pp 1240-1247, 2018, https://doi.org/10.1016/j.energy.2018.10.105
47. Alva, G., Lin, Y. X. and Fang, G. Y., Synthesis and Characterization of Chain-Extended and Branched Polyurethane Copolymers as Form Stable Phase Change Materials for Solar Thermal Conversion Storage, *Solar Energy Materials and Solar Cells*, Vol. 186, pp 14-28, 2018, https://doi.org/10.1016/j.solmat.2018.06.023
48. Allahbakhsh, A. and Arjmand, M., Graphene-Based Phase Change Composites for Energy Harvesting and Storage: State of the Art and Future Prospects, *Carbon*, Vol. 148, pp 441-480, 2019, https://doi.org/10.1016/j.carbon.2019.04.009
49. Gu, X. B., Liu, P., Bian, L. and He, H. C., Enhanced Thermal Conductivity of Palmitic Acid/Mullite Phase Change Composite with Graphite Powder for Thermal Energy Storage, *Renewable Energy*, Vol. 138, pp 833-841, 2019, https://doi.org/10.1016/j.renene.2019.02.031
50. Han, X. C., Zhang, X. L., Hua, W. S., Yuan, W. Y., Jia, X. Y. and Wang, Z. F., Preparation and Application of Composite EG/$Ba(OH)_2 \cdot 8H_2O$ Form-Stable Phase Change Material for Solar Thermal Storage, *International Journal of Energy Research*, Vol. 43, No. 6, pp 2227-2240, 2019, https://doi.org/10.1002/er.4438
51. Zhou, D. and Eames, P., Phase Change Material Wallboard (PCMW) Melting Temperature Optimisation for Passive Indoor Temperature Control, *Renewable Energy*, Vol. 139, pp 507-514, 2019, https://doi.org/0.1016/j.renene.2019.02.109
52. Saxena, R., Rakshit, D. and Kaushik, S. C., Phase Change Material (PCM) Incorporated Bricks for Energy Conservation in Composite Climate: A Sustainable Building Solution, *Solar Energy*, Vol. 183, pp 276-284, 2019, https://doi.org/10.1016/j.solener.2019.03.035
53. Garnier, C., Muneer, T. and Currie, J., Numerical and Empirical Evaluation of a Novel Building Integrated Collector Storage Solar Water Heater, *Renewable Energy*, Vol. 126, pp 281-295, 2018, https://doi.org/10.1016/j.renene.2018.03.041
54. Vanaga, R., Blumberga, A., Freimanis, R., Mols, T. and Blumberga, D., Solar Facade Module for Nearly Zero Energy Building, *Energy*, Vol. 157, pp 1025-1034, 2018, https://doi.org/10.1016/j.energy.2018.04.167
55. Vasquez, J., Reyes, A. and Pailahueque, N., Modeling, Simulation and Experimental Validation of a Solar Dryer for Agro-Products with Thermal Energy Storage System, *Renewable Energy*, Vol. 139, pp 1375-1390, 2019, https://doi.org/10.1016/j.renene.2019.02.085
56. Muhumuza, R., Zacharopoulos, A., Mondol, J. D., Smyth, M., Pugsley, A., Giuzio, G. F. and Kurmis, D., Experimental Investigation of Horizontally Operating Thermal Diode Solar Water Heaters with Differing Absorber Materials Under Simulated Conditions, *Renewable Energy*, Vol. 138, pp 1051-1064, 2019, https://doi.org/10.1016/j.renene.2019.02.036
57. Ryms, M. and Klugmann-Radziemska, E., Possibilities and Benefits of a New Method of Modifying Conventional Building Materials with Phase-Change Materials (PCMs),

Construction and Building Materials, Vol. 211, pp 1013-1024, 2019, https://doi.org/10.1016/j.conbuildmat.2019.03.277

