THERMAL PERFORMANCE AND ENERGY EFFICIENCY OF PCM INTEGRATED BUILDINGS IN EIGHT CITIES LOCATED IN SNOW, FULLY HUMID WITH WARM SUMMER CLIMATE REGION

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DECLARATION

I hereby, declare that this manuscript, entitled "*Thermal Performance and Energy Efficiency of PCM Integrated Buildings in Eight Cities Located in Snow, fully humid with warm summer Climate Region",* is the result of my own work except for quotations and citations which have been duly acknowledged.
I also declare that, to the best of my knowledge and belief, it has not been previously or concurrently submitted, in whole or in part, for any other degree or diploma at Nazarbayev University or any other national or international institution.

Name: Baurzhan Jangeldinov

Date: December, 2018

Abstract

Phase change materials have been applied into building framework to reduce energy and fossil fuel consumption as well as make building sector more sustainable.. In this study, the energy consumption assessment of lightweight two-storey PCM-enhanced residential house placed at different eight locations (Helsinki, Kiev, Saint-Petersburg, Moscow, Stockholm, Toronto, Montreal and Kiev) restricted by Dfb climate region will be evaluated. The number of iterations were performed by DesignBuilder software combined with Energy Plus engine by applying eleven melting temperature ranges of PCM. The output shows that the optimal PCMs have reduced the temperature swings up to 2.4 °C. The performance of PCM is not constant for the monthly assessment basis, hence every month different PCM have performed efficiently. The optimal PCM variance is between the thermal comfort zone (20-26°C) and depends on the geographical parameters. For the indicator cities, the energy consumption varies from 2,81% to 5,72%. The volumetric assessment may be shows that the efficient performance of PCM increases with expansion of surface area combined with reduction of thickness. Overall, the enhancement of PCM into building framework in residential building located in Dfb climate region is feasible option.

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Chapter 1 - Introduction

1.1. Background

The building sector energy use devoted a crucial influence on the total energy demand [1]. The recent reports state that the space heating and cooling account increases from 30 to 50 % in cold climate region [1]. The climate change and the increased growth of urbanization and wealth [2] and its corresponding effects such as urban heat island effects [3] are increasing cooling energy demand and global warning. Beyond on, there is also knows that the energy production (80 %) resulting from combustion of fossil fuels is linked to emission of harmful gases such as CO_2, environmental pollution and human health issues. Furthermore, the energy demand will increase up to 50 % in 2050 if energy savings technology used in building will not improve the existing energy systems [4].

In recent decade, sustainability of buildings and breaking dependence on fuel sources succeeded in building industry by thermal energy storage (TES) systems investigations. The main successors in TES systems, phase change materials (PCM's) were based on releasing of absorbing the heat according to the phase change temperature fluctuations [5]. Therefore, application of PCMs into building envelope is replied to reduction on energy demand by Heating Ventilation Air-Conditioning (HVAC) system. A extensive number of research findings on implementation PCM into building envelope have been conducted during last three decades which collide in noticeable amount of information regarding PCM parameters, PCM enhancement approaches, placements for installation and effect on energy savings , thermal air parameters and energy consumption.

Efficiency of Phase Change materials is based on several parameters including their thermo-chemical properties: specific heat and thermal conductivity combined with physical properties such as volumetric indicator and density. For the external parameters, climatic conditions plays an crucial part in the performance of PCMs. The mentioned above indicators have been investigated by the comprehensive number of studies [6-11]. However, those research works, the energy efficiency of buildings with PCMs have been confined to one country. In this framework, in this work I am focused on optimization the energy saving potential of PCM enhanced two story building in Dfb-climate through eight cities. Moreover, the evaluation will be done according the building envelope which i adapted according to local practices.

1.2. Research objectives

The purpose of this work is focused on evaluating impact on evaluating the impact of PCM-enhanced lightweight two story residential building in terms of annual, monthly heating and cooling account combined with thermal response analysis.

Objectives of the research are as follows:

- To optimize the PCM for each city evaluated

- To evaluate thermal behavior of PCM applied to residential two-storey residential building.

- To carry out parametrical study including determination of optimal thickness, volumetric assessment and placement of PCM

1.3. Research significance

There is a broad number of scientific studies related to the potential of PCMs in evaluation energy consumption at different climates including both cold and hot climate regions. However, there is no study related to the optimization of PCM restricted to the one specific climate specification. Moreover, despite the importance of Dfb climate zone, the research findings describing the severe cold climates are limited.

Chapter 2 – Literature review

In this chapter, theoretical background of the building envelope importance, thermal energy storage details and PCM integration methods were studied. Then, the research works related to the incorporation of PCM into different building frameworks were investigated.

2.1. Building Framework

Enhancing the building framework according to thermal comfort is an appropriate approach for reducing the energy demand account [6,7]. The crucial part of energy in building maintenance is spent on air conditioning system. There are several technologies to decrease the energy consumption including insulation materials [8], solar thermal power generator [9], heat insulation glasses [10] and window reversible systems [11]. For the main solution, the thermal insulation has been used to minimize the heat dissipation created by building environment [12]. Despite the presence of above solutions, the main aspect affecting to lifetime of lightweight buildings represented by ability to decently regulate inside building environment due to energy performance limitations created by overheating problem [13]. Thus, the building framework should regulate the heat transfer between outside and inside building environment, depend upon energy conditions and residents comfort and flexible in integration with new building materials.

2.2. Energy System

Thermal energy storage systems which incorporated into building envelope are coordinated by latent heat thermal energy storage to provide balance between diurnal and nocturnal energy consumption [14]. Latent heat storage rely on temperature enthalpy to acquire heat in short changes, contribute more energy in comparison to sensible heat solution with the same temperature gradient. The limitation is the volumetric expansions generated during the melting process[15]. Convenient materials for latent heat storage in house frameworks are phase change materials (PCM) [16]. The extensive number of literature has been contributed on the utilization of PCM into the building framework due to unique asset for thermal regulation [17-22]. The main difference between PCM and other thermal energy materials is an ability to store massive heat in short temperature changes due to strong heat capacity. Thus, convenient element properties should be evaluated to proper enhancement into the building envelope. According to nature, PCMs can be differentiated into organic and inorganic. Benefits of organic PCMS are non-subcooling, physical and thermal stability, corrosive resistance combined with low parameters in phase-change enthalpy, thermal conductivity and flammability. For the non-organic PCMs salt hydrates [21] are used due to higher change enthalpy. However, they show subcooling, corrosion behavior combined with phase separation, thus, they are thermal instable [16,23]. Based on mentioned above properties, the selection should be done according to design requirements

2.3. PCM integration methods

There are different methods of incorporation PCM into the building framework including direct incorporation, encapsulation (both micro and macro), immersion and shape-stabilization [19,24]. During direct integration, the Phase Change Material is combined with concrete or porous material in such way that as temperature rises up, the heat goes directly into the pores, settled by PCM. For the immersion case, the pre immersed liquid phase material (concrete wallboard or block) absorbing PCM through capillary action. The shape-stabilization technique characterized by complex action where PCM is mixed up with supporting material under extreme heat, then cooled under solidification stage of supporting material. The macroencapsulation mechanics based on placement extensive number of PCM formed as tubes, packages and spheres into containers. Despite the wide variety of techniques, most them are not appropriate to the integration due to possibility of leakage after several thermal cycles, low thermal conductivity or either solidification PCM at corners.

The microencapsulation represented by the inclusion of small liquid or solid particles into thin, high molecular film which can be adapted into any building envelope. The preference of microencapsulation method can be expressed by avoidance the free movement of liquid phase of PCM through building envelope and contact with construction material, absence of leakage and evaporation, minimization of PCM loss during incorporation and ability to form composite materials [16,20]. Thus, the enhancement PCM into the building framework represented in various approaches including gypsum plasterboard with microencapsulated paraffin [25], concrete with microencapsulated paraffin [26], PCM-bricks [27] and PCM-wood [28]. Further, the locations of application are varied: PCM has been incorporated into slabs [29] and floors [30].

2.4. Research investigations

Extensive number of authors have discovered the thermal evaluation and energy assessment of PCM integrated around the world [31-37]. Alam et al. [38] investigated the PCM -enhanced one-storey residential building model for eight cities in Australia in EnergyPlus. For the cities evaluated the annual energy savings ranges from 17 to 23 percent with an exception for Darwin city. The results revealed that performance of PCM depends on several factors including the local climate, thickness and surface area of PCM, location of PCM inside the building envelope and human comfort range. Mi et al.[39] analysis of three-storey PCM-incorporated office residency in 5 cities in China. For the evaluation PCM with 27°C melting temperature were applied in Design Builder Software . The results showed prominent output for Shenyang, Zhengzhou located in cold climate region and with combined economic analysis, unacceptable output for Hong-Kong. Pajek et al. [40] evaluated the thermal assessment of lightweight timber building frameworks in Helsinki, Vienna and Madrid, location plays a major role in the reduction of temperature fluctuations by PCM-enhanced building envelope. Vautherot et al [41] performed investigation for two-storey residential house in Auckland. The assessment described that integration of PCM 21-26℃ decrease the temperature amplitude fluctuation up to 7,5 ℃ in summer.

The selection of optimum PCM and proper thickness resulted to be important due to minimizing economic losses and maximizing efficiency. Soares et al [42] using of optimization analyses, described the influence of replacement the internal gypsum drywalls by PCM in a living room using annual and monthly energy savings. In the study, the thermo-physical parameters, location and thickness of PCM-drywalls were evaluated. The optimum temperature and energy savings were found to be higher in warmer climates, whereas the solar absorptance was higher in colder climates. Saffari et al [43] studied the optimum peak melting temperature of PCM incorporated into gypsum board of an office building. The study performed by terms of single-objective optimization to define energy savings for heating, cooling and total energy performances for wide range of locations. The results showed that optimum peak temperature of PCM rises from cold to hot climate zones and energy savings can be recognized in most of the places around world. Lei et al [44] described performance of Phase Change Material incoporated cubic model for Singapore country. In the study, the PCM with 28°C melting temperature was placed to exterior surface of vertical walls with changes in heat gains (21 to 32%). Marin et al [45] performed extensive study to compare the energy saving potential of lightweight single zone building integrated with PCM in variety of climate zones. The results expressed that PCM-enhanced buildings perform better in arid and warm temperate climates whether the output for tropical and snow climates were limited.

According to the literature review, it is evident that numerous papers have compared the thermal and energy saving assessment of PCM-enhanced buildings around the world. However, the detailed investigation using thermal performance, monthly and annual energy savings and optimization of PCM restricted by Dfb-climate classification has not been performed yet. In addition, in this study, the local construction details will be considered to imitate real-life conditions as well as the effect of thickness and surface area of PCM-drywall.

Chapter 3 – Research methodology

The chapter includes the approach for problem, the climate characterization, Energy Plus PCM model details and parameters of reference building.

3.1. Approach for problem

In this research, the characterization of the application of Phase Change Materials in two-story residential apartment in Dfb climate classification zone is investigated. The annual energy savings acquired after incorporation of PCM into the building were studied by a simulation-based approach. The scheme is designed by the combination of Energy Plus with graphical interface of Design Builder. Design Builder allows to rewrite the input files for Energy Plus by switching the independent variables studied and , to extract the extensive number of output values. In the next runs, new input parameters are applied to repeat the process again until described number of PCMs are evaluated for each indicator city.

A reference to two-storey residential building for climate illustrated in Section 3.2 is described in Section 3.4. The annual and monthly assessment are contributed for each two-storey building and compared by the iterations to the overall heating and cooling energy consumptions of adjacent PCM-incorporated house. The comparison is made by changing the parameters of PCM, such as melting temperature, the thickness and surface area. The room/building chosen for the experiment is maintained under the set of constant parameters throughout all iterations. This framework is also described in Section 3.4.

3.2. Characterization of the climate

Despite the wide variety of climate classifications, Koppen –Geiger classification is one of the most optimal and appropriate [46]. The Figure 3.1 represents the digital map of global temperature and precipitation data sets [46].

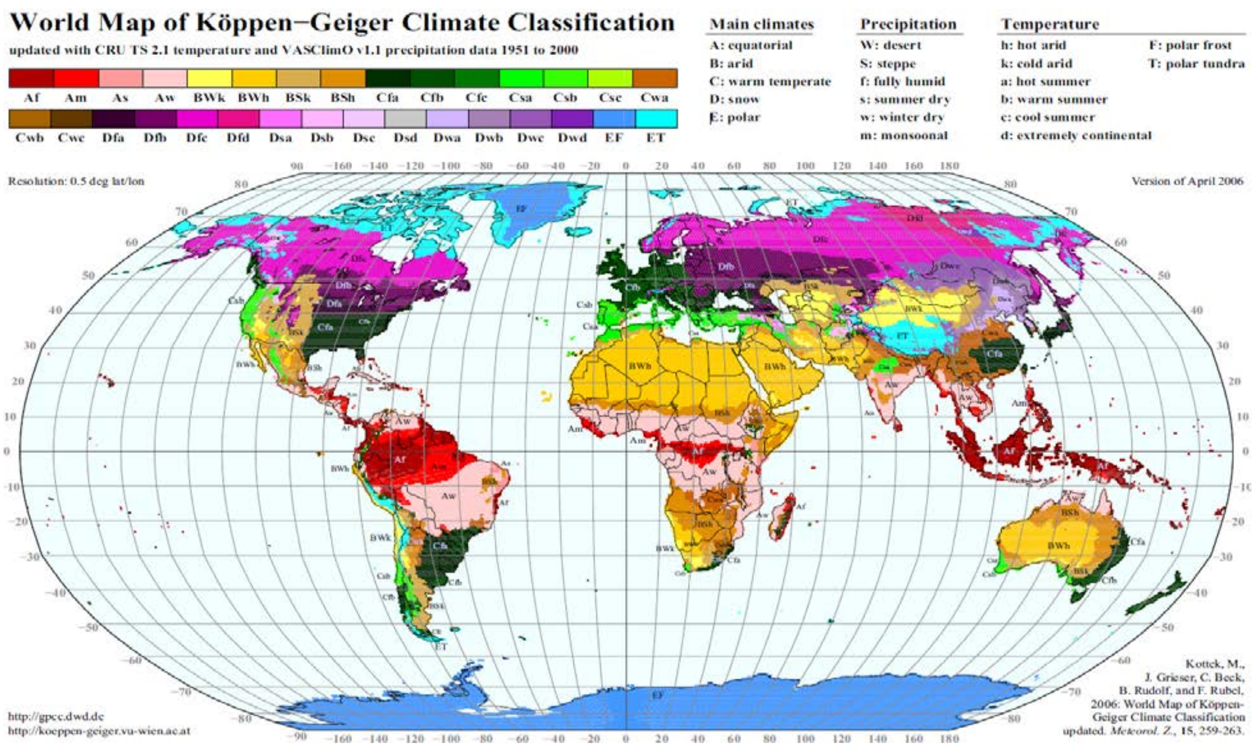


Figure 3.1. World Map of Köppen-Geiger climate classification

The Koppen Geiger climate classification is subdivided into three letter combination, where the first letter represents plants by geographical zones: the equatorial zone (A), the arid zone (B), the warm temperate zone (C), the snow zone

(D) and the polar zone (E). The second letter describes precipitation, while third one shows mean air temperature in the region[46]. This research study takes into consideration only cold climate region, thus parameters of snow zone(D) will be used for further study.

According to Peel et al [47], the snow zone D dominates in the territories of Europe (44,4%) and North America (54.5%) mentioned in Figures 3.2 and 3.3.

