Financial Viability of PCMs in Countries with Low Energy Cost: A Case Study of Different Climates in Iran

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Abstract

Properties of desirable weight, latent heat capacity, and energy storage capability of phase change materials (PCMs) have led to extensive use of these materials in the building industry as productive thermal mass. This study investigated the feasibility of the utilization of PCMs through numerical simulations in residential buildings located in different Iranian climates in Tehran, Tabriz, Yazd, and Bandar Abbas. In so doing, the optimal PCM for each city was selected based on its impact on annual energy consumption, and then its effects on the indoor temperature and thermal load of the model in the hottest and coldest months of the year were examined. The results showed that the use of PCMs does not lead to significant energy conservation in the hot and humid climate of Bandar Abbas compared with other climates. In the second part of the study, the economic feasibility of PCMs and the payback period of such investment were investigated based on the current local electricity and natural gas prices. It was found that although the use of PCMs leads to significant energy conservation in most of these climates, with the current prices of energy and PCMs in Iran, the use of these materials will not be cost-effective, as the return periods for such investment in Tehran, Tabriz, Yazd, and Bandar Abbas will be 42, 179, 102, and 114 years, respectively.

Keywords: Phase change Materials, PCMs, Energy Storage, Economic Analysis, Passive Design

1. Introduction

According to the U.S. Energy Information Administration [1], energy consumed in residential and commercial buildings accounts for 20.1% of the total delivered energy in the period of 2012 to 2040. It is also predicted that this ratio will see a 1.5% annual increase globally and 2.1% annual increase in non-OECD countries. More than one-third of the energy consumed in buildings is for heating and cooling purposes [2]. One of the main components of energy conservation in buildings is the building envelope, the design and construction of which can have a 20-60% impact on energy consumption [3]. According to Sadineni et al. [3], there are two strategies for optimizing energy consumption in buildings. Active strategies include the optimization of HVAC and artificial lighting systems, and passive strategies include the optimization of the building envelope to reduce energy demand. One of the main passive strategies of energy conservation is the use of Thermal Energy Storage (TES) and thermal inertia for maintaining desired indoor thermal comfort and reducing the energy demand of the building [4-7]. Past studies have demonstrated the significant impact of thermal inertia on the thermodynamic behavior of buildings and recommended the use of PCMs as one of the main ways of utilizing thermal inertia to achieve energy conservation in buildings [8, 9].

Research has shown that PCMs can reduce cooling load by reducing internal temperature fluctuations [10-15], and shifting the heating and cooling load from high-peak to off-peak periods [16, 17]. It is known that using a PCM with a melting temperature close to the comfort zone can reduce peak indoor temperature, prolong the period when the indoor temperature remains within the comfort zone, and reduce the energy demand and hence the energy bill [18]. PCMs can be used in HVAC systems actively such as cylinder tanks [19, 20] and heat pumps for space heating or cooling [21, 22]. Some studies have investigated the performance of energy storage tanks and the influence of different geometric and thermal parameters on PCM melting time, based on PCM types and tank configurations, and these studies have also performed economic assessments in relation to renewable energy systems [23, 24].

Numerical modeling can serve as a powerful method for evaluating the application of PCMs in building [25, 26]. Lei et al. [27] evaluated the energy performance of a building envelope integrated with 10mm-PCM in the tropical climate of Singapore. This study showed that the use of PCMs reduces the annual heat gain through the building envelope by about 21-32%. In addition, the best performance was achieved by the use of PCMs at the outer surface of the wall, which resulted in highest efficiency and cost-effectiveness. Jin and Zhang [28] used numerical modeling to analyze the thermal efficiency of two layers of PCMs that are integrated into the building floor. They used two PCM layers with different melting temperatures to store energy in the off-peak hours and release it in the peak hours. The study found that the optimum melting temperatures for heating and cooling were 38°C and 18°C respectively. It was concluded that, compared to an ordinary floor, a floor that is equipped with two layers of PCMs can release about 41.1% and 37.9% more energy during heating and cooling periods, respectively. Kenisirin and Mahkamov's studying [29] searched for the desirable melting temperatures of PCMs in residential buildings. With the room conditions assumed, based on a comfort range of 18-25°C, they found that the desirable PCM melting temperature for passive systems were about 13-32°C.

