TALLINN UNIVERSITY OF TECHNOLOGY
FACULTY OF CHEMICAL AND MATERIALS TECHNOLOGY
DEPARTMENT OF MATERIALS SCIENCE

SEASONAL HEAT STORAGE IN NORTHERN EUROPEAN BUILDINGS. SELECTION OF THE THERMAL STORAGE MEDIA AND THE OPTIMIZATION OF THE SYSTEM DESIGN BASED ON ESTONIAN CLIMATE.

Master Thesis

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Materials and Processes of Sustainable Energetics
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Declaration

Hereby I declare that this master thesis, my original investigation and achievement, submitted for the master degree at Tallinn University of Technology has not been submitted for any degree or examination.

Rosalio Rubio Alvarado

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Hooajaline päikeseenergia salvestamine faasiüleminekuga materjalides. Materjalide valik ning süsteemi optimeerimine Eesti kliimas.

Magistritöö

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Materjalid ja protsessid jätkusuutlikus energeetikas
2015

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Abbreviations and Acronyms

Symbol	Description	SI Unit
A	Solar collector efficiency constant	$W/m^2{}^\circ C$
A_{tank}	Surface area of storage tank	m^2
B	Solar collector efficiency constant	$W/m^2{}^\circ C^2$
C_{pHTF}	Specific heat capacity of heat transfer fluid	$J/kg{}^\circ C$
C_{psolid}	Specific heat capacity of phase change material at solid phase	$J/kg{}^\circ C$
D_p	Pipe outer diameter	m
D_t	Pipe total diameter with insulation	m
G	Solar radiation	W/m^2
k_p	Thermal conductivity of pipe insulation	$W/m{}^\circ C$
k_t	Thermal conductivity of tank insulation	$W/m{}^\circ C$
M_{solid}	Mass of phase change material at solid phase	kg
P_{coll}	Power collected from thermal panel	W
P_{pl}	Power loss from the pipes to the environment	W/m
$P_{tank\,loss}$	Power loss from the storage tank to the enviroment	W
Q_{HTF}	Power of the heat transfer fluid inside of storage tank	W
$Q_{insolation}$	Total insolation available for area of the thermal collectors	kWh
Q_{store}	Energy store with phase change materials	J
Q_{tank}	Energy of storage tank	J
$Q_{tank\,del}$	Energy deliver to storage tank	J
$Q_{\lambda PCM}$	Store latent heat energy	kWh
t_i	Thickness of tank insulation	m
T_a	Ambient temperature	${}^\circ C$
T_p	Pipe temperature	${}^\circ C$
T_{avg}	Average temperature of HTF in collector	${}^\circ C$
T_m	Melting temperature of phase change material	${}^\circ C$
T_{room}	Room temperature	${}^\circ C$
T_{1tank}	Initial temperature of storage tank	${}^\circ C$
T_{2tank}	Final temperature of storage tank	${}^\circ C$
T_1	Inlet temperature of thermal panel	${}^\circ C$
T_2	Outlet temperature of thermal panel	${}^\circ C$
T_3	Inlet temperature of storage tank	${}^\circ C$
T_4	Outlet temperature of storage tank	${}^\circ C$
U	Tank loss coefficient	$W/m^2{}^\circ C$
$\dot{m}_{HTF}$	Mass flow rate of heat transfer fluid	kg/s
η_{coll}	Efficiency of thermal panel	
η_{opt}	Optical efficiency of collector	
η_{sys}	Efficiency of thermal storage system	
λ_{PCM}	Latent heat of phase transition	J/kg
$\rho_{L\,PCM}$	Liquid density of phase change material	kg/m^3
PCMs	Phase change materials	
HTF	Heat transfer fluid	

1. INTRODUCTION

Energy is one of the most important topics discussed on national and international political levels. Perhaps the most important aspect of energy is related to security, since without steady and secure supply of energy, countries cannot advance with its production of goods and services. Paradoxically, European Union imports more then half of all the crude oil and natural gas it uses, making it the biggest import it consumes [1].

As a result, European Union has implemented a number of targets related to renewable energy production, storage and conservation. Its aim is to reduce the consumption of energy while decreasing the dependence on the energy it imports. One of the European Union's targets is well known as "20-20-20", which describes the aspired goals for European members to achieve by the year 2020. The goals are described as follows: a reduction in European Union greenhouse gas emissions of at least 20% by 2020, increasing the contribution of renewable energy to 20% by 2020 and improving the European Union energy efficiency by 20% by 2020 [2].

Another projection of energy management for the European Union members was done by the European commission titled Energy Roadmap 2050. In it are goals set for the European members, indicating the augmentation of renewable energy production by at least 55% of gross energy consumption by 2050 in all scenarios. In addition, the European commission stresses the importance of energy storage technologies in order to achieve the increase in renewable energy production by 2050 [3]. Therefore, in order to compensate for the fluctuations in energy production from renewable sources, energy storage systems must be implemented.

Estonia is part of the European Union and therefore must comply with all the mandates and projections drafted by the European Union. Estonia is a country with fairly high levels of energy utilization. In fact, the share of Estonian house hold energy consumption is one of the largest in the European Union. According to the data compiled in 2010, the share of household energy consumption in total was 27% in Europe and 35% in Estonia [4].

Estonia is located in the Northern Europe and has intense climate conditions. Estonia has lengthy winters with extreme temperature conditions that can reach down to -40 ˚C. In contrast, during the summer, the ambient temperature can reach up to +35 ˚C. Under these conditions it is clear that Estonian buildings need substantial amount of heating energy during winter. The annual solar resource in Estonia is about 1100 kWh/m^2 on optimally inclined surfaces. The biggest challenge in utilizing this energy comes from the very uneven distribution of the irradiation during the year. The average insolation on optimally inclined surface during the three darkest winter months is 20 kWh/m^2 per month. In contrast, the same number for the three summer months is 170 kWh/m^2 per month. In summary, the solar energy is least plentiful when it is needed the most. To overcome the phase shift between the heating demand and the solar energy supply, seasonal energy storage is required. Furthermore, increasing the renewable energy sharing in buildings where it utilizes most of its energy would help Estonia meet its European Union energy targets.

This thesis paper investigates the potential of phase change materials (PMCs) used for the seasonal thermal storage in northern European buildings. It discusses the storage system design and the selection of storage medium for a micro-scale thermal storage system under Estonian weather conditions. In addition, this thesis provides cost analysis of the thermal storage system.

2.1 Solar Thermal Technologies

The selection of solar harvesting technology is important to the operational behavior of the thermal storage system. The major types of solar thermal collector technologies are classified as tracking thermal collectors and stationary thermal collectors. These technologies are suitable for thermal energy storage systems. Solar thermal technologies have certain advantages and disadvantages when they are considered for specific applications.

The main tracking thermal technologies are parabolic trough collectors, parabolic dish collectors and central receiver collectors. The fundamental principle of the tracking technologies is to reduce the area from which the heat loss could occur. Some of the advantages of tracking thermal collectors are higher fluid temperatures that could be used for high temperature applications. The disadvantages of solar thermal tracking technologies include high initial cost. In addition, the installation of tracking technologies requires large areas and constant maintenance. The main disadvantage of tracking technologies, however, is that they collect little diffuse radiation [5].

2.1.1 Tracking solar thermal collectors

Parabolic trough is one of the most common solar thermal tracking technologies currently employed. The temperature for this technology ranges from 120 to 400°C. With this temperature array, parabolic trough technology is used for different types of high temperature applications. One common application for the trough technology is the production of electricity. Another application is the production of heat energy for industries that require heating or cooling to manufacturing goods.

Figure 1 shows the parabolic trough technology, which consists of a parabolic shape structure composed of reflectors that project the solar radiation into an absorber tube. The tube contains a heat transfer fluid that circulates trough the system, collecting heat from the reflected solar radiation. The trough collector is equipped with one-axis solar tracking system to ensure that the solar beam radiation falls parallel to the axis of the system [6].
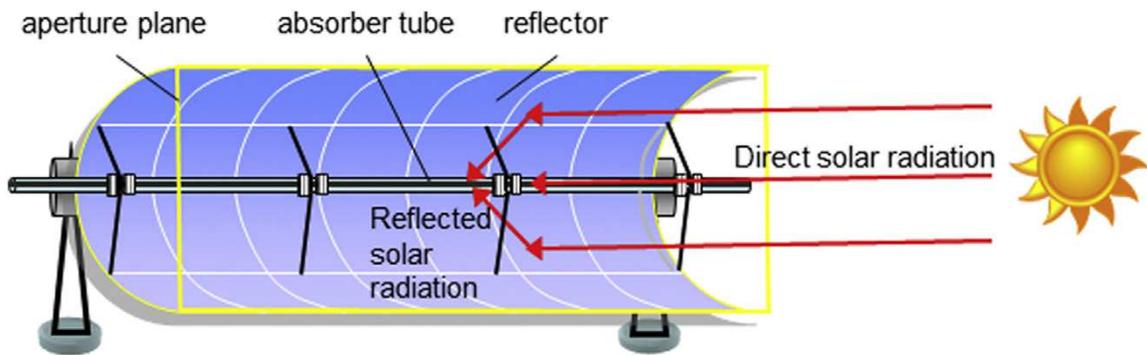
Figure. 1. Illustrates how the solar radiation gets reflected into the absorber tube and lists the main components of the parabolic trough technology [6].

Parabolic dish technology has the shape of a satellite with reflecting mirrors all around the surface of the dish. The mirrors reflect the sunlight into the focal point of the parabolic dish, which is located at the center tip of the dish. The location of the focal point depends on the specific design of the technology. Figure 2 illustrates the parabolic dish technology. The parabolic dish focal point can reach temperatures greater than 700˚C. The dish technology functions with two-axis tracking system to follow the movement of the sun. The dish technology operates with a heat engine that converts heat energy into electrical energy. The location of the heat engine is at the focal point of the technology.

