A comparison study of different latent thermal energy storage roles in heating systems with heat pump

Fran Torbarina*, Kristian Lenic, Anica Trp, Igor Wolf

[1] *University of Rijeka, Faculty of Engineering, Department of Thermodynamics and Energy Engineering*
**Corresponding author. Email: fran.torbarina@riteh.uniri.hr*

ABSTRACT

In this paper, energy efficiencies of two heating systems with heat pump, latent thermal energy storage (LTES) and solar collectors that are working in moderate continental climate conditions were numerically analysed and compared. The two considered LTES roles are the heat source for the heat pump (LTES on the evaporator side) and high temperature heat storage for directly supplying the consumers (LTES on the condenser side). In the first system, the purpose for using LTES is to provide more favourable working conditions for the heat pump by using previously collected and stored heat from solar collectors and increase its average coefficient of performance. In the second system, LTES is used for storing the collected solar heat on a sufficiently high temperature so it can be used directly for heating, avoiding the use of heat pump in those periods. The numerical investigations were performed for the whole heating period and the results were presented in terms of the share of renewable energy in total delivered energy, seasonal electricity consumption, system seasonal performance factor, total stored energy and average solar collector efficiency. System with LTES on the condenser side achieved a higher share of renewable energy and higher seasonal performance factor and also consumed less electricity than the system with LTES on the evaporator side.

Keywords: *latent thermal energy storage, phase change material, TRNSYS, dynamic system simulation.*

1. INTRODUCTION

With a decline in fossil fuel supply and due to the negative impact of burning fossil fuels on the environment, new efficient ways of producing and consuming energy that would suppress coal, petroleum and other harmful energy carriers are increasingly investigated. By proving the reliability of renewable energy sources, the majority of energy produced with conventional fuels could be replaced with renewable energy. The energy for heating takes up a share of 63.3% in total energy consumption in households in Europe [1] and recent predictions estimate an increase in primary energy consumption by 48% in the European Union, until 2040. [2]. This is why improvement of existing and development of new efficient heating systems represent a significant potential for preserving the environment and preventing further climate change. Solar energy is globally available renewable energy source and because of their simple design, solar thermal collectors represent a cost-effective means for harvesting solar energy [3]. However, periods of higher solar energy availability often do not coincide with periods of high energy demand. This has traditionally been solved with the usage of sensible thermal energy storages (STES) in which water was the storage medium. Thermal energy storages have become important elements in thermal energy systems and have been used to increase the thermal efficiency in different applications [4]. With the goal of improving the efficiency of thermal systems, recently latent thermal energy storages (LTES) with phase change materials (PCM) as storage medium have been increasingly investigated because of the PCMs' ability to store and release heat at a constant or nearly constant temperature. This can be beneficial in heating systems which use heat pumps, allowing for longer periods of higher evaporation temperatures in systems where LTES is used as a heat source for the heat pump, but also decreasing heat losses in systems where stored solar heat is directly supplied to consumers, compared to systems with STES [4-7].

Literature suggests that by using LTES it is possible to improve energy efficiency of heating systems that use heat pumps and increase renewable energy usage [8-11].

P. Droege and L. Quint (eds.), *Proceedings of the International Renewable Energy Storage and Systems Conference (IRES 2023)*,
Atlantis Highlights in Engineering 32,
https://doi.org/10.2991/978-94-6463-455-6_20

This paper focuses on analysis of various energy efficiency criteria for the two designs of heating systems with heat pump and LTES, most commonly found in literature [7,12,13]. The two designs have all the same elements, but the role of LTES in the system is different. In the first system, the LTES is used as a heat source for the heat pump to provide more favourable working conditions by using previously collected and stored heat from solar collectors. In the second system, LTES is used for storing the collected solar heat on a sufficiently high temperature so it can be used directly for heating, avoiding the use of heat pump in those periods.