In a study conducted by Saffari et al. [30], the optimal PCM melting temperature in residential buildings in different climates was determined through numerical simulation according to the World Map of Köppen-Geiger climate classification. The results showed that

the optimal PCM melting temperature is about 26°C (in the range of 24-28°C) for cooling dominant climates and about 20°C (in the range of 18-22°C) for heating dominant climates, and that for the climates with different Cooling Degree Days (CDD) and Heating Degree Days (HDDs), the optimal melting temperature can be between the lowest and the highest peak melting temperatures. In another analysis, Saffari et al. [31] used the EnergyPlus software to evaluate the impact of integration of PCMs into a building in the Madrid climate with the effect of melting temperature, thickness and payback period taken into consideration. Their results showed that given the operational schedule of office and residential buildings, the highest annual energy conservation can be achieved by the use of a PCM with a melting temperature of 27°C, and a thickness of 10 mm for residential buildings and 5 mm for office buildings. Also, payback time was found to be less than 2-3 years for residential buildings and about 6 years for office buildings. The optimal PCM melting temperatures that result in the highest energy conservation in summers and winters were found to be 27°C and 23°C respectively.

In an experimental study on two identical rooms with PCM impregnated gypsum boards, it was found that using PCMs with an undesirable control strategy may increase the energy demand of air-conditioning [32]. To improve energy storage, this study proposed the combined use of night ventilation and free cooling to discharge PCMs, as opposed utilizing air conditioning. It was reported that this approach leads to 73% electricity conservation over a 1-week period and 93% energy conservation and 92% cost saving over a 1-day period. Barzin et al. [33] conducted an experimental study on two rooms, one with an ordinary gypsum board finishing and the other with PCM impregnated gypsum boards, using the price-base control method. The results showed that with the climate conditions taken into account, the room with PCM achieved energy and cost savings as high as 90% over a day and 40% over an 11-day period. Zhu et al. [34] examined the effect of integration of shape-stabilized phase change material (SSPCM) into the envelope of office buildings in Hong Kong and Beijing, using time-based pricing and energy-plus-demand-based pricing policies. Their results showed that based on the time-based policy, this approach will lead to 11.44% and 11.29% reduction in the daily electricity cost of building in Hong Kong and Beijing, but based on the energy-plus-demand-based policy, these values will be 10.61% and 12.76% respectively.

Chan et al. [35] used the EnergyPlus software to simulate and study a conventional Hong Kong residential unit with PCMs integrated into the outer wall of the living room and bedroom. The results showed that this approach results in 2.9% and 1% annual cooling energy conservation for the living room and the bedroom respectively. The cost payback period was calculated to about 91 years, and the energy payback period was found to be about 23.4 years. The authors also reported that since PCMs had a melting temperature of 21.7°C but the wall surface had a temperature of more than 28°C, PCMs were not able to effectively absorb heat and release it at night. Thus, this climate requires the use of PCMs with a higher melting temperature. Sun et al. [36] conducted an energy and economic analysis on the application of PCM in buildings during the cooling season. This study found that a 100% saving in cooling energy and 13.1% average saving in electrical energy is achievable. The shortest and longest simple payback periods (SPP) were found to be 5.99 and 8.20 years for Kunming and Changsha, respectively. It was found that the optimal phase change temperature for achieving an acceptable SPP is 3°C above the average outdoor temperature. The energy and economic performance of a PCM integrated building in five cities in China was by Mi et al. [37]. In this study, PCMs were assumed to have a melting temperature of

27°C, and simulations were performed using the EnergyPlus software. The best energy savings were obtained for the Shenyang area (very cold climate), Zhengzhou area (cold climate), and Changsha area (hot summer - cold winter climate), with static payback periods of 5-7 years. This study reported that investments in PCM in these areas is cost-effective, but will not be economical in Hong Kong and Kunming.

According to Shilei et al. [38], integration of PCMs into the walls can reduce the cost of HVAC systems by shifting the peak load and filling the consumption valley. An article published by Shi et al. [39] reported that the integration of macro-encapsulated PCMs into concrete walls in a realistic room model led to the smoothing of fluctuations and shifting of energy load away from peak time, which means energy can be bought at lower prices in the off-peak periods. This study also investigated the use of PCMs in an ordinary residential unit in the Hong Kong climate, and found that the payback period of such projects will be about 11 years. Stovall and Tomlinson [40] analyzed the use of PCM wallboards in a solar passive system, and reported that this approach leads to an energy saving with a payback period of about 3-5 years. Kosny et al. [41] studied the performance of dispersed PCMs and estimated a payback period of shorter than 10 years for the use of these materials in the roof and walls. In another study, Peippo et al. [42] investigated the use of PCM impregnated gypsum board in a passive solar building, and reported an annual energy saving of 15% for Madison and 6% for Helsinki, as well as simple payback time of 10 and 20 years for Madison and Helsinki respectively. Zalba et al. [43] evaluated the overall cost of free cooling systems, and reported that PCM constitutes about 17% of the total cost of such a system. In a comparison between the storage system (PCM) and the conventional refrigeration system, they found that the PCM system requires 9% more investment, has a 3 to 4 year shorter payback period, and 9.4 times lower electricity consumption.