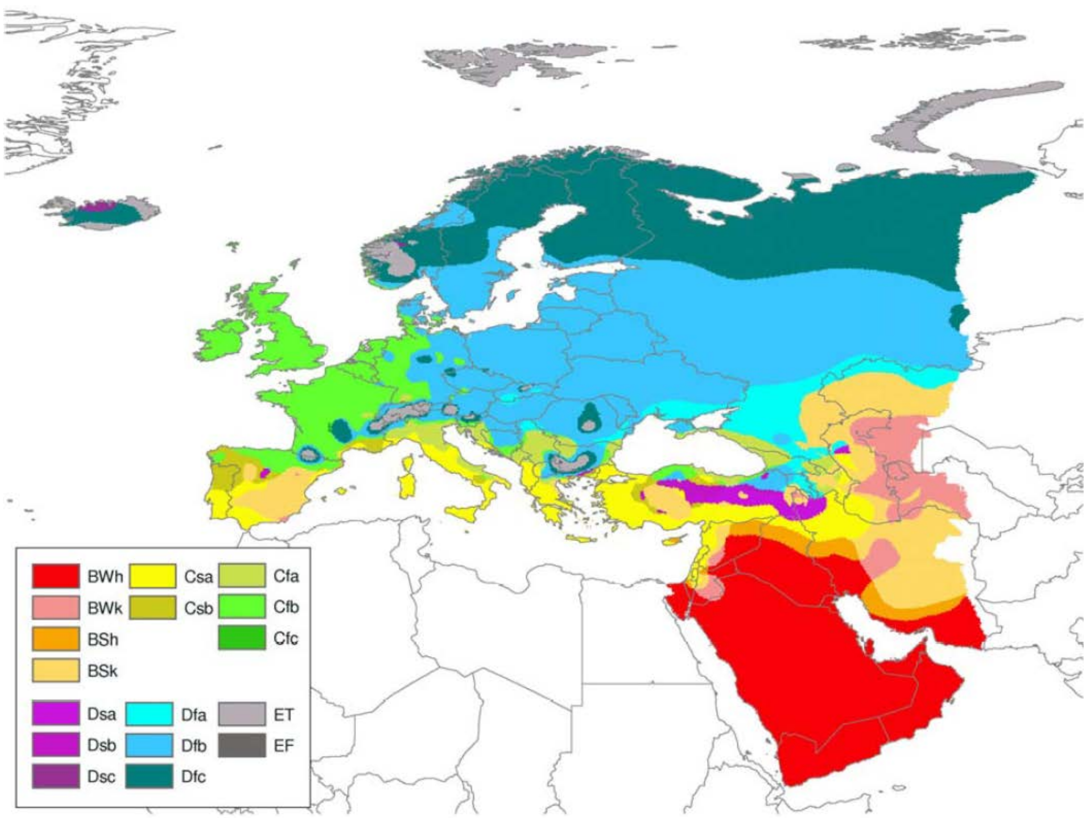


Figure 3.2. Koppen map of Europe

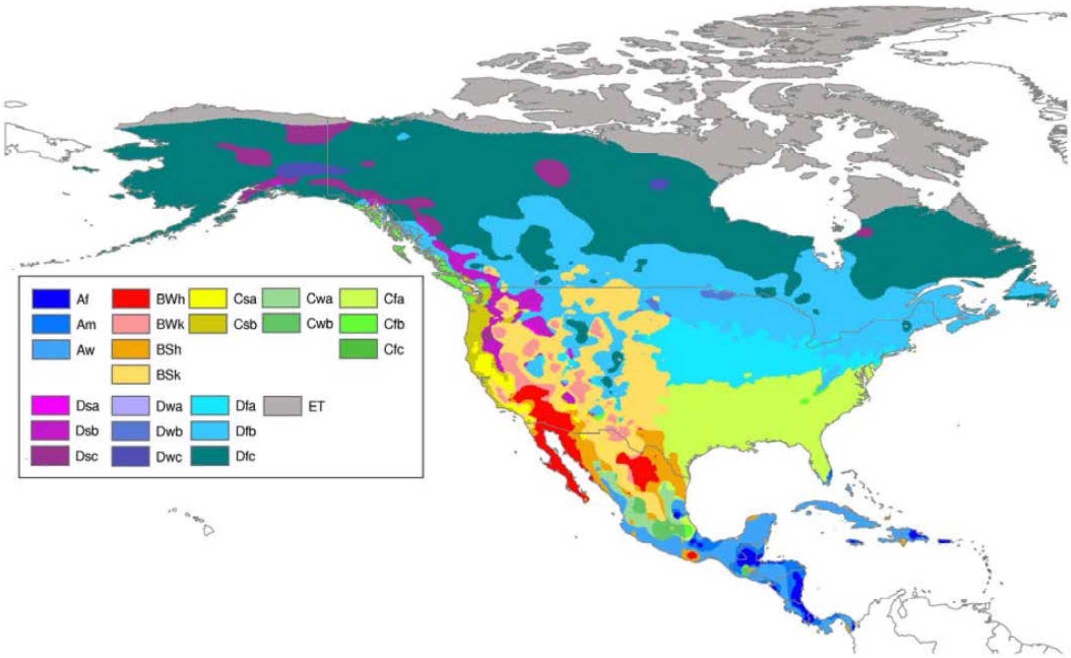


Figure 3.3. Koppen Map of North America

The Dfb climate region can be described as main group - snow (D) with several subtypes based on the values of precipitation – fully humid (f) and values of temperature – warm summer (b). More generally, Dfb climate behaves as moist continental climate with no dry season in latitude 30-60oN. Table 3.1 demonstrate the indicator cities with their coordinates, Koppen-Geiger classification and their elevation [46].

Table 3.1. Characterization of Dfb climate zone representatives

Koppen climate	City	Latitude	Longitude	Elevation (m)
Dfb	Helsinki, Finland	60° 12' N	24° 57' E	56
Dfb	Kiev, Ukraine	50° 27' N	30° 32' E	182
Dfb	Saint-Petersburg, Russia	59° 59' N	30° 20' E	12
Dfb	Moscow, Russia	55° 45' N	37° 37' E	151
Dfb	Stockholm, Sweden	59° 20' N	18° 03' E	14
Dfb	Toronto, Canada	43° 38' N	79° 24' W	79
Dfb	Montreal, Canada	45° 30' N	73° 39' W	50
Dfb	Ottawa, Canada	45° 25' N	75° 41' W	71

3.3. Design Builder PCM Model

Literature suggests that combination of energy simulation and optimum tool is contribute to the optimum the building envelope [43-45]. Various energy simulation instruments include ESP-r [48, 51-54], TRNSYS [49, 55-57] and EnergyPlus [38-45, 50], which can model PCMs dor different building applications. These tools apply different approaches, starting from empirical equivalent heat model to fully implemented finite mode[58]. For example, Tabares-Velasco applies onedimensional conduction finite-difference (CondFD) solution for EnergyPlus PCM model [58].

Design Builder incorporated with EnergyPlus 8.6 includes the conduction finite difference (CondFD) algorithm introduced by Pederson [59], then, revised by Tabares-Velasco [60]. The model is represented as implicit finite difference scheme, which accurately supports enthalpy-temperature curve for phase-change energy calculations. Eq. (1) describes the equation for an internal node:

$$\rho C_p \Delta x \frac{T_i^j - T_i^{j-1}}{\Delta t} = k_{int} \frac{T_{i+1}^j - T_i^j}{\Delta x} + k_{ext} \frac{T_{i-1}^j - T_i^j}{\Delta x} \tag{1}$$

Where

$$k_{int} = \frac{(k_{i+1}^j + k_i^j)}{2} \tag{2}$$

$$k_{ext} = \frac{(k_{i-1}^j + k_i^j)}{2} \tag{3}$$

$$\Delta x = \sqrt{c\alpha^* \Delta t} = \sqrt{\frac{\alpha^* \Delta t}{F_0}} \tag{4}$$

The indicators *j,i* refer to applicable time step and adjacent node. The *j* and *j-1* represent the present and previous time step, *i* refers to node being designed and *i-1* and *i+1* illustrate adjacent nodes to the outer and inner sides of the construction respectively. Δx is finite difference layer thickness, which defines the space between the nodes. In the algorithm, all elements are influenced by equation (4), which consists of space discretization constant c, the thermal diffusivity α^* andthe time step Δt as well as can be converted in terms of Fourier number F_0.

$$h_i = h(T_{i,j}) \tag{5}$$

$$k_i = k(T_{i,j}) \tag{6}$$

By incorporation Eqs. (5),(6) which defines enthalpy (h) and thermal conductivity (k) with Eq.(1), the specific heat capacity for the PCM is updated for each iteration by the governing equation:

$$C_P = \frac{h_i^j - h_i^{j-1}}{T_i^j - T_i^{j-1}} \tag{7}$$

Tabares-Velasco et al. describe several limitations for the application of CondFD [4]. The authors found that maximum allowable limit for time step is equal to 3 minutes and default CondFD model (with c=3) can be used for monthly and annual analysis. In this research, the CondFD model with 3 minutes time step is applied for the monthly and annual evaluation of energy consumption (for both reference and the PCM-incorporated house).

As it is mentioned above, the Design Builder PCM model depends on enthalpy-temperature and thermal conductivity functions, which are based on the external data. However, these functions are not linear for most PCMs, which makes data collection challenging. Tabares-Velasco [60] carried the extensive investigation on the energy impacts of non-linear behavior of enthalpy-temperature function. His findings describe that energy savings slightly sensitive to the linearization of the enthalpy-temperature curve. For hourly analysis, the linearization should be done in perspective that melting range covers up to 75 percent of latent heat [60].

In this work, the energy impact of linear enthalpy-temperature curve is examined for phase change material enhanced into building envelope. The BioPCM material mentioned in Alam et al. [38] was examined as a reference PCM-drywall. The material has non-linear enthalpy-temperature function, a melting temperature 20 ℃ with specific heat 1970 J/Kg K, 860 kg/m^3 density and 0.2 W/m K thermal conductivity. Based on the non-linear enthalpy-temperature curve, which covers melting range up to 80 percent, 10 different hypothetical PCM-drywalls are designed. The construction of hypothetical PCMs is based on the shifting the curve horizontally according to the desired PCM melting ranges. Therefore, PCM 18 to PCM 28 were developed with melting range of 4 ℃ (PCM 20 has melting range starting from 18 to 22 ℃) for the evaluation of the problem. Fig. 3.1 shows the enthalpy-temperature functions of designed hypothetical PCM-drywalls.

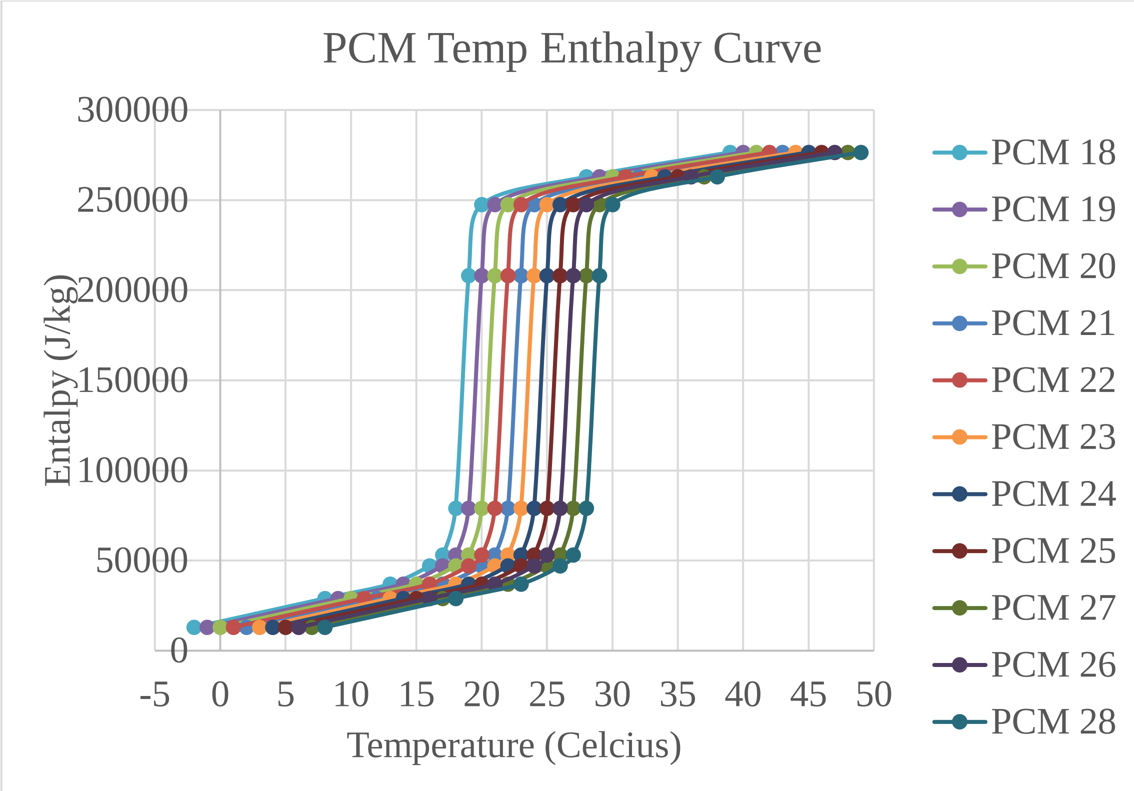


Figure 3.4. Phase Change Material Temperature Enthalpy Curve

The Design Builder PCM model uses only the enthalpy-temperature information as input parameter, which lead to several consequences, such as influence of strong hysteresis on accuracy and modelling changes in volume through phase transitions [58]. However, mentioned problems are not critical for the energy savings output of material. Therefore, in this study the strong hysteresis phenomena and changes in volume are not considered, while the density value is assumed to be constant for all iterations [38].

3.4. Reference Building

In order to perform the simulations in cold climate weather conditions, a convenient building model had to be chosen. In this study, a one family residential detached apartment was selected using DesignBuilder (Fig.2) models generated according 2009 International Energy Conservation Code (IECC). The low-rise residential building is a 315 m2 two-storey building with inclined pitched roof. The building has rectangular shape with 12.18 m width, 9.16 m length and 6.55 m height. The windows of 2.1m x 2.1m size are installed at 1m above the floor level, while the door of 1.2m x 2.1m size is placed on the south side. The floor area is 223.14 m2 with a slab on grade foundation.

The internal heat gains are generated by one typical family consisting of married couple with two children in residential activity with constant metabolic rate of 126 W/person. In order to simulate real-life conditions, the two storey residential building is considered empty from 8:00 to 16:00 during working days. The reference two-story residential house is incorporated with Fan-Coil with District Heating and Cooling HVAC system. According to Werner [61] HVAC systems incorporated with District Heating and Cooling are employed in 51 percent of buildings in the European Union, Russia and China. When the house is occupied, the thermostat values should vary from 20°C to 26°C according to European standards [62], so the heating is applied when temperature is below 20°C, while cooling is switches on for temperatures above 26°C. When the house is not occupied, the HVAC system is turned off for the purposes of energy savings.

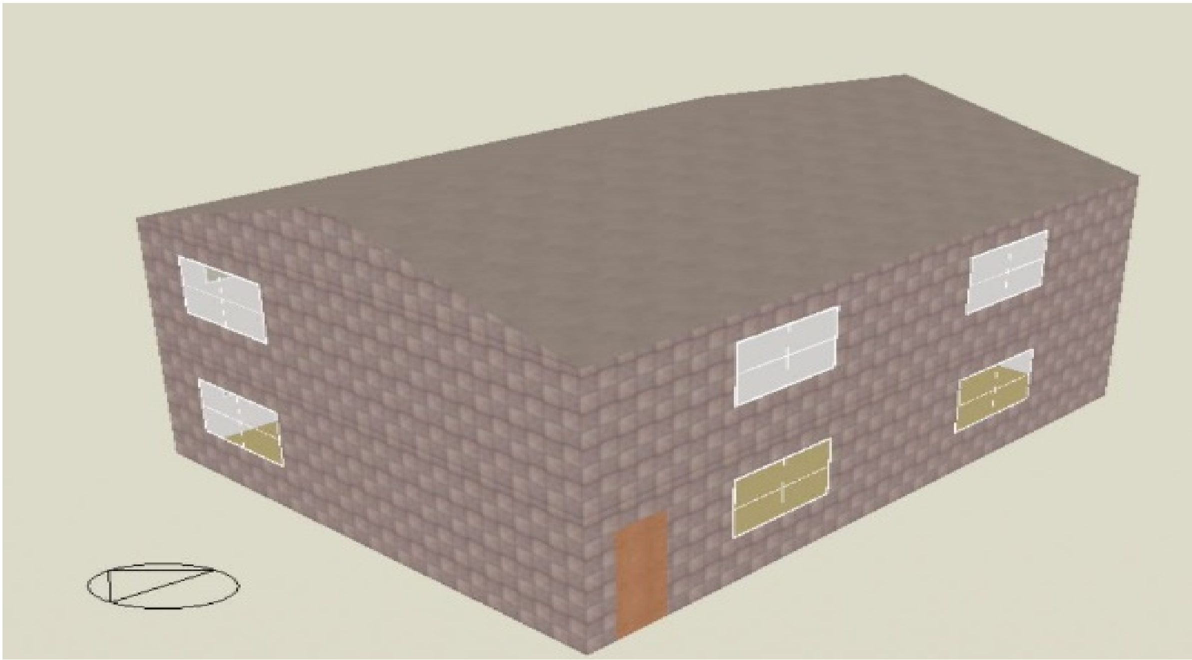
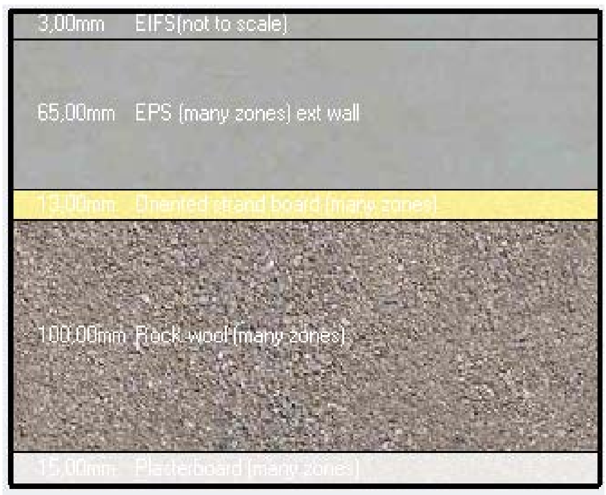
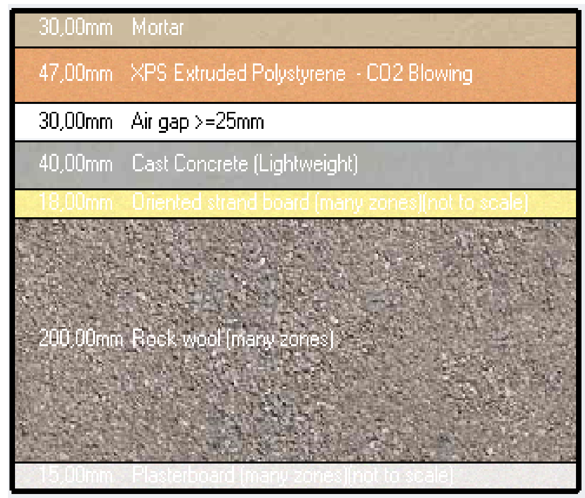


Figure 3.5. Two-story reference residential building.