58. Dehghan, M. and Pfeiffer, C., Modelling and Control of Collecting Solar Energy for Heating Houses in Norway, *Journal of Sustainable Development of Energy Water and Environment Systems*, Vol. 5, No. 3, pp 359-376, 2019, https://doi.org/10.13044/j.sdewes.d5.0147
59. Zhou, Y. K., Yu, C. W. F. and Zhan, G. Q., Study on Heat-Transfer Mechanism of Wallboards Containing Active Phase Change Material and Parameter Optimization with Ventilation, *Applied Thermal Engineering*, Vol. 144, pp 1091-1108, 2018, https://doi.org/10.1016/j.applthermaleng.2018.04.083
60. Bouhal, T., Meghari, Z., Fertahi, S. E. D., El Rhafiki, T., Kousksou, T., Jamil, A. and Ben Ghoulam, E., Parametric CFD Analysis and Impact of PCM Intrinsic Parameters on Melting Process Inside Enclosure Integrating Fins: Solar Building Applications, *Journal of Building Engineering*, Vol. 20, pp 634-646, 2018, https://doi.org/10.1016/j.jobe.2018.09.016
61. Tehrani, S. S. M., Shoraka, Y., Nithyanandam, K. and Taylor, R. A., Shell-And-Tube or Packed Bed Thermal Energy Storage Systems Integrated with a Concentrated Solar Power: A Techno-Economic Comparison of Sensible and Latent Heat Systems, *Applied Energy*, Vol. 238, pp 887-910, 2019, https://doi.org/10.1016/j.apenergy.2019.01.119
62. Shafieian, A., Khiadani, M. and Nosrati, A., Strategies to Improve the Thermal Performance of Heat Pipe Solar Collectors in Solar Systems: A Review, *Energy Conversion and Management*, Vol. 183, pp 307-331, 2019, https://doi.org/10.1016/j.enconman.2018.12.115
63. Asgharian, H. and Baniasadi, E., A Review on Modeling and Simulation of Solar Energy Storage Systems Based on Phase Change Materials, *Journal of Energy Storage*, Vol. 21, pp 186-201, 2019, https://doi.org/10.1016/j.est.2018.11.025
64. Fertahi, S. E. D., Jamil, A. and Benbassou, A., Review on Solar Thermal Stratified Storage Tanks (STSST): Insight on Stratification Studies and Efficiency Indicators, *Solar Energy*, Vol. 176, pp 126-145, 2019, https://doi.org/10.1016/j.solener.2018.10.028
65. Yuan, W. Q., Ji, J., Modjinou, M., Zhou, F., Li, Z. M., Song, Z. Y., Huang, S. J. and Zhao, X. D., Numerical Simulation and Experimental Validation of the Solar Photovoltaic/Thermal System with Phase Change Material, *Applied Energy*, Vol. 232, pp 715-727, 2018, https://doi.org/10.1016/j.apenergy.2018.09.096
66. Ma, T., Zhao, J. X. and Li, Z. P., Mathematical Modelling and Sensitivity Analysis of Solar Photovoltaic Panel Integrated with Phase Change Material, *Applied Energy*, Vol. 228, pp 1147-1158, 2018, https://doi.org/10.1016/j.apenergy.2018.06.145
67. Zhu, Y. T., Wang, B., Zhang, Q. R., Wang, H. G., Zhu, J. H., Liu, Y., Zhang, Y., Sun, X., Zhang, X., Yun, S., Jiang, H., Gao, F. and Kang, L., Paraffin Wax-$Cs_{0.33}WO_3$ Composite Windows with Excellent Near Infrared Shielding and Thermal Energy Storage Abilities, *Chemical Papers*, Vol. 73, No. 7, pp 1677-1684, 2019, https://doi.org/10.1007/s11696-019-00719-8
68. Liu, C. Y., Wu, Y. Y., Li, D., Ma, T. F., Hussein, A. K. and Zhou, Y. M., Investigation of Thermal and Optical Performance of a Phase Change Material-Filled Double-Glazing Unit, *Journal of Building Physics*, Vol. 42, No. 2, pp 99-119, 2018, https://doi.org/10.1177/1744259117708734