In Iran where the issue of using lightweight structures has recently received considerable attention, the implied resulting lack of sufficient and productive thermal mass means that the employment of PCMs as lightweight thermal energy storage is an attractive proposition [44]. However, there is not adequate information regarding the amount of energy conservation from the application of these materials based on the Iranian building codes, which has particular HVAC set-points for its different climates. It is also imperative to note that the energy tariff in Iran is relatively low compared to other countries, and the way that the energy price (both gas & electricity) is calculated because of subsidies is exceptional. To date, there has been no economic analysis of the use of these materials in the different climates of Iran based on the local prices of energy carriers for heating and cooling. Therefore, this study set out to investigate the effect of optimal PCMs on total energy saving and indoor thermal conditions in addition to their economic efficiency in different climates zones. To do so, in this study, we first determine the optimal PCMs for multiple climates within Iranian territory, then examine their effect on energy conservation and average indoor temperature, and finally perform an economic analysis on the use of these materials based on the price of natural gas and electricity.

2. Methodology

Due to there being no PCM implementations in Iran to date and a lack of laboratory equipment, there was no possibility of field measurements in all four existing climates. This study therefore is conducted with EnergyPlus software version 8.3 which enables users to simulate the parameters of PCMs by virtue of the “Conduction Finite Difference (CFD)” algorithm utilized to simulate the impact of PCMs. Furthermore, as the purpose of the

research is to understand the efficacy of PCMs in different locations and the resultant heating/cooling load differences, along with the financial saving, a representative single zone model is sufficient. Thus, in this research, the 600 case, which is a lightweight model, from the Building Thermal Envelope and Fabric Load Tests series of the ANSI/ASHRAE Standard 140-2014 (based on BESTEST) is considered as the qualified case [45]. The room studied in this study has dimensions of $8 \times 6 \times 2.7$ m and the zone air volume is 129.6 m³. The southern wall of the model is supplied with two double-glazed windows which have 3×2 m dimensions. The case has a 200-watt internal gain, and an infiltration rate of 0.5 ACH (air changes per hour). The roof and four walls are specified as the exterior surfaces exposed to ambient air; Table 1 provides a detailed description of the structure of the envelope utilized in the model, as well as the order and arrangement of the building materials. In order to reduce uncertainty concerning testing the other facets of simulating the building envelope, the floor insulation described in Table 1 has also been made very thick (approximately 1 meter) to efficaciously de-couple the floor from the ground in point of thermal considerations. It should be noted that the PCM used for the study is energy blankets (BioPCM) with a thickness of 1 cm [46], and the solar reflectance of the site ground surface is 0.2. This model will be applied for analysis in four cities namely Tehran, Tabriz, Yazd and Bandar Abbas, which vary in climate. Climatic characteristics of the aforementioned cities are presented in Fig. 1. It is imperative to note the thermostat cooling and heating set-points were set according to Building Code No. 19 of Iran, which are 20°C and 28°C for the hot-humid climate of Bandar Abbas and 20°C and 25°C for other climates, respectively [47].

Table 1. Specifications of the building elements [45]

Element	K, W/(m ² ·K)	Thickness, m	U, W/(m ² ·K)	R, (m ² ·K)/W	Density, kg/m ³	cp, J/(kg·K)
Exterior Wall (inside to outdoors)			x			
Interior surface coefficient			8.290	0.121		
Plasterboard	0.161	0.012	13.333	0.075	950	840
PCM	0.2	0.010			860	1620
Fiberglass quilt	0.040	0.066	0.606	1.650	12	840
Wood siding	0.14	0.009	15.556	0.064	530	900
Exterior surface coefficient			29.30	0.034		
Total air-air			0.514	1.944		
Total surf-surf			0.559	1.789		
Floor (inside to outdoors)						
Interior surface coefficient			8.290	0.121		
Timber flooring	0.140	0.025	5.60	0.179		
Insulation	0.040	1.003	0.040	25.075		
Total air-air			0.039	25.374		
Total surf-surf			0.040	25.254		
Roof (inside to outdoors)						
Interior surface coefficient			8.290	0.121		
Plasterboard	0.160	0.010	16	0.063	950	840
PCM	0.2	0.010			860	1620
Fiberglass quilt	0.040	0.1118	0.358	2.794	12	840
Roofdeck	0.140	0.019	7.368	0.136	530	900
Exterior surface coefficient			29.3	0.034		
Total air-air			0.318	3.147		
Total surf-surf			0.334	2.992

Fig 1. Average monthly weather data of (a) Tehran, (b) Tabriz, (c) Yazd, (d) Bandar Abbas [48]

