Phase change materials

Energy analysis of a complex heating system with PCM thermal storage in different climatic conditions

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Abstract

An energy analysis of the complex heating system for heating of buildings, consisting of solar collectors (SC), latent heat storage tank (LHS) and heat pump (HP) was performed. The analysis was made for the heating season within the time from October to March for different climatic conditions. These climatic conditions were defined using test reference years (TRL) for cities: Ljubljana, London, Rome and Stockholm. The energy analysis was performed using a program which allowed hourly dynamics calculation of losses and gains for a given system. It was found that the system could cover more than 50% of energy from the sun and the heat pump coefficient of performance (COP) reached 6.

Introduction

Buildings share of total energy consumption is estimated of about 40%. The buildings sector is increasing and this consequently also increases energy consumption. Because of this reason a reduction of energy consumption and use of energy from renewable sources represent important steps towards reduction of greenhouse gas emissions. Measures to reduce energy consumption could be the increased use of energy from renewable energy sources respecting the Kyoto Protocol and to meet both long-term commitment to maintain the global temperature rise below 2°C as well as a commitment that by 2020 total greenhouse gas emissions must be lower at least 20% and meet the requirements of the EPBD 2010/31/EU [1].

Reduced energy consumption and increased use of energy from renewable energy sources play an important role in promoting security of energy supply. One of the promising alternatives for heating is solar energy. The best way to store solar energy is heat storage device.

Energy storage in tanks can be integrated into various systems. One way is the integration in a heating system. A combination of tank and combustion of biomass gives an optimal performance because the heat which is not used for building heating is stored in heat storage and can be used for heating when the heating device does not work [2].

Sizing principles for sensible heat storage device, which is integrated into the heating system, are purposed by Viorel Badescu [3]. He presented two models. The results show that the smaller heat storage devices cool faster than larger ones and that the thermal energy stored per month and monthly energy used to drive the heat pump compressor increases with increasing length of the tank. Of course it is possible to integrate the storage device into the building. In this case heat storage device can have three working modes: charging with heat, heat discharging (while emptying) and contemporary charging and discharging. Such heat storage device with alcohol as working medium in termosifone gives the best results [4].

The media, used for filling heat storages devices are different. One possible medium for heat storing are substances that change the physical state (Phase Change Materials - PCM), which can be used in different systems for both heating and cooling. They are very successful in reducing the energy requirements of buildings [5]. Unfortunately, before their widespread use is necessary to solve many problems on research and development level. Above all a lot of attention must be paid to thermal characteristics of PCM [6].

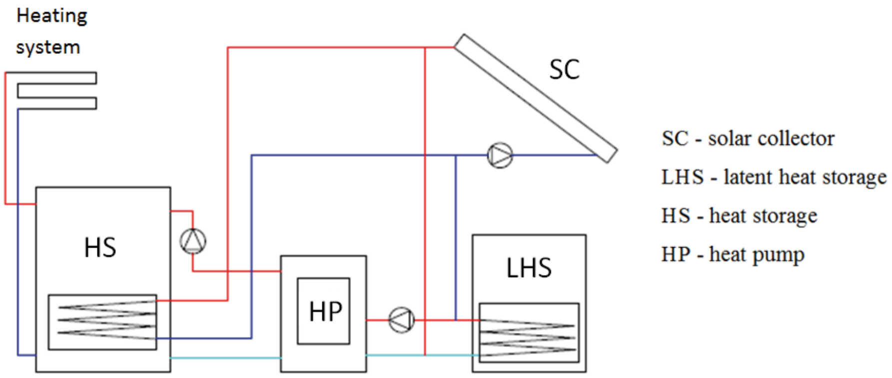


Figure 1. Scheme of the heating system.