Stirling engine is commonly used with parabolic dish technologies to convert the heat energy into electrical energy. However, dish technologies are very expensive and require constant maintenance to ensure appropriate energy conversion. Accordingly, due to the high cost and maintenance, dish technologies are generally used in solar farms for applications where high temperatures necessitate high demand for electrical energy [7].
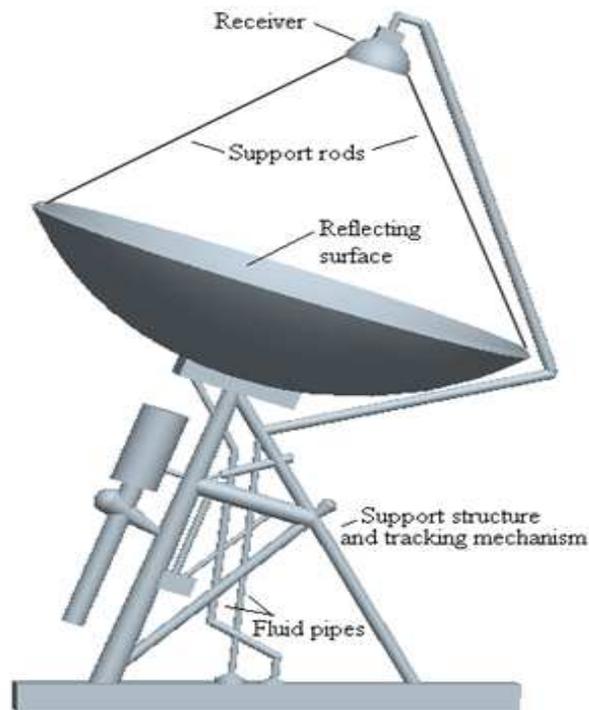
Figure. 2. Shows the main components and location of the receiver of the parabolic dish technology [8].

Central receiver collector technology makes use of a semicircular array of large mirrors that are controlled with a double tracking system to capture sunlight. The sunlight is then reflected to the central receiver, located at the top of a tower, at the center of the mirror farm. The central receiver collector technology is depicted in Figure 3. This technology uses heat transfer fluid to transfer the heat energy collected from the receiver to a storage tank, where steam is generated to power a turbine which produces electrical energy.

The central receiver technology can achieve temperatures greater than 1000˚C, enhancing efficiency of the power conversion system. This technology can be integrated in fossil power plants for hybrid operation [9]. Central receiver technology is used to produce great amounts of electrical power and therefore requires a large area for installation. This technology however is not cost effective for small applications.
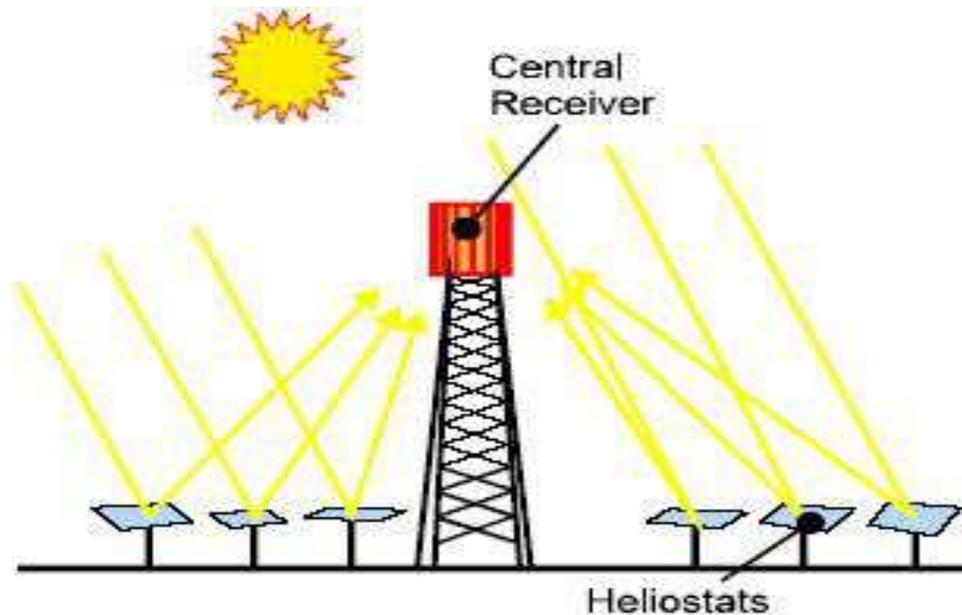
Figure. 3. Illustrates the main components of the central receiver technology and how the reflectors at the bottom of the tower redirect the sunlight to the receiver [10].

2.1.2 Stationary Solar Thermal Collectors

Stationary solar thermal collector technology is used for projects where a required temperature range is between 60 to 200˚C. This particular technology is capable of harvesting both direct and diffused radiation. This technology is usually installed at different angles depending on location in order to harvest the maximum solar radiation during the year. Stationary thermal solar collectors require minimum maintenance during the life time of the technology. The most widely available technologies include flat plate thermal solar collector and evacuated thermal solar collector. Both of these technologies require heat transfer fluid to convert sunlight into heat energy. In tropical conditions, the most common heat transfer fluid used is water, but locations where freezing temperatures occur, a mixture of antifreeze and water is used.

The basic flat plate solar thermal collector design is shown in Figure 4. It consists of a metal absorber in a flat rectangular casing, attached to a glass cover, on the top part of the casing. The bottom part of the casing has a cover of insulation to prevent heat loss to the environment. The metal absorber works as a heat exchanger that absorbs solar radiation. The solar radiation is then converted into heat and transferred to the heat transfer fluid circulating in the flat plate collector. Air is present between the metal absorber and the glass cover of the collector.

The temperature range for flat thermal collectors is between 30 to 80˚C, depending on environmental conditions. There are different types of flat plate collector designs with different performance rates. The flat plate collector is mainly used for water heating applications where high temperatures are not required. Furthermore, flat plate collectors can be used for direct heating in areas where it is needed.

Flat plate technology can be installed on a roof of a building or can be free standing [11].
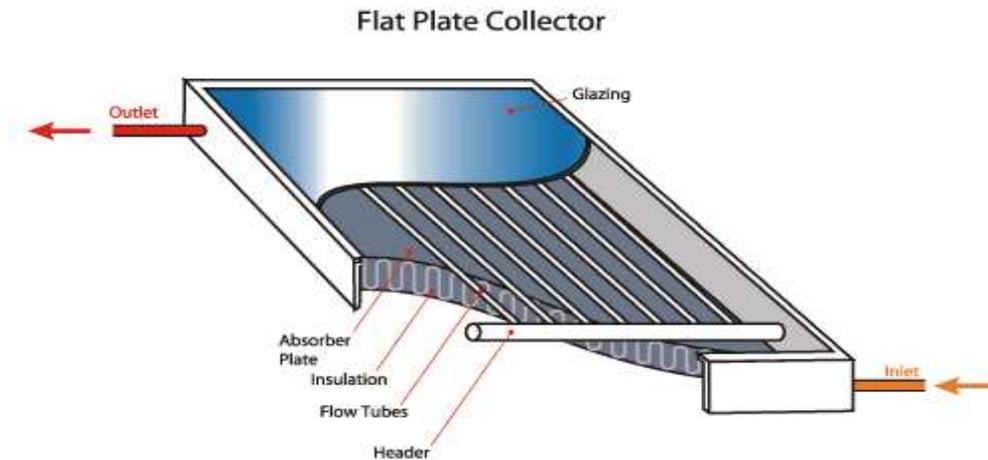

Figure. 4. Shows the main components of the flat plate collector technology and how it is assembled [12].

Evacuated solar thermal collectors consist of a heat pipe inside a vacuum sealed tube. The vacuum tube is coated with absorber material. The absorber coating is designed to take full advantage of the solar irradiance. Energy from the solar irradiance then passes through absorber material and gets transmitted to heat transfer fluid [13]. The vacuum reduces convection and conduction losses, so the collectors can operate at higher temperatures. The temperature range for evacuated thermal collector is between 50 and 200˚C, depending on location. There are two main types of evacuated thermal collectors: direct flow and heat pipe. Direct flow collectors have the same design principle as mentioned above, differing from the heat pipe collectors by having transfer fluid circulating through evacuated pipes.

The heat pipe evacuated collector shown in Figure 5 consists of a vacuum sealed tube. Small quantity of liquid inside of the tube acts as heat transfer medium that undergoes a change of state to transfer the heat collected from the solar irradiance. The main advantage of heat pipe technology is that the connections between the pipes and the heat exchanger are dry, which permits the exchange of pipes without complications. The evacuated solar thermal collectors have the same applications as the flat plate collectors, but the evacuated technology is capable of producing heat energy with low levels of solar irradiance [14].
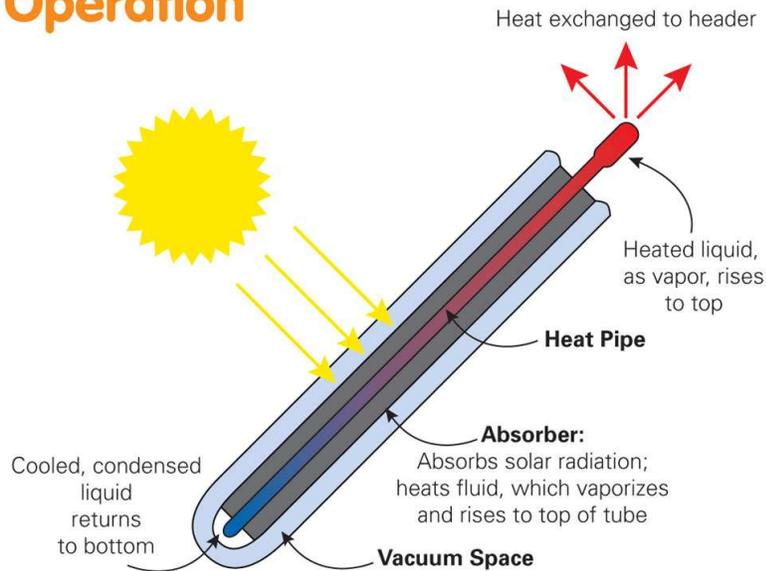
Figure. 5. Shows the components and how the system inside of the heat pipe works to deliver heat energy to the tip of the heat pipe [15].