3. Results and Discussions

3.1. Optimal PCMs

This section examines the impact of PCMs with melting temperatures of 19, 21, 23, 25, 27, and 29°C on annual energy consumption and conservation in four cities in Iran. As shown in Fig. 2, for Tehran, the cooling load (7002.2 kWh) is about 4 times the heating load (1827.78 kWh), and in the best case scenario, the use of PCMs with a melting temperature of 29°C can reduce the total energy consumption by 2969.5 kWh or 34%. Notably, since in this climate the major application of PCMs is for reducing cooling loads, the PCM with the transition temperature of 29°C, which is close to the cooling set-point temperature (28°C), has been the most efficient type. Thus, in this condition, HVAC systems are activated when the liquefaction process reaches close to the maximum set-point temperature, thereby optimizing PCM capability. However, in the cold climate of Tabriz, the main load belongs to heating (4218.60 kWh), and in the best case scenario, the use of PCMs with a melting temperature of 19°C will reduce the heating load and the total energy consumption by 22% and 20% respectively. Thus, in order to make the most of PCM potential in reducing heating loads, the

PCM with the transition temperature of 19°C, which is 1°C less than the heating set-point temperature (20°C), has been optimal, such that in this condition HVAC systems are activated when the solidification process reaches close to the minimum set-point temperature. Conversely, in the hot and dry climate of Yazd, it is the cooling load (6638.8 kWh) that constitutes the major portion of total energy consumption. For this city, the use of optimal PCMs with a melting temperature of 29°C will result in a 32.2% decrease in the total energy consumption and 1800.73 kWh decrease in cooling load. Therefore, just as Tehran reduce its dominant cooling loads in spring and summer, the use of PCMs with the transition temperature of 1°C higher than the cooling set-point temperature is also energy-efficient.

In the port city of Bandar Abbas, only a small portion of total energy consumption is dedicated to heating (151.9 kWh), as the dominant part of consumption (10185.72 kWh) is related to cooling during hot seasons. For this city, in the best case scenario, using a PCM with a melting temperature of 27°C can reduce the total energy consumption by about 10.9%, of which about 10% is related to cooling. Interestingly, for this climate the cooling set-point temperature, which is 25°C, is lower than other climates, the optimal phase change temperature is also lower than other climates. Thus, the most striking result to emerge from the data is that the optimal phase change temperature is contingent upon both HVAC set-point temperatures and climates. In conclusion, the figures indicate the highest energy conservation efficiency for Tehran, Tabriz, Yazd and Bandar Abbas can be achieved by the use of PCM-29°C, PCM-19°C, PCM-29°C and PCM-27°C respectively. In the following sections, these PCMs are selected for consideration as the optimal choice for the respective cities.

Fig 2: The impact of PCMs' melting temperature on the annual (a) heating and cooling (b) loads of the model

3.2. Impact of optimal PCMs on monthly heating and cooling loads

This section explores the effect of optimal PCM on monthly heating and cooling loads. As shown in Fig. 3, although the highest heating and cooling loads in Tehran (Fig. 3a) belong to the months of Jan and Aug, the greatest impact of PCM-29°C on these loads is in Feb (50% reduction) and Aug (48% reduction). The principal reason for this noticeable cooling load saving of Aug is that during this month ambient temperature conditions are within the range of the PCM transition temperature; as a consequence, the deployment of these materials can noticeably reduce the need for HVAC systems. The hottest month for this city is Jul with an average temperature of 30.3°C, but the impact of PCM on the load of this month is only 41 kWh or 5.1%. Notably, during this month, the outdoor temperature in most hours of the day exceeds the phase change temperature of PCM; however, in cooler months such as May, the decrease in cooling load reaches as high as 32%. In Tabriz (Fig. 3b), PCM-19°C has the highest impact on cooling and heating loads in the months of Nov and Oct that is, 191.4 and 108.4 kWh or 31% and 44% respectively. In comparison, the impact of PCM-19°C on the heating load in the coldest month of the year, i.e. Jan with an average temperature of -1.7 °C, is just 4.9%. The cause of this meager impact is the outdoor temperature being lower than the PCM transition temperature (19°C) in the majority of hours on the day. In contrast, in warmer months such as Mar, the reduction in heating load is as high as 31%.

In the case of the deployment of PCM-29°C in Yazd (Fig. 3c), the increase in thermal mass results in 3 more months having a heating load. In Jan, with the highest heating load, using this PCM leads to 27% reduction in heating load. In the warmest month of the year, i.e. Jul with an average temperature of 32°C, PCM-29°C can reduce the cooling load by just 4%, but in cooler months such as May (when temperature conveniently matches the phase change temperature in more hours of the day), cooling load can be decreased by up to 17%. The use of PCM-27°C in Bandar Abbas (Fig. 3d) completely eliminates its already negligible heating load throughout the entire year. For this port city, this PCM will have the greatest impact on the energy load in Jan and Dec, by reducing the corresponding cooling loads by about 50%. However, in the months between May and Oct, when the temperature is almost always above

30°C, PCM will not have a significant impact on the cooling load. The main reason for the low productivity of these materials in this climate in reducing its dominant cooling loads as opposed to the aforementioned climates is that during hot nights, high ambient temperatures prevent PCMs from losing stored heat, and consequently the solidifying process fails; thus, PCMs cannot be optimized. In stark contrast, however, in the hot dry climate of Yazd owing to cold nights in summer, PCMs usually solidify; therefore, this phenomenon can considerably optimize the PCM capability in reducing cooling loads.

