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Selection of phase change material suitable for building heating applications based on qualitative decision matrix

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ABSTRACT

Phase change materials (PCMs) are successful thermal energy storage mediums in many thermal systems, including buildings. Identifying the best PCM candidate is a critical incorporation parameter that influences building thermal performance. This paper discusses the selection of potential PCM candidates that could be applied for building heating applications in cold locations. A qualitative decision matrix (QDM) is applied for several commercial PCMs after an extensive analysis of relevant literature studies. The melting temperature, heat of fusion, thermal conductivity, compatibility, flammability and cost of each PCM are considered in the QDM to find the most suitable candidates with the best effective properties and features. PCM properties/features are assigned with scores and weights in the QDM based on their importance for the application. Three scenarios are investigated in this work, including and excluding the PCM cost with varying and equal weights. Results showed that RT28HC had the highest score in all scenarios, followed by SavE®HS29 in the first scenario (when the cost is included) and PureTemp 32 in the second scenario without considering the cost. The methodology and results presented in this work are believed to be as efficient as logical for future studies compared with the traditional methods that rely on investigating the PCM thermo-physical properties.

1. Introduction

Phase change materials (PCMs) are advanced materials used in thermal energy management in nowadays' thermal energy storage systems [1]. PCMs have been used in different heat-related applications to overcome the mismatch between heat supply and demand [2–4]. In building applications, PCMs have been used for thermal management when incorporating building envelope and elements [5–7]. PCMs could store and release a considerable amount of heat, in a latent form, during phase transition by up to 14 times more than construction materials' storage capacity [8]. This property allows controlling the heat entering and exiting the building, positively contributing to building energy improvements [9,10].

Generally, PCMs are categorised, according to their chemical composition, as organic, inorganic and eutectics [11]. Amongst others, organic PCMs are widely available materials and are mostly used in building applications. Organic PCMs are classified into paraffinic and non-paraffinic PCMs (such as salt hydrates, fatty acids, esters and glycols) [12]. Each PCM category has specific thermo-physical properties that allow being used for a particular building application, such as the melting temperature, heat of fusion, density and thermal conductivity [13,14]. PCM's suitability for building applications depends highly on the purpose of incorporation (heating/cooling), the passive or active incorporation technique adopted, and the building location [15].

Generally speaking, the number of publications dealing with PCM heating applications is lesser than those considering cooling applications [16]. This is because the PCM is more efficient under high solar radiation and hot locations [13,17]. PCMs have been incorporated in many forms with the building elements and construction materials for heating applications, showing impressive outcomes in heating energy conservation. Unambiguously, PCMs were practically applied with different building heating applications, such as:

- Gypsum-cement boards were used for interior finishing, saving 7.8% of heating energy [18].

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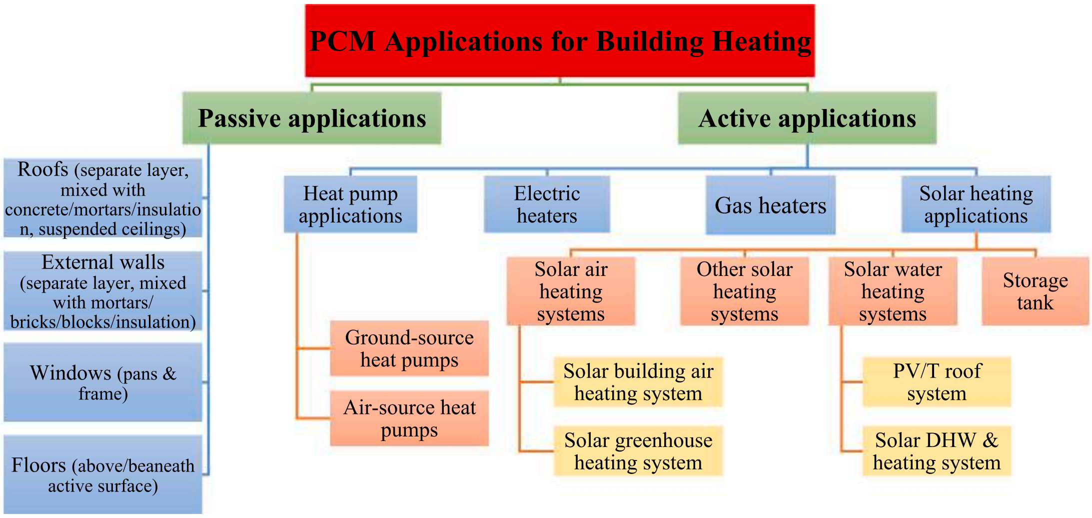

Fig. 1. Possible PCM techniques for building heating applications.

- Form-stable cement plaster has improved the walls thermal storage capacity by 51% [19].
- Cladding gypsum plaster with PCM has kept the building temperature in the range of 0.8 °C–2.3 °C for 48 min compared with the traditional gypsum plaster [20].
- Hollow plaster panels with PCM have improved the indoor temperature averagely by 0.78 °C [21].
- Wall opposing glazed façade integrated PCM has stored the sun heat for 6–8 h after sunset, reducing the daily temperature swing by up to 10 °C, and annual heating load by 17% [22].
- Solar air collector integrated Trombe wall-like PCM wall has improved and extended the heating effect [23].
- PCM included framed triple-pane window has saved the heating energy by up to 20% [24].
- PCM incorporated ventilated mortar blocks coupled with a hot air stream for floor heating has decreased the power consumption for heating by up to 41.5% [25].
- An underfloor heating system and PCM wallboards have saved the heating energy and cost by 32% and 42%, respectively, over ten testing days [26].

On the whole, PCMs are mainly applied for energy storage heating systems or incorporated directly with the building envelope elements passively or actively within the building structure [27–30]. Fig. 1 shows the possible passive and active incorporation of PCMs for building heating applications as indicated in studies reviewed in this work.

In all indicated techniques, the main influential parameters that affect the PCM thermal performance in buildings are the melting temperature (Tm), PCM position within the building structure, and the thickness (quantity) to be incorporated [31,32]. The PCM melting temperature is a critical parameter associated with the PCM type and building location. Therefore, careful attention should be paid to selecting the PCM type for beneficial and effective use.

The main objective of this work is to specify the best PCM candidates suitable for building-integrated heating systems under cold conditions. Three scenarios are considered in which the PCM cost is included or excluded with diverse and equal weights. More than seventy recent literature studies are reviewed and analysed to show the contribution of PCM to building heating energy-saving and compare the potential of PCM candidates following a unique qualitative decision matrix. The matrix relies on several thermo-physical, technical, and economic considerations to select the best PCM candidate that fits future work. The methodology followed in this work is believed to provide an excellent and logical basis for future studies to select the best PCM type simply and efficiently.

2. Literature review

Several researchers have investigated the potential of PCMs for building heating applications in which most studies were conducted passively against limited active applications. The criteria followed by researchers to select the appropriate PCM type was by analysing several PCM candidates and picking up the best thermally-performing [33,34] or a specified candidate chosen based on several desired properties, mostly related to its thermo-physical ones [35,36]. In both cases, the PCM candidate(s) tested over a specific period, namely for days, season or annual basis, and the PCM type is still a critical key parameter in many applications. Among studies that considered several PCM types, Araújo et al. [37] numerically analysed the thermal performance of a 110 m^2 single-family house in northern Portugal for annual heating and cooling applications using EnergyPlus software. The authors studied eight PCMs with melting temperatures in the thermal comfort range, namely RT 15, RT 18, RT 21, RT 22, RT 24, RT 25, RT 26 and RT 28. Results revealed that RT 22 showed the best performance in which the heating requirements were reduced by 8.22 kWh/m^2/year, equivalent to 13.2% energy-saving. Seong and Lim [38] numerically studied various PCMs had Tm of 20 °C, 21 °C, 24 °C and 29 °C, applied to a lightweight building in Seol, Korea. For heating purposes, the PCM with a melting temperature of 21 °C showed the highest heating load reduction annually. Using this PCM, the building peak heating load decreased by 3.19% with an indoor temperature increment of 0.86 °C. Saffari et al. [39] studied several PCMs combined gypsum boards, having Tm in the range of 18 °C–27 °C, integrated with a four-story building and tested for different climates specified by Köppen-Geiger classification. Considering the heating dominant climate, they have found that the effective PCM temperature lies near 20 °C, which showed the best annual heating energy-saving. Pirasaci [40] numerically studied the effect of incorporating eight PCM types (RT12, RT15, RT18HC, RT21, RT21HC, RT22HC, RT24 and RT25HC) with building envelope on the winter heating energy requirements in Ankara, Turkey. PCMs were placed in different positions within surfaces in which the position close to the indoor space was the most effective as it is near the heat source (central hot water radiators). Numerical results indicated that on an annual basis, RT21HC (Tm = 20 °C–23 °C) had the maximum heating energy saving of about 6%, mainly in a sensible form. In contrast, RT18HC (Tm = 17 °C–19 °C) showed better utilisation of PCM latent storage along with annual heating energy-saving of 3%, which was suitable with the fixed indoor temperature.