2. SYSTEM MODELING

2.1. System description

Two configurations of systems with heat pump, LTES and solar collectors are considered. The system in which the heat from LTES can be used as a heat source for the heat pump, providing more favourable working conditions (System A) and the system in which the heat from LTES can be used directly for heating, avoiding the use of heat pump in those periods (System B). In literature, investigations with PCMs with different melting temperatures can be found, but generally, in systems where LTES is used as a heat source for the heat pump PCMs with melting temperatures lower than 30 °C are usually used [4,11,15,16] and in systems in which the heat from LTES can be used directly for heating, PCMs with melting temperatures higher than 40 °C are usually used [10,17-19].

The System A, schematically showed in Figure 1, operates in such a way that in periods with higher solar energy availability (T5-T3 > 5 °C), the circulation pump CP1 is switched on and the energy collected with solar collectors is stored in the LTES, while the heat pump operates as an air-source heat pump. When the temperature of the heat transfer fluid (HTF) at the outlet of the solar collectors drops below the temperature of the PCM inside the LTES (T5 < T3), the circulation pump CP1 is switched off. The regulation valve RV1 in not yet switched until temperatures of the two available heat sources are compared and it is determined which heat source could provide better operating conditions. If the temperature of the PCM is higher than the temperature of the outside air (T3 > T8), both regulation valves RV1 and RV2 are switched which enables the heat pump to use the heat from LTES as the heat source. When the HTF temperature at LTES outlet drops below the temperature of the outside air (T4 < T8), the regulation valves are again switched and the heat from outside air is again used as the heat source. Temperature of the HTF in inertial STES is maintained between 45 °C and 50 °C and the air temperature inside the building is maintained between 22 °C and 25 °C. The auxiliary heater is only rarely used when the final temperature of the HTF is less than 42 °C, for example during defrost cycles.

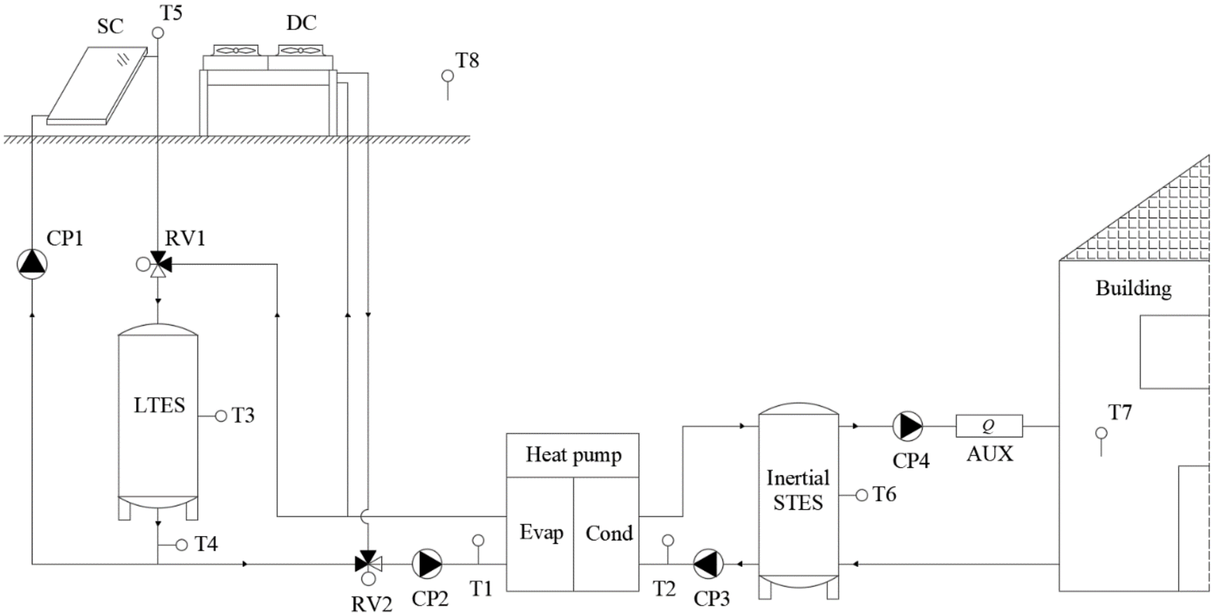

Figure 1 Schematic representations of the System A in which the heat from LTES can used as a heat source for the heat pump.