The lightweight hybrid steel-framed construction mentioned in [47] is applied for the building framework. The properties of external wall, pitched roof and ground floor were modified according to Dfb climate region [42]. To incorporate the PCM-drywall into the building, the building framework was slightly changed and PCM materials were placed on the inner surface of the exterior walls and roof before the plasterboard. Figure 3.6 and Table 3.2 represent the material composition and thermophysical properties of external wall, pitched roof and ground floor without the use of PCM.



a) Wall composition



b) Roof composition

c)Intermediate floor

d) Slab-on-grade

Figure 3.6. Details of wall, roof, and floors.

Table 3.2. Thermophysical properties of building materials.

Material	Thermal Conductivity (W/mK)	Specific Heat (J/kgK)	Density (kg/m^3)
EIFS finish	1,151	1501	1051
EPS	0,041	1401	16
PCM	0,21	860	1971
XPS	0,031	1401	36

Rockwool	0,041	841	31
OSB	0,131	1701	651
Plasterboard	0,251	1001	1201
Mortar Slab	0,881	897	2801
Cast Concrete	0,381	1001	1201
Gravel	2,801	801	2501
Interior Finishing	0,171	1401	1201
Steel	50,01	451	7801
Ceramic tiles	1,1	841	2501
Reinforced concrete	1,59	881	2289
Gypsum plaster	0,381	841	1121

Chapter 4 – Results and Discussion

In this chapter the assessment of iterations for two storey residential building with pitched roof model with and without PCM was described. First, monthly assessment of PCM integrated two -storey residential building model was evaluated. Then the annual assessment was conducted to define the optimum PCM for each city evaluated. In addition, the thickness and surface area analysis comparison were performed.

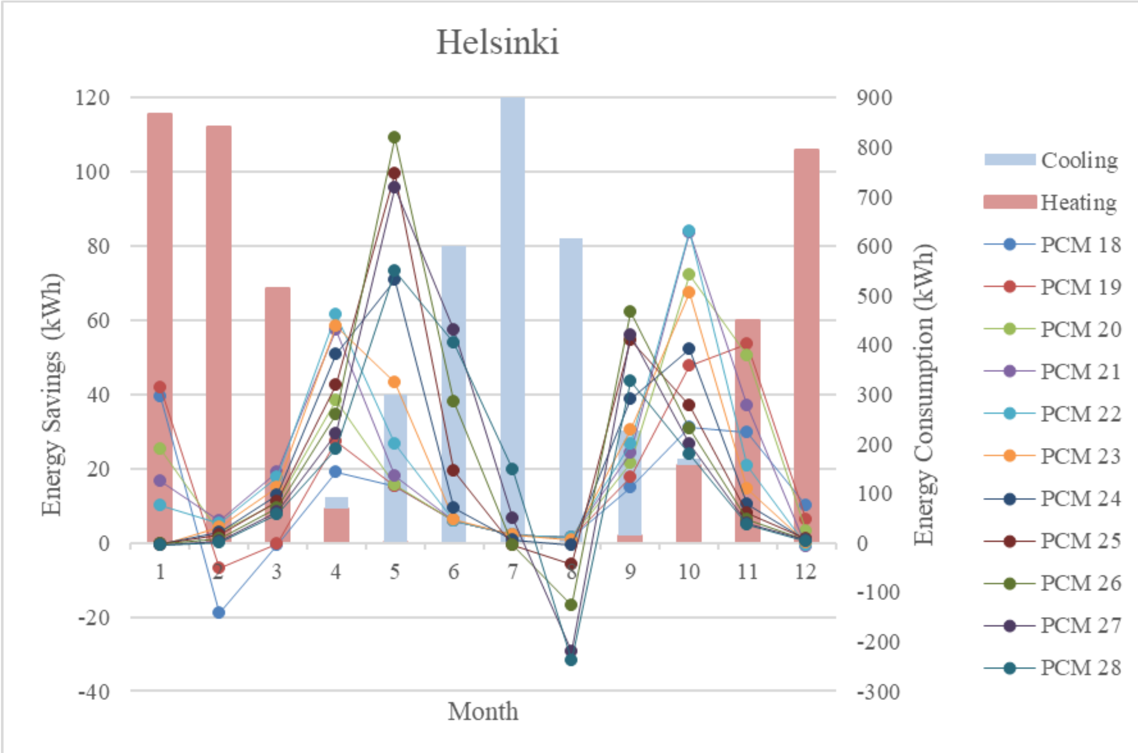
4.1. Monthly Results

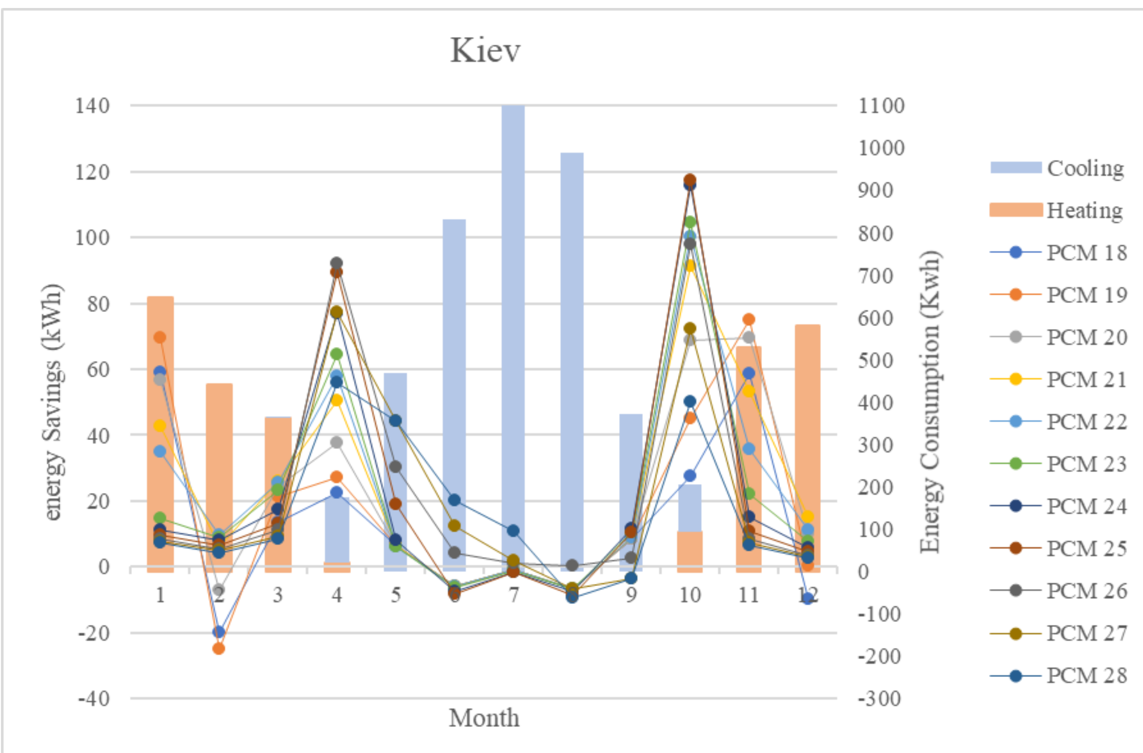
In following part, the monthly evaluation of the energy savings for heating and cooling are described. Figure 4.1 describes the monthly demands for base house and associated monthly energy savings of the different PCM which were incorporated into the reference building. The bars interpolate to the heating and cooling energy consumptions for the house in each city located in Dfb climate. The bullets on the colored graphs represented the monthly energy savings for PCM range (18-28°C) incorporated.

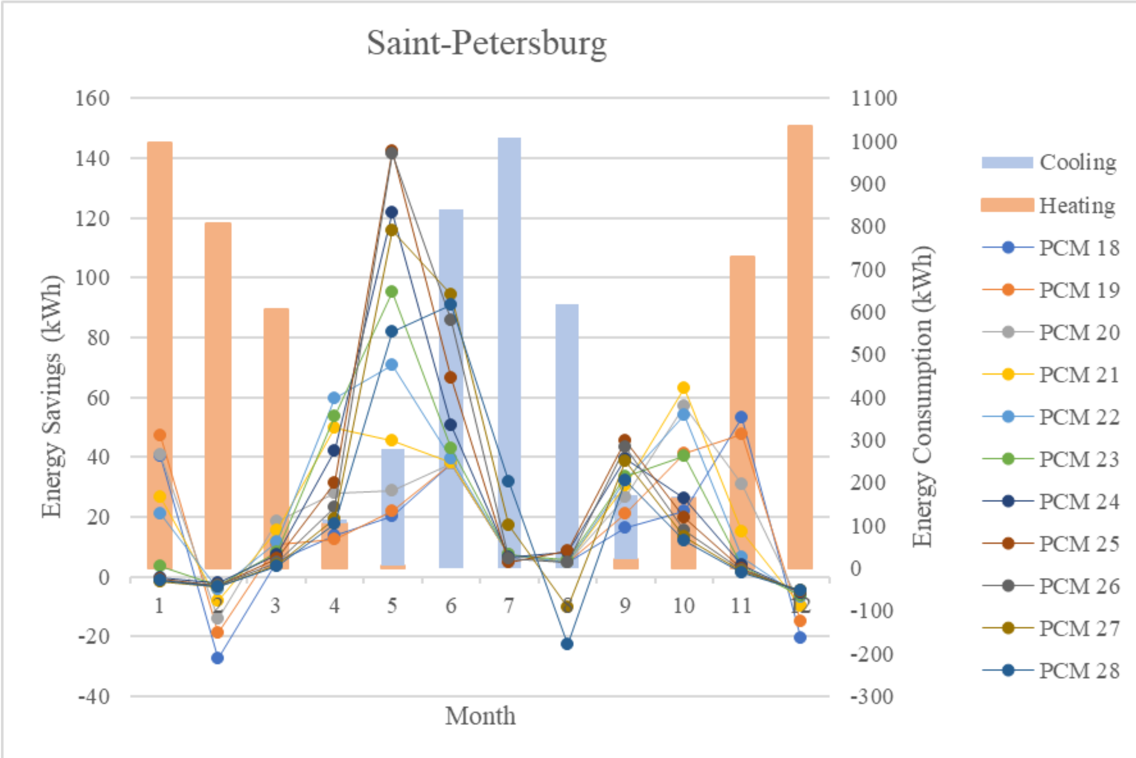
For the clear understanding, only the graphs of Helsinki and Toronto will be explained in detail. These cities belong to the European and North-American part of Dfb-climate zone. For the Helsinki (see Fig 4.1), the heating demand was required in January, February, March, November and December ranged from 448.77 to 867 kWh. The energy savings of low melting temperature PCMs (PCM 18-21) during those months are up to 41.68 kWh. The energy savings of high melting temperature PCMs (PCM 25-28) during those months are mostly identical and relatively small (ranged from 8.11 to 0.03 kWh). The cooling demand was required in June, July and August ranged from 600.19 kWh to 912.66 kWh. The energy savings for high-melting temperature PCMs in these months are raised up to 53.99 kWh. For low melting temperature PCMs, the energy savings are negligible (from 1.56 to 5.97 kWh). Despite the relatively small total energy consumption in April (92.77 kWh) , May (298.95 kWh), September (226.63 kWh) and October (169.77 kWh), the energy savings are on higher side and ranged from 61.42 kWh (April) up to 109.34 kWh (May).

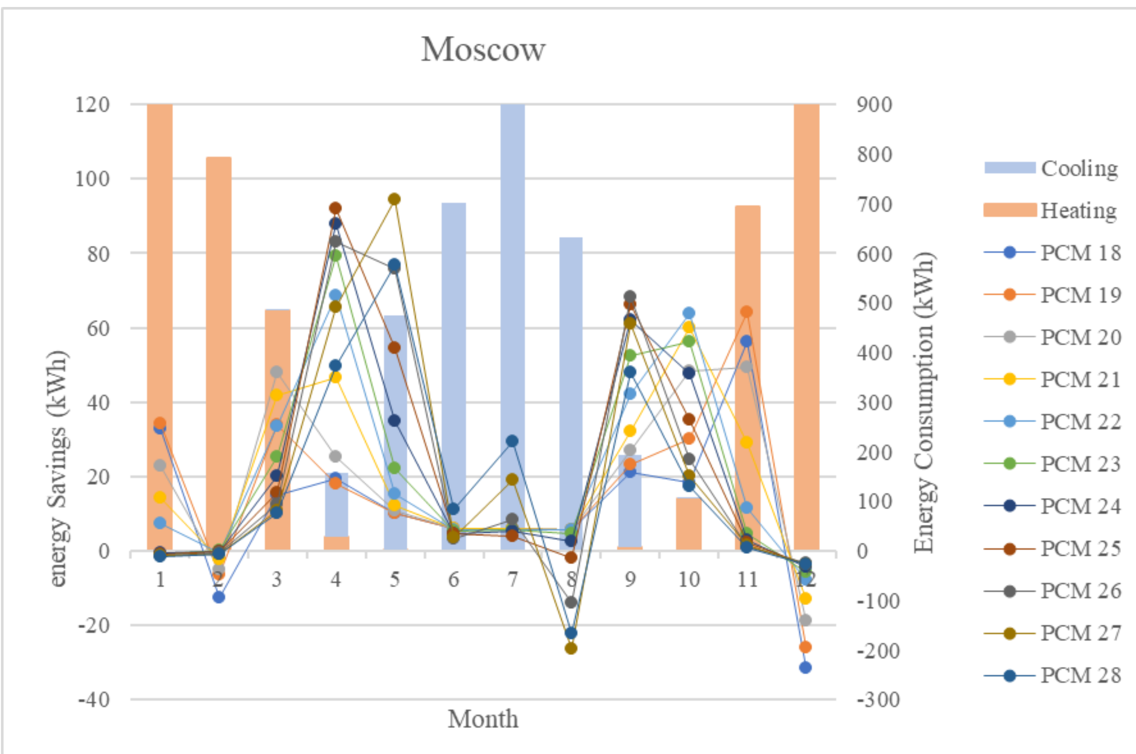
In Toronto, the heating, cooling and total energy demand patterns is similar to Helsinki. However, the cooling demand is on the higher side starting from 741 to 1040.43 kWh. During the months where heating consumption was on the higher side (January, February, March, November and December) the low-melting temperature PCMs showed higher energy savings (up to 81 kWh). During June, July and August, the energy savings are on the lower side (up to 15 kWh) and high-melting temperature PCMs (25-28) were inefficient. During the April, May, September and October, the energy savings are maximum starting ranging from 58.31 kWh (October) to 128.34 kWh (May).

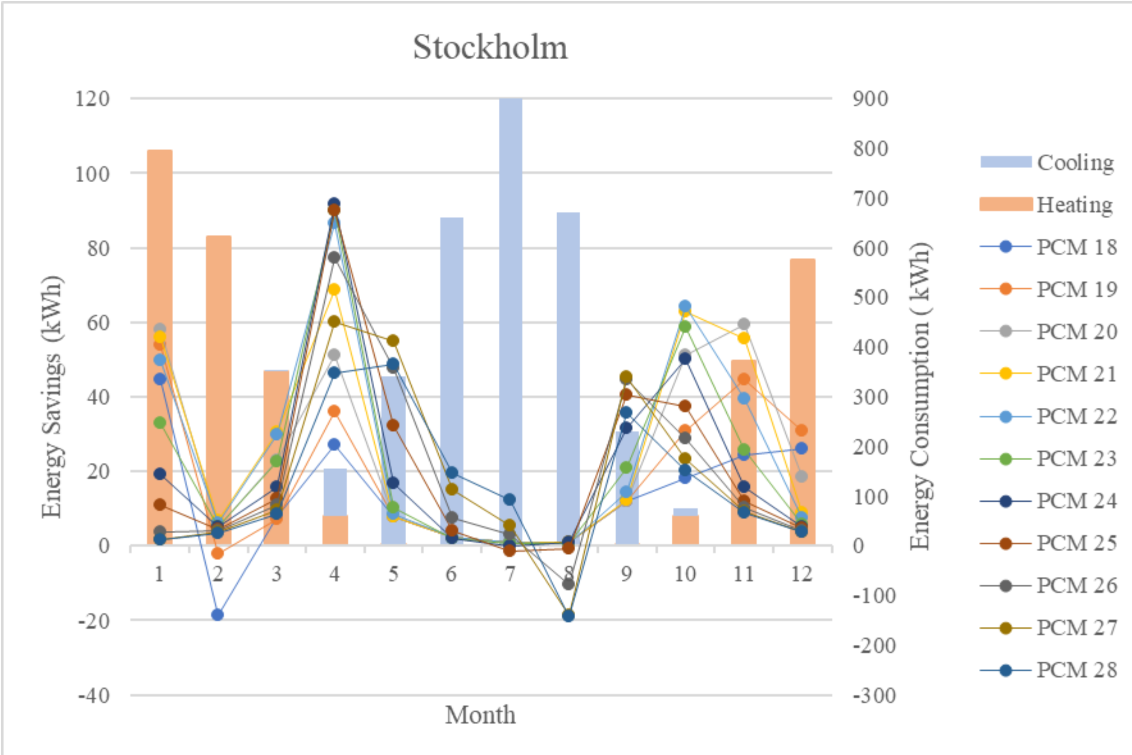
The trends mentioned in Helsinki and Toronto can be justified by restrictions of material parameters to complete the phase change cycle. Moreover, small energy savings during January, February, March, November and December by the high melting temperature PCMs was due to the reason that PCM is in permanent solid state and will not accomplish the phase change cycle. Similarly, during June, July and August low-melting temperature PCMs showed small energy savings due to the reason that PCM is in liquid state and inability to complete phase change cycle. For the April, May, September and October the maximum energy savings contributed to the completion of phase change cycle by all PCMs. Thus, the maximum peaks of energy savings in Kiev, Saint-Petersburg, Moscow, Stockholm, Montreal and Ottawa were in those months and were equal to 117.5, 142.14, 94.28, 91.88, 126.73 and 67.79 kWh respectively.