Fig 3: The impact of optimal PCMs on monthly heating and cooling loads of (a) Tehran, (b) Tabriz, (c) Yazd, (d) Bandar Abbas

3.3. Impact of optimal PCM on average indoor temperature

This section discusses the effect of PCM on the highest and lowest average indoor temperatures in the hottest and coldest months of the year, which in all cities, are Jan and Jul, respectively. As shown in Fig. 4a, in Tehran, the difference between the highest and lowest average indoor temperatures without PCM is 33.5°C, but can be reduced to 22.5°C by the use of PCM-29°C. The use of this PCM leads to a 3.8°C decrease in this temperature difference in Jul. This PCM also reduces the average maximum indoor temperature in the hottest month by 1.9°C and increases the average minimum indoor temperature in the coldest month by 3.2°C. For the city of Tabriz (Fig. 4b), the use of PCM-19°C leads to a 2.9°C and 3°C reduction in the difference between the average maximum and minimum temperatures in Jan and Jul respectively. The lowest impact of PCM on the maximum and minimum indoor

temperatures (1.6°C decrease in the average maximum temperature in Jul and 1°C increase in the average minimum temperature in Jan) is seen in this city. The cause of this limited impact is the cold winters and hot summers of this city, when air temperatures are usually beyond the functional range of PCM. In Yazd (Fig. 4c), using PCM-29°C results in 2°C decrease in the average maximum temperature in Jul and a 2.5°C increase in the average minimum temperature in Jan. As shown in Fig. 4d, the use of PCM in the port city of Bandar Abbas decreases the average maximum temperature and increases the average minimum temperature in the hottest and coldest months by 4.7°C and 7.7°C respectively. Although the impact of PCM in this city is related to a rather short period, the convenient match between average outdoor temperature during this period and the phase change temperature of PCM amplifies the effect. Taken together, in all climates, the utilization of PCMs reduces average maximum temperatures; and also ameliorates average minimum temperatures, but the results vary according to the climate and PCM types. That is, the closer the air temperature is to the functional range of PCMs, the higher the indoor improvement can be attained.

Fig 4: The impact of optimal PCMs on average indoor temperature of (a) Tehran, (b) Tabriz, (c) Yazd, (d) Bandar Abbas

3.4. Economic analysis

3.4.1. Effect of PCM on cooling cost (electricity bills)

This section investigates the impact of optimal PCMs in the cooling cost or electricity consumption in the studied cities. In Iran, electricity is billed based on the increasing block tariff (IBT), with the blocks adjusted for different climates so that warmer regions have access to cheaper electricity during hotter months (Table 2). According to the classification of Iran's Ministry of Energy [49], Bandar Abbas belongs to the category of Hot Regions (1) and has 9 hot months with cheaper electricity (Mar to Nov). According to the same classification, Yazd belongs to the category of Hot Regions (2) and has six hot months with cheaper electricity (Apr to Oct). The tariffs for the remaining months of these two cities and all months of Tehran and Tabriz are calculated based on the normal rates of IBT.

Table 2. Electricity tariffs for different regions and periods [49]

Average monthly energy consumption (kWh per month)	0-100	100-200	200-300	300-400	400-500	500-600	>600	High Peak	Off-peak
Tariffs for normal regions and non-hot months	450	525	1125	2025	2325	2926	3226	450	225
Base price per kilowatt hour (Rials)									
Tariffs for warm months in Hot Regions (1)	150	166	180	750	1351	1726	2025	150	75
Base price per kilowatt hour (Rials)									
Tariffs for warm months in Hot Regions (2)	330	750	1275	1575	1876	2025	2176	300	150
Base price per kilowatt hour (Rials)									
Tariffs for warm months in Hot Regions (3)	375	976	1726	1876	2025	2176	2325	300	150
Base price per kilowatt hour (Rials)									
Tariffs for warm months in Hot Regions (4)	361	421	750	1200	1726	2251	2701	300	150
Base price per kilowatt hour (Rials)									