69. Abuska, M., Sevik, S. and Kayapunar, A., Experimental Analysis of Solar Air Collector with PCM-Honeycomb Combination Under the Natural Convection, *Solar Energy Materials and Solar Cells*, Vol. 195, pp 299-308, 2019, https://doi.org/10.1016/j.solmat.2019.02.040
70. Egolf, P. W., Amacker, N., Gottschalk, G., Courret, G., Noume, A. and Hutter, K., A Translucent Honeycomb Solar Collector and Thermal Storage Module for Building

Facades, *International Journal of Heat and Mass Transfer*, Vol. 127, Part A, pp 781-795, 2018, https://doi.org/10.1016/j.ijheatmasstransfer.2018.06.111

71. Abuska, M., Sevik, S. and Kayapunar, A., A Comparative Investigation of the Effect of Honeycomb Core on the Latent Heat Storage with PCM in Solar Air Heater, *Applied Thermal Engineering*, Vol. 148, pp 684-693, 2019, https://doi.org/10.1016/j.applthermaleng.2018.11.056
72. Wang, Z. X., Sun, S. T., Lin, X. N., Liu, C., Tong, N., Sui, Q. and Li, Z. T., A Remote Integrated Energy System Based on Cogeneration of a Concentrating Solar Power Plant and Buildings with Phase Change Materials, *Energy Conversion and Management*, Vol. 187, pp 472-485, 2019, https://doi.org/10.1016/j.enconman.2019.02.094
73. Mousa, H., Naser, J. and Houche, O., Using PCM as Energy Storage Material in Water Tanks: Theoretical and Experimental Investigation, *Journal of Energy Storage*, Vol. 22, pp 1-7, 2019, https://doi.org/10.1016/j.est.2019.01.018
74. Zhou, Z. H., Liu, J. W., Wang, C. D., Huang, X., Gao, F., Zhang, S. and Yu, B., Research on the Application of Phase-Change Heat Storage in Centralized Solar Hot Water System, *Journal of Cleaner Production*, Vol. 198, pp 1262-1275, 2018, https://doi.org/10.1016/j.jclepro.2018.06.281
75. Bouhal, T., El Rhafiki, T., Kousksou, T., Jamil, A. and Zeraouli, Y., PCM Addition Inside Solar Water Heaters: Numerical Comparative Approach, *Journal of Energy Storage*, Vol. 19, pp 232-246, 2018, https://doi.org/10.1016/j.est.2018.08.005
76. Mahdi, M. S., Hasan, A. F., Mahood, H. B., Campbell, A. N., Khadom, A. A., Karim, A. M. A. and Sharif, A. O., Numerical Study and Experimental Validation of the Effects of Orientation and Configuration on Melting in a Latent Heat Thermal Storage Unit, *Journal of Energy Storage*, Vol. 23, pp 456-468, 2019, https://doi.org/10.1016/j.est.2019.04.013
77. Josyula, T., Singh, S. and Dhiman, P., Numerical Investigation of a Solar Air Heater Comprising Longitudinally Finned Absorber Plate and Thermal Energy Storage System, *Journal of Renewable and Sustainable Energy*, Vol. 10, No. 5, Article ID: 055901, 2018, https://doi.org/10.1063/1.5035136
78. Reyes, A., Pailahueque, N., Henriquez-Vargas, L., Vasquez, J. and Sepulveda, F., Analysis of a Multistage Solar Thermal Energy Accumulator, *Renewable Energy*, Vol. 136, pp 621-631, 2019, https://doi.org/10.1016/j.renene.2018.12.103
79. Al-Musawi, A. I. A., Taheri, A., Farzanehnia, A., Sardarabadi, M. and Passandideh-Fard, M., Numerical Study of the Effects of Nanofluids and Phase-Change Materials in Photovoltaic Thermal (PVT) Systems, *Journal of Thermal Analysis and Calorimetry*, Vol. 137, No. 2, pp 623-636, 2019, https://doi.org/10.1007/s10973-018-7972-6