Figure 2 shows the schematic representations of the System B. The heat pump in System B always operates as an air-source heat pump. When the temperature of the HTF at the solar collectors' outlet is 5 °C higher that the temperature of the PCM inside LTES (T5-T3 > 5 °C) the circulation pump is switched on and the regulation valve RV1 is in the position for storing the collected solar heat in LTES. Heat pump is used for heating whenever there is enough available solar energy so that it can be stored in LTES. When the temperature of the HTF at solar collectors' outlet drops below the PCM temperature (T5 < T3), circulation pump CP1 is switched off. If at the end of a charging period the PCM temperature is higher than 45 °C, the regulation valves are switched so that directly using the heat from LTES is enabled.

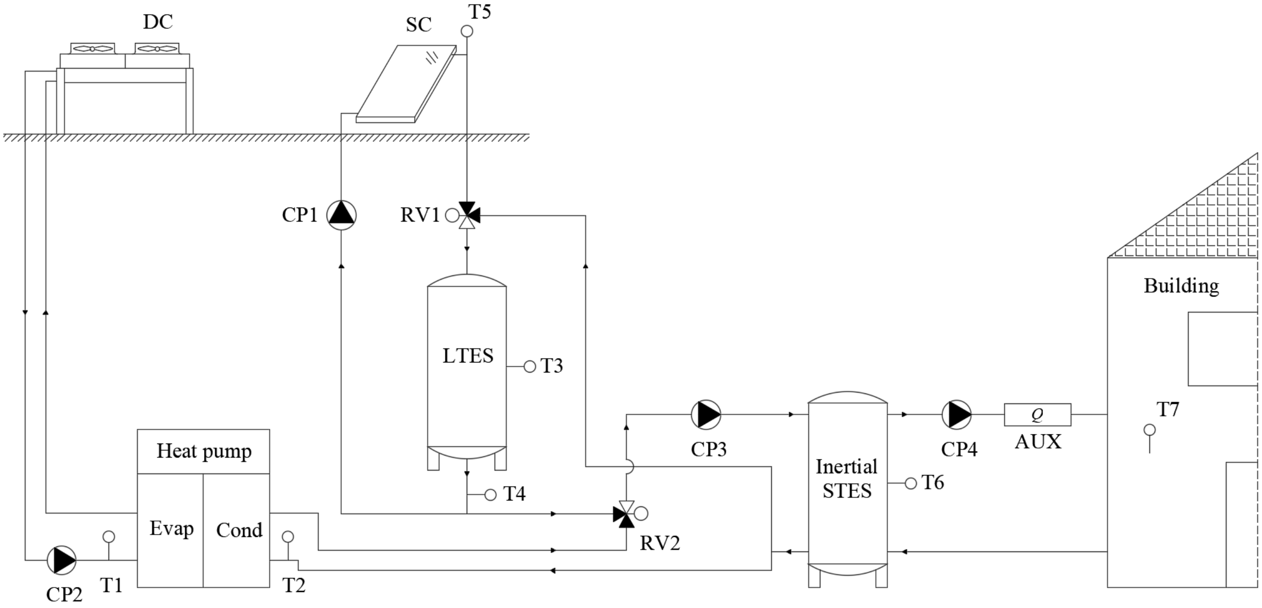

Figure 2 Schematic representations of the System B in which the heat from LTES is used directly for heating

The heat from LTES is used for heating until temperature of the HTF at the LTES outlet drops below 42 °C, when the regulation valves are again switched and using outside air as the heat source is enabled. This ensures that the HTF temperature is sufficiently high so as to avoid using the simultaneous use of the auxiliary heater and LTES.