2.1.3 Selection of Harvesting Technology

For residential applications the harvesting technology has to be able to perform without constant supervision. To ensure that the selection of the harvesting technology is appropriate for the Estonian weather conditions, one must take into consideration the following criteria:

- Ability to harvest direct and diffused radiation
- Low maintenance during life time of the technology
- Low heat losses to the environment
- Operation temperature between 30 to 200˚C
- Minimum number of moving parts
- Use minimal area for installation

2.2 Selection of the Storage Media

Thermal energy can be stored in many different ways as depicted in Figure 6. Thermal chemical storage will not be discussed in this paper; however this mode of energy storage has great potential for future development of storage technologies. Thermal energy can be defined as change in internal energy of a material. There are two types of thermal energy storage: sensible heat storage and latent heat storage. Sensible heat storage is possible by raising the temperature of a liquid or solid. Sensible heat system uses heat capacity and change of temperature of the material during the process of storing thermal energy. The quantity of thermal energy stored depends on specific heat of the medium. The most common materials used for sensible thermal energy storage are rocks, concrete and water. Water is the best material for sensible thermal energy storage due to its high specific heat capacity.

Latent heat thermal storage depends on heat accumulation when a material undergoes a phase change from liquid to liquid or liquid to gas or solid to liquid [16].
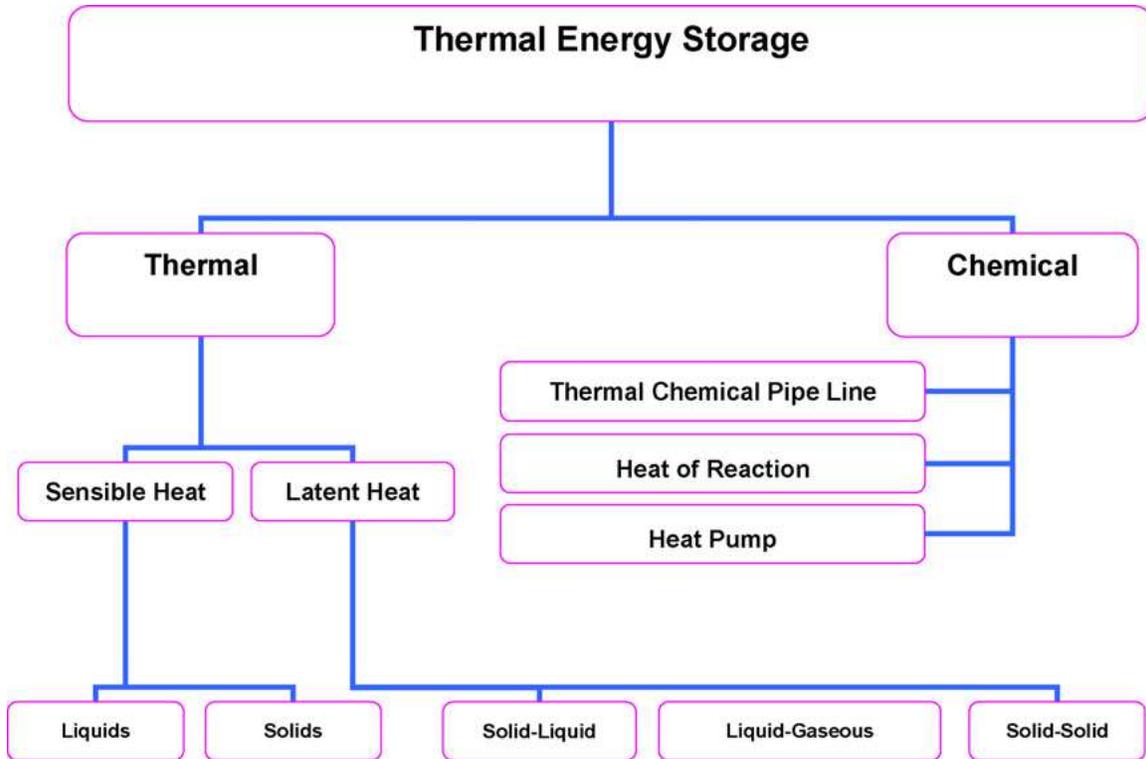
Figure. 6. Illustrates the different types of solar thermal energy storage [16].

2.2.1 PCM Criteria

A phase-change material (PCM) is a substance with a high heat of fusion. When melting and solidifying at a certain temperature, it is capable of storing and releasing large amounts of energy as depicted in Figure 7. For this particular investigation when the material melts, it absorbs energy as a form of heat. Consequently, when the material temperature decreases, the energy gets emitted into the surroundings.
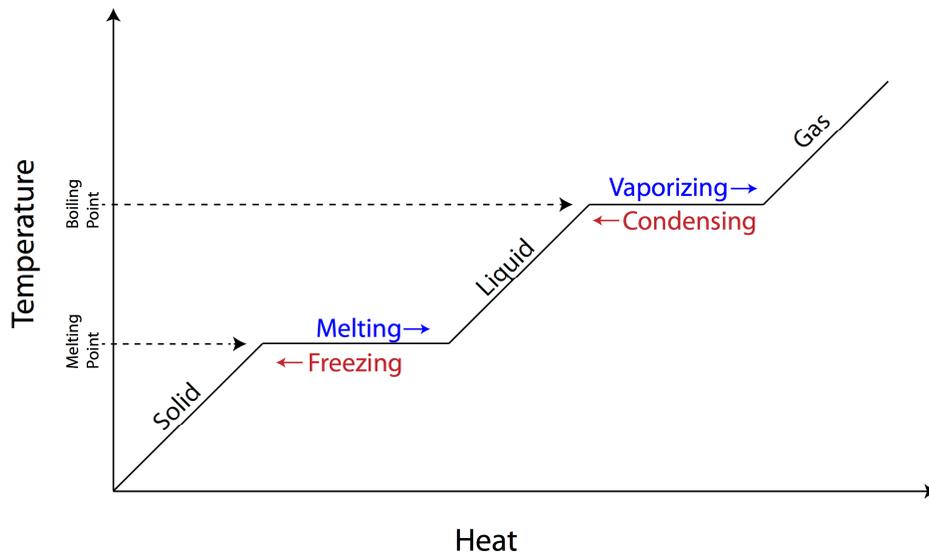
Figure. 7. Shows the thermal behavior of PCM's during phase transition. The temperature of the material remains constant during phase transformation [17].

When one is trying to utilize phase change materials, there are many criteria that one must take into consideration. The most challenging criteria when selecting phase change materials is to find the PCM with a melting point of desired operating temperature. Another challenge while working with PCMs is the long term thermal behavior of the material. The most essential criteria that the phase change storage materials must meet while undergoing a solid - liquid or a solid - solid phase transition are as follows [18]:

- High transition enthalpy per unit mass
- Ability to fully reverse the transition
- Adequate transition temperature
- Chemical stability and compatibility with storage container
- Limited volume change with the transition
- Non toxicity
- Low cost, in relation to the foreseen application

In addition, when selecting phase change materials thermodynamic, kinetic, chemical, technical and economical criteria must be take into account.

Thermodynamic Criteria

- Melting point at desired operating temperatures
- High latent heat of fusion per unit mass
- High density
- High specific heat
- High thermal conductivity
- Congruent melting
- Small volume change during phase transition

Kinetic Criteria

- No supercooling
- Sufficient crystallization rate

Chemical Criteria

- Chemical stability
- No susceptibility to chemical decomposition
- Noncorrosive behavior
- Nonflammable, nontoxic, non explosive

Technical Criteria

- Simplicity
- Applicability
- Effectiveness
- Reliability
- Compatibility

Economic Criteria

- Commercial availability
- Low cost

Information retrieved from [18]

2.2.2 Categorization of PCM

Great number of phase change materials is available at different temperature ranges. Phase change materials are "categorized as organic (paraffins and non-paraffins), inorganic (salt hydrates and metallics), and eutectics (organic eutectics, and inorganic eutectics)" [19]. Organic PCMs can melt and freeze several times with congruent melting and they have the ability to crystallize with minimum or no supercooling. Organic PCMs are generally not corrosive materials [19]. Figure 8 illustrates further the classifications of the PCMs. Inorganic PCMs (salt hydrates) on the other hand, have nearly twice the energy storage capacity per unit volume as the organic PCMs. In addition, inorganic materials have higher melting temperatures than other PCMs, although inorganic PCMs are more likely to experience corrosion and subcooling problems [20]. Each categorization of phase change materials have different physical, thermal and chemical criteria. Therefore, one must take into consideration all the information available when selecting the phase change material for a given application.