The majority of literature studies that studied one PCM candidate have counted on the suitability of the PCM melting temperature with a

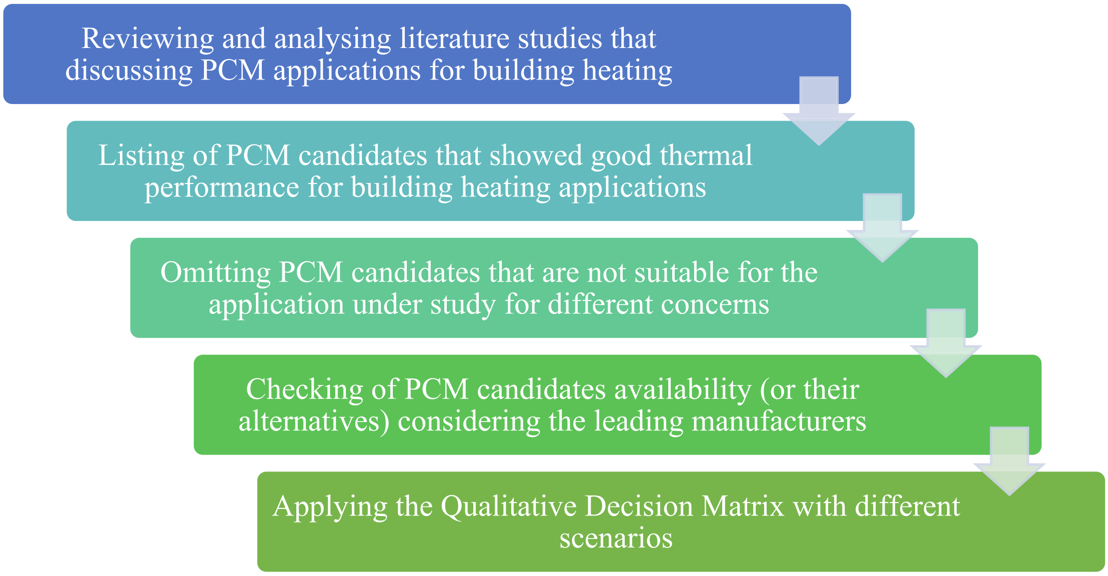

Fig. 2. Methodology steps considered in the present work.

specific location temperature variation. For instance, Barzin et al. [41] experimentally studied PT20 (Tm = 20 °C) impregnated gypsum board installed inside one of two identical Huts (rooms) and tested under winter weather conditions of Auckland, New Zealand. Based on previous studies considering the exact location, this PCM was explicitly selected as the best option for passive building heating. The study was conducted for 11 days, and the main results showed that the average energy saving was 31% over the experimental days, and as high as 90% for one best day performance was achieved. Hu and Yu [42] numerically investigated the thermal response of building walls by integrating micro-encapsulated PCM boards (60% paraffin has Tm = 21.7 °C) in five Chines cities. Under Nanjing cold conditions, the PCM boards had minimised the heating loads by 14% in November, 10% in December, 4% in January, and 9%-13% in March. Arkar et al. [43] numerically and experimentally studied a solar air heating system coupled with PX-21 (Tm = 19.6 °C) for a lightweight building under weather conditions of Ljubljana, Slovenia. The PCM is contained in a concentric tube, placed inside the processed space, and connected with a vacuumed solar air collector. The heat charged during day hours at constant airflow and discharged later in the night. The study findings demonstrated that the PCM is highly recommended with solar systems wherein the solar heating fraction reached 63%, and 34 kWh/m^2 of building heating demand was overcome. Navarro et al. [44] experimentally investigated a hybrid system of PCM macroencapsulated aluminium tubes with an air-based flat plate solar collector integrated with a hollow concrete slab under conditions of Puigverd de Lleida, Spain. RT-21 (Tm = 21 °C–22 °C) was selected as a compelling candidate with high heat storage capacity, long-term stability, no corrosion and suitable for thermal comfort applications. The study revealed that the PCM slab saved energy by about 20% under partial PCM activation and 55% under complete melting/solidification cycles. Furthermore, the energy-saving under severe and mild conditions reached 25% and 40% for the PCM slab compared with the reference one. Plytaria et al. [45] numerically investigated BioPCM Q29/M91 incorporated active floor heating system (the PCM layer placed beneath the active concrete floor) for a 100 m^2 office building under Greece weather conditions using TRNSYS software. This PCM (Tm = 29 °C) was selected among four options, namely 23 °C, 25 °C, 27 °C and 29 °C, based on its performance according to previous studies and its suitability with the solar system that produces hot water with 45 °C. The study outcomes revealed that using the PCM layer saved the heating load and grid electricity by 40% and 42%, respectively. Besides, an increase in the indoor temperature by 1 °C was achieved, which improved the comfort conditions of the building. Guo et al. [46] experimented with a microencapsulated PCM's thermal performance (Tm = 28 °C–30 °C) mixed with mortar concrete blocks for floor heating application. The authors involved the same PCM quantity (~0.8 kg) into three blocks with different distributions to compare the thermal management against reference block without PCM under three scenarios; single heating, heating-ventilation and intermittent heating. Results demonstrated that PCM distribution within the blocks significantly influences the thermal performance of blocks, and the heating-ventilation scenario had the best performance. In the heating scenario, the PCM blocks consumed 11.4%- 18% more heating energy than the reference block, meaning that more heat was stored, which improved the storage capacity of blocks. In the heating-ventilation scenario, the heating demand was extended by 22.7%-25.6% for the PCM blocks compared to the reference one. Kong et al. [47] fabricated and tested a novel hybrid solar-PCM system consisting of composite perlite/PCM wallboard (a passive system) coupled with a solar water heating active system. Paraffin of Tm = 24.92 °C was used for the composite wallboard preparation due to its low cost and suitability for such building applications. Two test rooms (one with a traditional heating radiator and the other integrated with the hybrid system) were tested over three days under Tianjin, China, winter conditions. In the room based hybrid system, the water heated during day hours was passing into the wallboard via capillaries and heat was stored continuously to be used after sunset. Findings indicated that around 44.16% of daily heating energy consumption was minimised in the room with the hybrid system compared to the room with radiators.

3. Methodology

The methodology followed in this work has considered several steps to reach the final decision regarding the best PCM candidate for building heating applications integrated with a solar thermal system. The methodology is summarised in steps indicated in Fig. 2.

Step 1: The state-of-the-art literature studies are analysed and discussed to show the energy contribution of PCM when applied to buildings as a passive element or actively integrated with heating and solar systems. This step is essential to cope with the PCMs investigated by researchers and pick up the best among them.

Step 2: The best thermally acted PCM candidates are listed in this step based on the analysis applied in Step 1. This list shows the thermo-physical properties, namely Tm, latent heat of fusion (Hf), and thermal

Table 1
Weight values of QDM for Scenario A.

Feature/ property	Tm	Hf	k	Compatibility	Flammability	Cost	Total
Weight	15%	20%	10%	20%	10%	25%	100%

Table 2
Weight values of QDM for Scenario B.

Feature/ property	Tm	Hf	k	Compatibility	Flammability	Total
Weight	20%	25%	15%	25%	15%	100%

conductivity (k), for each PCM candidate (as available). Moreover, the list provides a range of PCM types and their categories which is necessary to show the main types used and shed light on the other types that are not investigated yet.

Step 3: Many PCM candidates are omitted to finalise the list of potential ones that should not be applied in the qualitative decision matrix (QDM). The PCM will be eliminated for the following reasons:

i. It was used as a composite PCM (mixed with the building materials), not a pure PCM.
ii. It has missed information which makes the comparison hard with other PCM candidates when applying QDM.
iii. PCMs prepared/fabricated in the laboratory will be omitted as they are not commercially available in most cases.
iv. PCMs with severe hysteresis (i.e., the PCM melting and solidification temperatures are not the same) or showing subcooling and/or supercooling. However, all numerical studies assumed that the PCM has no hysteresis during phase transition, which applied only for pure PCMs [48], also omitted.
v. Hazardous PCMs have a negative impact on humans and the environment in terms of poisoning or severe flammability [49].
vi. Since this paper aims to select the potential PCMs to be coupled with solar heating systems, only those with Tm in the range of 20 °C–30 °C will be included in the modified list. Nevertheless, such PCMs are in the range of human indoor functioning temperatures in many cold regions.
vii. One PCM candidate will be kept in the modified table for studies investigating similar PCMs of the similar manufacturer and thermo-physical properties.

Step 4: In this step, the PCMs available in local and international markets will only be considered because most companies/manufacturers update their product information and specifications from time to time. Availability of PCMs that remain after Step 3 will be checked, and the information of the new (or alternative) candidate will be applied in the QDM.

Step 5: In this step, the QDM will be applied. QDM will consider some properties and features to select the best PCM candidate to be used for the building heating application. These features could be set based on several thermo-physical, technical, environmental and economic concerns. In this study, the main properties and features that will be considered are Tm, Hf, k, compatibility with aluminium containers, PCM flammability and cost. A specific weight will be given for each property/feature based on its importance, and then, a scoring range from 1 to 3 (1-weak, 2-moderate and 3-good) will be assigned to each weighted property/feature to present the final total scores. Three scenarios will be considered, namely:

- Scenario A: the weighting values shown in Table 1 will be considered.
- Scenario B (the cost will be excluded and the weighting values applied are shown in Table 2)
- Scenario C (the cost will be excluded and all properties/features have the same weight values of 20%).

The scoring range of PCM properties/features considered in the present work are shown in Table 3.

The thermo-physical properties of PCM candidates considered in this work (i.e., Tm, Hf and k) are the most investigated and discussed in the literature studies as they are directly influencing the thermal performance of PCMs in building applications [14].