2.2. System modelling

Thermal system performance analyses can be performed using dynamic system simulations which are based on modelling the production, distribution and transmission of energy, system control and transient thermal behaviour of buildings [20,21].

The simulation models analysed in this paper, for which the schematics are showed in Figure 1 and Figure 2 were created in Trnsys. Figure 3 shows the dynamic system simulation model of the System A in Trnsys. The LTES model is one-dimensional model, specifically developed model for Trnsys, which describes transient heat transfer between the HTF and the PCM in shell and finned tube LTES [14]. The operation of a single stage compression heat pump was modelled using an adapted, existing Trnsys heat pump model Type 927 wherein the steady state operating characteristics of the heat pump were taken from available performance data of domestic scale heat pumps [22]. Type 539 flat plate solar collectors' model was used for modelling the solar collectors and Type 511 was used for modelling a dry cooler.

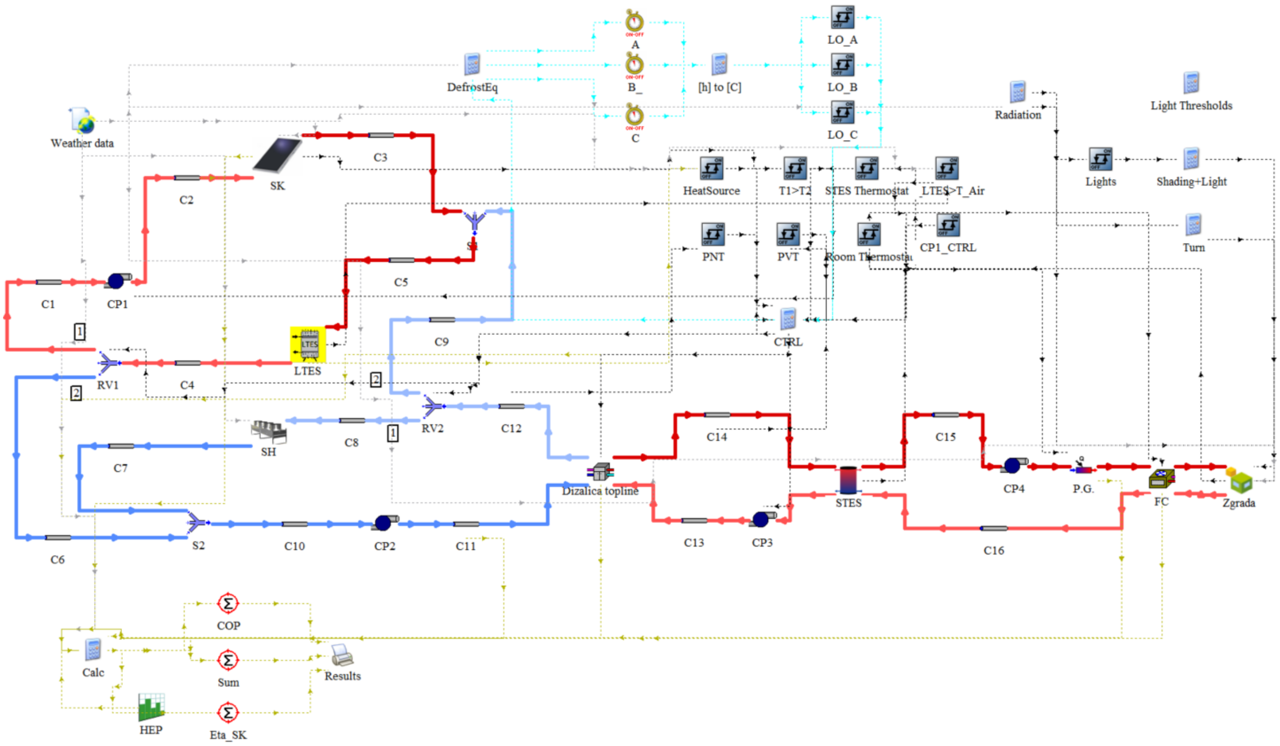

Figure 3 Dynamic system simulation model of the System A in Trnsys.