Latent heat storage is becoming increasingly important. The use of latent heat storage in buildings has some advantages. By using the proper PCM and its proper installation latent heat storage devices can be economically efficient in heating and cooling of buildings. For mass use, it is necessary to solve some problems of reliability and practicality [7]. Over the past twenty years PCM and energy storage has been and important subject for research. Review of publications on thermal energy storage using a solid-liquid phase change was made by Zalba and other authors [8].

Energy storage can be carried out according to the melting/solidification characteristics of PCM. For the base three different types of paraffin with different melting temperatures were taken. The impact of Reynolds and Stefan number on melting and solidification of PCM was determined [9]. In analysing the behaviour of PCM - paraffin in capsules was found that the phase change occurs in the temperature interval. Use of enthalpy method showed that the melting process depends mainly on the size of the Stefan's number, the temperature at which phase change occurs and the diameters of capsules [10]. Latent heat storage devices can be used in heating systems together with solar collectors and heat pump. Simulation was performed for the system with latent heat storage device with measurements of inlet and outlet temperature of latent heat storage device filled with PCM [11]. In such a system some design factors are important for the performance of the system [12]. Design factor can be for example fins on heat storage device. A comparison was made between a flat heat storage device and a heat storage device with fins. It turned out that in the heat storage with fins PCM melting time was reduced [13].

Much interest in the last ten years was also attracted by sorption and thermochemical heat storage devices. In this area some project concerning absorption and adsorption heat storage devices are carried out. Their use is limited due to high prices of materials. The advantage of this technology is the possibility of long-term heat storage [14].

Description of the system

Solar radiation is a sustainable source of energy. The annual amount of solar energy that falls on Earth is more than eight thousand times larger than the annual global demand for primary energy.

Local distribution of the total annual amount of solar energy is determined by climatic and meteorological factors that are highly dependent on their location.

For exploitation of solar energy a system composed of solar energy collector, low-temperature (latent) heat storage device, heat pump and heating system, which is linked to heat storage device, can be used. System is presented in **Figure 1**.

Functioning of the system:

Solar energy collector absorbs solar energy, which is then transmitted by the heat exchanger to the latent heat storage device, which is filled with a phase changing material (PCM) - paraffin. The phase change material store energy in the process of changing in their physical state from solid to liquid. In our case the melting temperature was 30°C.

Thermal energy is then used by the heat pump from the latent heat storage device to a higher temperature level. This energy is stored in heat storage device and then sent through a heat exchanger into the heating system which is used for heating of building. In this way a space temperature of 20°C can be provided. The temperature of the heating system is 40°C.

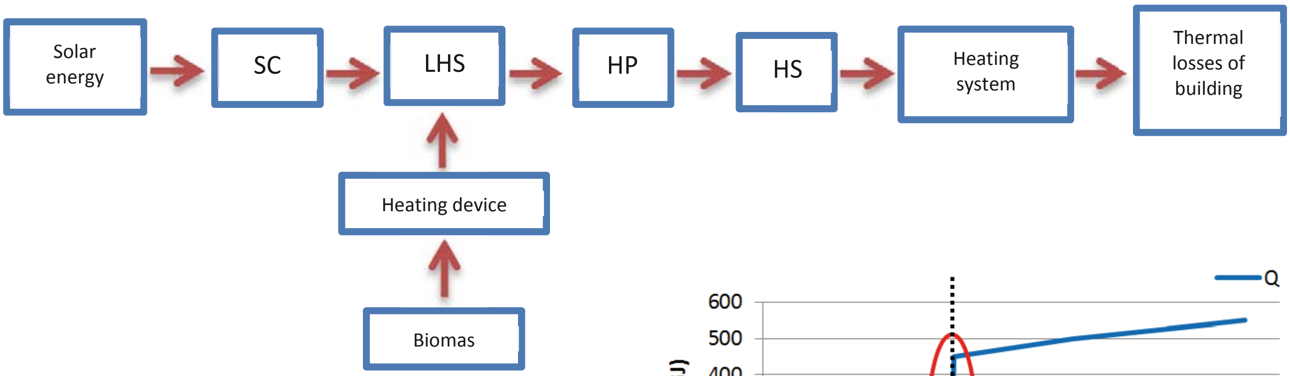


Figure 2. Scheme of the calculation.