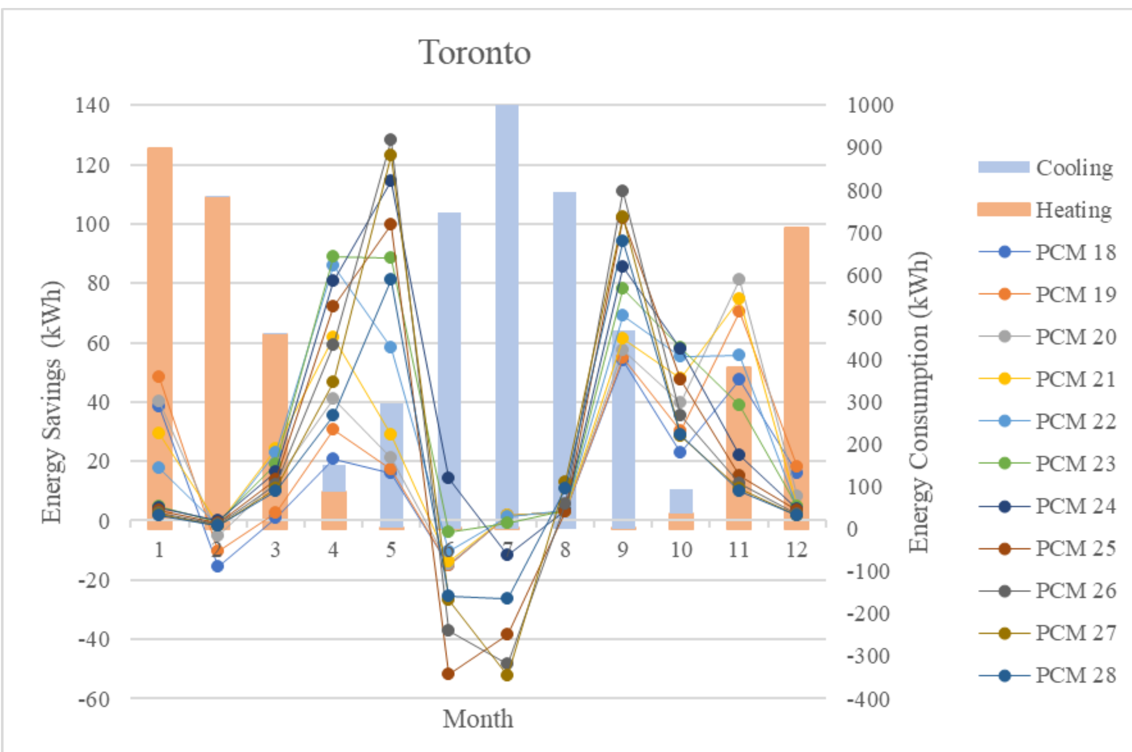

Helsinki
Energy Savings (kWh)
Energy Consumption (kWh)
Month
120
100
80
60
40
20
0
-20
-40
900
800
700
600
500
400
300
200
100
0
-100
-200
-300
1 2 3 4 5 6 7 8 9 10 11 12
Cooling
Heating
PCM 18
PCM 19
PCM 20
PCM 21
PCM 22
PCM 23
PCM 24
PCM 25
PCM 26
PCM 27
PCM 28

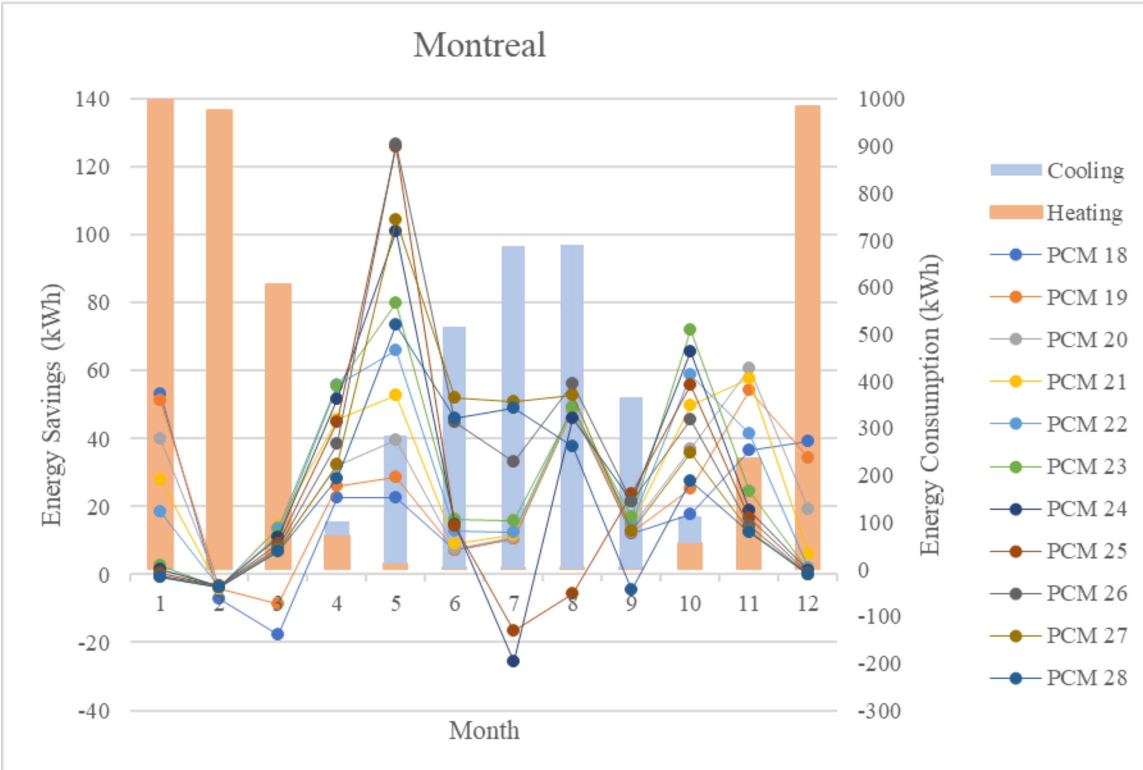

Kiev
energy Savings (kWh)
Energy Consumption (Kwh)
Month
140
120
100
80
60
40
20
0
-20
-40
1100
1000
900
800
700
600
500
400
300
200
100
0
-100
-200
-300
1 2 3 4 5 6 7 8 9 10 11 12
Cooling
Heating
PCM 18
PCM 19
PCM 20
PCM 21
PCM 22
PCM 23
PCM 24
PCM 25
PCM 26
PCM 27
PCM 28


Saint-Petersburg
Energy Savings (kWh)
Energy Consumption (kWh)
Month
Cooling
Heating
PCM 18
PCM 19
PCM 20
PCM 21
PCM 22
PCM 23
PCM 24
PCM 25
PCM 26
PCM 27
PCM 28


Moscow
energy Savings (kWh)
Energy Consumption (kWh)
Month
Cooling
Heating
PCM 18
PCM 19
PCM 20
PCM 21
PCM 22
PCM 23
PCM 24
PCM 25
PCM 26
PCM 27
PCM 28


Stockholm
Energy Savings (kWh)
Energy Consumption (kWh)
Month
Cooling
Heating
PCM 18
PCM 19
PCM 20
PCM 21
PCM 22
PCM 23
PCM 24
PCM 25
PCM 26
PCM 27
PCM 28


Toronto
Energy Savings (kWh)
Energy Consumption (kWh)
Month
Cooling
Heating
PCM 18
PCM 19
PCM 20
PCM 21
PCM 22
PCM 23
PCM 24
PCM 25
PCM 26
PCM 27
PCM 28



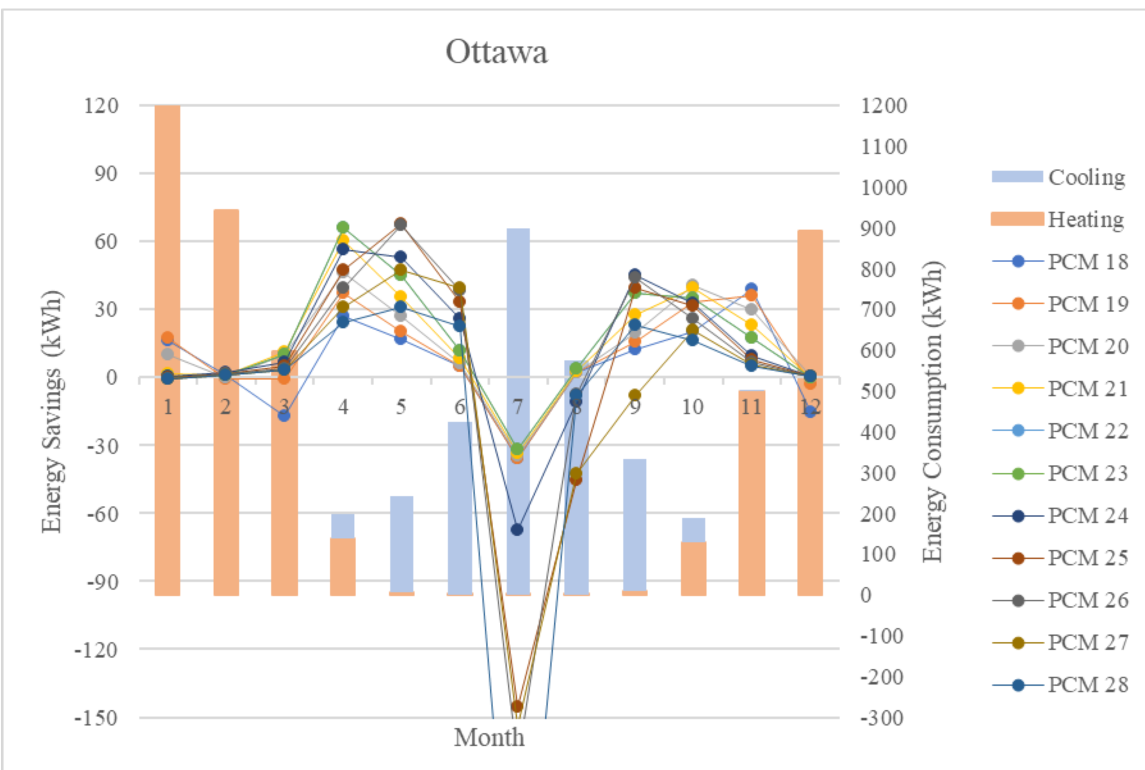


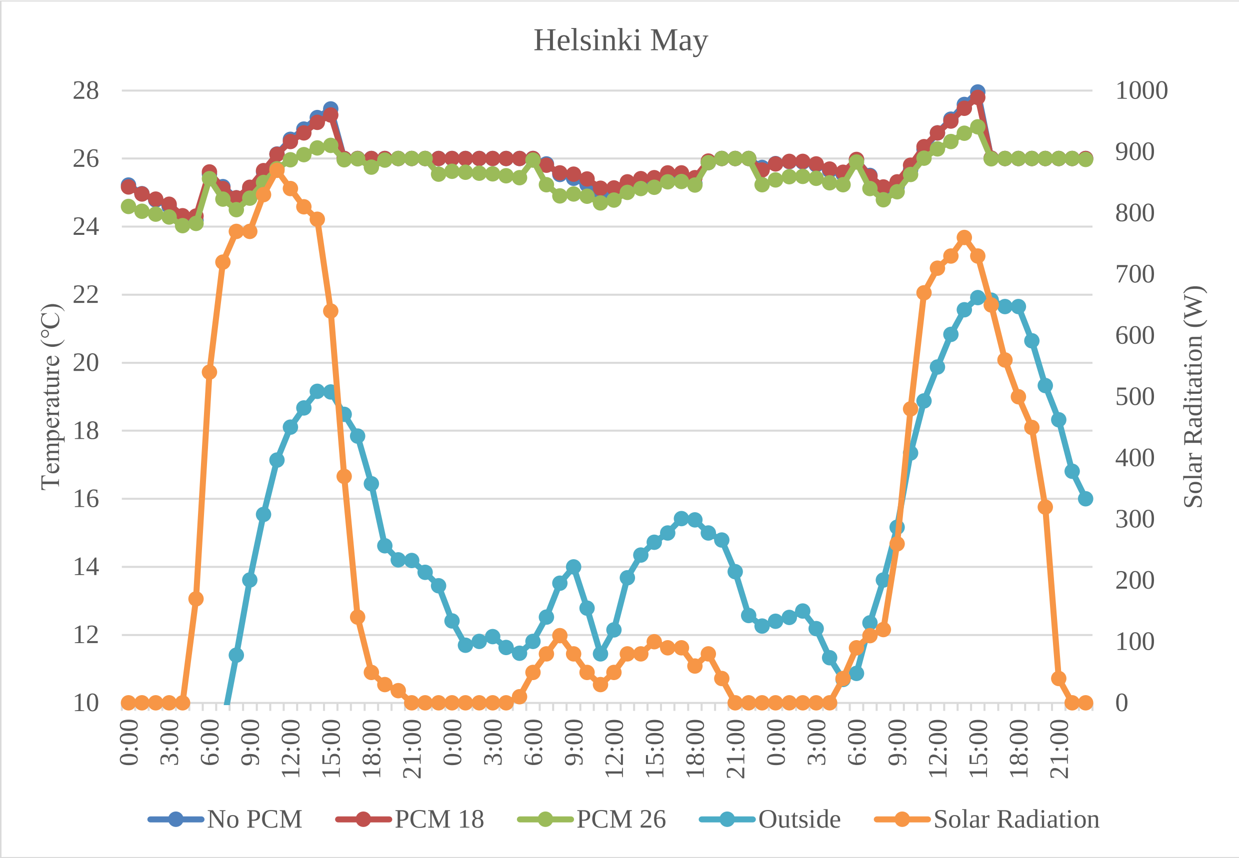
Figure 4.1. Monthly energy savings for all cities.

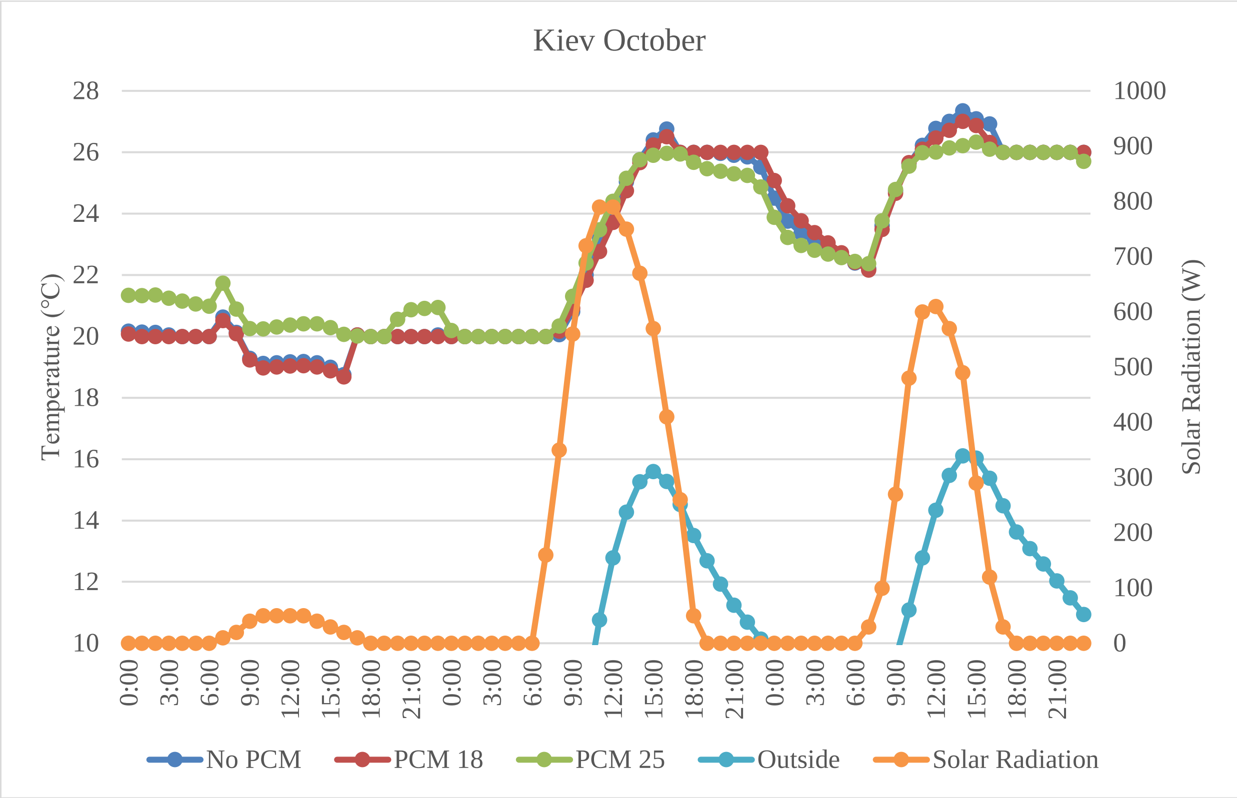
4.2. Thermal Response Under Controlled Temperature Conditions