The appropriate PCM **Tm** is the topmost property-focused by authors as it influences the whole building performance. Accordingly, PCM's effectiveness depends primarily on its Tm and the daily temperature range in the passive and active building applications to guarantee complete charging/discharging cycles [51]. When a PCM of high melting temperature is applied for a specific application, the PCM would be partially melted (the other part remains in a solid-state), and the sensible heat would be activated more than the latent heat [13]. Therefore, part of its thermal storage capacity will be utilised when the application's temperature exceeds the PCM melting temperature. On the contrary, the PCM of low melting temperature would be entirely melted within a short time (fast charging). This would cause an issue, especially for passive applications where the PCM works as a heat source and the heat uncontrollably dissipates towards the conditioned space during peak hours [17]. According to the above reasons, the Tm of PCMs was weighted with 15% (in Scenario A), which is a moderate value, because all PCM melting temperatures investigated in the literature studies were effective. However, higher PCMs melting temperature is preferable for this work considering active heating systems. Although the scope of this work is limited to the PCMs application in cold location buildings, it is worth mentioning that Tm is also the main property considered to select the proper PCM candidate in hot location applications. The PCM Tm used in cold locations is usually lower than that used for hot locations. This is because Tm is associated with the range of temperatures during the day under each location. The Tm of PCMs applied for hot location building applications can reach the height of 44 °C [52] and 52 °C [53].

The **Hf** of PCMs (also called heat storage capacity [54]) is another crucial property because it determines the amount of heat stored and released in the PCM within building applications. PCMs have different heat storage capacity range based on their types and chemical composition. All PCMs have Hf within the range of 120–280 kJ/kg, regardless of the PCM category [55]. However, inorganic PCMs have higher thermal storage capacity than organics (at the same Tm). Moreover, salt hydrates have higher Hf than other types [55]. In this work, PCMs of high Hf are preferred to store as much heat as possible from the solar

Table 3
Scoring of studied properties/features (based on authors' experience and [50]).

Tm		Hf		k		Compatibility		Flammability		Cost ($/kg)	
20–23	1	<160	1	Up to 0.2	1	Not compatible	1	Low flammable	1	1–6	1
24–26	2	160–200	2	>0.2 and < 0.5	2	—	—	—	—	>6 and < 12	2
27–30	3	> 200	3	0.5 or more	3	Compatible	3	Non-flamable	3	> 12	3

Table 4
Summary of studies applied QDM/MCDM for different PCM applications.

Application(s)	Considered properties/ features	No of PCMs investigated	Ref.
Thermal storage for cooling, heating and domestic hot water	Tm, enthalpy, availability, maximum working temperature, cost	19	[50]
Building façade	Tm, Hf, k, specific heat, density, cycling stability, supercooling, toxicity, flammability, corrosiveness, recyclability and embodied energy, initial cost.	29	[77]
ground source heat pump	Hf, k, specific heat (liquid and solid), density, volume change, vapour pressure, supercooling, phase separation, recyclability, toxicity, flammability, cost.	8	[78]
Electronic devices cooling	Tm, Hf, k, specific heat (liquid and solid), density, cost	10	[79]
Thermal Energy Storage in Solar Air Conditioning Systems	Tm, Hf, k, specific heat (liquid and solid), density	10	[80]
Domestic water heating	Hf, k (liquid and solid), specific heat (liquid and solid), density (liquid and solid), cost	15	[81]
Low-temperature heat storage	Tm, Hf, k, specific heat, density, cycle stability, compatibility, melting/ solidification time	5	[82]
Thermal comfort in buildings	Tm, Hf, k, specific heat, density (solid)	8	[83]
Electronic devices thermal management	Hf, k, specific heat, density, subcooling, stability, Incongruent melting, corrosion, toxicity, volume expansion, cost	30	[84]

thermal system during sunshine hours. Therefore, 20% of the total weight was assigned to this property (in Scenario A).

PCMs are generally characterised by their low **thermal conductivity** due to their crystal structure [56]. This issue causes time delay to reach a completed charging and discharging phases [57], which then influences the thermal performance of building applications. However, the PCM behaves as insulation under hot weather conditions by interrupting heat flow towards the indoor environment, and low thermal conductivity might be considered an advantage [13]. Organic PCMs have a low thermal conductivity ranging from 0.2 to 0.25 W/m.K [28]. Different enhancement techniques have been applied to overcome this issue, such as mixing conductive nanoparticles, adding metal foam structures, expanded graphite carriers, adopting extended fins geometries and macroencapsulation techniques [58–64]. Although PCM thermal conductivity is still one of the main properties that should be adequately studied, it was weighted with only 10% in Scenario A, as it is considered to be macroencapsulated by high thermal conductivity containers made of aluminium (the most popular macroencapsulation material).

The **compatibility** of PCMs with the encapsulation containers is among the most important features because it affects their long-term effectiveness [65]. Some PCMs have a negative compatibility effect on metal containers, and others have less in terms of the corrosion rate [66,67]. In the current work, the compatibility of PCMs with aluminium containers will be considered (with 20% weight in Scenario A) because aluminium has high thermal conductivity, available widely in different shapes and sizes, and have a low bearing effect on buildings due to its lightweight.

PCM **flammability** is another critical feature in building applications as the PCM is applied to serve for a long term and may experience leakage. High flammable PCMs will be eliminated, as mentioned in Step 3, and only those with low flammability (or non-flammable) will be considered. This feature weighted 10% in Scenario A, which is relatively low compared with the others, considering that PCMs would be well encapsulated. Both compatibility and flammability of PCMs will be

Table 5
Thermo-physical properties of PCMs based on analysed literature studies.

PCM type	Category	Tm (°C)	Hf (kJ/kg)	k (W/m.K) (Liquid/Solid)	Ref.
RT18HC	Organic (paraffin)	17–19	N/A	0.2	[40]
CA–MA–PA (capric-myristic-palmitic acid)	Organic (Fatty acid)	18.61	128.2	0.45	[86]
PX-21	Organic (paraffin)	19.6	170	0.05	[43]
CA–PA–SA (capric-palmitic-stearic)	Organic (Fatty acid)	19.93	129.4	N/A	[87]
PT20	Organic (BioPCM)	20	180	N/A	[41]
RT 22	Organic (paraffin)	20–23	190	0.2	[37]
Heptadecane	Organic (paraffin)	21	230	0.33	[38]
RT 21	Organic (paraffin)	21	148	0.2	[88,89]
RT-21	Organic (paraffin)	21–22	134	N/A	[44]
TIM-PCM	Eutectic	21.3	152	0.182	[90]
PureTemp 23	Organic (BioPCM)	22.23–24.17	170.71	0.15/0.25	[91 92]
$\text{CaCl}_2\cdot 6\text{H}_2\text{O}$	Organic (Fatty acid)	24	140	0.54/1.09	[93]
Paraffin wax	Organic	24.92	153.06	0.23	[47]
Q25/M91	Organic (BioPCM)	25	175	0.15	[94]
SP-25 A8	Inorganic	26	180	0.6	[95]
CA–PA (capric acid/palmitic acid)	Organic (Fatty acid)	26.2	177	2.2	[96]
CADE (capric acid/1-dodecanol)	Organic (Fatty acid)	26.5	126.9	0.2/0.12	[97]
HS29	Organic (paraffin)	26–29	190	0.55/1.05	[98]
Paraffin wax	Organic	27–29	245	0.2	[99]
RT 27	Organic (paraffin)	28	179	0.2	[100]
TH-ME28	Organic	28.54	102.67	N/A	[46]
RT 27	Organic (paraffin)	28–30	179	0.15/0.24	[101]
SP 29	Inorganic	28–30	190	0.6	[102]
TH29	Organic (Fatty acid)	29	175	1.0	[103]
Q29/M91	Organic (BioPCM)	29	180	N/A	[45]
LA–MA–SA (lauric–myristic–stearic acid ternary eutectic mixture)	Organic (Fatty acid)	29.05	137.1	0.26	[104]
$\text{CaCl}_2\cdot 6\text{H}_2\text{O}$	Organic (Fatty acid)	29.9	187	0.53/1.09	[53]

Table 6
Modified PCM candidates, alternatives and their properties applied in the QDM.

PCM type (from Table 5)	Commercial PCM alternative (Category)	Manufacturer	Tm (°C)	Hf (kJ/kg)	k (W/m. K)	Ref.
RT 21	RT21 (Organic)	Rubitherm®	18–23	155	0.2	[89]
RT 22	RT22HC (Organic)	Rubitherm®	20–23	190	0.2	[89]
PureTemp 23	PureTemp 23 (BioPCM)	PureTemp®	23	201	0.15/0.25	[74]
SP-25 A8	SP25E2 (Inorganic)	Rubitherm®	24–26	180	0.5	[114]
HS29	SavE® HS29 (Inorganic)	Pluss®	29	190	0.382/0.478	[72]
Paraffin wax 27, RT 27	RT28HC (Organic)	Rubitherm®	27–29	250	0.2	[89]
SP 29	SP29E2 (Inorganic)	Rubitherm®	29–30	160	0.5	[114]