80. Choubineh, N., Jannesari, H. and Kasaeian, A., Experimental Study of the Effect of Using Phase Change Materials on the Performance of an Air-Cooled Photovoltaic System, *Renewable & Sustainable Energy Reviews*, Vol. 101, pp 103-111, 2019, https://doi.org/10.1016/j.rser.2018.11.001
81. Rabie, R., Emam, M., Ookawara, S. and Ahmed, M., Thermal Management of Concentrator Photovoltaic Systems Using New Configurations of Phase Change Material Heat Sinks, *Solar Energy*, Vol. 183, pp 632-652, 2019, https://doi.org/10.1016/j.solener.2019.03.061
82. Motte, F., Notton, G., Lamnatou, C., Cristofari, C. and Chemisana, D., Numerical Study of PCM Integration Impact on Overall Performances of a Highly Building-Integrated Solar Collector, *Renewable Energy*, Vol. 137, pp 10-19, 2019, https://doi.org/10.1016/j.renene.2017.12.067
83. Xaman, J., Vargas-Lopez, R., Gijon-Rivera, M., Zavala-Guillen, I., Jimenez, M. J. and Arce, J., Transient Thermal Analysis of a Solar Chimney for Buildings with Three Different Types of Absorbing Materials: Copper Plate/PCM/Concrete Wall,

Renewable Energy, Vol. 136, pp 139-158, 2019, https://doi.org/10.1016/j.renene.2018.12.106

84. Fadaei, N., Yan, W. M., Tafarroj, M. M. and Kasaeian, A., The Application of Artificial Neural Networks to Predict the Performance of Solar Chimney Filled with Phase Change Materials, *Energy Conversion and Management*, Vol. 171, pp 1255-1262, 2018, https://doi.org/10.1016/j.enconman.2018.06.055
85. Abu-Arabi, M., Al-harahsheh, M., Mousa, H. and Alzghoul, Z., Theoretical Investigation of Solar Desalination with Solar Still Having Phase Change Material and Connected to a Solar Collector, *Desalination*, Vol. 448, pp 60-68, 2018, https://doi.org/10.1016/j.desal.2018.09.020
86. Swami, V. M., Autee, A. T. and Anil, T. R., Experimental Analysis of Solar Fish Dryer Using Phase Change Material, *Journal of Energy Storage*, Vol. 20, pp 310-315, 2018, https://doi.org/10.1016/j.est.2018.09.016
87. Yadav, S., Lingayat, A. B., Chandramohan, V. P. and Raju, V. R. K., Numerical Analysis on Thermal Energy Storage Device to Improve the Drying Time of Indirect Type Solar Dryer, *Heat and Mass Transfer*, Vol. 54, No. 12, pp 3631-3646, 2018, https://doi.org/10.1007/s00231-018-2390-7
88. Amirifard, M., Kasaeian, A. and Amidpour, M., Integration of a Solar Pond with a Latent Heat Storage System, *Renewable Energy*, Vol. 125, pp 682-693, 2018, https://doi.org/10.1016/j.renene.2018.03.009
89. Plytaria, M. T., Bellos, E., Tzivanidis, C. and Antonopoulos, K. A., Numerical Simulation of a Solar Cooling System with and Without Phase Change Materials in Radiant Walls of a Building, *Energy Conversion and Management*, Vol. 188, pp 40-53, 2019, https://doi.org/10.1016/j.enconman.2019.03.042
90. Wei, F. R., Li, Y. Z., Sui, Q., Lin, X. N., Chen, L., Chen, Z. and Li, Z. T., A Novel Thermal Energy Storage System in Smart Building Based on Phase Change Material, *IEEE Transactions on Smart Grid*, Vol. 10, No. 3, pp 2846-2857, 2019, https://doi.org/10.1109/TSG.2018.2812160