Phase change materials that are commercially available have thermal properties listed in the data sheet; however the name of the chemical composition of the phase change material is not given. One has to make decisions based on the data sheet and the categorization of the material. For the most part, information given by the makers of phase change material is sufficient to make preliminary decisions regarding given design parameters.
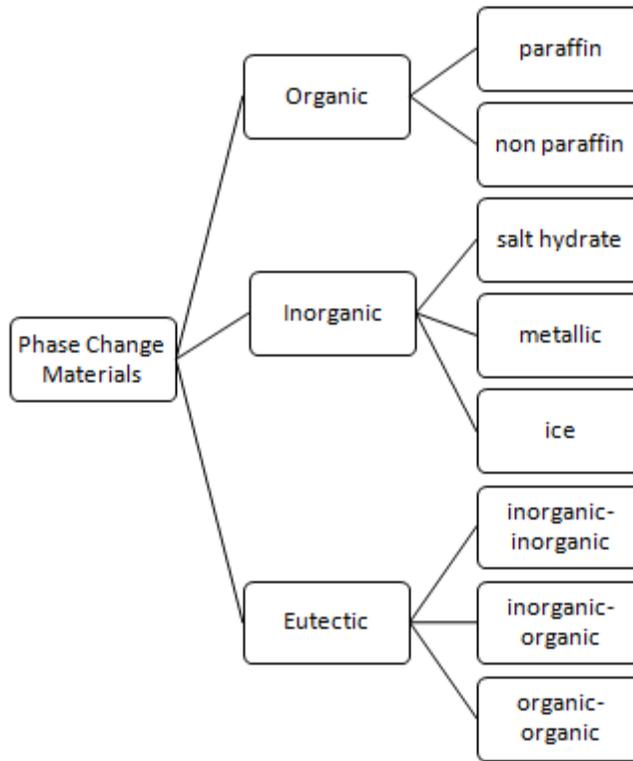
Figure. 8. Shows the categorization of phase change materials [21].

3.1 Energy performance analysis

In order to understand the performance of the thermal storage system, a thermal model was built. It describes the harvesting of the solar energy and the thermal behavior of the storage medium. As depicted in Figure 9, the storage system consist of two evacuated thermal panel and a storage tank.
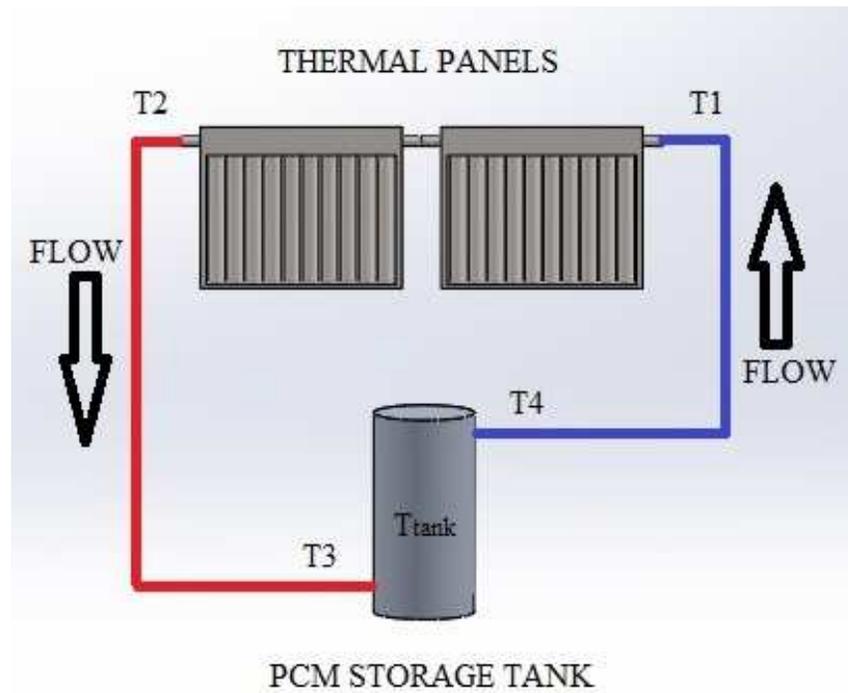

Figure. 9. Seasonal storage system description.

The first part of the model deals with the energy transfer from the solar irradiation to the heat carrier in the solar collector. The second part of the model deals with the storage of energy in the tank. The model was build to perform hourly calculations of the solar energy that was harvested by the solar thermal collector. This was done by taking into consideration technical data of the thermal solar collector and the hourly Estonian

irradiance data. Lastly, the amount of power collected from the thermal solar panels was recorded, along with the energy that was stored every hour for one year, under Estonian weather conditions.

3.1.1 Storage System Description

For this investigation, solar irradiation and ambient temperature data of Estonian weather conditions was recorded hourly for one year.

The system that was considered for this analysis consists of two solar thermal panels connected in series. The thermal panels are connected to a storage tank like shown in Figure 9. The storage tank consists of a tank, heat exchanger and the phase change material. The heat transfer fluid circulates through the system delivering heat energy to the tank. The phase change materials inside of the tank stores the heat energy delivered by the heat transfer fluid. The phase change material is in a solid phase at room temperature. As heat is delivered to the tank, the PCM retains the heat. When the heat inside of the tank reaches melting temperature of the PCM, the heat inside of the tank is then stored as a form of latent heat. When the storage of the latent heat takes place in the storage tank, the temperature of the tank remains constant. When all the possible latent heat has been stored in the tank, the process stops and a new tank begins to be heated.

As depicted in Figure 9, the storage system consists of two evacuated thermal panels and a storage tank. In order to perform a thermal analysis of the storage system, the following representations of the different temperatures within the system where made. T_1 represents the inlet temperature of the first thermal panel; the heat transfer fluid is cold when entering the thermal panel. T_2 is the outlet temperature of the thermal panels. The heat transfer fluid gains heat energy from the thermal panels. T_3 represents the incoming temperature of the heat transfer fluid entering the storage tank. T_{tank} represents the temperature of the tank. T_{1tank} is the initial temperature of the tank and T_{2tank} is the final temperature of the tank. Lastly, T_4 is the outlet temperature of the heat transfer fluid leaving the storage tank after delivering the heat energy to the PCMs inside of the tank.

3.1.2 Assumptions and Constant Parameters

In order to perform thermal calculations of the storage system, a number of assumptions and constant parameters were used:

- Total aperture area of the thermal collectors 4.3 m^2
- The installation of the thermal panels is at a plane tilted 45˚ south
- Heat transfer fluid (HTF) is considered to be incompressible
- Specific heat of the heat transfer fluid is 3800 J/kg ˚C
- Mass flow rate of heat transfer fluid is 0.04 kg/sec
- Room temperature of the system is 18˚C
- At the beginning of each day, the temperature of HTF is set at room temperature
- T_{1tank} is set at room temperature
- Most of the system piping is well insulated and set indoors, to ensure minimum heat loss to the environment
- Heat transfer between the heat exchanger and the PCMs is presumed to be 100%
- Based on the above presumption, $T_{2tank} = T_4$
- During the accumulation of latent heat, the temperature of the tank remains constant at PCM melting temperature
- PCMs are homogeneous and isotropic
- PCM encapsulation is not taken into consideration during this study

3.1.3 Equations

The following equations were used to build the model that describes the thermal behavior of the seasonal storage thermal system. The conservation of energy approach was utilized during this research.

Equation (1) was utilized to calculate the power collected by the thermal panel and delivered to the heat transfer fluid [22].

$$P_{coll} = \dot{m}_{HTF} \, C_{pHTF} \, (T_2 - T_1) \quad \text{(W)} \tag{1}$$

Equation (2) relates the optical efficiency and thermal correction values given by the manufacturer of the evacuated thermal collectors along with the average temperature of the heat transfer fluid inside of the thermal collectors and the solar irradiance [22]. With equation (1) and equation (2) it was possible to calculate the outlet temperature of the thermal panels T_2.

$$\eta_{coll} = \eta_{opt} - A*(T_{avg} - T_a) \, / \, G - B*(T_{avg} - T_a)^2 \, / \, G \tag{2}$$

The power loss from the pipes to the environment was calculated by making use of the geometry of the pipes, the properties of the insulation used in the pipes and the length of the pipes. Equation (3) relates all this information to calculate the power loss from the pipes to the environment [23].

$$P_{pl} = 2 \, \pi \, k_p \, (T_p - T_a) \, / \, Ln \, (D_i / D_p) \quad \text{(W/m)} \tag{3}$$

The energy of the tank was calculated by taking into consideration the mass of the solid state of the PCM, the specific heat capacity of the solid state of the PCM and the final and initial temperatures of the storage tank [24].

$$Q_{tank} = M_{solid} C_{psolid} (T_{2tank} - T_{1tank}) \quad \text{(J)} \tag{4}$$

The energy delivered to the tank was calculated by taking into consideration the mass of the solid state of the PCM, the specific heat capacity of the solid state of the PCM and the temperature difference between T_3 and T_4 [24].

$$Q_{tank\,del} = M_{solid} C_{psolid} (T_3 - T_4) \quad \text{(J)} \tag{5}$$

The power of the heat transfer fluid inside of the tank was calculated by taking into consideration the mass flow rate of the heat transfer fluid inside of the tank, the specific heat capacity, along with the inlet and the outlet temperatures of the tank [24].

$$Q_{HTF} = \dot{m}_{HTF} C_{pHTF} (T_3 - T_4) \quad \text{(W)} \tag{6}$$

The power loss from the tank to the environment was calculated by taking into consideration the overall loss coefficient of the tank (UA) and the temperature difference between the tank and the room where the tank was located [24].

$$P_{tank\,loss} = U_{Atank} (T_{2tank} - T_{room}) \quad \text{(W)} \tag{7}$$

A_{tank} is the surface area of the tank, $U = k_t / t_i$, where K_t is the thermal conductivity of the tank insulation and t_i is thickness of the tank insulation.

The amount of energy stored in the tank with PCMs was calculated using the following equation [24]:

$$Q_{store} = M_{solid} C_{psolid} (T_3 - T_4) + M_{solid} \lambda_{PCM} \quad \text{(J)} \tag{8}$$

Where, λ_{PCM} is the latent heat of the phase change material

The efficiency of the thermal seasonal storage system can be defined by the ratio of the store latent heat energy during one year period to the total insolation available for the aperture area of the thermal panels during one year period.

$$\eta_{sys} = Q_{\lambda PCM} / Q_{Insolation} \tag{9}$$

3.1.4 Technology Data

The technologies used during this research consist of evacuated thermal panels, phase change materials and storage tank. The following technical information was obtained from data sheets provided by the manufactures of the technologies.