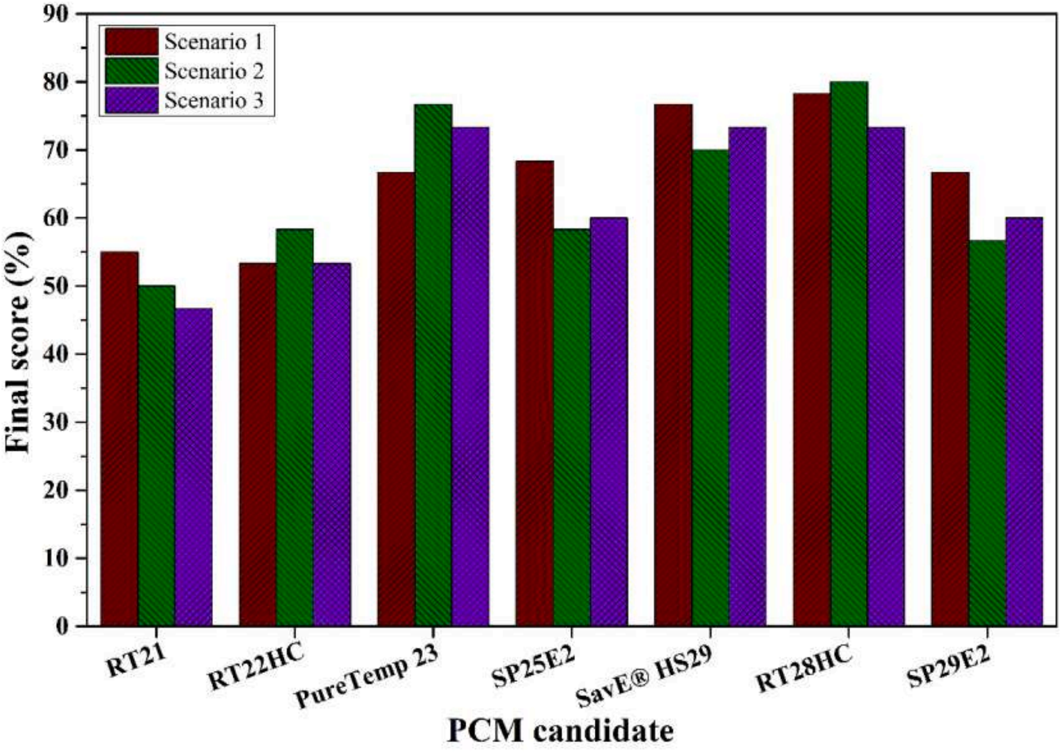

Fig. 3. Final QDM scores of all weighted properties/features in all scenarios.

gathered from the technical datasheet (or safety sheet) provided by the manufacturer for each PCM.

The **cost** of PCMs is the essential feature considered in this work, with 25% of the total weight in Scenario A, and equal to 0% in Scenario B and C. PCM cost significantly impacts system feasibility, especially in building applications due to the vast incorporated PCM amount [68–70]. The cost will be defined based on direct contact (via email) with the leading companies selling such products for each PCM candidate remaining in the modified list. The well-known companies in this regard are Rubitherm® Technologies GmbH [71] in Germany, Pluss® LLC [72] in India, Phase Change Solution (PCS) [73], PureTemp® LLC [74] and its partner Microtek laboratories inc. [75] in the US. The cost will be identified for each kg of pure PCM product (without packaging or encapsulation) in the dollar (USD) currency.

It is worth mentioning that the QDM, also referred to as "multi-criteria decision-making (MCDM) method", is a popular method applied to select the best PCM candidate in many applications. This method generally has better and reasonable results for selecting the best option compared with the traditional ones, especially when several properties/features are considered [76]. Table 4 lists some of the recently studied PCMs using this method for different applications.

4. Results and discussion

Based on the literature review analysed in Section 2, the PCM candidates and their main thermo-physical properties are shown in Table 5. The table included only PCMs within the range of 17 °C–30 °C that are suitable for thermal comfort in building heating applications [28]. Moreover, only the best-performed PCM for studies investigating several PCM types has been included in the table, such as those indicated in [37–40,85].

Table 5 indicate that most of the studied PCMs were organics. Paraffins and fatty acids were studied extensively against a limited number of BioPCMs, due to their high cost and limited manufacturers compared with the organics [105]. This table shows the suitability of organic PCMs for passive and active building heating applications due to their appropriate melting range and other desired properties [106–109].

As mentioned in Section 3 (Step 3), some PCMs should be eliminated from the table for different reasons to reach the final list of potential candidates that could be applied in the QDM. Accordingly, PCMs with missed information, such as RT18HC, PT20, RT-21, TH-ME28 and Q29/M91, were omitted as they are hard to be compared in the QDM. Moreover, PCMs prepared in the laboratories, such as CA–MA–PA, CA–PA–SA, CA–PA, CADE and LA–MA–SA, also omitted as they have only their thermo-physical studies with no information regarding their stability and cost, not to mention some reported hazardous issues about

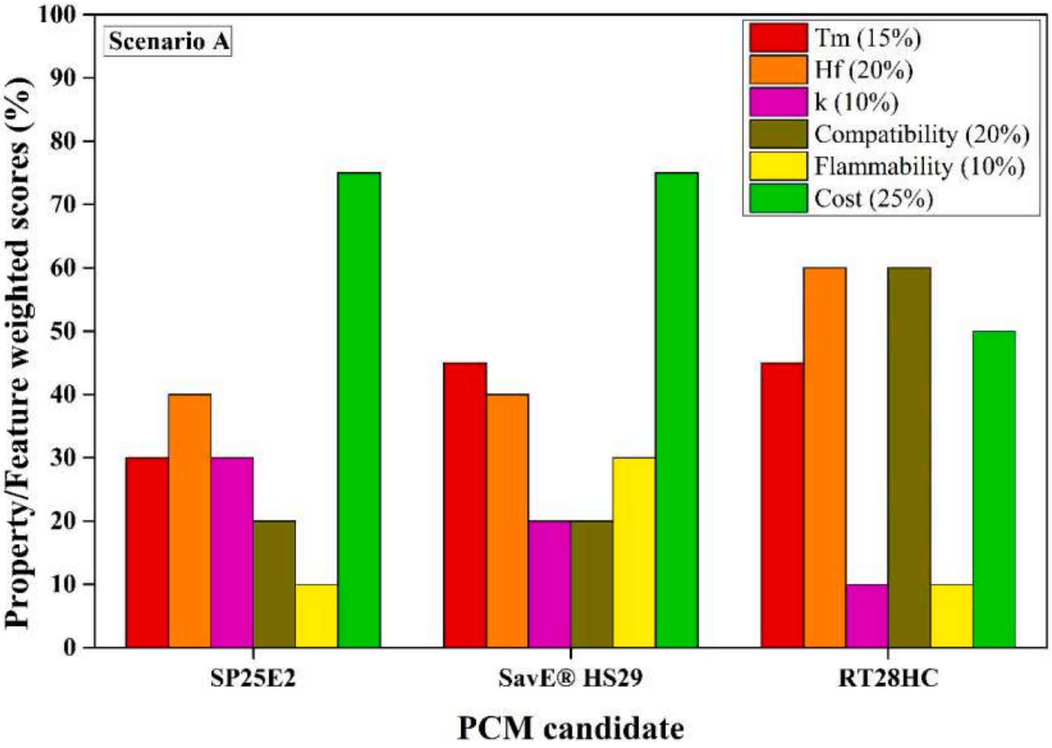

Fig. 4. Weighted scores of properties/features for the top three PCM candidates in Scenario A.

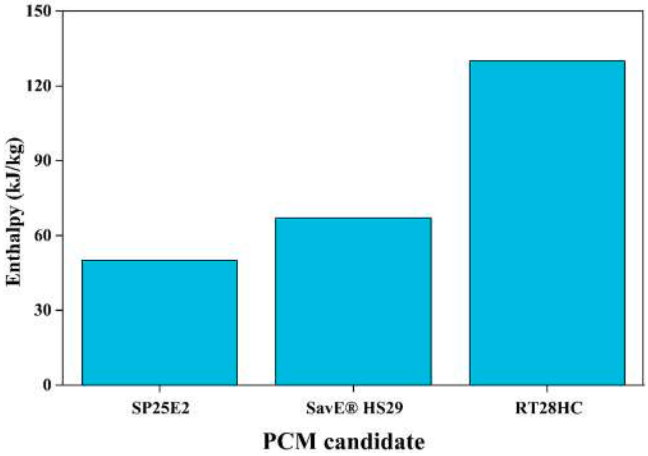

Fig. 5. Enthalpy value of SP25E2, SavE®HS29 and RT28HC as indicated in their technical datasheet [72,115,116].

them [110]. Besides, for PCMs that have the same thermo-physical properties, such as Paraffin wax and RT 27, only one of them was counted after careful checking for their similar properties in the manufacturer database. Some omitted PCMs are sold with special packages that are unsuitable for future applications, such as Q25/M91, produced by Avarvio Australia Co. [111]. Salt hydrates were omitted from Table 5 because some studies indicated that they are suffering from segregation issues after many cycles [55,112], as well as supercooling issues in most products [113], and health hazard concerns [49]. The final modified list of PCM candidates, including their alternatives and manufacturers, are presented in Table 6.

Fig. 3 shows the results obtained by applying the QDM method on the PCM candidates indicated in Table 6 for Scenario A, Scenario B and Scenario C. These results were generated by multiplying the scores and weights in all scenarios for each PCM property/feature individually and then divided by the highest score and weight.

According to the results, RT28HC has the highest score in all scenarios with 78.3% in Scenario A and 80% in Scenario B. SavE®HS29 has the second high score in Scenario A with 76.67%, and PureTemp 23 has the second-best score in Scenario B. Furthermore, all these PCMs indicated the highest score of 73.3% in Scenario C compared with the other PCM candidates. Conversely, RT21, RT22HC and SP29E2 had the lowest QDM scores in all scenarios.