In general, the energy cost is calculated in three classes: medium-peak (7:00-19:00), high-peak (19:00-23:00), and off-peak (23:00-7:00), the relevant rates of in the year 2017 are listed in Table 2. It should be noted that the medium-peak bill is calculated based on the listed blocks, and the total energy bill is equal to the sum of high-peak and medium-peak bills minus the off-peak bill. The energy consumption estimates in the presence and absence of PCM in the studied cities based on the above tariffs are given in Table 3. As can be seen, the use of PCM has reduced the cooling load of Bandar Abbas by 10%, but because of subsidized electricity consumption in this hot region, the corresponding decrease in the electricity bill is 33%. In contrast, in Tabriz, where there is no such subsidy and the use of PCM has decreased the cooling load by 15%, the decrease in the electricity bill is only 17%. In both Tehran and Yazd, the use of PCM has resulted in a 28% reduction in the cooling load. However, while the subsidized electricity bill in Yazd has decreased by 42%, the unsubsidized electricity bill in Tehran has reduced by 31%. In all cities, the use of PCM has significantly decreased the medium-peak, off-peak, and as such total electricity bills, but has resulted in a 1.5 times increase in the high-peak bill. The cause of this increase is that the use of PCMs has encouraged the shift of consumption towards peak hours.

Table 3. Economic analysis of cooling cost with and without PCMs

		Total cooling load (kWh)	Total consumption during medium-peak hours (kWh)	Total bill of medium-peak consumption (Rial)	Total consumption during high-peak hours (kWh)	Total bill of high-peak consumption (Rial)	Total consumption during off-peak hours (kWh)	Total bill of off-peak consumption (Rial)	Total IRR
Tehran	without PCM	7002.9	6858.6	12033678.0	129.6	58314.2	14.8	3324.3	12088668.0
	PCM29	5017.1	4768.5	8317905.4	195.0	87769.7	53.6	12051.3	8393623.8
Tabriz	without PCM	2497.6	2447.5	2766475.7	49.9	22450.0	0.2	39.5	2788886.2
	PCM19	2115.7	2042.3	2281670.5	73.0	32835.2	0.5	102.1	2314403.6
Yazd	without PCM	6638.3	6418.0	3132368.3	192.0	57587.6	28.3	4251.5	3185704.4
	PCM29	4837.6	4509.7	1786196.6	262.9	78856.1	65.0	9755.1	1855297.7
Bandar Abbas	without PCM	10185.7	9178.5	4365079.9	531.2	79678.0	476.1	35704.9	4409052.9
	PCM27	9207.6	7190.0	2889835.0	931.6	139736.4	1086.0	81450.0	2948121.3

3.4.2. Effect of PCM on heating cost (natural gas bills)

In Iran, buildings are heated by natural gas. Like electricity, natural gas is billed based on IBT, with the blocks adjusted to subsidize cold regions during cold months (Nov 7 to Apr 4). In the remaining months of the year (Apr 5 to Nov 6), the price of gas in all regions is calculated according to the normal rates of IBT (Table 4). According to the National Iranian Gas Company [36], gas bills are calculated based on the four climates. In the case of cities considered in this paper, Tabriz belongs to Climate No. 1, Yazd and Tehran are located in Climate No. 3, and Bandar Abbas belongs to Climate No. 4. As shown in Table 5, the cold climate of Tabriz results in it having the highest heating cost (183096 Rials) among the four cities. The use of PCMs reduces the annual heating load of this city by 22%, thereby decreasing the heating cost by 27% to 134250 Rials. In Bandar Abbas, PCMs eliminates the already negligible heating cost (5910 Rials). In Yazd and Tehran, where the heating cost is almost the same (68630 and 74871 Rials, respectively), the use of PCMs reduces the heating cost by about 52% (unlike the case of electricity, the two cities receive the same subsidy on the gas bill). Overall, with the effect of subsidies taken into account, the highest impact of PCM on the heating costs will be seen in Tabriz (48846 Rials), Tehran (41970 Rials), Yazd (37093 Rials) and Bandar Abbas (5918 Rials) in that order.

Table 4. Natural gas tariffs for the household sector [50]

During the cold period (climate adjusted-IBT)												
Consumption Block	1st	2nd	3rd	4th	5th	6th	7th	8th	9th	10th	11th	12th
Consumption volume (m ³) Climate (1)	<300	301-400	401-500	501-600	601-700	701-800	801-900	901-1000	1001-1100	1101-1200	1201-1300	>1300
Consumption volume (m ³) Climate (2)	<250	251-350	351-450	451-550	551-650	651-750	751-850	851-950	951-1050	1051-1150	1151-1250	>1250
Consumption volume (m ³) Climate (3)	<200	201-300	301-400	401-500	501-600	601-700	701-800	801-900	901-1000	1001-1100	1101-1200	>1200
Consumption volume (m ³) Climate (4)	<150	151-250	251-350	351-450	451-550	651-750	651-750	751-850	851-950	951-1050	1051-1150	>1150
2017 Price (Rials/m ³)	410	690	960	1240	1510	2200	2620	3030	3450	3860	441	483
During the warm period (IBT)												
Consumption Block	1st	2nd	3rd	4th	5th	6th	7th	8th	9th	10th	11th	12th
Consumption volume (m ³)	<45	45-95	96-145	146-195	196-245	246-295	296-345	346-395	396-445	446-495	496-545	>545
2017 Price (Rials/m ³)	1080	1310	1650	2110	2570	2800	3150	3490	3720	3950	418	430