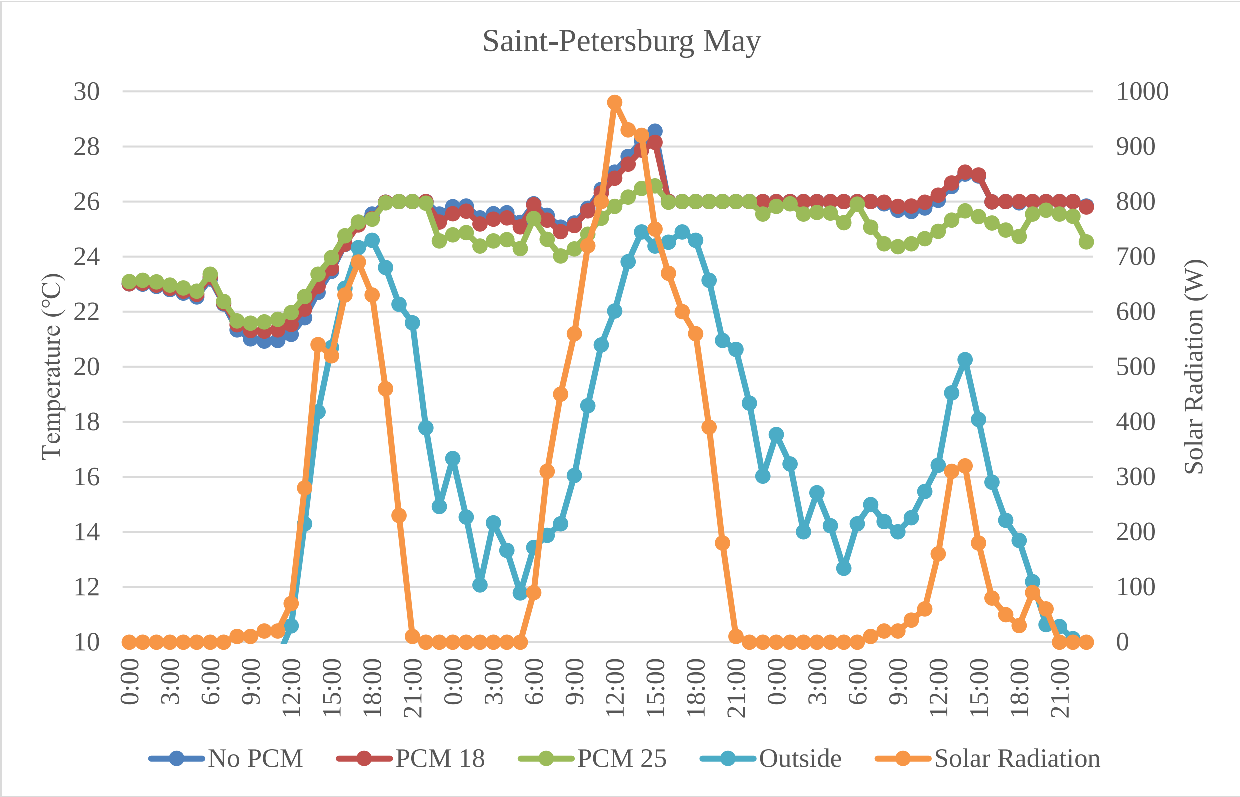
For the order to investigate behavior of the PCM the indoor hourly air temperature profiles in each examined city was compared in buildings with and without PCM. For this purpose, the months representing the maximum and minimum output in terms of monthly energy savings were defined. The months for the maximum energy savings devoted to April, May, September and October. The optimum PCM for Helsinki, Kiev, Saint-Petersburg, Moscow, Stockholm, Toronto, Montreal and Ottawa in those months were represented by PCMs 24-26. The minimum energy savings in these months represented by low-melting temperature PCMs (18-21). Figure 4.2 indicates the indoor temperature for reference house and associated air temperature of the optimum and worst PCM which was incorporated into the reference building combined with outside temperature and solar radiation.

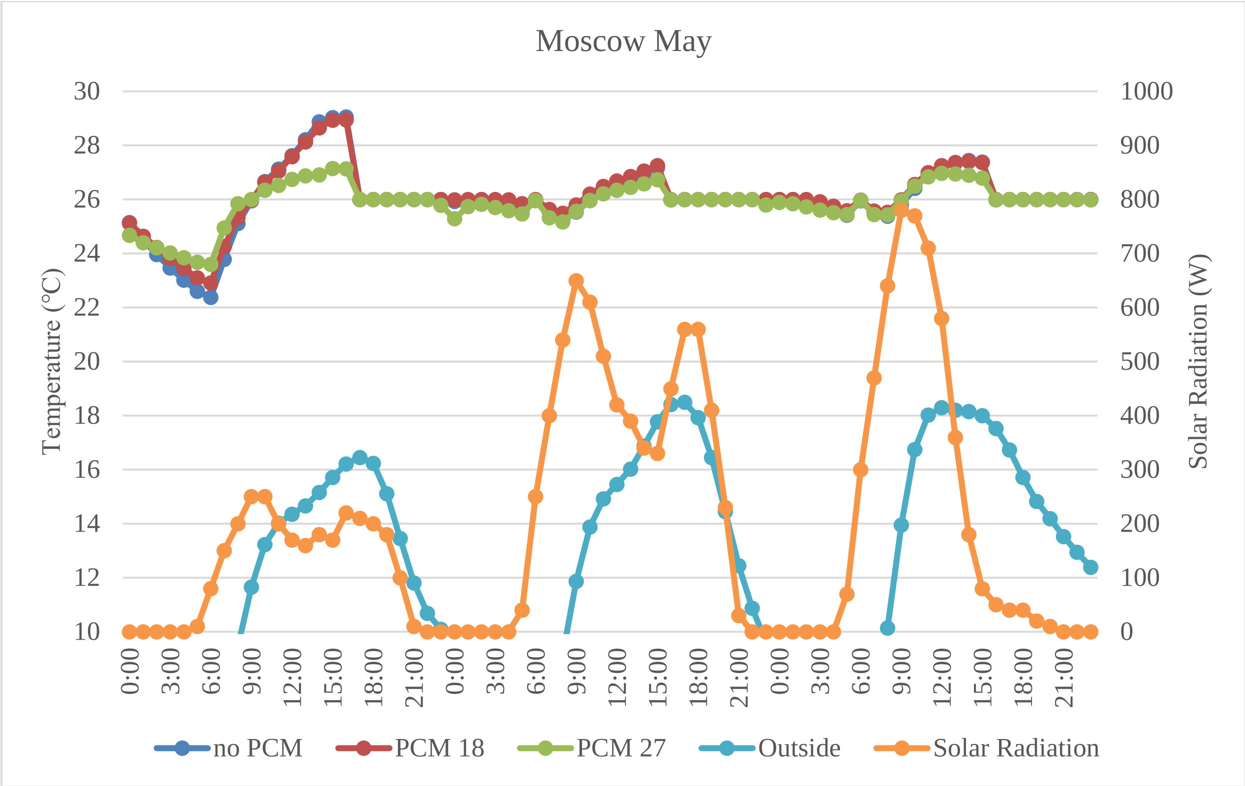
For detailed evaluation, the plot of temperature profile of PCM 26, PCM 18 and without PCM case along with solar radiation and outside temperature in Helsinki was chosen. From Figure 4.2 (a), during the sunshine period, the internal air temperature was increased due to high values of outside temperature (19 °C) and solar radiation (815 W/m^2). It has to be mentioned, that the model with PCM, especially PCM26, the absorbed heat prevented the overheating of the zone. Consequently, during the night time where outside temperature substantially reduced, the PCM26 is allowed to complete phase change cycle. However, the behavior of temperature profile for PCM18 is similar to No PCM temperature profile. Such behavior can be explained by low value of temperature necessary for solidification of PCM18 - 16°C , which is unable to achieve during nighttime and, thus, deactivates ability of PCM to complete the phase change cycle and therefore reacts as a thermal mass.

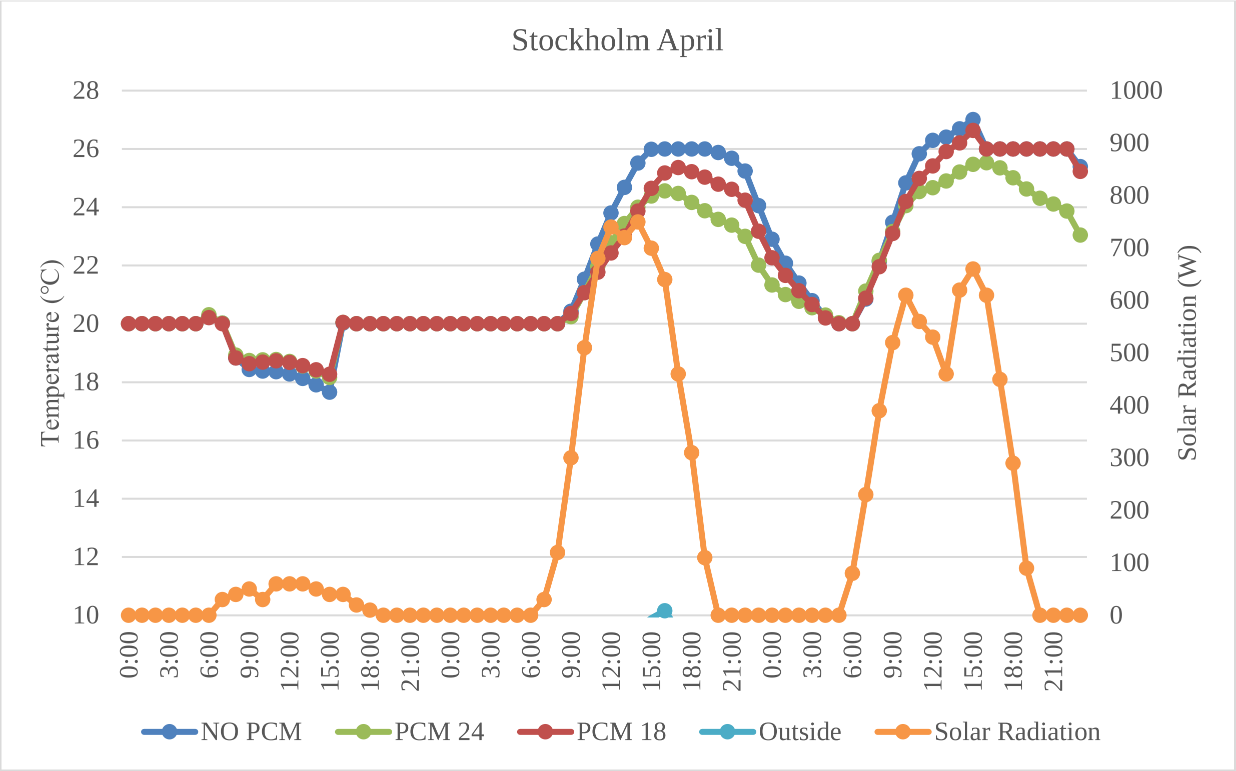
The results of other temperature profiles showed the similar trend for the months where maximum peaks were achieved and are clarified in Figure 4.2. The Figure 4.2 indicates that for all cities except Kiev, the higher energy savings were in the April or May. The maximum temperature for the residential house without PCM located in other cities were found to be up to 32.52°C while the maximum temperature in the residential house integrated with optimum PCMs in these cities reached 30.3°C. Hence it can be defined that the peak air internal temperature in these cities diminished by up to 2.21°C. Thus, the part of the overheating charge has been taken by the PCM by reducing cooling demand in sunshine period.

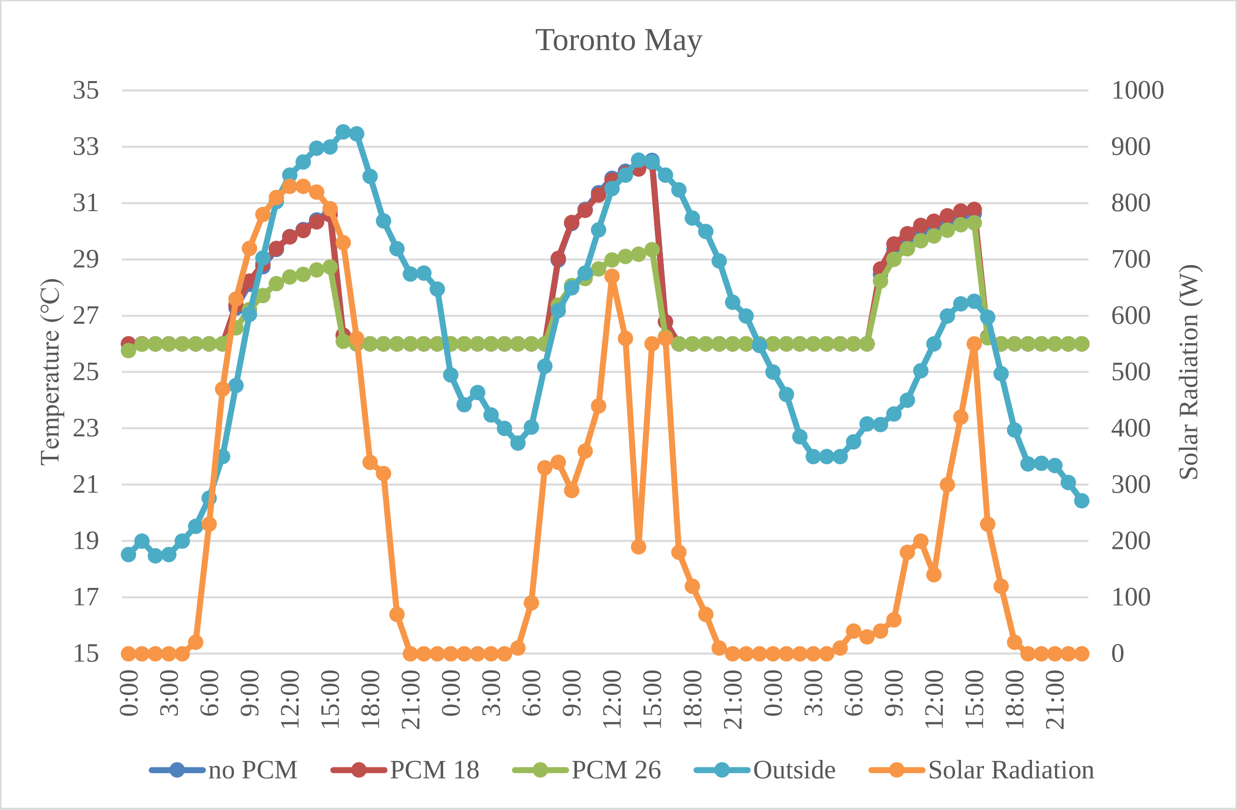

Helsinki May
Temperature (°C)
Solar Raditation (W)
28
26
24
22
20
18
16
14
12
10
1000
900
800
700
600
500
400
300
200
100
0
0:00
3:00
6:00
9:00
12:00
15:00
18:00
21:00
No PCM
PCM 18
PCM 26
Outside
Solar Radiation

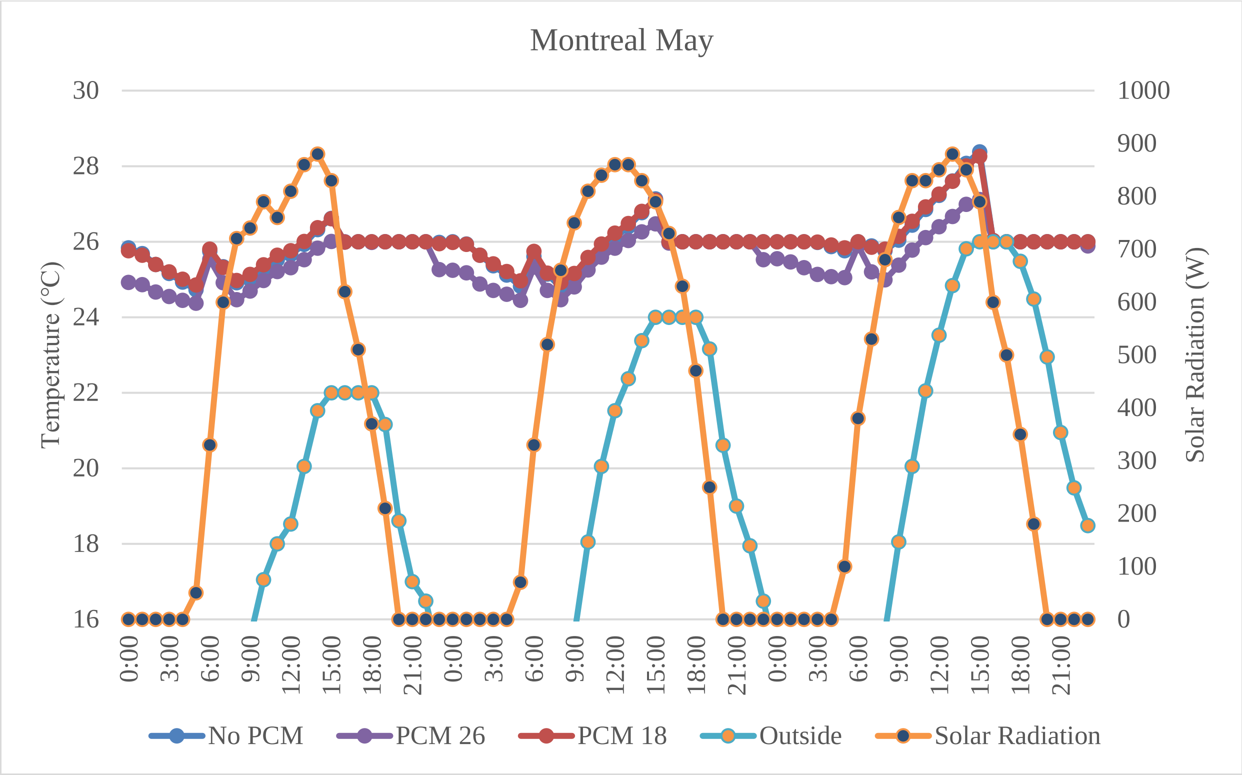

Kiev October
Temperature (°C)
Solar Raditation (W)
28
26
24
22
20
18
16
14
12
10
1000
900
800
700
600
500
400
300
200
100
0
0:00
3:00
6:00
9:00
12:00
15:00
18:00
21:00
No PCM
PCM 18
PCM 25
Outside
Solar Radiation