In Scenario A, RT28HC has the best Tm, Hf and compatibility, while SavE®HS29 has a better score considering the Tm and PCM cost. SP25E2 was the best third candidate in this scenario, and it showed the best scores in terms of the thermal conductivity and the cost, as shown in Fig. 4.

Regardless of the high scores obtained above, the Enthalpy-Temperature relation provided in the manufacturers' technical datasheet shows that the RT28HC has a much higher enthalpy value compared with SavE®HS29 and SP25E2, not only in terms of the presented QDM, as shown in Fig. 5. This PCM property is essential with the Hf as they influence the heat charging and discharging throughout the PCM working period [50].

As mentioned before, the PCM cost is essential in building applications due to the large amount of PCM applied, which influences system feasibility. However, this feature has been excluded in Scenario B and C to investigate the PCM selection from the technical side of view. In Scenario B, the weight of each property/feature has increased by 5% (as indicated in Table 2), and the top 3 PCM candidates became RT28HC, PureTemp23 and SavE®HS29 with respectively 80%, 76.67% and 70%. The detailed weighted scores of these PCMs are shown in Fig. 6.

As shown in Fig. 6, RT28HC has the highest scores for Tm, Hf and [CM compatibility. In contrast, PureTemp 23 has the best scores for Hf, compatibility and flammability, the common desired properties of Bio-PCMs [105]. Moreover, SavE®HS29 showed the highest scores in terms of Tm and flammability only. These results show that RT28HC and SavE®HS29 are the best candidates with or without cost consideration.

The QDM results for Scenario C (where the cost feature is excluded and all properties/features have the same weight) are shown in Fig. 7.

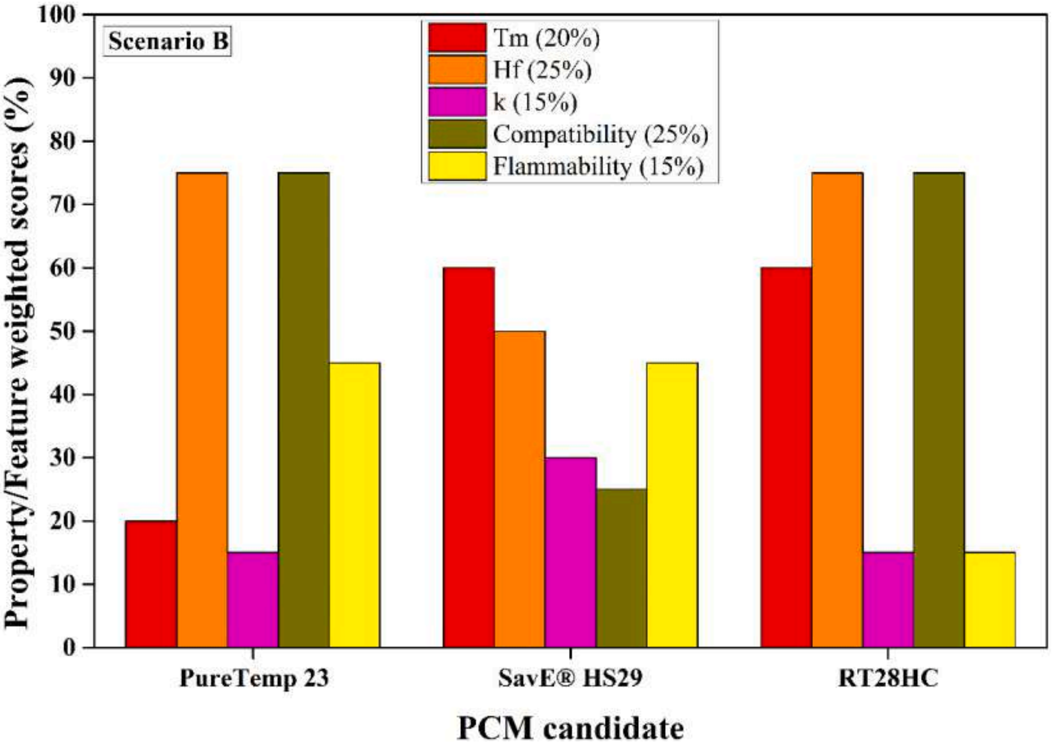

Fig. 6. Weighted scores of properties/features for the top three PCM candidates in Scenario B.

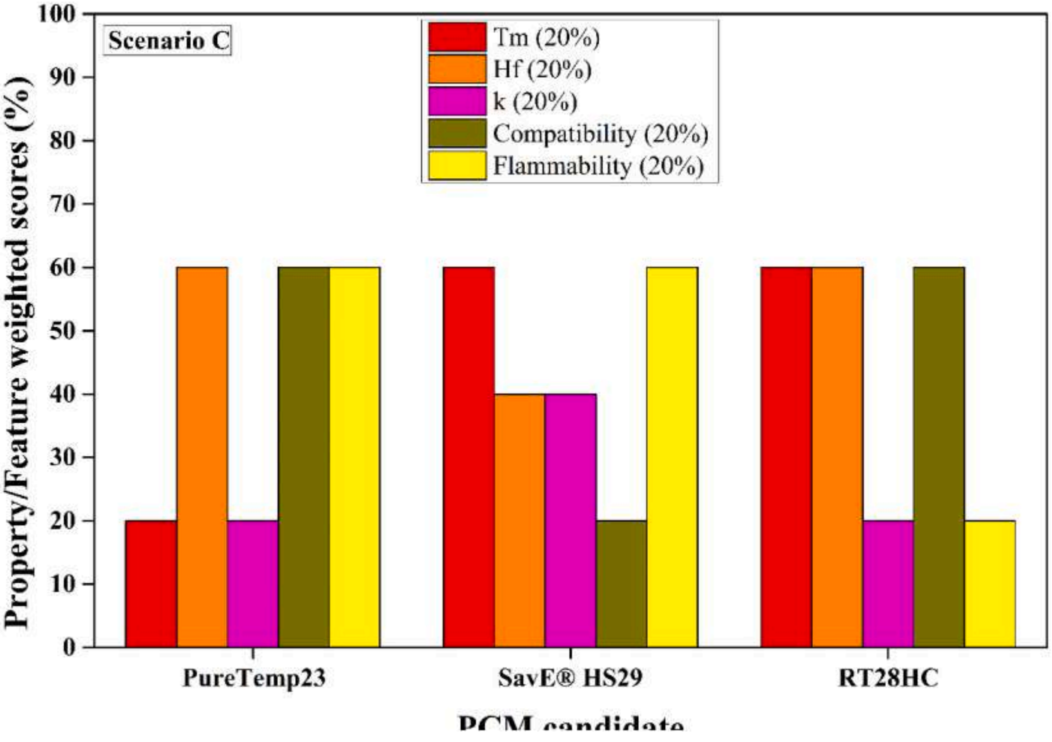

Fig. 7. Weighted scores of properties/features for the top three PCM candidates in Scenario C.

The results indicated that the top 3 candidates of Scenario B are repeated with the same score of 73.3%.

Overall, regardless of applying QDM, the top 3 PCM candidates obtained in each scenario have better thermo-physical properties and features than the others, allowing them to be used successfully and efficiently in building applications.

5. Conclusion

The current paper investigates the best PCM candidates that could be applied for building heating applications under cold weather conditions. A QDM has applied for several commercial PCM candidates. After careful and extensive analysis of the state-of-the-art literature studies. The PCM melting temperature, the heat of fusion, and thermal conductivity were considered in the QDM as effective properties in PCM building heating applications. Moreover, the PCM compatibility, flammability and cost are also considered in the QDM as essential features. Scores and weights were assigned for each property/feature based on their importance. The total scores obtained were presented according to three scenarios (Scenario A, including the PCM cost with different weights, Scenario B excluding the cost with different weights and Scenario C excluding the PCM cost with equal weights for the properties/features). The results showed that RT28HC has the best potential in this application in all scenarios with 78.3%, 80% and 73.3% in Scenario A, Scenario B and Scenario C. SavE®HS29 and SP25E2 showed the best second and third PCM candidates in Scenario A with scores of 76.67%, and 68.33%, respectively. PureTemp 23, the BioPCM, showed the second-best PCM candidate in Scenario B and C. However, this PCM (i.e., PureTemp 23) has the highest cost compared with all investigated PCMs, limiting its use in PCM practical building applications.

This methodology could also be applied to select the best PCM candidate under hot weather locations. In this case, the melting temperature range would be different (usually higher), and the preferable Tm depends on the position of the PCM layer concerning the other envelope materials. Moreover, the weights of PCM properties/features could also be different, especially the PCM thermal conductivity as the PCM serves as insulation under hot location applications.

The results presented in this work also can be extended to include more properties and features such as the PCM density, specific heat, enthalpy, crystallisation, subcooling/supercooling and safety concerns, supported with simulation tools.

CRediT authorship contribution statement

Qudama Al-Yasiri: Conceptualization, Methodology, Data curation, Formal analysis, Investigation, Writing – original draft, Writing – review & editing. **Márta Szabó:** Conceptualization, Methodology, Writing – review & editing, Supervision, Funding acquisition.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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References

[1] Lin Y, Jia Y, Alva G, Fang G. Review on thermal conductivity enhancement, thermal properties and applications of phase change materials in thermal energy storage. Renew Sustain Energy Rev 2018;82:2730–42.

[2] Yang L, Jin X, Zhang Y, Du K. Recent development on heat transfer and various applications of phase-change materials. J Clean Prod 2021;287:124432. https://doi.org/10.1016/j.jclepro.2020.124432.