The parameters that are presented in table 1, table 2 and table 3 were utilized to perform calculations during this research. Table 1 shows the characteristics of the thermal collector [25].

Table. 1. Shows the technical data of the thermal collector.

Thermo Max	
Type DF 100	
Number of tubes	20
Collector area (m^2)	2
Aperture area (m^2)	2.15
Efficiency (optical)	0.773
Thermal constant 1(W/m$^{2\circ}$C)	1.43
Thermal constant 2(W/m$^{2\circ}$C^2)	0.0059
Flow rate (kg/sec)	0.04

Table 2 illustrates the technical data of the phase change materials made by PCM products. The organic phase change materials are easy to handle and do not require encapsulation [26]. The final selection of the phase change material was based on the thermodynamic, kinetic, technical and economic criteria mentioned in this paper. While most of the phase change materials in the market claim almost the same thermodynamic

and kinetic criteria, the economic criteria is the one that makes the difference between phase change material providers.

Table. 2. Shows the technical data of the phase change material that was used during this investigation.

PCM $_{type\ Organic\ (A)\ Range}$	A60H
$T_m (\degree C)$	60
$C_{psolid}\ (J/kg\degree C)$	2150
$\lambda_{PCM}\ (J/kg)$	212000
$\rho_{L\ PCM} (kg/m^3)$	800

Table 3 shows the parameters of the storage tank used for the containment of the phase change materials [27].

Table. 3. Shows the technical data of the storage tank that was utilized in this research.

Storage Tank	
Type	RBC-300HP
Size	300 kg
Exchanger surface area (m^2)	3.8
Radius (m)	0.305
High (m)	1.71

3.2 Results and Discussion

An analysis was done to calculate possible latent heat energy via PCMs that could be stored during one year under Estonian weather conditions. A model was created to perform hourly calculations of harvested energy and storage energy during a one year period. The analysis of this model gives the heat quantity and thermal losses at different stages of the storage system. The model shows that seasonal heat storage via PCM materials may considerably reduce the heat load of the Northern European houses during the winter season.

The first part of the model deals with the harvesting of solar energy. The irradiance data was collected at in-plane tilted 45° south during one year. The data was then utilized for hourly calculations. As presented in Figure 10, the monthly irradiance under Estonian weather conditions shows an uneven distribution of solar irradiation during the year. During the fall and winter seasons, the solar irradiation is low compared to the spring and summer seasons. This information is critical for the prediction of how much solar energy could be harvested.
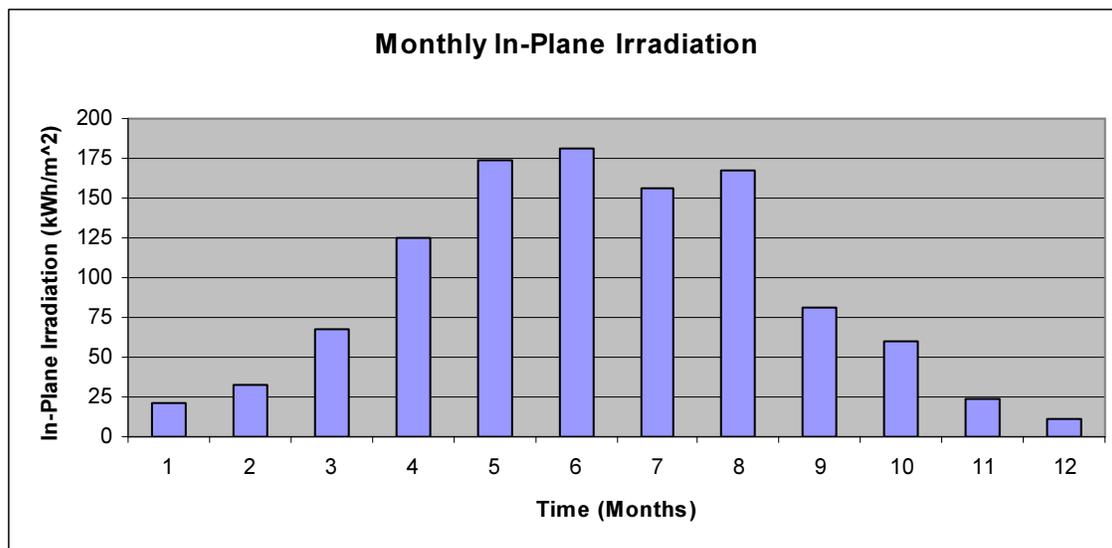

Figure. 10. Illustrates the in-plane tilted 45° south and solar irradiation based on measurements from a standard year. The measurements were done in Tallinn University of Technology.

The total insolation at the site of the thermal panels is calculated by the product of the aperture area of the thermal panels and the available solar irradiation. This parameter is important because indicates how much energy is available for the thermal panels to convert to useful heat energy.

Figure 11 illustrates the total insolation available at the location of the thermal panels. The distribution of the total energy is similar to the distribution of the in-plane solar irradiation. The total insolation available also changes with the seasons of the year, making the harvesting of the solar energy challenging during the dark periods in Estonia.
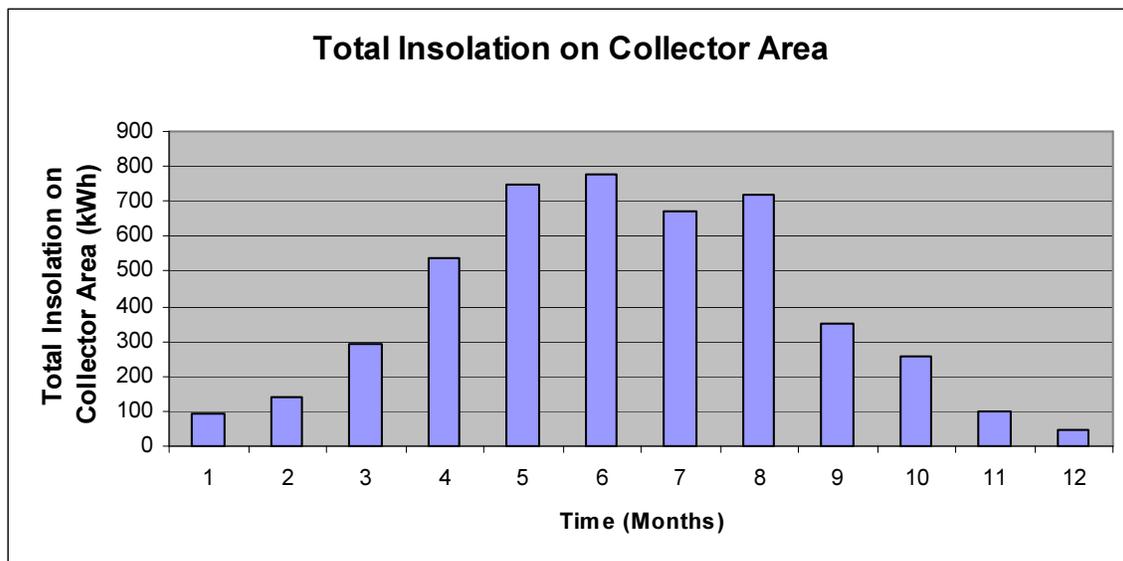

Figure. 11. Shows the total insolation based on 4.3 m^2 of aperture area of the thermal panels under Estonia climate conditions.

The energy collected by the thermal panels was obtained from equations (1) and (2). Two thermal panels were connected in series with a total aperture area of 4.3 m^2. As depicted in Figure 12, the energy collected by the thermal panels was highest during the summer time. The best month was June, with 497 kWh of energy collected. On the other hand, December was the lowest month, with only 22 kWh of thermal energy collected.
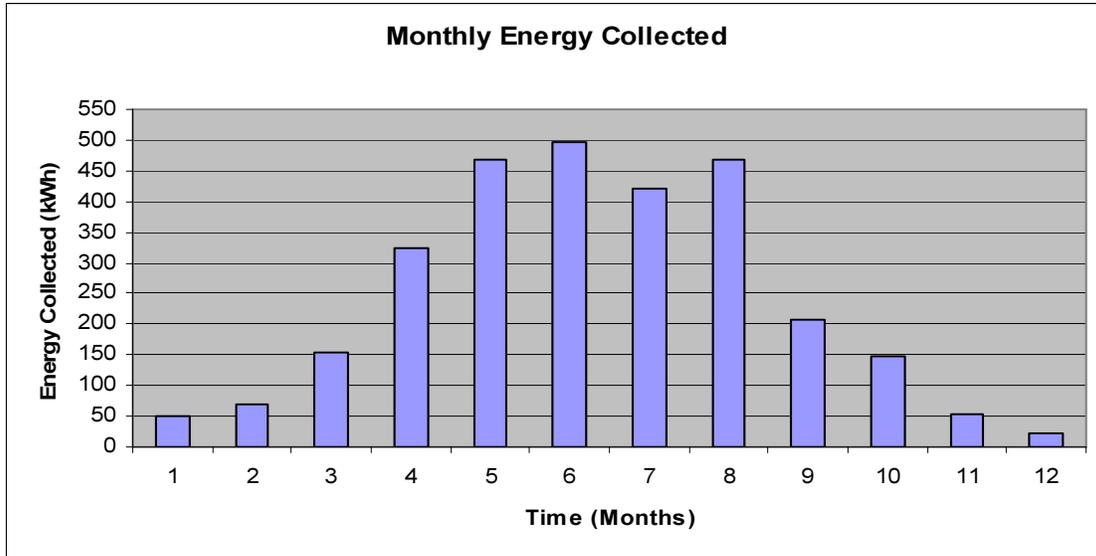
Figure. 12. Shows the monthly thermal energy collected form the thermal panels under Estonian weather conditions