Saint-Petersburg May
Temperature (°C)
Solar Radiation (W)
30
28
26
24
22
20
18
16
14
12
10
1000
900
800
700
600
500
400
300
200
100
0
0:00
3:00
6:00
9:00
12:00
15:00
18:00
21:00
No PCM
PCM 18
PCM 25
Outside
Solar Radiation


Moscow May
Temperature (°C)
Solar Radiation (W)
30
28
26
24
22
20
18
16
14
12
10
1000
900
800
700
600
500
400
300
200
100
0
0:00
3:00
6:00
9:00
12:00
15:00
18:00
21:00
no PCM
PCM 18
PCM 27
Outside
Solar Radiation


Stockholm April
Temperature (°C)
Solar Radiation (W)
28
26
24
22
20
18
16
14
12
10
1000
900
800
700
600
500
400
300
200
100
0
0:00
3:00
6:00
9:00
12:00
15:00
18:00
21:00
NO PCM
PCM 24
PCM 18
Outside
Solar Radiation


Toronto May
Temperature (°C)
Solar Radiation (W)
35
33
31
29
27
25
23
21
19
17
15
1000
900
800
700
600
500
400
300
200
100
0
0:00
3:00
6:00
9:00
12:00
15:00
18:00
21:00
no PCM
PCM 18
PCM 26
Outside
Solar Radiation



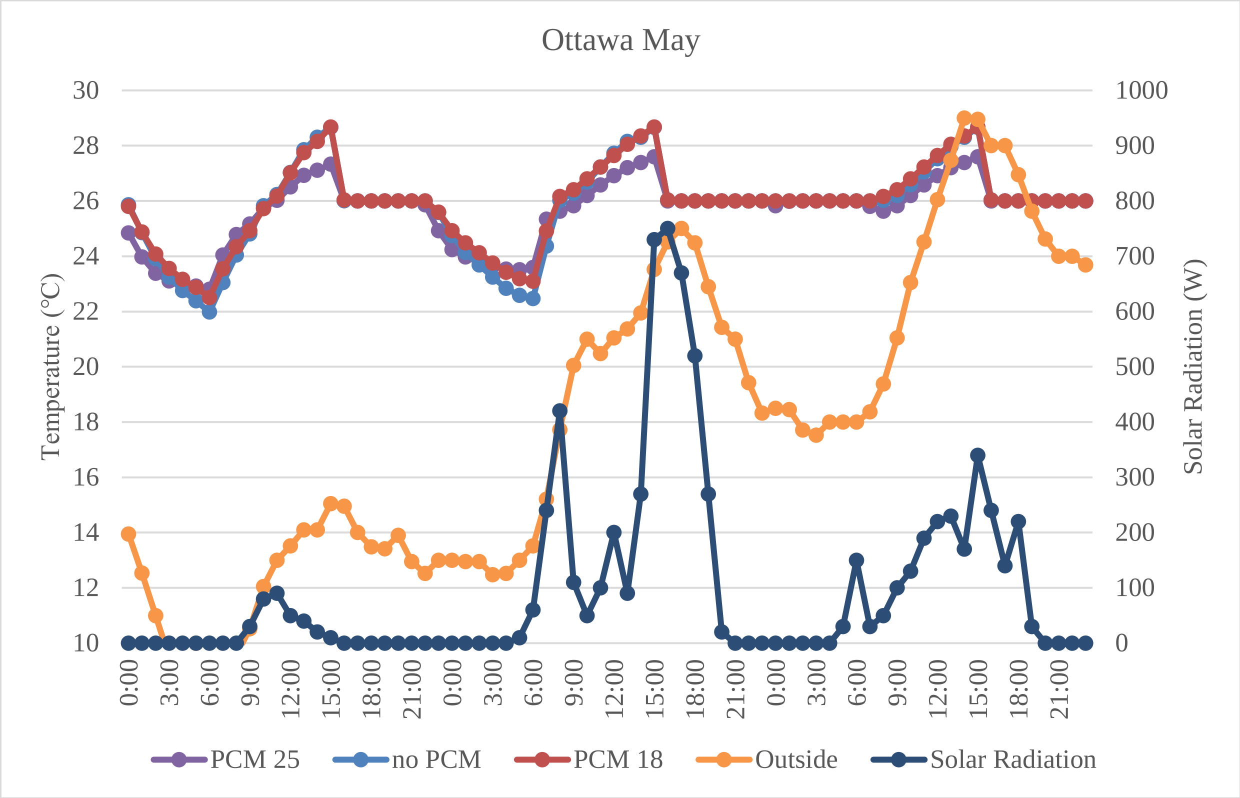
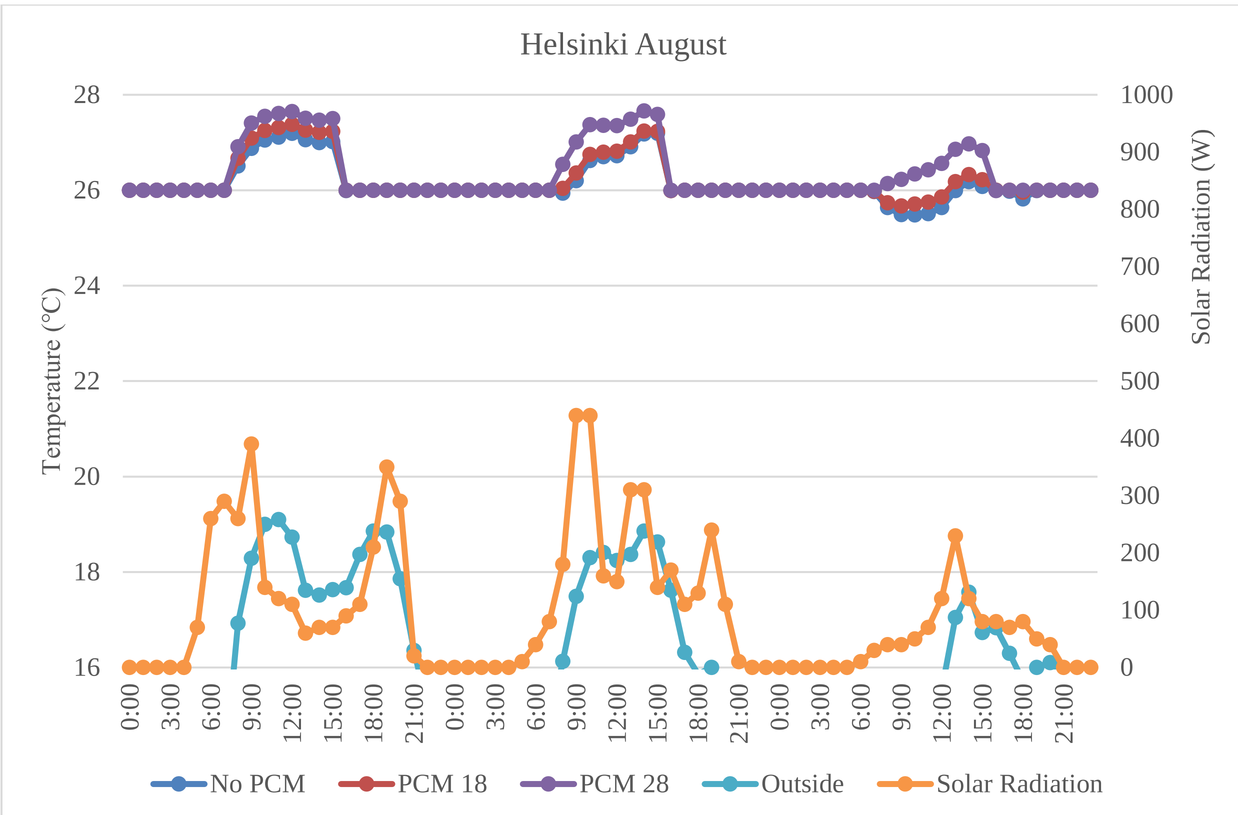
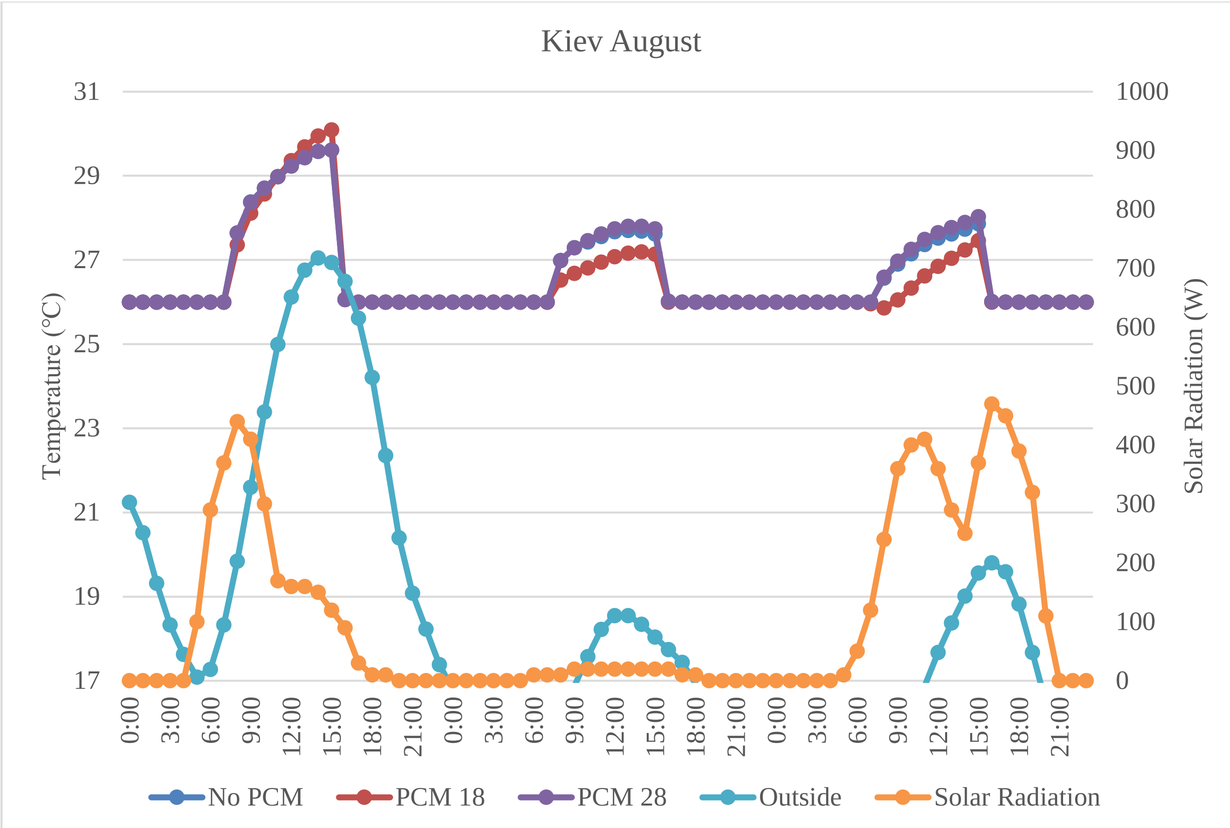


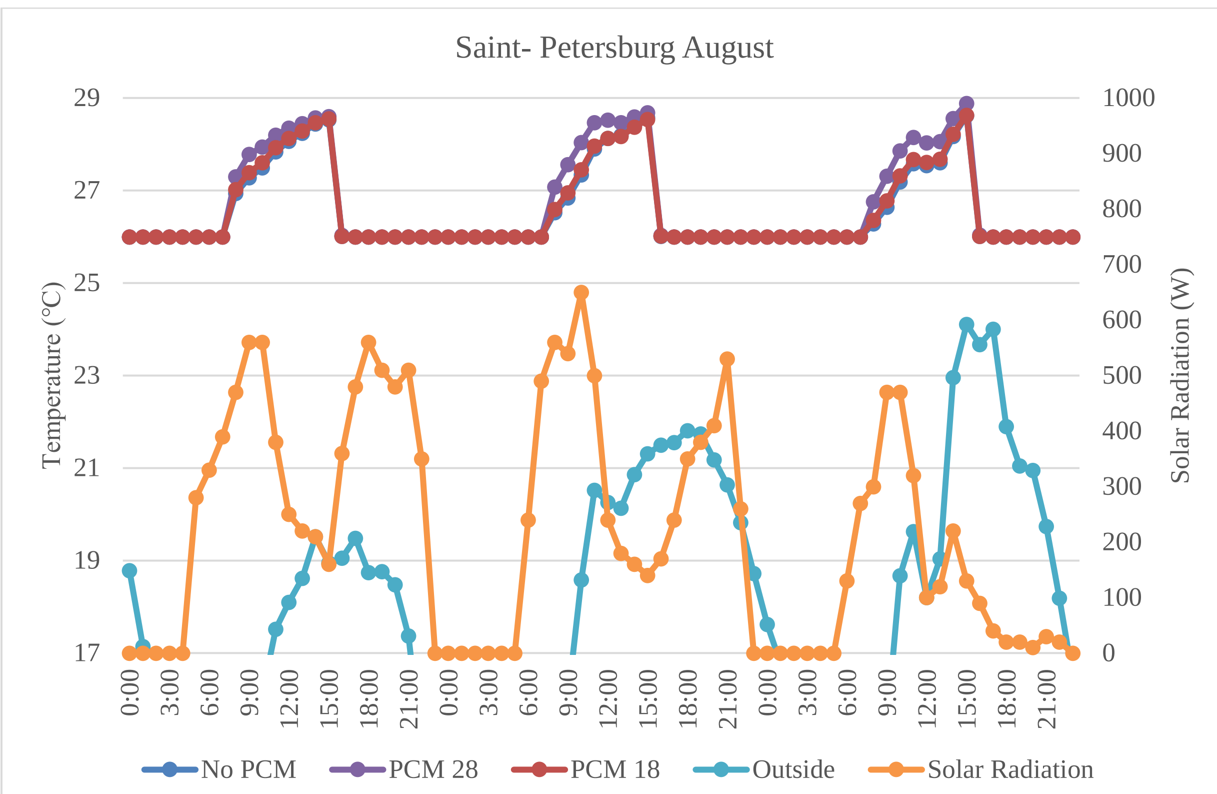
Figure 4.2. Temperature profiles for all cities in months with the highest energy savings.

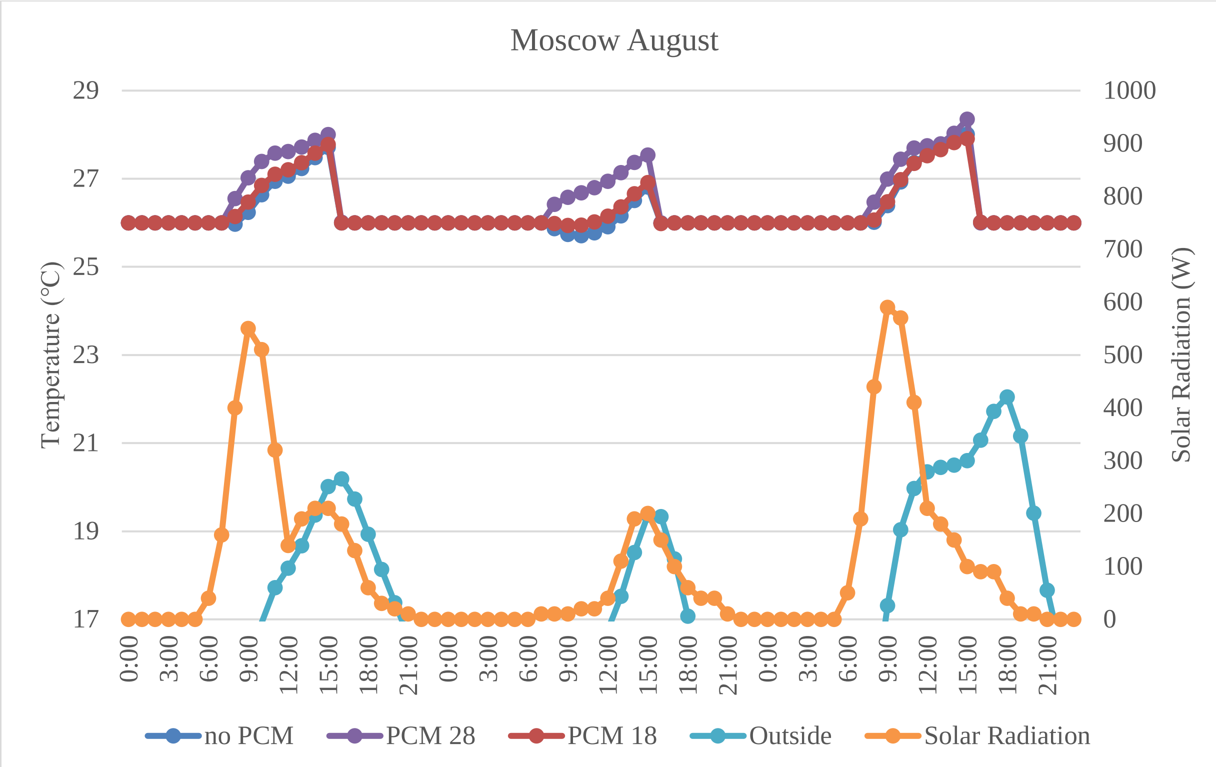
The months with the minimum energy savings devoted to June, July and August. According to monthly assessment, the inefficient PCMs for Helsinki, Kiev, Saint-Petersburg, Moscow, Stockholm, Toronto, Montreal and Ottawa in these months were represented by PCM 28-27 while the stable results shown by low-melting temperature PCMs 18-21. For the detailed explanation, the plot of temperature profile of PCM 28, PCM 18 and without PCM case along with solar radiation and outside temperature in Saint-Petersburg was chosen (see Figure 4.3). During the sunshine hours, the maximum peak temperature reached by internal environment of building incorporated with PCM28 is 28.88℃ combined with outside temperature 24.11℃ and 220 W/m^2 of solar radiation. Despite the absorbance of the heat during the sunshine, the temperature profile of PCM28 are on the higher side than temperature profile without PCM. The reason for that during the sunshine a PCM28 will depend upon extra energy for added insulation layer. Further, during the nighttime, where outside temperature substantially drops, PCM 28 is incapable to execute the phase change cycle completely. Further, these actions proceed to in added demand of energy and lowered the efficiency of PCM28. The temperature profile of PCM18 have similar pattern to temperature profile without PCM. The reason for that can be explained by low value of temperature necessary for solidification of PCM18 - 16℃, which deactivates ability of PCM to complete the phase change cycle.