[3] Huang J, Luo Y, Weng M, Yu J, Sun L, Zeng H, et al. Advances and Applications of Phase Change Materials (PCMs) and PCMs-based Technologies. ES Mater Manuf 2021. https://doi.org/10.30919/esmm5f458.

[4] B K, Pandey AK, Shahabuddin S, Samykano M, M T, Saidur R. Phase change materials integrated solar thermal energy systems: Global trends and current practices in experimental approaches. J Energy Storage 2020;27:101118. https://doi.org/10.1016/j.est.2019.101118.

[5] Singh Rathore PK, Shukla SK, Gupta NK. Potential of microencapsulated PCM for energy savings in buildings: A critical review. Sustain Cities Soc 2020;53:101884. https://doi.org/10.1016/j.scs.2019.101884.

[6] Arıcı M, Bilgin F, Nižetić S, Karabay H. PCM integrated to external building walls: An optimization study on maximum activation of latent heat. Appl Therm Eng 2020;165:114560. https://doi.org/10.1016/j.applthermaleng.2019.114560.

[7] Saafi K, Daouas N. Energy and cost efficiency of phase change materials integrated in building envelopes under Tunisia Mediterranean climate. Energy 2019;187:115987. https://doi.org/https://doi.org/10.1016/j.energy.2019.115987.

[8] Alvi JZ, Feng Y, Wang Q, Imran M, Khan LA, Pei G. Effect of Phase Change Material Storage on the Dynamic Performance of a Direct Vapor Generation Solar Organic Rankine Cycle System. Energies 2020;13:5904. https://doi.org/10.3390/en13225904.

[9] Zeinelabdein R, Omer S, Gan G. Critical review of latent heat storage systems for free cooling in buildings. Renew Sustain Energy Rev 2018;82:2843–68. https://doi.org/10.1016/j.rser.2017.10.046.

[10] Song M, Niu F, Mao N, Hu Y, Deng S. Review on building energy performance improvement using phase change materials. Energy Build 2018;158:776–93. https://doi.org/10.1016/j.enbuild.2017.10.066.

[11] Lu S, Li Y, Kong X, Pang B, Chen Y, Zheng S, et al. A Review of PCM Energy Storage Technology Used in Buildings for the Global Warming Solution. In: Zhang X, Dincer I, editors. Energy Solut. to Combat Glob. Warm., Cham: Springer International Publishing; 2017, p. 611–44. https://doi.org/10.1007/978-3-319-26950-4_31.

[12] Faraj K, Khaled M, Faraj J, Hachem F, Castelain C. Phase change material thermal energy storage systems for cooling applications in buildings: A review. Renew Sustain Energy Rev 2020;119:109579. https://doi.org/10.1016/j.rser.2019.109579.

[13] Kośny J. PCM-Enhanced Building Components: An Application of Phase Change Materials in Building Envelopes and Internal Structures. Springer 2015. https://doi.org/10.1007/978-3-319-14286-9.

[14] Madad A, Mouhib T, Mouhsen A. Phase change materials for building applications: A thorough review and new perspectives. Buildings 2018;8. https://doi.org/10.3390/buildings8040063.

[15] Markarian E, Fazelpour F. Multi-objective optimization of energy performance of a building considering different configurations and types of PCM. Sol Energy 2019;191:481–96. https://doi.org/10.1016/j.solener.2019.09.003.

[16] Al-Yasiri Q, Szabó M. Incorporation of phase change materials into building envelope for thermal comfort and energy saving: A comprehensive analysis. J Build Eng 2021;36:102122. https://doi.org/10.1016/j.jobe.2020.102122.

[17] de Gracia A. Dynamic building envelope with PCM for cooling purposes – Proof of concept. Appl Energy 2019;235:1245–53. https://doi.org/10.1016/j.apenergy.2018.11.061.

[18] Jeong SG, Wi S, Chang SJ, Lee J, Kim S. An experimental study on applying organic PCMs to gypsum-cement board for improving thermal performance of buildings in different climates. Energy Build 2019;190:183–94. https://doi.org/10.1016/j.enbuild.2019.02.037.

[19] Sarı A, Bicer A, Karaipekli A, Al-Sulaiman FA. Preparation, characterization and thermal regulation performance of cement based-composite phase change material. Sol Energy Mater Sol Cells 2018;174:523–9. https://doi.org/10.1016/j.solmat.2017.09.049.

[20] Karaipekli A, Sarı A. Development and thermal performance of pumice/organic PCM/gypsum composite plasters for thermal energy storage in buildings. Sol Energy Mater Sol Cells 2016;149:19–28. https://doi.org/10.1016/j.solmat.2015.12.034.

[21] Wi S, Jeong S-G, Chang SJ, Lee J, Kim S. Evaluation of energy efficient hybrid hollow plaster panel using phase change material/xGnP composites. Appl Energy 2017;205:1548–59. https://doi.org/10.1016/j.apenergy.2017.08.156.

[22] Guarino F, Athienitis A, Cellura M, Bastien D. PCM thermal storage design in buildings: Experimental studies and applications to solaria in cold climates. Appl Energy 2017;185:95–106. https://doi.org/10.1016/j.apenergy.2016.10.046.

[23] Luo C, Xu L, Ji J, Liao M, Sun D. Experimental study of a modified solar phase change material storage wall system. Energy 2017;128:224–31. https://doi.org/10.1016/j.energy.2017.04.020.

[24] Jiang W, Liu Bo, Zhang X, Zhang T, Li D, Ma L. Energy performance of window with PCM frame. Sustain Energy Technol Assessments 2021;45:101109. https://doi.org/10.1016/j.seta.2021.101109.

[25] Guo J, Zou B, Wang Y, Jiang Y. Space heating performance of novel ventilated mortar blocks integrated with phase change material for floor heating. Build Environ 2020;185:107175. https://doi.org/10.1016/j.buildenv.2020.107175.

[26] Devaux P, Farid MM. Benefits of PCM underfloor heating with PCM wallboards for space heating in winter. Appl Energy 2017;191:593–602. https://doi.org/10.1016/j.apenergy.2017.01.060.

[27] Teamah HM. Comprehensive review of the application of phase change materials in residential heating applications. Alexandria Eng J 2021;60:3829–43. https://doi.org/10.1016/j.aej.2021.02.053.

[28] Al-Yasiri Q, Szabó M. Performance Assessment of Phase Change Materials Integrated with Building Envelope for Heating Application in Cold Locations. Eur J Energy Res 2021;1:7–14. https://doi.org/https://doi.org/10.24018/ejenergy.2021.1.1.5.

[29] Faraj K, Khaled M, Faraj J, Hachem F, Castelain C. A review on phase change materials for thermal energy storage in buildings: Heating and hybrid applications. J Energy Storage 2021;33:101913. https://doi.org/10.1016/j.est.2020.101913.

[30] Li Y, Nord N, Xiao Q, Tereshchenko T. Building heating applications with phase change material: A comprehensive review. J Energy Storage 2020;31:101634. https://doi.org/10.1016/j.est.2020.101634.

[31] Sharma V, Rai AC. Performance assessment of residential building envelopes enhanced with phase change materials. Energy Build 2020;208:109664. https://doi.org/10.1016/j.enbuild.2019.109664.

[32] Li ZX, Al-Rashed AAAA, Rostamzadeh M, Kalbasi R, Shahsavar A, Afrand M. Heat transfer reduction in buildings by embedding phase change material in multi-layer walls: Effects of repositioning, thermophysical properties and thickness of PCM. Energy Convers Manag 2019;195:43–56. https://doi.org/10.1016/j.enconman.2019.04.075.

[33] Vukadinović A, Radosavljević J, Đorđević A. Energy performance impact of using phase-change materials in thermal storage walls of detached residential buildings with a sunspace. Sol Energy 2020;206:228–44. https://doi.org/10.1016/j.solener.2020.06.008.

[34] Tunçbilek E, Arıcı M, Krajčík M, Nižetić S, Karabay H. Thermal performance based optimization of an office wall containing PCM under intermittent cooling operation. Appl Therm Eng 2020;179:115750. https://doi.org/10.1016/j.applthermaleng.2020.115750.

[35] Al-Yasiri Q, Szabó M. Thermal performance of concrete bricks based phase change material encapsulated by various aluminium containers: An experimental study under Iraqi hot climate conditions. J Energy Storage 2021;40:102710. https://doi.org/10.1016/j.est.2021.102710.

[36] Vicente R, Silva T. Brick masonry walls with PCM macrocapsules: An experimental approach. Appl Therm Eng 2014;67(1-2):24–34. https://doi.org/10.1016/j.applthermaleng.2014.02.069.

[37] Araújo C, Pinheiro A, Castro MF, Bragança L. Phase Change Materials as a solution to improve energy efficiency in Portuguese residential buildings. IOP Conf Ser Mater Sci Eng 2017;251:012110. https://doi.org/10.1088/1757-899X/251/1/012110.

[38] Seong YB, Lim JH. Energy saving potentials of phase change materials applied to lightweight building envelopes. Energies 2013;6:5219–30. https://doi.org/10.3390/en6105219.

[39] Saffari M, de Gracia A, Fernández C, Cabeza LF. Simulation-based optimization of PCM melting temperature to improve the energy performance in buildings. Appl Energy 2017;202:420–34. https://doi.org/10.1016/j.apenergy.2017.05.107.