Mathematical model

In analysis of complex heating system a computer program - application that allowed simulation of behaviour of the heating system in different climatic conditions was used. To implement the simulation input data were: hourly solar radiation, the corresponding external temperature, characteristics of the solar energy collector, latent heat storage device filled with paraffin Rubitherm RT 31, heat pump characteristic and low-energy house characteristic. For weather data Test Reference Year (TRY) was used.

The calculation scheme is presented in **Figure 2**.

The following are the physical parameters of the system components:

- Solar energy collector - (SC).

The solar energy collector is designed to convert solar energy into heat. In analysed system two solar collectors were used. The characteristic of each collector is presented in **Table 1**.

Table 1. Characteristic of the solar collector.

F'	A_{SC} [m²]	$G_{glob.\beta}$ [W/m²]	T_{cover}	α_{abs}	U_{SC} [W/m²K]	T_{mid} [K]
0.95	25	500	1	0.95	1.5	30

The amount of heat generated by the sun is calculated using **Equation 1**.

$$Q_{SC} = F' \cdot A_{SC} \cdot [G_{glob.\beta} \cdot \tau_{cover} \cdot \alpha_{abs} - kU_{SC} \cdot (T_{mid} - T_{amb})] \quad (1)$$

where:

F' Dimensionless efficiency factor of the absorber
A_{SSE} Solar energy collector area (m²)
$G_{glob.\beta}$ Global solar radiation in the plane of the collector cover (W/m²)
τ_{cover} Transitivity of the solar energy collector cover
α_{abs} Absorptivity of solar radiation on the absorber
U_{SC} Thermal conductivity of the solar collector (W/m²K)
T_{mid} Mean temperature of the liquid in the collector (K)
T_{amb} Ambient temperature (K)

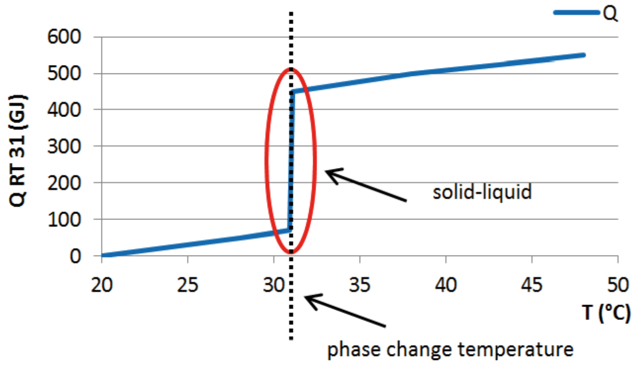


Figure 3. Temperature distribution in the latent heat storage device with RT 31.

- Latent heat storage (LHS) with paraffin Rubitherm RT 31

For energy storage at low temperature level, we have used latent heat storage with paraffin Rubitherm RT 31 with following characteristics:

Table 2. Characteristic of paraffin RT 31.

$C_{p\ solid}$ [kJ/kgK]	$C_{p\ liquid}$ [kJ/kgK]	ρ_{solid} [kg/m³]	ρ_{liquid} [kg/m³]	$T_{melting\ point}$ [°C]
1.8	2.4	880	760	31

Characteristics that paraffin have is that they store a greater amount of energy without changing their temperature at phase change (solid - liquid and vice versa) as shown in **Figure 3**. In this case the temperature at which the phase change occurs was 31°C.