The optimization of the storage tank was done by comparing the size of the tank, the latent heat stored in the tank, and the number of tanks that were needed to store the latent heat energy within one year period. As depicted in Figure 13, the tanks with more mass capacity store less latent heat energy, because it takes longer time for the material to reach the phase change. At the same time, the bigger the mass capacity of the tanks, the greater the heat loss to the environment. The tanks with mass of 300 and 200 kilograms of phase change material store 951 kWh of latent heat energy. Figure 14 illustrates that if 200 kilograms tanks are used, than 81 tanks will be required, but if 300 kilogram tanks are utilized, than 54 tanks are necessary. Based on these results the optimal size of the tank selected for storage system is the tank with the mass capacity of 300 kilograms. In addition, the 300 kilogram mass tank can reduce the heat loss to the environment and possibly prevent incongruent melting of the PCMs.
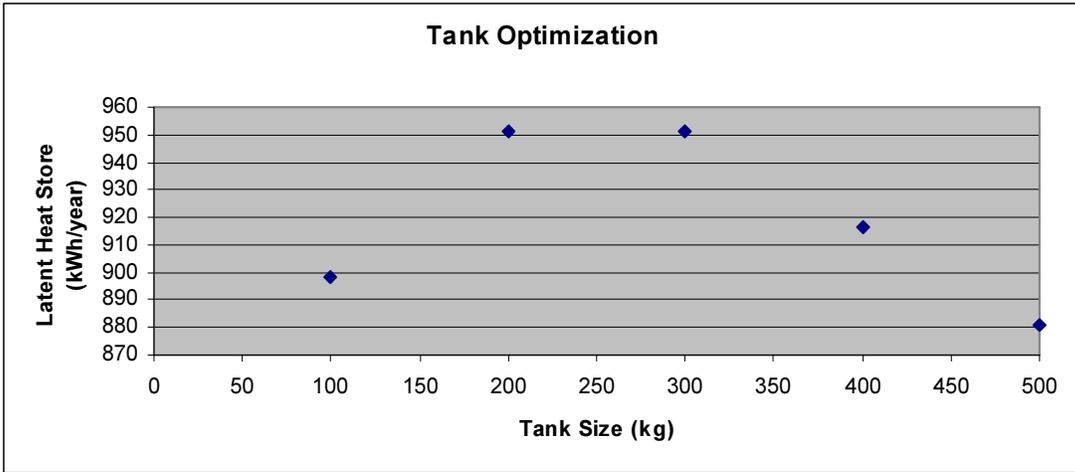
Figure. 13. Shows the optimization of the tank based on the latent heat store with different amounts of PCMs
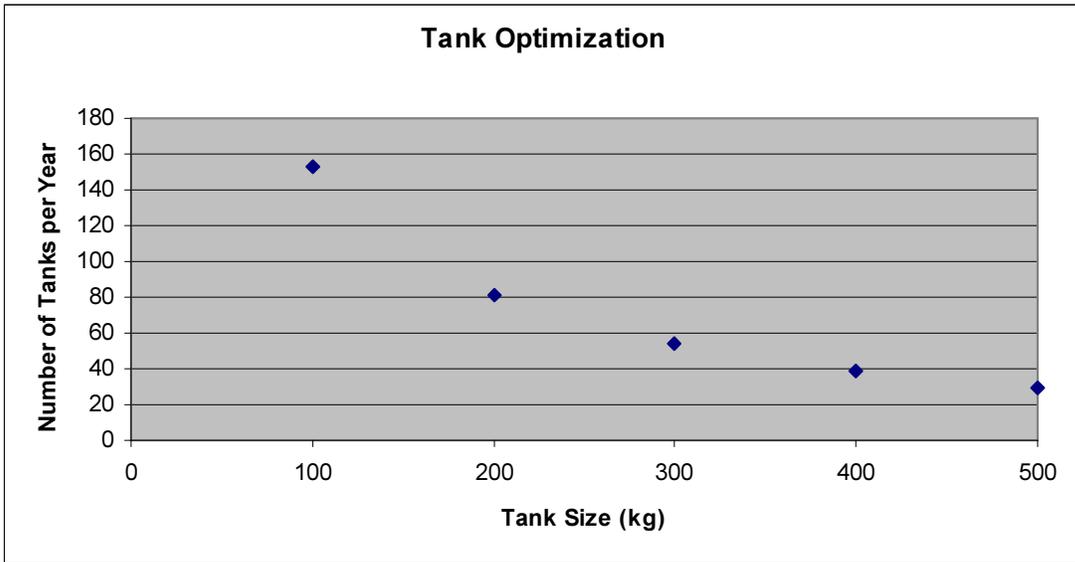

Figure. 14. Illustrates the optimization of the storage tank based on the size of the tank to minimize the number of tanks that can be utilized in the storage system

The power loss to the environment due to heat loss from the pipes was calculated with equation (3). Based on the assumptions mention above, most of the piping in the system is enclosed and well insulated, therefore the heat loss through the pipes is minimum. Equations (4), (5), (6) and (7) were utilized to calculate the final temperature of the tank every hour and to find the amount of energy delivered to the tank every hour as shown in Figure 15. In addition, equation (7) was used to calculate the heat loss to the environment from the tank every hour for the entire year. The heat losses of the tank to the environment are minimum because the tank is well insulated and the tank is located indoors. The energy delivered to the tank was the highest in June with 347 kWh. The lowest energy delivered to the tank was during the winter season with 8.27 kWh delivered in December.
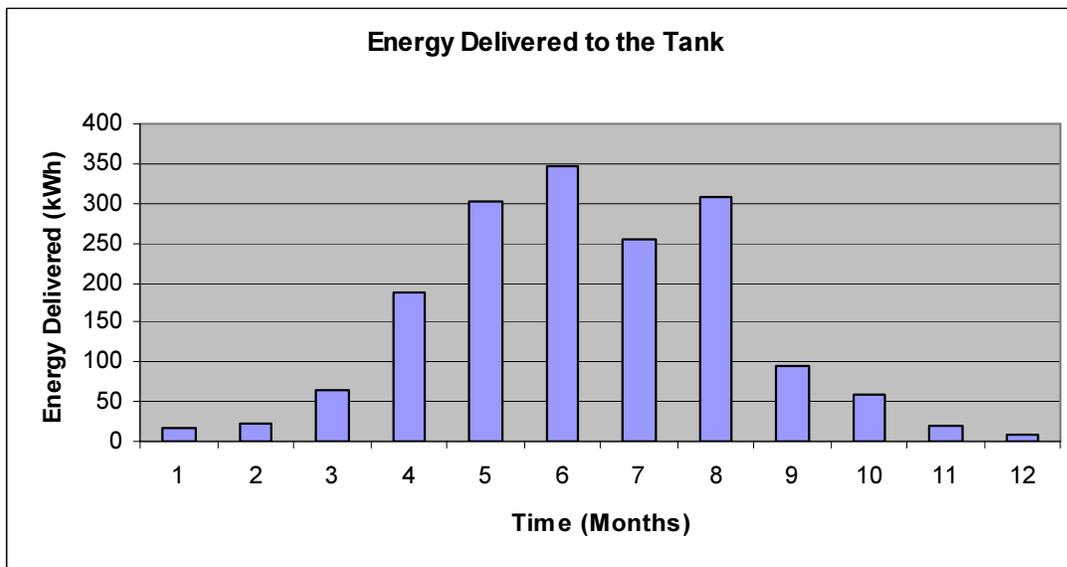

Figure. 15. Shows the monthly thermal solar energy delivered to the storage tank during one year period under Estonian climate conditions

The energy delivered to the tank was utilized to bring the phase change material to the melting point. Then, once the phase change material inside of the tank had reached the melting temperature, the model was programmed to retain the temperature of the storage tank at the melting temperature of the phase change material 60˚C. At this point, the heat

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energy was stored as latent heat. Figure 16 illustrates the monthly storage of latent heat during the year. The latent heat is the heat energy store that can be used for seasonal thermal heating. The model was design in such a way that when the storage tank reached the latent heat capacity of the material, the process of heating the tank stopped and a new tank with the same characteristics was started. The process repeated itself during the year. The latent heat distribution depicted in Figure 16 shows that the optimal time to store energy under Estonian weather conditions is during the summer season. The highest month for storage of latent heat was June, with 211 kWh, followed by May and August with 193 kWh of latent heat storage. The total latent heat store during the year was 951kWh.
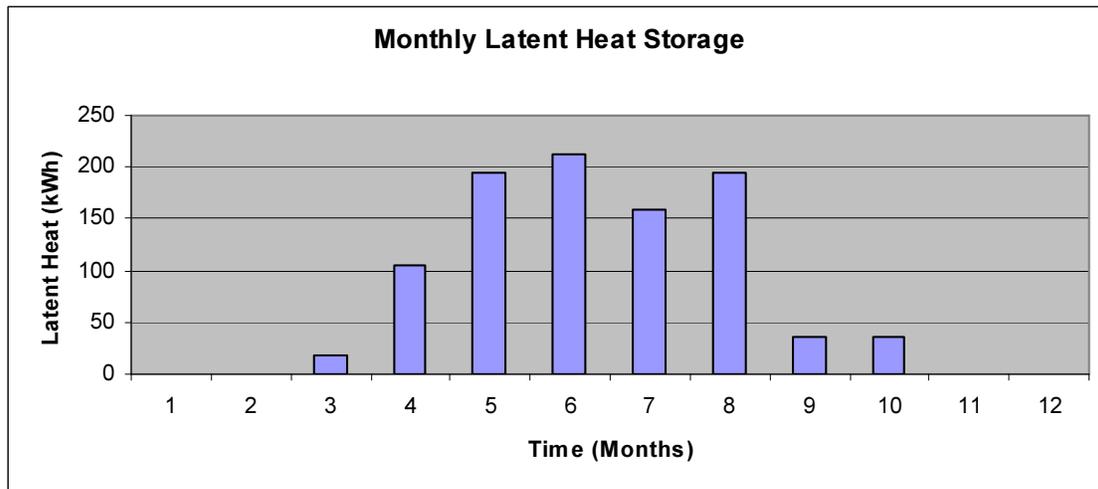