[40] Pirasaci T. Investigation of phase state and heat storage form of the phase change material (PCM) layer integrated into the exterior walls of the residential-apartment during heating season. Energy 2020;207:118176. https://doi.org/10.1016/j.energy.2020.118176.

[41] Barzin R, Chen JJJ, Young BR, Farid MM. Application of weather forecast in conjunction with price-based method for PCM solar passive buildings – An experimental study. Appl Energy 2016;163:9–18. https://doi.org/10.1016/j.apenergy.2015.11.016.

[42] Hu J, Yu X. Thermo and light-responsive building envelope: Energy analysis under different climate conditions. Sol Energy 2019;193:866–77. https://doi.org/10.1016/j.solener.2019.10.021.

[43] Arkar C, Medved S. Optimization of latent heat storage in solar air heating system with vacuum tube air solar collector. Sol Energy 2015;111:10–20. https://doi.org/10.1016/j.solener.2014.10.013.

[44] Navarro L, de Gracia A, Castell A, Cabeza LF. Experimental study of an active slab with PCM coupled to a solar air collector for heating purposes. Energy Build 2016;128:12–21. https://doi.org/10.1016/j.enbuild.2016.06.069.

[45] Plytaria MT, Tzivanidis C, Bellos E, Antonopoulos KA. Energetic investigation of solar assisted heat pump underfloor heating systems with and without phase change materials. Energy Convers Manag 2018;173:626–39. https://doi.org/10.1016/j.enconman.2018.08.010.

[46] Guo J, Jiang Y, Wang Y, Zou B. Thermal storage and thermal management properties of a novel ventilated mortar block integrated with phase change material for floor heating: an experimental study. Energy Convers Manag 2020;205:112288. https://doi.org/10.1016/j.enconman.2019.112288.

[47] Kong X, Wang L, Li H, Yuan G, Yao C. Experimental study on a novel hybrid system of active composite PCM wall and solar thermal system for clean heating supply in winter. Sol Energy 2020;195:259–70. https://doi.org/10.1016/j.solener.2019.11.081.

[48] Bhamare DK, Rathod MK, Banerjee J. Proposal of a unique index for selection of optimum phase change material for effective thermal performance of a building envelope. Sol Energy 2021;218:129–41. https://doi.org/10.1016/j.solener.2021.02.027.

[49] Chandel SS, Agarwal T. Review of current state of research on energy storage, toxicity, health hazards and commercialization of phase changing materials. Renew Sustain Energy Rev 2017;67:581–96. https://doi.org/10.1016/j.rser.2016.09.070.

[50] Zsembinszki G, Fernández AG, Cabeza LF. Selection of the appropriate phase change material for two innovative compact energy storage systems in residential buildings. Appl Sci 2020;10:2116. https://doi.org/10.3390/app10062116.

[51] Zhu N, Li S, Hu P, Wei S, Deng R, Lei F. A review on applications of shape-stabilized phase change materials embedded in building enclosure in recent ten years. Sustain Cities Soc 2018;43:251–64. https://doi.org/10.1016/j.scs.2018.08.028.

[52] Al-Yasiri Q, Szabó M. Case study on the optimal thickness of phase change material incorporated composite roof under hot climate conditions. Case Stud Constr Mater 2021;14:e00522. https://doi.org/10.1016/j.cscm.2021.e00522.

[53] Hichem N, Noureddine S, Nadia S, Djamila D. Experimental and numerical study of a usual brick filled with PCM to improve the thermal inertia of buildings. Energy Procedia 2013;36:766–75. https://doi.org/10.1016/j.egypro.2013.07.089.

[54] Kirkham MB. Chapter 3 - Structure and Properties of Water. In: Kirkham MB, editor. Princ. Soil Plant Water Relations (Second Ed. Second Edi, Boston: Academic Press; 2014, p. 27–40. https://doi.org/https://doi.org/10.1016/B978-0-12-420022-7.00003-3.

[55] Xie N, Huang Z, Luo Z, Gao X, Fang Y, Zhang Z. Inorganic salt hydrate for thermal energy storage. Appl Sci 2017;7(12):1317. https://doi.org/10.3390/app7121317.

[56] Yıldız Ç, Arıcı M, Karabay H. Comparison of a theoretical and experimental thermal conductivity model on the heat transfer performance of Al2O3-SiO2/water hybrid-nanofluid. Int J Heat Mass Transf 2019;140:598–605. https://doi.org/10.1016/j.ijheatmasstransfer.2019.06.028.

[57] Peng B, Huang G, Wang P, Li W, Chang W, Ma J, et al. Effects of thermal conductivity and density on phase change materials-based thermal energy storage systems. Energy 2019;172:580–91. https://doi.org/10.1016/j.energy.2019.01.147.

[58] Amaral C, Vicente R, Marques PAAP, Barros-Timmons A. Phase change materials and carbon nanostructures for thermal energy storage: A literature review. Renew Sustain Energy Rev 2017;79:1212–28. https://doi.org/10.1016/j.rser.2017.05.093.

[59] Qureshi ZA, Ali HM, Khushnood S. Recent advances on thermal conductivity enhancement of phase change materials for energy storage system: A review. Int J Heat Mass Transf 2018;127:838–56. https://doi.org/10.1016/j.ijheatmasstransfer.2018.08.049.

[60] Shang B, Hu J, Hu R, Cheng J, Luo X. Modularized thermal storage unit of metal foam/paraffin composite. Int J Heat Mass Transf 2018;125:596–603.

[61] Al-Yasiri Q, Szabó M. Experimental evaluation of the optimal position of a macroencapsulated phase change material incorporated composite roof under hot climate conditions. Sustain Energy Technol Assessments 2021;45:101121. https://doi.org/10.1016/j.seta.2021.101121.

[62] Nižetić S, Jurčević M, Arıcı M, Arasu AV, Xie G. Nano-enhanced phase change materials and fluids in energy applications: A review. Renew Sustain Energy Rev 2020;129:109931.

[63] Shehzad SA, Alshuraiaan B, Kamel MS, Izadi M, Ambreen T. Influence of fin orientation on the natural convection of aqueous-based nano-encapsulated PCMs in a heat exchanger equipped with wing-like fins. Chem Eng Process - Process Intensif 2020:108287. https://doi.org/https://doi.org/10.1016/j.cep.2020.108287.

[64] Mohaghegh MR, Alomair Y, Alomair M, Tasnim SH, Mahmud S, Abdullah H. Melting of PCM inside a novel encapsulation design for thermal energy storage system. Energy Convers Manag X 2021;11:100098. https://doi.org/https://doi.org/10.1016/j.ecmx.2021.100098.

[65] Al-Yasiri Q, Szabó M. Influential aspects on melting and solidification of PCM energy storage containers in building envelope applications. Int J Green Energy 2021;18:966–86. https://doi.org/https://doi.org/10.1080/15435075.2021.1890082.

[66] Devanuri JK, Gaddala UM, Kumar V. Investigation on compatibility and thermal reliability of phase change materials for low-temperature thermal energy storage. Mater Renew Sustain Energy 2020;9:1–16. https://doi.org/10.1007/s40243-020-00184-4.

[67] Browne MC, Boyd E, McCormack SJ. Investigation of the corrosive properties of phase change materials in contact with metals and plastic. Renew Energy 2017;108:555–68. https://doi.org/10.1016/j.renene.2017.02.082.

[68] Baniassadi A, Sajadi B, Amidpour M, Noori N. Economic optimization of PCM and insulation layer thickness in residential buildings. Sustain Energy Technol Assessments 2016;14:92–9. https://doi.org/10.1016/j.seta.2016.01.008.

[69] Feng GuoHui, Liang D, Huang KaiLiang, Wang YuHan. Thermal performance difference of phase change energy storage units based on tubular macro-encapsulation. Sustain Cities Soc 2019;50:101662. https://doi.org/10.1016/j.scs.2019.101662.

[70] Mi X, Liu R, Cui H, Memon SA, Xing F, Lo Y. Energy and economic analysis of building integrated with PCM in different cities of China. Appl Energy 2016;175:324–36. https://doi.org/10.1016/j.apenergy.2016.05.032.

[71] Rubitherm® GmbH. Available online: https://www.rubitherm.eu/en//index.html.

[72] PLUSS® Co. Available online: https://pluss.co.in/product-range-PCM.php.

[73] Phase Change Solutions (PCS). Available online: https://phasechange.com/.

[74] PureTemp LLC. Available online: http://www.puretemp.com/.

[75] Microtek Laboratories Inc. Available online: https://www.microteklabs.com/company.

[76] Royo P, Ferreira VJ, Ure Z, Gledhill S, López-Sabirón AM, Ferreira G. Multiple-Criteria Decision Analysis and characterisation of phase change materials for waste heat recovery at high temperature for sustainable energy-intensive industry. Mater Des 2020;186:108215. https://doi.org/10.1016/j.matdes.2019.108215.

[77] Mukhamet T, Kobeyev S, Nadeem A, Memon SA. Ranking PCMs for building façade applications using multi-criteria decision-making tools combined with energy simulations. Energy 2021;215:119102. https://doi.org/10.1016/j.energy.2020.119102.

[78] Yang K, Zhu N, Chang C, Wang D, Yang S, Ma S. A methodological concept for phase change material selection based on multi-criteria decision making (MCDM): A case study. Energy 2018;165:1085–96. https://doi.org/10.1016/j.energy.2018.10.022.