- Heat pump (HP)

The role of heat pump in the heating system is to raise the thermal energy from a lower temperature level to

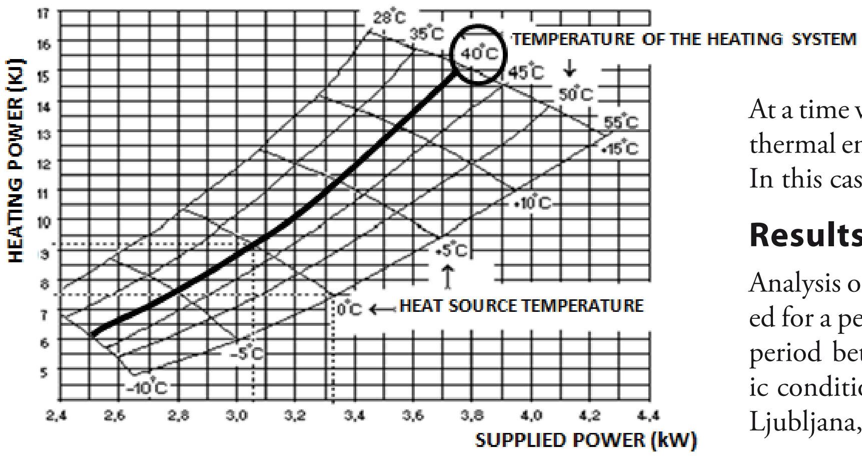


Figure 4. Diagram for determining COP.

a higher temperature level. COP (coefficient of performance) of heat pumps have been calculated using **Equation 2** for each heat source temperature according to **Figure 4** for the output temperature of the heating system (water flow) of 40°C. The temperature of the stored heat source in a latent heat storage device has varied depending on solar gains.

$$\mathrm{COP}_{heating} = \frac{Q_C + P_{HP}}{W_{HP}} \qquad (2)$$

where:
$\mathrm{COP}_{heating}$ Coefficient of performance for heating
Q_C Heat from a heat source (kWh)
W_{HP} Heat pump supplied energy (kWh)

- Low energy building

The installed system was used for heating of low energy building with the following characteristics:

Table 3. Characteristics of low energy building.

A [m²]	U [W/m²K]	T_i [°C]	$T_{syst.}$ [°C]
150	0.4	20	40

Calculation of the losses has been made by the **Equation 3**.

$$Q_{loss} = A \cdot U \cdot (T_i - T_e) \qquad (3)$$

where:
Q_{loss} Heat losses (kWh)
A Building envelope area (m²)
U Overall thermal transmittance of building (W/m²K)
T_i Internal temperature (K)
T_e External temperature (K)

At a time when the sun was not able to provide sufficient thermal energy secondary heating system is switched on. In this case the biomass boiler.

Results and analysis

Analysis of a complex heating system has been conducted for a period of heating season, which we define as the period between October and March. Data on climatic conditions have been obtained for the cities: Rome, Ljubljana, London and Stockholm.

The analysis showed that the maximum solar gains through the entire heating season are highest in Rome, the lowest in Stockholm, where during the months November, December and January they are almost zero. Most solar gains for all cities are obtained in March (**Figure 5**).

Heat losses in the heating season are the largest in Stockholm, and the smallest in Rome. For all the considered sites maximal losses are in January (**Figure 6**).

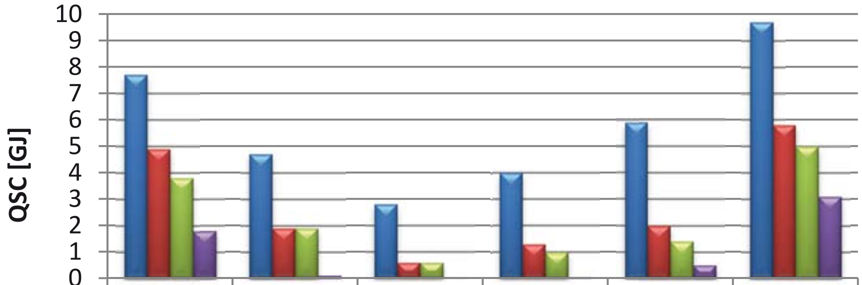
Figure 7 presents data of heat obtained with a heat pump by month during the heating season. From the diagram we can see that it is possible to get more heat in March. This fact is linked to a sufficient amount of sun energy during this month.