Figure. 16. Shows the monthly latent heat storage during one year period under Estonian climate conditions

During the period of one year, a total of 54 storage tanks can be filled. Figure 17 shows the filling distribution of the tanks. In order to implement the storage system, a big area will be needed for the storage tanks. Most of the storing of the latent thermal energy occurs during the summer, with most of the tanks being filled during this time. In spring and fall the storage of energy is low. Winter time brings no latent heat energy storage, therefore no tanks are being filled during this time.
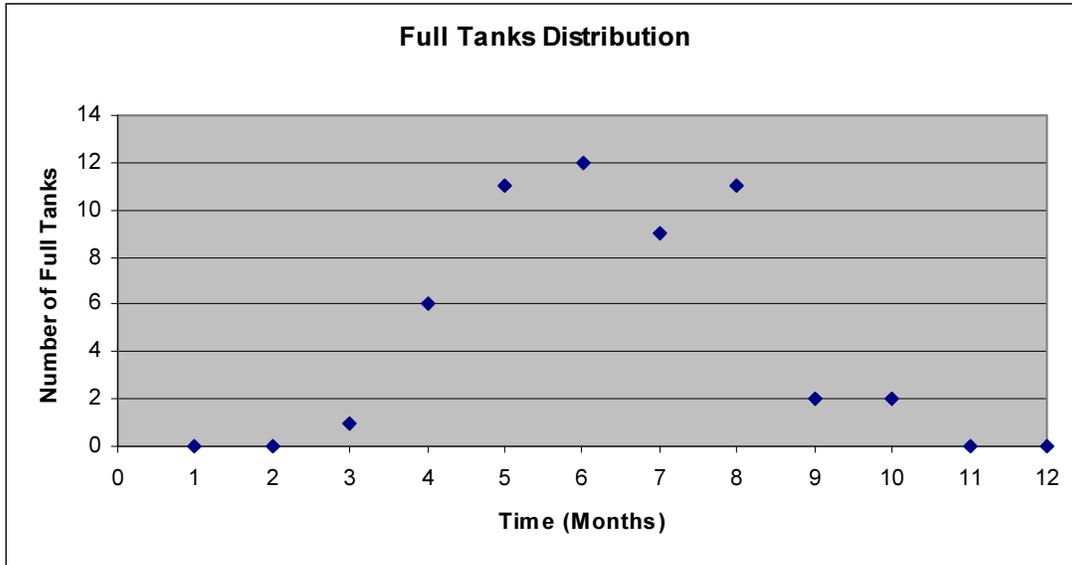
Figure. 17. Illustrates the monthly number of tanks that can be filled with latent heat energy under Estonian climate conditions

The system efficiency was calculated monthly for the duration of the year as depicted in Figure 18. The system efficiency was calculated from the latent heat store and the total insolation. During winter months, the efficiency is zero because there was no storage of latent heat during this period. In June the system efficiency was the highest with 27 %. The overall year efficiency of the system was 20%.
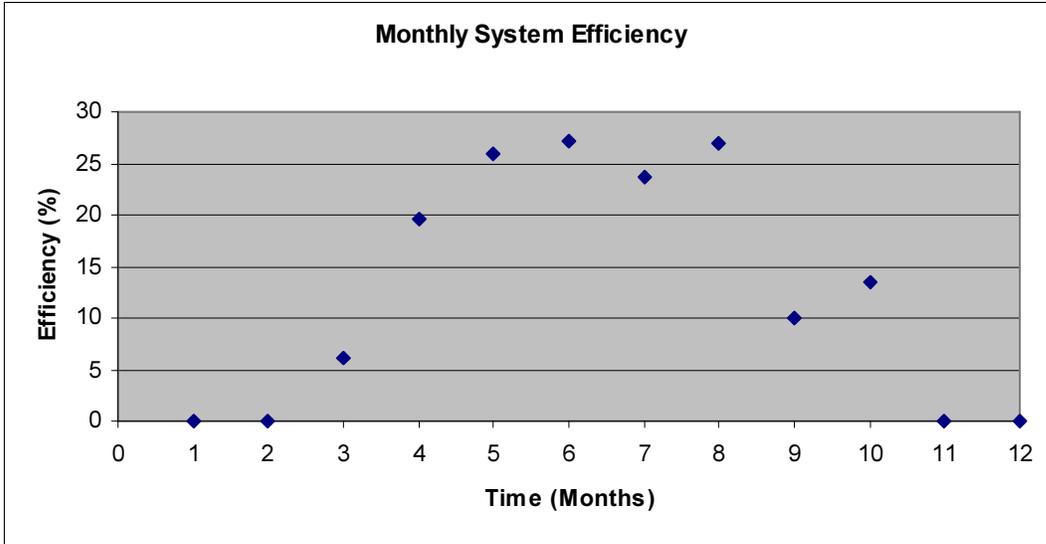
Figure. 18. Illustrates the monthly system efficiency under Estonian climate conditions

3.3 Cost-Analysis

The initial coast analysis of the system is predicted by taking into consideration the life time of the technology. During this study the calculations are based on 20 year life time of the system. The cost of the energy is calculated by considering only the most important parts of the system which in turn are the most expensive parts. The parts that are considered in the total cost of the system are as follows:

- Phase change materials
- Thermal panel technology
- Storage tanks technology
- Installation cost

3.3.1 Cost of Technology

The storage of heat energy with phase change materials has been developing over the years, making the cost of the phase change materials more affordable. At the present time there are many companies that supply phase change materials to the market. During this investigation the cost of change material from other companies were obtained. The price of latent heat energy stored in one kilogram of material and their properties are depicted in Table 4. The price of store energy is high but the advantages are that the technology can be used for many cycles. Table 4 shows the cost of selected phase change materials offered by PureTemp [28].

Table. 4. Illustrates the properties of phase change materials and the cost of latent heat energy store in one kilogram of material.

PCM $_{type}$	$T_{m\ (°C)}$	$C_{psolid\ (J/kg°C)}$	$\lambda_{PCM\ (J/kg)}$	$\rho_{L\ PCM\ (kg/m^3)}$	Price $_{Euro/\ kWh}$
PureTemp 53	53	2360	225000	840	150.34
PureTemp 60	61	2380	220000	870	153.75
PureTemp 68	68	1850	213000	870	158.81
PureTemp 103	103	2090	160000	1220	211.41
PureTemp 151	151	2060	217000	1360	155.88

As depicted in Table 5, the cost of phase change materials offered by the company savENRG is in the same range as the previous company [29]. The price of latent heat energy stored in one kilogram of material and their properties are shown in Table 5. Most of the companies that provide high quality phase change materials have the same price range.

Table. 5. Shows the properties of phase change materials and the cost of the latent heat energy stored in one kilogram of material.

PCM $_{type}$	$T_{m\ (°C)}$	$C_{psolid\ (J/kg°C)}$	$\lambda_{PCM\ (J/kg)}$	$\rho_{L\ PCM\ (kg/m^3)}$	Price $_{Euro/\ kWh}$
PCM-OM37P	37	N/A	218000	880	138.11
PCM-OM55P	55	N/A	210000	840	93.51
PCM-OM65P	65	N/A	210000	840	141.82

The phase change material selected for this investigation is made by PCM Products. The price of the phase change material selected has the lowest price of the previous companies shown in Table 6.

Table. 6. Shows the properties of the selected phase change materials for this study and the cost of the latent heat energy stored in one kilogram of material.

PCM $_{type}$	$T_{m\ (°C)}$	$C_{psolid\ (J/kg°C)}$	$\lambda_{PCM\ (J/kg)}$	$\rho_{L\ PCM\ (kg/m^3)}$	Price $_{Euro/\ kWh}$
A60H	60	2150	212000	800	51.08

The price per item of the technologies that were utilized during this analysis is presented in Table 7. For the installation cost it is assumed that two people will do the installation in 20 hours and each person will get pay 12.50 euros per hour of work.

Table. 7. Shows the price per item of the technologies used in the seasonal thermal storage system.

Technology	Quantity	Cost (euro)
20 tubes evacuated thermal panel [30]	1	457.79
RGC 300 kg storage tank [31]	1	603.20
Installation		500
A60H phase change material	1 kg	3

3.3.2 System Cost

The cost distribution of the seasonal storage system is illustrated in Figure 19. The cost of the phase change materials is the highest cost of the system followed by the storage tanks and the thermal panel technology. The cost of the phase change materials is very high at the moment.
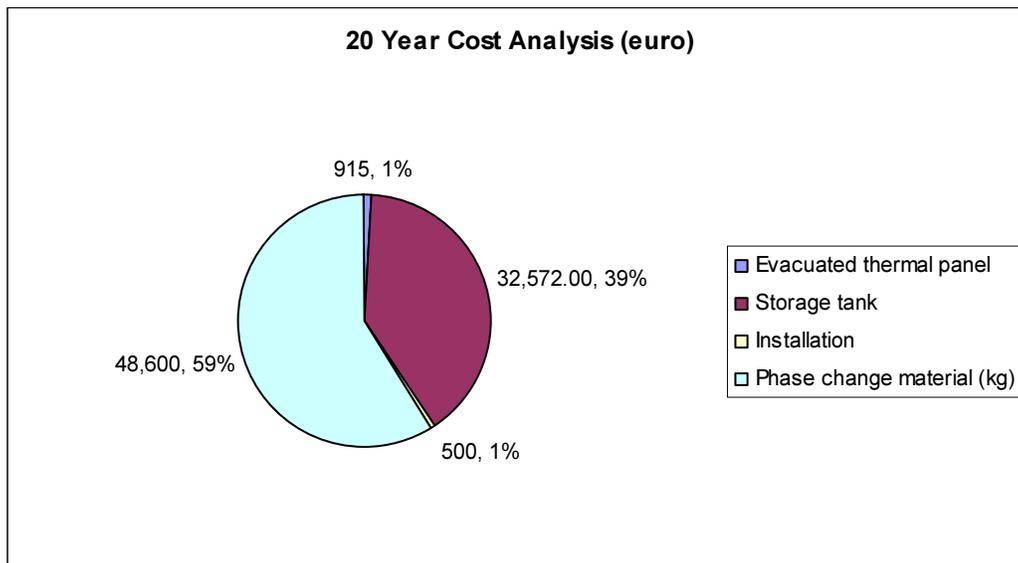

Figure. 19. Shows the 20 year cost analysis of the storage system under Estonian climate conditions

The economic analysis of the system was predicted by assuming that the cost of the system was going to be paid by taking a 20 year home loan with an interest rate of 3.5%. Details of cost prediction are presented in Table 8 [32]. The cost of the energy stored as latent heat for the life time of the technology is 6.04 euro/kWh of heat energy. In 2013 a study done by the International Renewable Energy Agency (IRENA) and the Energy Technology Systems Analysis Programme (ETSAP) which predicted that the cost of energy storage with phase change materials will be in the range of 10-50 euro/ kWh in 2013 [33].The cost of the storage system based under Estonian weather conditions is currently lower than the 2013 IRENA-ETSAP predictions.