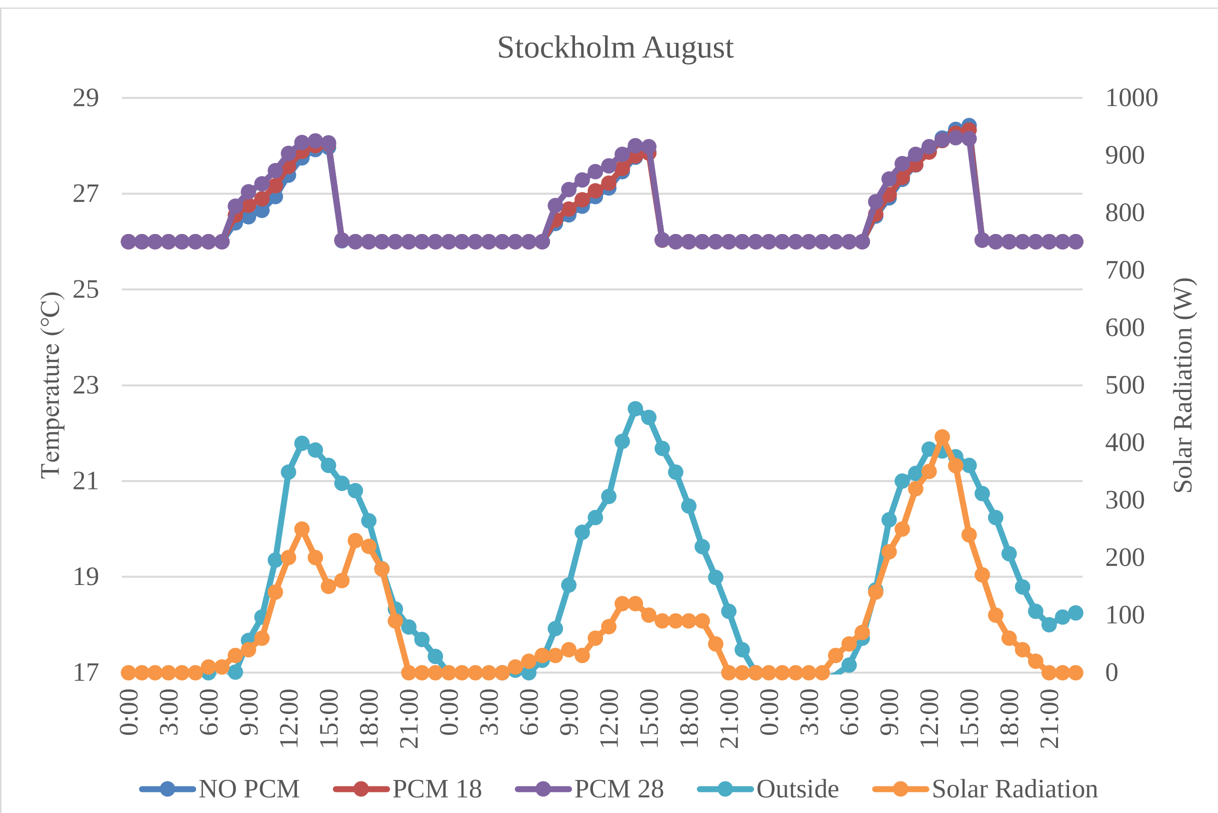
The similar trend can be seen to other temperature profiles where minimum energy savings were achieved and are illustrated in Figure 4.3.The maximum temperature for the residential house without PCM located in Helsinki, Kiev, Saint-Petersburg, Moscow, Stockholm, Toronto, Montreal and Ottawa were found to be up to 30.04ºC while the associated with optimum PCMs in these cities reached to 30.41ºC.

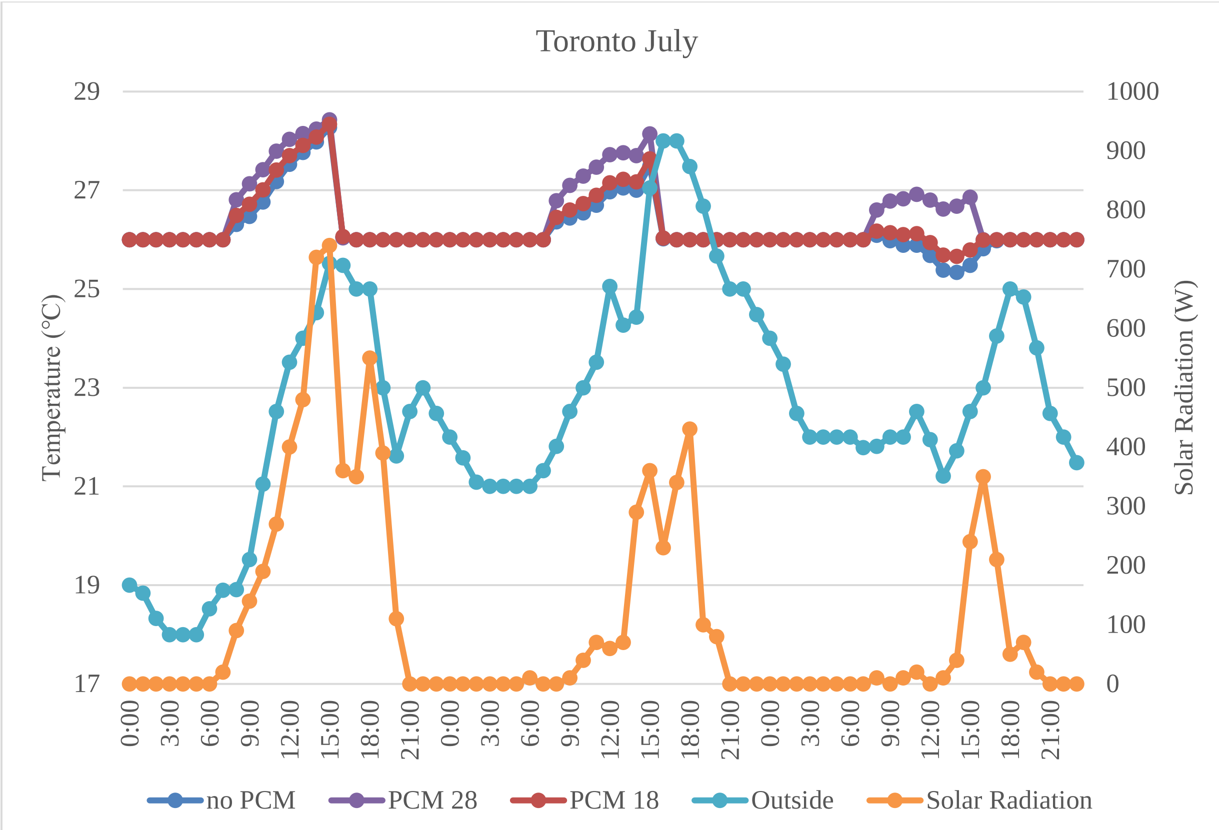


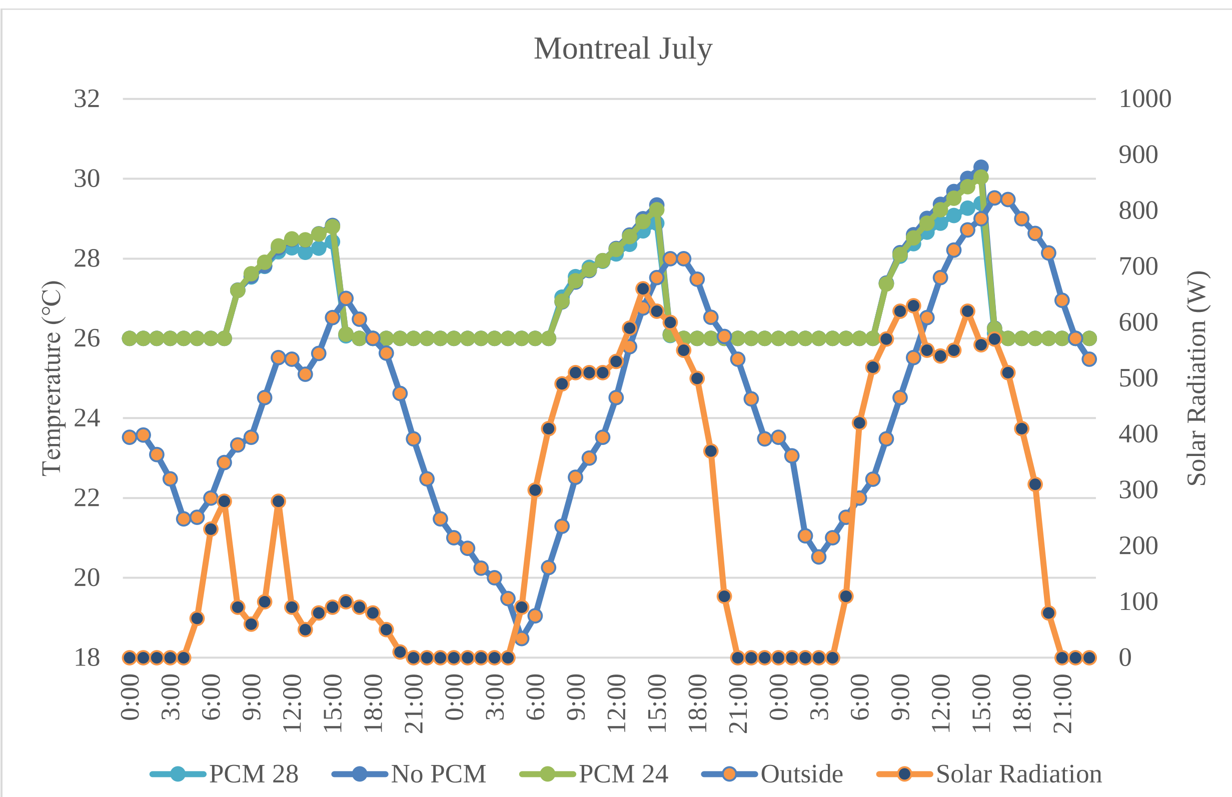

Kiev August
Temperature (°C)
Solar Radiation (W)
31
29
27
25
23
21
19
17
1000
900
800
700
600
500
400
300
200
100
0
0:00
3:00
6:00
9:00
12:00
15:00
18:00
21:00
No PCM
PCM 18
PCM 28
Outside
Solar Radiation


Saint- Petersburg August
Temperature (°C)
Solar Radiation (W)
29
27
25
23
21
19
17
1000
900
800
700
600
500
400
300
200
100
0
0:00
3:00
6:00
9:00
12:00
15:00
18:00
21:00
No PCM
PCM 28
PCM 18
Outside
Solar Radiation


Moscow August
Temperature (°C)
Solar Radiation (W)
29
27
25
23
21
19
17
1000
900
800
700
600
500
400
300
200
100
0
0:00
3:00
6:00
9:00
12:00
15:00
18:00
21:00
no PCM
PCM 28
PCM 18
Outside
Solar Radiation


Stockholm August
Temperature (°C)
Solar Radiation (W)
29
27
25
23
21
19
17
1000
900
800
700
600
500
400
300
200
100
0
0:00
3:00
6:00
9:00
12:00
15:00
18:00
21:00
NO PCM
PCM 18
PCM 28
Outside
Solar Radiation


Toronto July
Temperature (°C)
Solar Radiation (W)
29
27
25
23
21
19
17
1000
900
800
700
600
500
400
300
200
100
0
0:00
3:00
6:00
9:00
12:00
15:00
18:00
21:00
no PCM
PCM 28
PCM 18
Outside
Solar Radiation


Montreal July
Temperature (°C)
Solar Radiation (W)
32
30
28
26
24
22
20
18
1000
900
800
700
600
500
400
300
200
100
0
0:00
3:00
6:00
9:00
12:00
15:00
18:00
21:00
PCM 28
No PCM
PCM 24
Outside
Solar Radiation

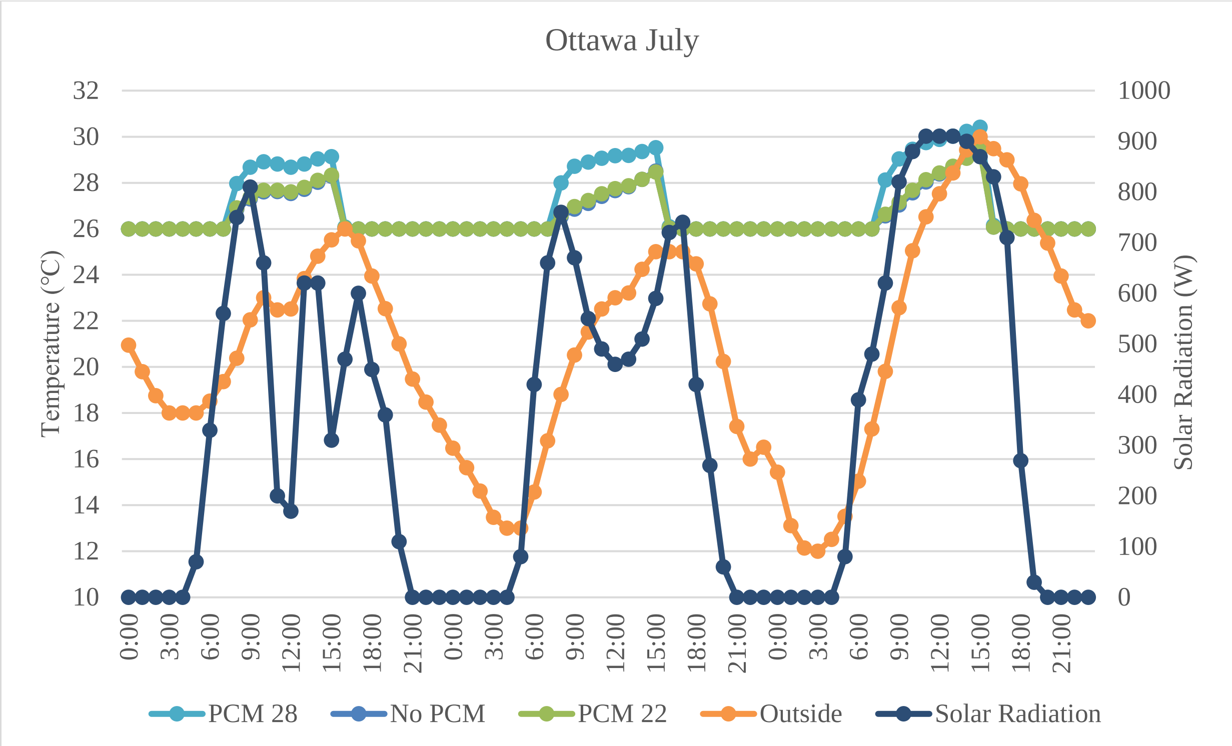


Figure 4.3. Temperature profiles for all cities in months with the lowest energy savings.

4.3. Annual Results

In this part, the annual assessment of energy savings including both heating and cooling demands are described. Table 4.1 indicates the total consumption including both heating and cooling demands for with and without PCM incorporated buildings for each indicated city. Furthermore, Table 4.1 provides the detailed information according to the annual energy savings considering the optimal PCM. It can be clearly seen, that the Dfb-climate region can be either heating or cooling dominant zone. The reason for that can be variance of energy consumption between heating and cooling. The heating consumption ranged from 2681 to 4470 kWh, while the cooling consumption ranged from 2617 kWh to 4079 kWh. The heating demand dominant cities includes Helsinki, Saint-Petersburg, Moscow, Montreal and Ottawa while cooling demand dominant cities are Kiev, Stockholm and Toronto.