Table 5. Economic analysis of cooling cost with and without PCMs

	Tehran		Tabriz		Yazd		Bandar Abbas	
	Without PCM	PCM29	Without PCM	PCM19	Without PCM	PCM29	Without PCM	PCM27
Natural gas								
Heating Energy [kWh](Hourly)	1827.8	844.0	4218.6	3278.6	1693.7	809.7	151.9	0.0
Total cost (IRR)	74871	32901	183096	134250	68630	31538	5918	0.0

3.4.3. Effect of PCMs on total energy cost

To conduct the economic evaluation, this research utilizes the Static Payback Period (SPP) method. The method considers the project construction commencement date and the project annual net income, which is the subtraction of annual expenditure from annual income. Due to its simplicity, this method has been employed in many technical economic analyses. For PCM application, the SPP is given by the following equation [37].

$$SPP = \frac{C_{pcm}}{S} \quad (1)$$

Where **SPP** is a static payback period, **C_{PCM}** is the extra initial investment for PCM application, and **S** is the income generated from energy saving. Assuming that each square meter of PCM costs 38.58 USD [46], based on Eq. (1) and the energy cost savings listed in Table 6, the use of PCMs in Tehran, Tabriz, Yazd, and Bandar Abbas will have a payback period of 42, 179, 102 and 114 years respectively. As a consequence, in the Iranian construction industry with a 30 year common service life of buildings [51], the use of these materials is not cost-effective. As illustrated, the amount of energy saving in Tehran and Yazd are approximately the same; however, the SPP of Yazd due to its economic subsidy is more than double that of Tehran. Similarly, owing to subsidy the SPP for Tabriz and Bandar Abbas, which have almost the same amount of energy saving, is high; however, since generally the gas price is lower than electricity, the SPP of the heating dominant climate of Tabriz is 65 years more than Bandar Abbas. Therefore, in a best-case scenario, Tehran with the highest energy saving and the lowest subsidy has 42 years payback period, which is still higher than the common service life of buildings in Iran.

Overall, there is an inverse relation between energy subsidies and the return period of the PCM capital cost. Because the higher the energy subsidy is, the lower the cost of energy in the demand section and the amount of energy savings is gained, thereby increasing the return period of the investment. Evidently, regarding economic feasibility, the combination of high capital cost of PCMs with low energy prices is the crucial deterrent to the successful deployment of PCM in residential buildings of Iran. Thus, with increasing energy rates and possible decreasing PCM costs, future investment stimulus might be economically viable.

Table 6. Economic analysis of PCM application

City	Tehran	Tabriz	Yazd	BandarAbbas
Energy savings (kWh)	2969.65	1321.85	2684.71	1128.10
Energy savings (Rial)	4114740	962940	1701330	1519340
SPP (Year)	42	179	102	114

3.5. Discussion

The main goal of this study was to investigate the feasibility of utilizing PCMs in residential buildings of four different Iranian climates, by taking into account their total energy saving, as well as economic efficiency. Many studies have been carried out in this subject and these climates [30, 38, 52-54], and are summarized in Table 7 to compare their results with those of this study.

Table 7. Optimum PCM peak melting temperature for total annual energy consumption [30, 52-55]

Climate zones	Cities	Optimum melting point for heating and cooling	Total heating & cooling savings	
		(°C)	(kWh)	(%)
Csa	Seville (Spain)	26.0	811	3.5
	Cagliari (Italy)	26.0	450	1.7
BSk	Albuquerque (USA)	20.0	1381	2.5
	Midland (USA)	20.0	1300	3.0
	Ceduna (Australia)	25.0	987	7.3
BWk	Calama (Chile)	25.6	317	7.5
	Las Vegas (USA)	26.0	1018	2.6
	Yumenzen (China)	26.0	5213	3.3
BWh	Abu Dhabi (UAE)	26.0	975	1.8
	Jaisalmer (India)	25.9	770	1.4
	Phoenix (USA)	26.0	1018	2.7

The main reason for the differences in PCM transition temperatures is the variety of HVAC thermostat control set-points for various standards in different countries. That is, for the climates of Csa, BWk, and BSk and considering the cooling/heating set-point of 21 and 28°C in our research, the optimal PCM transition temperatures were 19°C and 29°C for dominant heating and dominant cooling load demand climates, respectively. However, as shown in Table 7, prior studies have noted that in the same climates but with different HVAC set-points (the set-point for cooling and heating is 20°C and 26°C), so the optimum PCM transition temperatures for dominant heating and cooling load demand climates were 20°C and 26°C, respectively. In this table, since the HVAC set-point for the BWh climate is the same as other climates, PCM-26°C was optimal; however, as in Bandar Abbas the cooling set-point is 25°C, PCM-27°C was optimal; resulting overall in reinforcing the significance of HVAC set-points along with climate types in defining the optimal PCM transition temperature. Additionally, the noticeable difference in energy conversion for similar climates is mainly related to the duration of simulations or experiments (daily, monthly or annually), the calculated area of the model, the thickness of PCMs, and the thermal characteristics of the insulation. Naturally, factors such as sunshine, wind characteristic, precipitation intensity, amount of cloud cover, daily temperature, altitude, and relative humidity are also important, and are not considered in the Koppen-Geiger climate classification [53, 54].