91. Mao, Q. J., Chen, H. Z. and Yang, Y. Z., Energy Storage Performance of a PCM in the Solar Storage Tank, *Journal of Thermal Science*, Vol. 28, No. 2, pp 195-203, 2019, https://doi.org/10.1007/s11630-019-1076-x
92. Bilardo, M., Fraisse, G., Pailha, M. and Fabrizio, E., Modelling and Performance Analysis of a New Concept of Integral Collector Storage (ICS) with Phase Change Material, *Solar Energy*, Vol. 183, pp 425-440, 2019, https://doi.org/10.1016/j.solener.2019.03.032
93. Zhao, J., Yuan, Y. P., Haghighat, F., Lu, J. and Feng, G. H., Investigation of Energy Performance and Operational Schemes of a Tibet-Focused PCM-Integrated Solar Heating System Employing a Dynamic Energy Simulation Model, *Energy*, Vol. 172, pp 141-154, 2019, https://doi.org/10.1016/j.energy.2019.01.125
94. Hirmiz, R., Teamah, H. M., Lightstone, M. F. and Cotton, J. S., Performance of Heat Pump Integrated Phase Change Material Thermal Storage for Electric Load Shifting in Building Demand Side Management, *Energy and Buildings*, Vol. 190, pp 103-118, 2019, https://doi.org/10.1016/j.enbuild.2019.02.026
95. Gulfam, R., Zhang, P. and Meng, Z. N., Advanced Thermal Systems Driven by Paraffin-Based Phase Change Materials – A Review, *Applied Energy*, Vol. 238, pp 582-611, 2019, https://doi.org/10.1016/j.apenergy.2019.01.114
96. Kazemian, A., Salari, A., Hakkaki-Fard, A. and Ma, T., Numerical Investigation and Parametric Analysis of a Photovoltaic Thermal System Integrated with Phase Change Material, *Applied Energy*, Vol. 238, pp 734-746, 2019, https://doi.org/10.1016/j.apenergy.2019.01.103
97. Jimenez-Xaman, C., Xaman, J., Moraga, N. O., Hernandez-Perez, I., Zavala-Guillen, I., Arce, J. and Jimenez, M. J., Solar Chimneys with a Phase Change Material for

Buildings: An Overview Using CFD and Global Energy Balance, *Energy and Buildings*, Vol. 186, pp 384-404, 2019, https://doi.org/10.1016/j.enbuild.2019.01.014

98. Vargas-Lopez, R., Xaman, J., Hernandez-Perez, I., Arce, J., Zavala-Guillen, I., Jimenez, M. J. and Heras, M. R., Mathematical Models of Solar Chimneys with a Phase Change Material for Ventilation of Buildings: A Review Using Global Energy Balance, *Energy*, Vol. 170, pp 683-708, 2019, https://doi.org/10.1016/j.energy.2018.12.148
99. Reyes, A., Vasquez, J., Pailahueque, N. and Mahn, A., Effect of Drying Using Solar Energy and Phase Change Material on Kiwifruit Properties, *Drying Technology*, Vol. 37, No. 2, pp 232-244, 2019, https://doi.org/10.1080/07373937.2018.1450268
100. Elbahjaoui, R. and El Qarnia, H., Performance Evaluation of a Solar Thermal Energy Storage System Using Nanoparticle-Enhanced Phase Change Material, *International Journal of Hydrogen Energy*, Vol. 44, No. 3, pp 2013-2028, 2019, https://doi.org/10.1016/j.ijhydene.2018.11.116
101. Elbahjaoui, R. and El Qarnia, H., Thermal Performance of a Solar Latent Heat Storage Unit Using Rectangular Slabs of Phase Change Material for Domestic Water Heating Purposes, *Energy and Buildings*, Vol. 182, pp 111-130, 2019, https://doi.org/10.1016/j.enbuild.2018.10.010