Meteorological data was read and interpolated in timesteps using Type 15 data reader and processor. Data for a location with temperate continental climate (Zagreb, Croatia) were used. Heat load was introduced in the model through the Trnsys subroutine TRNBuild, wherein the typical example of a building in Croatia from period 1971 to 1986 was considered, with the net usable area 200 m^2, organized in two floors. Figure 4 shows the transient heat load profile during heating period for the selected building and location.

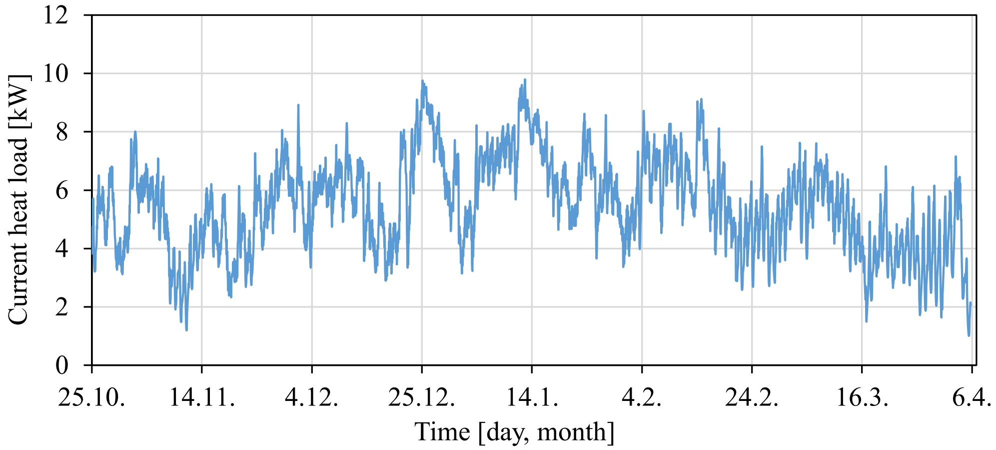

Figure 4 Transient heat load profile for the selected building during the heating season.

The highest heat load in the entire heating season was 9.89 kW and the total energy required for heating throughout the entire heating season was 50.5 GJ.

3. RESULTS AND DISCUSSION

Using the described dynamic simulation models, the performances of the two considered systems were analysed and compared.

3.1. Operating parameters

In order to investigate the differences in the operation of the two systems, transient temperature variations of the PCM temperature (T3), outside air temperature (T8), heat pump COP, solar radiation intensity (Q_{Sol}) and periods in which the heat pump works in the defrosting of the dry cooler regime are showed for two selected 5-days periods with different average temperatures of outside air and different total available solar energies.

Figure 5 and 6 show transient temperature variations of the PCM temperature (T3), outside air temperature (T8), heat pump COP, solar radiation intensity (Q_{Sol}) and periods in which the heat pump works in the defrosting of the dry cooler regime for the period from December 17 to 22 of the reference year, for System A and System B, respectively.

The average outside air temperature in the period from December 17 to 22 of the reference year was 6.1 °C, and the total radiated energy of solar radiation on the horizontal surface was 12.2 MJ/m^2.

Transient variations of the heat pump COP, showed in Figures 5 and 6 show that the COP is mostly higher in Figure 5, which refers to System A than in Figure 6 which refers to System B. This can be explained by the fact that the purpose of using LTES in System A is to provide a favourable heat source for the heat pump, with the aim of increasing its efficiency. On the other hand, the purpose of using LTES in System B is to use the stored heat directly for heating, avoiding the need to operate the heat pump in those periods. However, in order to be able to do so, it is necessary to store the heat at higher temperatures in LTES in System B than in LTES in System A. It can also be observed that the amount of available solar energy during the selected 5-days period in December was most of the selected time period large enough to store enough heat in the LTES in System A to enable more favourable operating conditions of the heat pump, but insufficient enough to use it directly for heating and avoid the use of the heat pump.