In given location the maximum possible average gain of heat for heating is in Rome. Maximum heat gain can be achieved in Ljubljana in March, but the lowest results are in Stockholm in November, December and January.

Efficiency of the heat pump or coefficient of performance (COP) gives us the ratio between produced heat and input energy (electricity). In the presented system COP reached values during the heating season between 0 and 5.69. Value of 0 means that there was no heat source from which heat pump could draw the heat, and raises it at a higher temperature level.

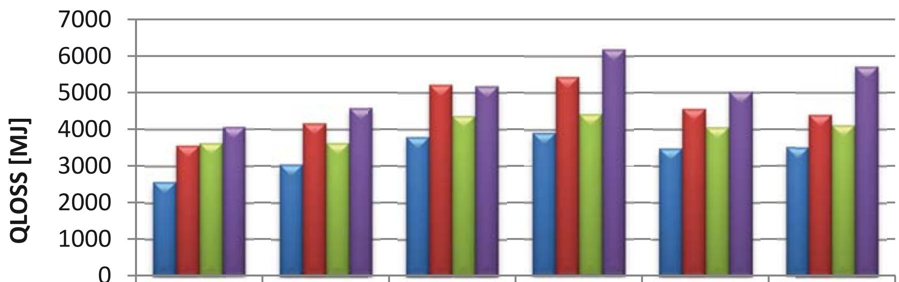
As presented in **Figure 8**, the value 0 was reached in Stockholm in December and January. The maximum value of COP is 5.69, which was reached in Rome, Ljubljana and London. In Rome this value was reached in the months October, November, February and March, in Ljubljana in October and March and in London in the months of October and March. In Stockholm, the maximum value of COP was 5.12.

Because through the all heating season there is not enough sun for heating and in consequence reheat-



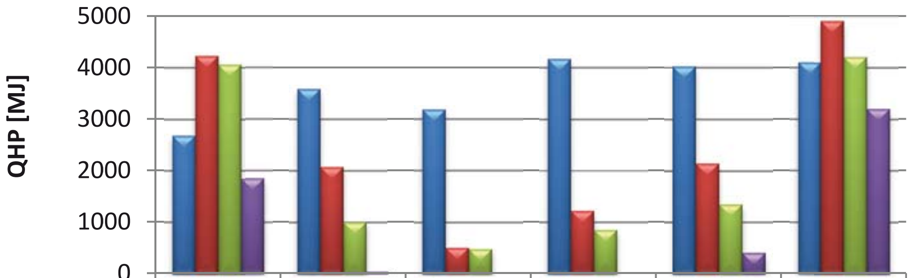
	OCTOBER	NOVEMBER	DECEMBER	JANUARY	FEBRUARY	MAREC
ROME	7,7	4,7	2,8	4	5,9	9,7
LJUBLJANA	4,9	1,9	0,6	1,3	2	5,8
LONDON	3,8	1,9	0,6	1	1,4	5
STOCKHOLM	1,8	0,1	0,01	0,03	0,5	3,1

Figure 5. Solar gains during the heating season - $Q_{SC.}$



	OCTOBER	NOVEMBER	DECEMBER	JANUARY	FEBRUARY	MARCH
ROME	2580	3059	3800	3929	3490	3519
LJUBLJANA	3570	4175	5227	5441	4566	4401
LONDON	3641	3641	4374	4442	4066	4121
STOCKHOLM	4070	4588	5187	6193	5031	5714

Figure 6. Heat losses during the heating season for the concerned city – $Q_{loss.}$



	OCTOBER	NOVEMBER	DECEMBER	JANUARY	FEBRUARY	MARCH
ROME	2679	3590	3187	4171	4026	4105
LJUBLJANA	4230	2076	508	1220	2150	4910
LONDON	4063	1006	486	852	1347	4211
STOCKHOLM	1853	44	0	0	413	3206