Indoor air temperature is also one of the factors which influences the integration of PCMs in a building - in this case, decreasing in warm months and increasing in cold months - and is usually evaluated in two ways: average indoor air temperatures and peak indoor air temperatures [12, 56, 57]. For example, due to the use of PCMs in a building in Algiers (Csa), the average indoor temperature and peak indoor temperature increased by 1.5°C and 1°C in winter, and dropped by 8.5°C and 9°C in summer, respectively [58]. This study confirms the improvement of indoor temperature in all climates; however, the amount of

improvement differed according to the varying climate. That is, for the climate where the indoor temperature is mainly in the range of PCM transition temperature, the application of these materials can have a remarkable impact on either reducing indoor temperature in hot months or increasing it in cold months. However, for the climates where the indoor temperature mainly goes beyond the PCM functional temperature, the productive effect of PCMs dwindled. In these climates in order to optimize PCMs, the application of supplementary energy efficient techniques such as night ventilation can be productive [59, 60].

The main factors in the economic assessment of utilizing phase change materials are gas tariffs, electricity tariffs, capital cost of PCMs, and bank interest [14, 21, 23-33], and considering these factors the resultant payback periods vary for different cities. For instance, the PCM payback period for the city of Shenzhen was 11 years [39], which is shorter than its building average life span (60 years), the use of PCMs is thus cost effective. Likewise, in the cities of Atlanta, Bakersfield, Fort Worth, Miami and Phoenix, the payback period was estimated at 7-10 years [41]. However, in Iran, in the best scenario, the payback period of using PCMs was 42 years, which is more than its common building service. Thus, despite considerable improvement in total energy conservation and indoor thermal conditions, the use of PCMs in Iran is uneconomical due mainly to low energy tariffs, high capital cost of these materials, and subsidy.

4. Conclusion

This study set out to examine the effect of PCMs on energy consumption, conservation, cost, and indoor temperature conditions in different climates of Iran. Results showed that the optimal PCMs melting temperature to be used was contingent upon both HVAC set-point temperatures and climate conditions. As such for the climates where their defined set-point for heating and cooling was 20 and 28°C, PCM-19°C and PCM-29°C respectively were optimal for reducing heating loads of cold climates and cooling loads of hot climates. However, for hot-humid climates, where the defined set-point was 20-25°C, PCM-27°C was optimal. The greatest impact of PCMs on annual energy consumption was a 34% reduction obtained for Tehran (Csa) and a 32.2% reduction calculated for Yazd (BWk), and the smallest was a 10.9% reduction obtained for Bandar Abbas (BWh). The main reason for this low efficacy of PCMs in reducing cooling loads of the hot-humid climate was due to the prevention of PCMs from losing stored heat during hot nights, and the consequent failure of the solidifying process. However, in hot dry climates owing to cold nights in summer, PCMs could be solidified, thereby maximizing the PCM potential in reducing cooling loads.

Investigation of the impacts of PCMs during the hottest and coldest months of the year showed that in the hot climates, the use of PCM was not as effective during hot months, and in the cold climates, the use was not as effective during cold months of the year. This is because during these months, the average temperature was usually beyond the range of PCM transition temperatures. However, for moderate months that had average temperatures within the range of PCM functional temperatures, the energy saving was remarkable. Thus, climates with more moderate conditions can benefit more from the deployment of PCM.

In all climates, the use of PCMs respectively reduced and increased the maximum and minimum average temperatures, which meant a less fluctuating and more balanced indoor

temperature could be achieved, but the results varied according to the climate and PCM types. That is, the closer the air temperature is to the functional range of PCMs, the greater the improvement in indoor temperature can be attained. Additionally, in spite of increasing high-peak cost in all cities, the use of PCMs led to dramatically reduced off-peak, medium-peak, and as such total electricity costs. Based on the 2017 prices of energy carriers and PCMs, in the case of using PCMs, the corresponding payback periods for Tehran, Tabriz, Yazd, and Bandar Abbas, due to current inexpensive energy tariffs along with subsidies, and the high price of these materials were found to be 42, 179, 102, and 114 years, respectively, which renders the use of these materials in the Iranian construction industry with 30 years common service life uneconomical.

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