102. Allouhi, A., Msaad, A. A., Amine, M. B., Saidur, R. and Mahdaoui, M., Optimization of Melting and Solidification Processes of PCM: Application to Integrated Collector Storage Solar Water Heaters, *Solar Energy*, Vol. 171, pp 562-570, 2018, https://doi.org/10.1016/j.solener.2018.06.096
103. Sarbu, I. and Dorca, A., Review on Heat Transfer Analysis in Thermal Energy Storage Using Latent Heat Storage Systems and Phase Change Materials, *International Journal of Energy Research*, Vol. 43, No. 1, pp 29-64, 2019, https://doi.org/10.1002/er.4196
104. Forzano, C., Baggio, P., Buonomano, A. and Palombo, A., Building Integrating Phase Change Materials: A Dynamic Hygrothermal Simulation Model for System Analysis, *Journal of Sustainable Development of Energy Water and Environment Systems*, Vol. 7, No. 2, pp 325-342, 2019, https://doi.org/10.13044/j.sdewes.d6.0255
105. Raul, A., Jain, M., Gaikwad, S. and Saha, S. K., Modelling and Experimental Study of Latent Heat Thermal Energy Storage with Encapsulated PCMs for Solar Thermal Applications, *Applied Thermal Engineering*, Vol. 143, pp 415-428, 2018, https://doi.org/10.1016/j.applthermaleng.2018.07.123
106. Augspurger, M., Becker, J., Buchholz, J. and Udaykumar, H. S., Three-Dimensional Numerical and Experimental Investigation of the Behavior of Solar Salts Within Thermal Storage Devices During Phase Change, *Applied Thermal Engineering*, Vol. 143, pp 791-811, 2019, https://doi.org/10.1016/j.applthermaleng.2018.07.134
107. Faegh, M. and Shafii, M. B., Experimental Investigation of a Solar Still Equipped with an External Heat Storage System Using Phase Change Materials and Heat Pipes, *Desalination*, Vol. 409, pp 128-135, 2017, https://doi.org/10.1016/j.desal.2017.01.023
108. Khan, M. M. A., Saidur, R. and Al-Sulaiman, F. A., A Review for Phase Change Materials (PCMs) in Solar Absorption Refrigeration Systems, *Renewable and Sustainable Energy Reviews*, Vol. 76, pp 105-137, 2017, https://doi.org/10.1016/j.rser.2017.03.070
109. Silva, T., Vicente, R. and Rodrigues, F., Literature Review on the Use of Phase Change Materials in Glazing and Shading Solutions, *Renewable and Sustainable Energy Reviews*, Vol. 53, pp 515-535, 2016, https://doi.org/10.1016/j.rser.2015.07.201
110. Liu, L., Su, D., Tang, Y. and Fang, G., Thermal Conductivity Enhancement of Phase Change Materials for Thermal Energy Storage: A Review, *Renewable and Sustainable Energy Reviews*, Vol. 62, pp 305-317, 2016, https://doi.org/10.1016/j.rser.2016.04.057

111. Kapsalis, V. and Karamanis, D., Solar Thermal Energy Storage and Heat Pumps with Phase Change Materials, *Applied Thermal Engineering*, Vol. 99, pp 1212-1224, 2016, https://doi.org/10.1016/j.applthermaleng.2016.01.071
112. Rodriguez-Hidalgo, M. C., Rodriguez-Aumente, P. A., Lecuona, A., Gutierrez-Urueta, G. L. and Ventas, R., Flat Plate Thermal Solar Collector Efficiency: Transient Behavior Under Working Conditions. Part I: Model Description and Experimental Validation, *Applied Thermal Engineering*, Vol. 31, No. 14-15, pp 2394-2404, 2011, https://doi.org/10.1016/j.applthermaleng.2011.04.003

Paper submitted: 10.06.2019
Paper revised: 06.02.2020
Paper accepted: 20.02.2020