Figure 4.4 indicates total energy savings considering both heating and cooling saving of the optimum PCM which were incorporated into the reference building for each city. The bullets on the colored graphs described the heating and cooling energy savings in each indicated city located in Dfb climate. The bars represented the optimum melting operating temperature for each city where PCM was incorporated. Marin et al.[45] suggests that the wide range of optimum can be explained through the strong correlation between heating and cooling energy requirements. However, the results of energy savings indicates the different pattern. The reason for that is dependent on the varying performance of PCM in Dfb-climate zone during the year. According to the monthly assessment, the PCM in Dfb climate working well only in April, May, September and October while in other months it saving energy partially. Thus, the patterns of energy savings strongly depends on the potential PCM in these months and stable results during the remaining months. Thus, in Kiev and Stockholm the low-melting temperature PCM 21 showed good performance, whether the high-melting temperature PCMs (24-26) are on the higher side for Helsinki, Saint-Petersburg, Moscow, Toronto and Montreal. For the Ottawa, both heating and cooling savings are similar and thus, the mild-melting temperature PCMs 22 pattern are on the higher side. The results in Montreal, Moscow and Stockholm for optimum melting temperature are in line with Saffari et al. [6]. The authors referred that for mentioned cities the optimum PCMs for both heating and cooling demands are PCMs 25.44°C, 24.31°C and 21.5°C respectively. Based on above discussion, it can be concluded that although the eight cities are located in one climate zone (Dfb) the optimum PCM-drywall differs for each city.

Table 4.1. Annual consumption and energy savings for the with and without PCM incorporated two-storey building for Dfb-climate region with optimum PCM melting temperature

Annual Energy Consumed (kWh yr)		Helsinki	Kiev	Saint-Petersburg	Moscow	Stockholm	Toronto	Montreal	Ottawa
Heating	Ref	3707,5	2680,68	4469,07	4180,69	2835,87	3361,97	3960,99	4424,35
	PCM	3647,43	2459,23	4408,21	4120,51	2602,48	3265,65	3905,92	4329,97
	Savings	60,07	221,45	60,86	60,18	233,39	96,32	55,07	94,38
Cooling	Ref	2674,24	4079,67	2901,21	3212,42	3014,86	3467,72	2617,14	2582,5
	PCM	2459,47	4014,57	2643,53	3004,63	2934,27	3172,97	2287,19	2480,33
	Savings	214,77	65,1	257,68	207,79	80,59	294,75	329,95	102,17
Total	Ref	6381,74	6760,35	7370,28	7393,11	5850,73	6829,69	6578,13	7006,85
	PCM	6106,9	6473,8	7051,74	7125,14	5536,75	6438,62	6193,11	6810,3
	Savings	274,84	286,55	318,54	267,97	313,98	391,07	385,02	196,55

Total Energy Consumption Reduction (ECR)	4,31%	4,24%	4,32%	3,62%	5,36%	5,72%	5,85%	2,81%
Optimum PCM melting temperature	26℃	21℃	25℃	25℃	21℃	24℃	26℃	22℃

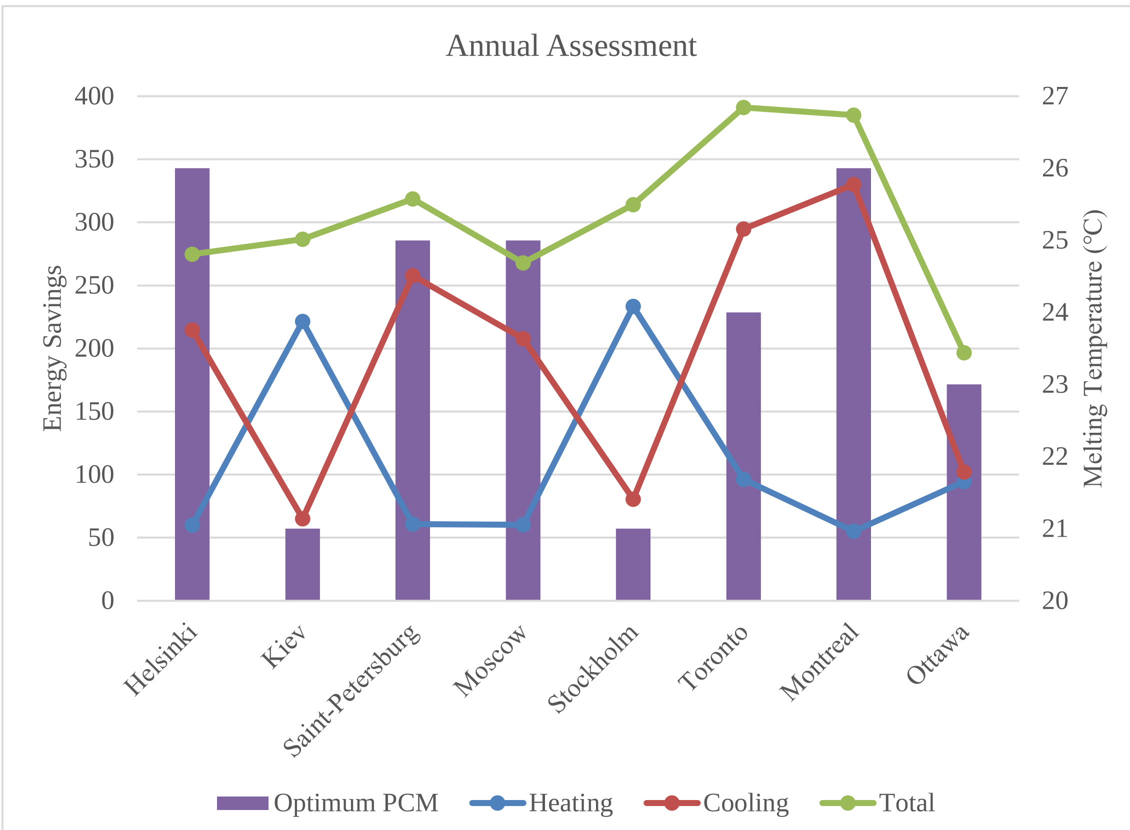


Figure 4.4 Annual heating, cooling and total savings for each city indicated with optimum PCM melting temperature

The outcome of total annual energy saving along with energy consumption reduction (ECR) calculated by Eq. 8 for identification cities are shown in Table 4.1.

$$\mathrm{ECR} = \frac{\mathrm{EC\ (no\ PCM)} - \mathrm{EC\ (PCM)}}{\mathrm{EC\ (no\ PCM)}} x100\% \quad (8)$$

The Table 4.1 describes that more energy required to fulfill heating requirement rather than cooling. That behavior can be expressed by the type of climate: humid continental climate with at least 4 month with average temperature 10oC. For three cities considered in Humid continental climate zone, Saffari et al. [6] found that PCM was slightly effective in reducing both heating and cooling demand. In another study presented by Soares et al.[42], the results showed the slightly efficiency in cooling and heating energy reduction in Warsaw. The output presented in Table 4.1 supports the external findings by the results with PCM integrated building required approximately 5% less energy. Overall, the results of integration PCM-drywalls in house framework is effective approach for maintenance the energy efficiency of buildings.

4.4. Thickness Comparison

In this section, the thickness comparison was performed by applying optimum PCM for each city. For impact evaluation, energy consumption reduction per mm indicator varying from 10 mm to 40 mm were considered. For description purpose, only the results of two cities, namely Saint-Petersburg and Kiev are presented at Table 4 and Figure 9. Despite the increasing energy savings through the increasing thickness of PCM-drywall, the efficiency per mm of the PCM-drywall is decreased which indicates the improvement of the efficiency and financial side for thin PCM-drywalls The findings are in line with Lei et. al [44] research where the PCM-drywalls placed interior and exterior were evaluated from 3 to 20 mm. By looking at the Energy Consumption reduction per mm indicator, the PCM with thickness of 10 mm is the most optimum option. It is pertinent to mention here that for all other cities, the efficiency of 10mm thick PCM layer was found to be optimum.

Table 4.2. Energy savings as a function of PCM thickness

City	Thickness (mm)	ES, KWh	ECR,%	ECR per mm, %/mm
Saint-Petersburg	10 mm	318,51	4,32	0,432
	15 mm	367,05	4,98	0,332
	20 mm	408,67	5,54	0,277
	25 mm	431,11	5,85	0,234
	30 mm	509,96	6,92	0,231
	35 mm	564,57	7,66	0,219
	40 mm	618,86	8,40	0,210
Kiev	10 mm	243,72	3,61	0,361
	15 mm	295,29	4,37	0,291
	20 mm	321,29	4,75	0,238
	25 mm	351,66	5,20	0,208
	30 mm	382,98	5,67	0,189

	35 mm	418,27	6,19	0,177
	40 mm	450,2	6,66	0,166

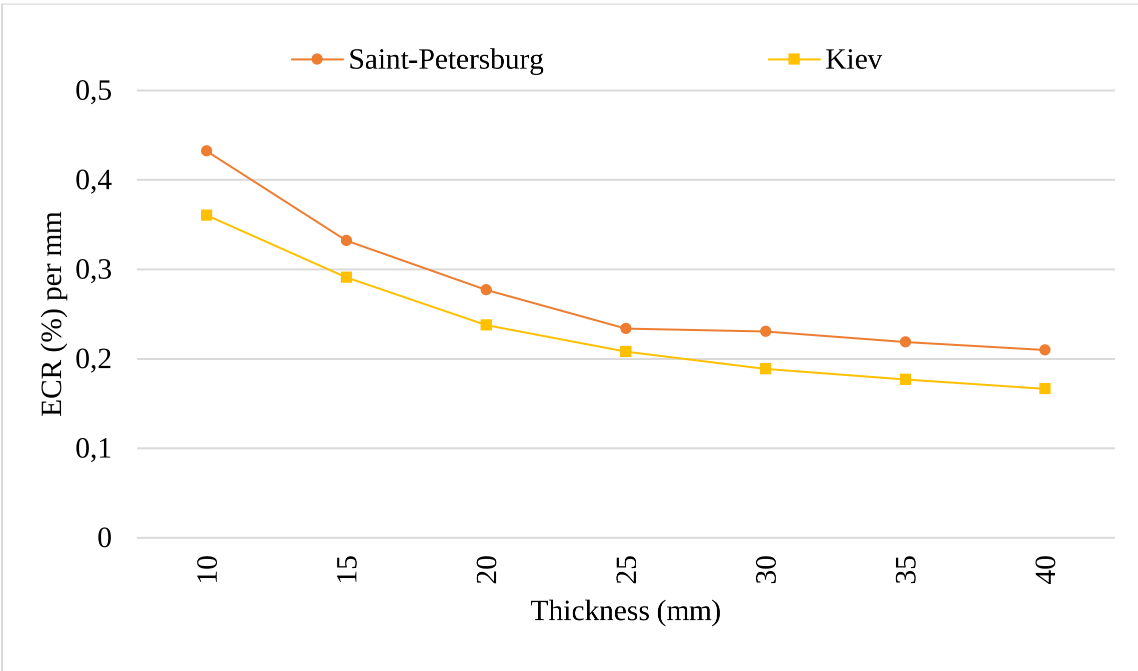


Figure 4.4. Thickness Comparison of Saint-Petersburg and Kiev

4.5 PCM Volumetric Assessment

In this particular section, the influence of volumetric assessment to energy savings by applying different thickness and surface area. The description regarding location can be found on Table 4.5. For the comparison of energy savings potential , the volumetric parameter of PCM-drywall integrated was kept constant. The surface area was determined by the framework of each location investigated whether the thickness of PCM-drywall is derived through dividing the constant volume to surface area of examined location.

Table 4.3. Volumetric Assessment of PCM-drywall with constant volume of 3.5 m^3 (Helsinki)

Place Integration	Area (m^2)	Thickness (mm)	Energy Consumption (kWh)	Energy Savings (%)
Reference house	0	0	6381,74	0
Roof	116,45	30,06	6211,36	2,670
West Wall	53,72	65,16	6239,03	2,236
North Wall	63,09	55,49	6269,95	1,752
All Walls	233,63	14,98	6173,56	3,262
All Walls and Roof	350,08	10,00	6106,9	4,307

Figure 4.5 illustrates the dependence of energy savings to parameters: energy savings increased during maximization of surface area and minimization of PCM-drywall thickness. Such behavior can be expressed through the growth of heat transfer rate between PCM and living zone combined with improved transition process inside the PCM-drywall during the expansion of surface area and reduction in thickness respectively [38]. However, the Figure 4.5 also highlights the higher energy savings for west wall comparing to the north although the dominance in the surface area and PCM-drywall thickness characteristics for north wall. The reason

for that might be the placement of the wall respect to the sun movement through the day [38]. Overall, the optimum solution will be enhancement 10 mm PCM-drywall inside all walls and roof of two storey residential building.

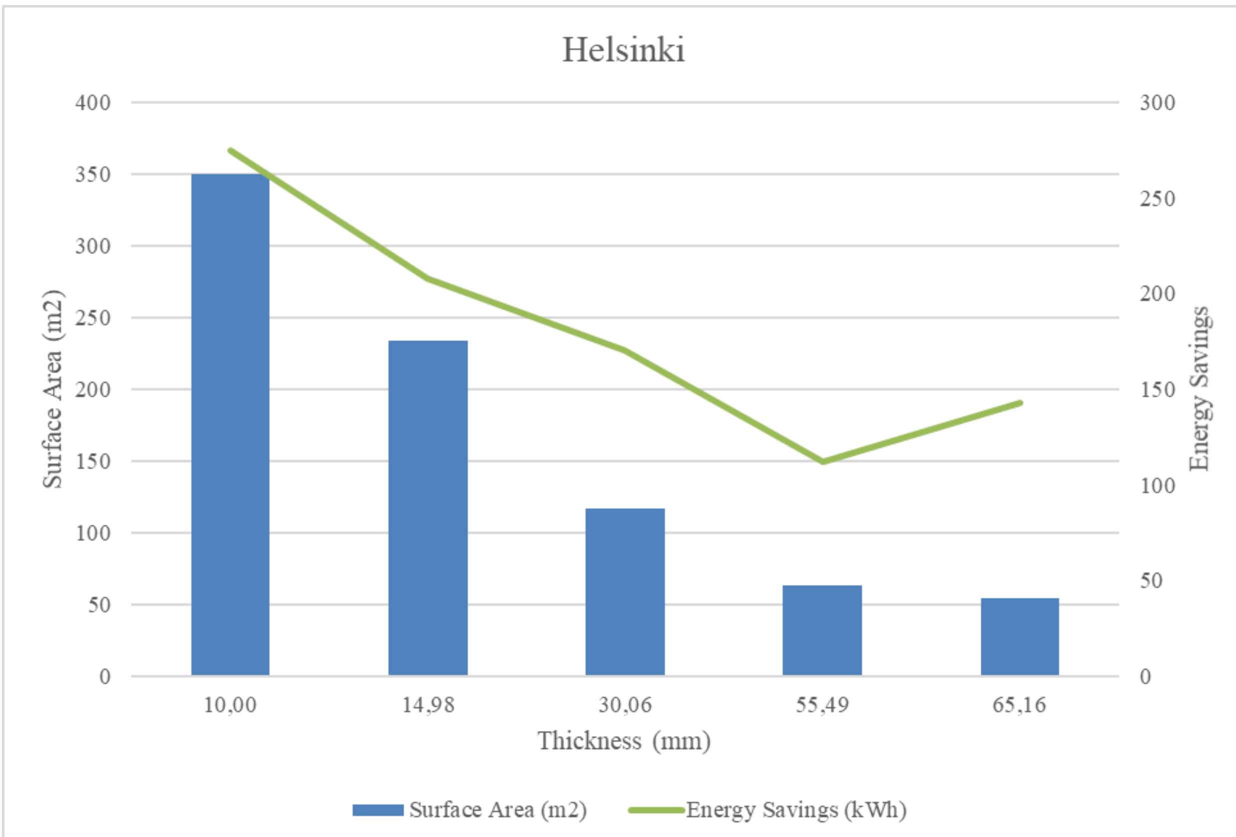


Figure 4.5. Surface Area and Thickness Assessment

Chapter 5 – Conclusion

The main conclusions are as follows.

- For all eight cities, the maximum monthly energy savings in two-storey residential house enhanced with PCM were achieved in April, May, September and October months. The maximum energy savings during mentioned months were up to 142 kWh. During these months, the maximum temperature in PCM integrated buildings located in these cities reduced by up to 2.21^{o}C suggesting that part of the heating load has been taken by the PCM.
- For the June, July and August, the temperature profiles indicates that high melting temperature PCMs are inefficient in terms of energy savings. However, still PCM integrated residential building was able to reduce the temperature fluctuation by up to 0.48^{o}C and hence it makes comfortable living conditions inside the building.
- The optimum PCM for Kiev and Stockholm are low-melting temperature PCM 21. For the Helsinki, Saint-Petersburg, Moscow, Toronto and Montreal the results of high melting temperature PCMs (24-26) are on the higher side. For the Ottawa, where heating and cooling savings are similar, the mild-melting temperature PCM 22 on the maximum. The reason for that

represented by potential of PCM to perform phase change cycle in April, May, September and October, and low results for the remaining months.

- The energy savings ranges from 196.55 to 391.07 kWh while ECR ranged from to 2.81 to 5,72 %. Results described the PCM integration into house framework is an effective approach for improving the energy efficiency of buildings.
- For all cities, the optimum thickness of PCM layer incorporated in walls and roof of residential house was found to be 10 mm. For constant volume, it was found that the PCM efficiency depends upon the increase in the surface area and reduces with the increase in the thickness of PCM layer.

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