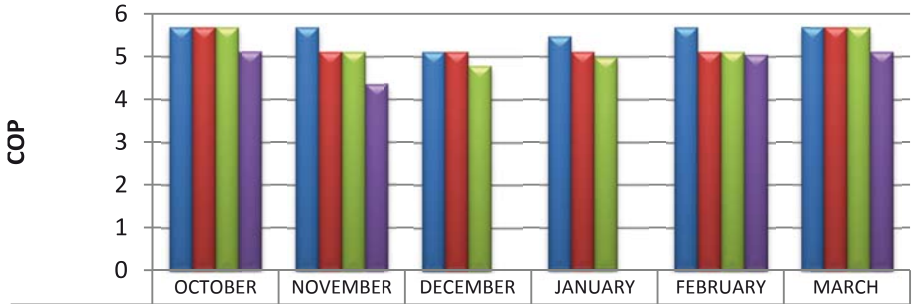
Figure 7. Heating with a heat pump in the heating season for the concerned city – $Q_{HP.}$

ing is needed. As a secondary source of heat biomass has been chosen. As shown in **Figure 9** the greatest need for the latter is in Stockholm. It is necessary through all the heating season. In Ljubljana, reheating is not required in the month of October, the highest value is reached in Stockholm in January. Through the heating season, the reheating is necessary at lower rates in Rome.

Conclusion

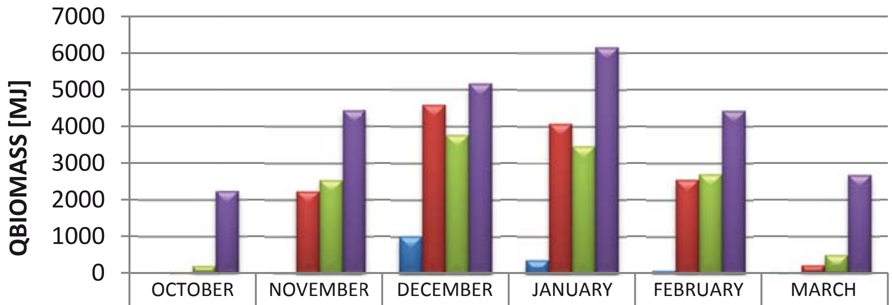
Because of unsustainable use of organic fossil fuels on which the energy supply of mankind relies, it is necessary to introduce advanced technologies for heating. Among the environmentally friendly technologies that are used for heating solar energy is one of them. Solar energy in combination with a heat pump and a latent heat storage device represents an economical and efficient heating system.

To the economy of this system contributes its geographical position in first place because of the following reason: more we move towards the equator, more solar energy is available and vice versa. When solar energy does not provide sufficient thermal energy to cover losses of the building we need reheating. In this case the heating system becomes less economical, since reheating is payable and solar energy is free of charge. With this kind of system one can use solar energy to provide approximately 50% of the annual heat requirements for a low energy house. The amount of sun also has an impact on the coefficient of performance (COP) of heat pump. In accordance with the geographical position the latter can reach a value of nearly 6.



	OCTOBER	NOVEMBER	DECEMBER	JANUARY	FEBRUARY	MARCH
ROME	5,69	5,69	5,12	5,48	5,69	5,69
LJUBLJANA	5,69	5,12	5,12	5,12	5,12	5,69
LONDON	5,69	5,12	4,79	4,99	5,12	5,69
STOCKHOLM	5,12	4,37	0	0	5,05	5,12

Figure 8. Maximum COP values during the heating season.



	OCTOBER	NOVEMBER	DECEMBER	JANUARY	FEBRUARY	MARCH
ROME	5	19	1029	374	88	26
LJUBLJANA	22	2248	4597	4090	2564	223
LONDON	209	2554	3781	3481	2717	505
STOCKHOLM	2239	4443	5175	6162	4435	2682

Figure 9. Additional heating with biomass in the heating season for the concerned city.

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