[79] Loganathan A, Mani I. A fuzzy based hybrid multi criteria decision making methodology for phase change material selection in electronics cooling system. Ain Shams Eng J 2018;9:2943–50. https://doi.org/10.1016/j.asej.2017.11.005.

[80] Xu H, Sze JY, Romagnoli A, Py X. Selection of Phase Change Material for Thermal Energy Storage in Solar Air Conditioning Systems. Energy Procedia 2017;105:4281–8. https://doi.org/10.1016/j.egypro.2017.03.898.

[81] Gadhave P, Prabhune C, Pathan F. Selection of Phase Change Material for Domestic Water Heating Using Multi Criteria Decision Approach. Aust J Mech Eng 2020:1–21. https://doi.org/10.1080/14484846.2020.1842297.

[82] Gaddala UM, Devanuri JK. A Hybrid Decision-Making Method for the Selection of a Phase Change Material for Thermal Energy Storage. J Therm Sci Eng Appl 2020;12:041020. https://doi.org/10.1115/1.4046056.

[83] Socaciu LG, Unguresan PV. Using the Analytic Hierarchy Process to Prioritize and Select Phase Change Materials for Comfort Application in Buildings. Math Model Civ Eng 2014;10:21–8. https://doi.org/10.2478/mmce-2014-0003.

[84] Kumar A, Kothari R, Sahu SK, Kundalwal SI. Selection of phase-change material for thermal management of electronic devices using multi-attribute decision-making technique. Int J Energy Res 2021;45:2023–42. https://doi.org/10.1002/er.5896.

[85] Omara AAM, Abuelnuor AAA. Trombe walls with phase change materials: A review. Energy Storage 2020;2:1–28. https://doi.org/10.1002/est2.123.

[86] Yuan Y, Yuan Y, Zhang N, Du Y, Cao X. Preparation and thermal characterization of capric–myristic–palmitic acid/expanded graphite composite as phase change material for energy storage. Mater Lett 2014;125:154–7. https://doi.org/10.1016/j.matlet.2014.04.002.

[87] Yuan Y, Li T, Zhang N, Cao X, Yang X. Investigation on thermal properties of capric–palmitic–stearic acid/activated carbon composite phase change materials for high-temperature cooling application. J Therm Anal Calorim 2016;124(2):881–8. https://doi.org/10.1007/s10973-015-5173-0.

[88] Cao VD, Bui TQ, Kjøniksen A-L. Thermal analysis of multi-layer walls containing geopolymer concrete and phase change materials for building applications. Energy 2019;186:115792. https://doi.org/10.1016/j.energy.2019.07.122.

[89] Rubitherm GmbH RT-PCM Line. Available online: https://www.rubitherm.eu/en/index.php/productcategory/organische-pcm-rt.

[90] Berthou Y, Biwole PH, Achard P, Sallée H, Tantot-Neirac M, Jay F. Full scale experimentation on a new translucent passive solar wall combining silica aerogels and phase change materials. Sol Energy 2015;115:733–42. https://doi.org/10.1016/j.solener.2015.03.038.

[91] Navarro L, Solé A, Martín M, Barreneche C, Olivieri L, Tenorio JA, et al. Benchmarking of useful phase change materials for a building application. Energy Build 2019;182:45–50. https://doi.org/10.1016/j.enbuild.2018.10.005.

[92] PureTemp Company. PureTemp ® Thermal Energy Storage Materials PureTemp 48 Technical Information. 2020.

[93] Daghigh R, Zandi P. An air and water heating system based on solar gas combined with nanofluids and phase change materials. J Clean Prod 2021;311:127751. https://doi.org/10.1016/j.jclepro.2021.127751.

[94] Plytaria M, Tzivanidis C, Bellos E, Alexopoulos I, Antonopoulos K. Thermal behavior of a building with incorporated phase change materials in the South and the North Wall. Computation 2019;7(1):2. https://doi.org/10.3390/computation7010002.

[95] Castell A, Martorell I, Medrano M, Pérez G, Cabeza LF. Experimental study of using PCM in brick constructive solutions for passive cooling. Energy Build 2010;42(4):534–40. https://doi.org/10.1016/j.enbuild.2009.10.022.

[96] Sayyar M, Weerasiri RR, Soroushian P, Lu J. Experimental and numerical study of shape-stable phase-change nanocomposite toward energy-efficient building constructions. Energy Build 2014;75:249–55. https://doi.org/10.1016/j.enbuild.2014.02.018.

[97] Kong X, Lu S, Huang J, Cai Z, Wei S. Experimental research on the use of phase change materials in perforated brick rooms for cooling storage. Energy Build 2013;62:597–604. https://doi.org/10.1016/j.enbuild.2013.03.048.

[98] Kumar S, Arun Prakash S, Pandiyarajan V, Geetha NB, Antony Aroul Raj V, Velraj R. Effect of phase change material integration in clay hollow brick composite in building envelope for thermal management of energy efficient buildings. J Build Phys 2020;43(4):351–64. https://doi.org/10.1177/1744259119867462.

[99] Sun X, Jovanovic J, Zhang Y, Fan S, Chu Y, Mo Y, et al. Use of encapsulated phase change materials in lightweight building walls for annual thermal regulation. Energy 2019;180:858–72. https://doi.org/10.1016/j.energy.2019.05.112.

[100] Sun X, Medina MA, Lee KO, Jin X. Laboratory assessment of residential building walls containing pipe-encapsulated phase change materials for thermal management. Energy 2018;163:383–91. https://doi.org/10.1016/j.energy.2018.08.159.

[101] Qi D, Pu L, Sun F, Li Y. Numerical investigation on thermal performance of ground heat exchangers using phase change materials as grout for ground source heat pump system. Appl Therm Eng 2016;106:1023–32. https://doi.org/10.1016/j.applthermaleng.2016.06.048.

[102] Meng E, Yu H, Zhou B. Study of the thermal behavior of the composite phase change material (PCM) room in summer and winter. Appl Therm Eng 2017;126:212–25. https://doi.org/10.1016/j.applthermaleng.2017.07.110.

[103] Evers AC, Medina MA, Fang Y. Evaluation of the thermal performance of frame walls enhanced with paraffin and hydrated salt phase change materials using a dynamic wall simulator. Build Environ 2010;45:1762–8. https://doi.org/10.1016/j.buildenv.2010.02.002.

[104] Liu C, Yuan Y, Zhang N, Cao X, Yang X. A novel PCM of lauric–myristic–stearic acid/expanded graphite composite for thermal energy storage. Mater Lett 2014;120:43–6. https://doi.org/https://doi.org/10.1016/j.matlet.2014.01.051.

[105] Gassar AAA, Yun GY. Energy saving potential of PCMs in buildings under future climate conditions. Appl Sci 2017;7(12):1219. https://doi.org/10.3390/app7121219.

[106] Reza Vakhshouri A. Paraffin as Phase Change Material. In: Soliman FS, editor. Paraffin - an Overv., “ IntechOpen”; 2019. https://doi.org/DOI: 10.5772/intechopen.90487.

[107] Iten M, Liu S, Shukla A. A review on the air-PCM-TES application for free cooling and heating in the buildings. Renew Sustain Energy Rev 2016;61:175–86. https://doi.org/10.1016/j.rser.2016.03.007.

[108] Kahwaji S, Johnson MB, Kheirabadi AC, Groulx D, White MA. Fatty acids and related phase change materials for reliable thermal energy storage at moderate temperatures. Sol Energy Mater Sol Cells 2017;167:109–20.

[109] Al-Yasiri Q, Szabó M, Kazem H, Szabo M, Darwish ASK. Paraffin As a Phase Change Material to Improve Building Performance: An Overview of Applications and Thermal Conductivity Enhancement Techniques. Renew Energy Environ Sustain 2021;6:38. https://doi.org/10.1051/rees/2021040.

[110] Carlroth Co. Saf Data Sheet Calcium Chloride Hexahydrate 2021:T886. bWFzdGVyfHNlY3VyaXR5RGF0YXNoZWV0c3wyMjY3MTB8YXBwbGljYXRpb24vcGRmfHNlY3VyaXR5RGF0YXNoZWV0cy9oMmIvaDJhLzkwMjE2MTk1Njg2NzAucGRmfGYzNGIwOWFkMjFiZjhlM2ZhYTkwYjE1MzRlOWIxMGZmZmYxMDQ0YmIwNTc1YWI0NTUyZGM5YTk0YTc3ZTllMmQ.

[111] Avarvio Australia. Available online: http://arvio.com.au/.

[112] Dannemand M, Johansen JB, Furbo S. Solidification behavior and thermal conductivity of bulk sodium acetate trihydrate composites with thickening agents and graphite. Sol Energy Mater Sol Cells 2016;145:287–95.

[113] Safari A, Saidur R, Sulaiman FA, Xu Y, Dong J. A review on supercooling of Phase Change Materials in thermal energy storage systems. Renew Sustain Energy Rev 2017;70:905–19. https://doi.org/https://doi.org/10.1016/j.rser.2016.11.272.

[114] Rubitherm GmbH SP-PCM Line. Available online: https://www.rubitherm.eu/en/index.php/productcategory/anorganische-pcm-sp.

[115] Rubitherm GmbH-SP25E2 Technical datasheet. Available online: https://www.rubitherm.eu/media/products/datasheets/Techdata_-SP25E2_EN_09112020.PDF.

[116] Rubitherm GmbH-RT28HC Technical datasheet. Available online: https://www.rubitherm.eu/media/products/datasheets/Techdata_-RT28HC_EN_09102020.PDF.