Table. 8. Shows the economical analysis of the storage system based on Estonian climate conditions

20 Year Cost Analysis	
Energy storage first year (kWh)	951.32
Energy storage life time (kWh)	19026.40
Interest Rate (%)	3.5
System total Cost	82588.38
Total interest expenses	32366.51
Total	114954.51
Price of store energy life time (euro/kWh)	6.04

3.3.3 PCM's Cost Mechanism

There are two main components that drive the price of the phase change materials. One is the supply and demand relationship, and the other is the cost of the raw materials that is used to manufacture the phase change materials. The most important factor is the demand and supply of the PCMs. At the moment the market for the PCMs is not fully developed, which contributes to the high cost of the PCMs. New applications for PCMs are being developed for building materials that could contribute to energy storage in new buildings, which could increase the demand for PCMs and reduce the cost in the near future. In addition, new government policies requiring energy efficiency in buildings will add value to the phase change material industry.

The cost of raw materials is another important factor in the production of phase change materials. In order for the phase change material to perform many thermal cycles, the material has to be as pure as possible. This fact not only increases the complexity of the manufacturing of the material but also increases the cost of the final product. Another aspect that has to be considered in regards to the cost of the PCMs is that depending on the application, some materials may need encapsulation to prevent the contamination of the PCMs. The process of encapsulation increases the cost of the material [34].

In order to reduce the cost of the phase change material, demand for technology has to increase. Perhaps the phase change materials technology will mimic the photovoltaic technology market when it comes to the cost reduction of the technology. Over the years, due to the increase in the demand of the photovoltaic technology, the price has decreased drastically. If this were the case, phase change material technology could contribute to the energy conservation in the building sector worldwide.

3.3.4 Cost of Heat Energy

During this investigation it was determined that the cost of heat energy stored with phase change materials under Estonian weather conditions is 6.04 euro/kWh. At the moment the cost of heat energy provided to residential buildings by district heating company in Estonia is 0.0614 euro/kWh [35]. This makes the cost of heat energy with phase change materials 98 times more expensive than the heat energy provided by the district heating company in Estonia. The cost of electricity for a medium size household in Estonia in 2014 was reported to be 0.1307 euro/kWh [36].

On the other hand, an underground heat pump with an average coefficient of performance of 2.5 is used to provide heating to a residential building [37]. The cost of heat energy by operating heat pump with a coefficient of performance of 2.5, with the cost of electrical energy reported in 2014 is be in the range of 0.0522 euro/kWh. Therefore, the cost of heat energy with phase change material is 115 times more costly than producing heat energy with an under ground heat pump. As a result, the implementation of seasonal storage systems with phase change materials under Estonian climate conditions is not competitive at the present time.

4 Conclusion

The main purposes of this research was to select the storage media, design and optimize the micro-scale thermal storage system under Estonian weather conditions and to perform cost analysis of the thermal system. This was done in order to demonstrate that the seasonal heat storage system via PCMs could considerably reduce the heat load of the Northern European buildings during the winter season.

The phase change material selected was a PCM organic (A) range with a phase change temperature of 60°C. Since the technology is not yet fully developed, there are some technical challenges relating to the storage media, such as premature decay of the thermodynamic, kinetic and chemical criteria, which may disrupt the lifetime of the technology.

The storage system design consists of two 20 tubes evacuated thermal collectors and a storage tank. The storage tank was equipped with a heat exchanger and phase change materials. The results of this investigation show that during one year period 951 kWh of latent heat energy was accumulated under Estonian climate conditions by using phase change materials as the storage media. The highest accumulation of latent heat energy occurred during June with 211 kWh. The period from November to February zero accumulation of latent heat energy was registered. These results show that the seasonal heat storage system via PCMs could considerably reduce the heat load of the Northern European buildings during the winter season.

The system utilizes two thermal collectors with total aperture area of 4.3 m^2. In addition, the system uses 54 storage tanks with an optimum mass capacity of 300 kg of phase change material per tank to store the maximum amount of latent heat energy, preventing excess heat loss and using the least number of tanks for the storage system. The efficiency of the thermal storage system is 20%.

The cost of latent heat energy stored with phase change materials was calculated to be 6.04 euro/kWh. The cost of heat energy with phase change materials is found to be 98 times more expensive than the heat energy provided by the district heating company in Estonia. Currently the implementation of seasonal storage systems with phase change materials is not competitive with other providers of heat energy in Estonia.

Résumé

During this research, a micro-scale thermal storage system used in Estonian weather conditions was designed and optimized. The results of this investigation show that during one year period it is possible to store 951 kWh of latent heat energy under Estonian climate conditions by using phase change materials as the storage media. The system utilizes two thermal collectors with total aperture area of 4.3 m^2 along with 54 storage tanks with an optimum mass capacity of 300 kg of phase change material per tank to prevent excess heat loss and incongruent melting of the PCMs. The efficiency of the thermal storage system was 20%. The storage of latent heat energy under Estonian weather conditions mostly takes place during the spring and summer seasons. The results of this research show that latent heat energy stored during the summer months could be utilized to alleviate the heat demand of Estonian buildings during the winter season.

Since the technology is not fully developed, there are some technical challenges relating to the storage media. The first issue is the possible premature decay regarding the thermodynamic, kinetic and chemical criteria, which disrupts the life time of the technology used. Another technical challenge is the constraints of the needed storage area required to harvest the thermal energy and the storage of latent heat energy. Likewise, there are economic challenges pertaining to the implementation of seasonal storage system. During this investigation, it was determined that the cost of latent heat energy stored with phase change materials was 6.04 euro/kWh. At the present time, however, the implementation of seasonal storage systems with phase change materials is not competitive with other heat energy providers in Estonia, especially since the storage technology is still developing and the current price of storage media and certain storage system adaptations are not cost effective.

As it is demonstrated in this paper, the potential of phase change materials for the seasonal thermal storage in northern European buildings is promising. The biggest issue is the cost of the storage media, which could be reduced if the demand for the technology increases and the reliability of the technology gets enhanced.

Resümee

Käesoleva uurimistöö raames uuriti hooajalise soojusenergia salvestamist Eesti kliimas mikrosüsteemi näitel. Uurimistöö tulemusena selgus, et ühe aasta jooksul on Eesti kliimatingimustes võimalik faasiüleminekuga materjale kasutades salvestada 951 kWh latentset soojusenergiat. Uuritud süsteem koosneb kahest soojuskollektorist kogupindalaga 4.3 m^2 ja 54st salvestuspaagist optimaalse mahutavusega 300 kg faasiüleminekuga materjali paagi kohta, et vältida liigset soojuskadu ning faasiüleminekuga materjalide ebaproportsionaalset sulamist. Soojussalvestussüsteemi efektiivsus oli 20%. Eesti kliimatingimustes toimub latentse soojusenergia salvestamine valdavalt kevadel ja suvel. Käesoleva uurimistöö tulemused näitavad, et suvekuudel salvestatud latentset soojusenergiat on võimalik kasutada Eesti hoonete küttevajaduse rahuldamiseks talvel.

Kuna vastav tehnoloogia on veel täielikult välja arendamata, vajab lahendamist mitu seotud tehnilist probleemi. Esimene neist on kasutatava tehnoloogia eluiga mõjutav enneaegne lagunemine termodünaamilisi, kineetilisi ja keemilisi kriteeriume silmas pidades. Teine tehniline probleem on seotud piirangutega pindala osas soojusenergia kogumisel ja latentse soojusenergia salvestamisel. Lisaks sellele on hooajalise salvestussüsteemi kasutuselevõtuga seotud ka majanduslikud probleemid. Uurimistöö tulemused näitavad, et latentse soojusenergia salvestamine faasiüleminekuga materjalide abil maksab 6.04 EUR/kWh. Tuleb möönda, et praegusel hetkel ei ole faasiüleminekuga materjalidel põhinev hooajaline salvestussüsteem Eestis teiste soojusenergia allikatega võrreldes konkurentsivõimeline. Seda seetõttu, et antud salvestustehnoloogia on veel väljaarendamisel ning faasiüleminekuga materjalide praegune hind ja salvestussüsteemi komponendid ei ole piisavalt kulutõhusad.

Nagu käesolev uurimistöö näitab, omab faasiüleminekuga materjalide kasutamine hooajaliseks soojussalvestuseks Põhja-Euroopa hoonetes suurt potentsiaali. Suurimaks probleemiks on salvestusvahendi hind, mis võib väheneda, kui nõudlus selle tehnoloogia järele tõuseb ja tehnoloogia usaldusväärsus suureneb.

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