Figure 7 and 8 show transient temperature variations of the PCM temperature (T3), outside air temperature (T8), heat pump COP, solar radiation intensity (Q_{Sol}) and periods in which the heat pump works in the defrosting of the dry cooler regime for the period from March 7 to 12 of the reference year, for System A and System B, respectively.

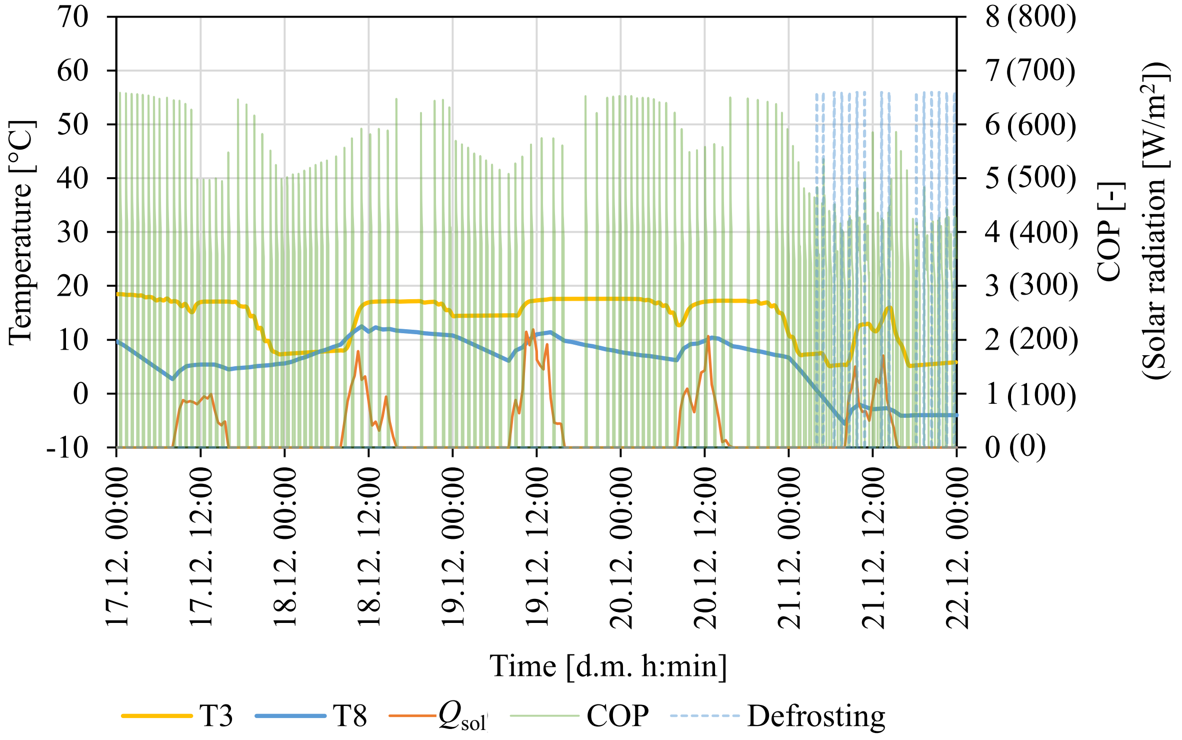

Figure 5 Transient temperature variations of the PCM temperature (T3), outside air temperature (T8), heat pump COP, solar radiation intensity (Q_{Sol}) and periods in which the heat pump works in the defrosting of the dry cooler regime (Defrosting), for the period from December 17 to 22 of the reference year, for System A

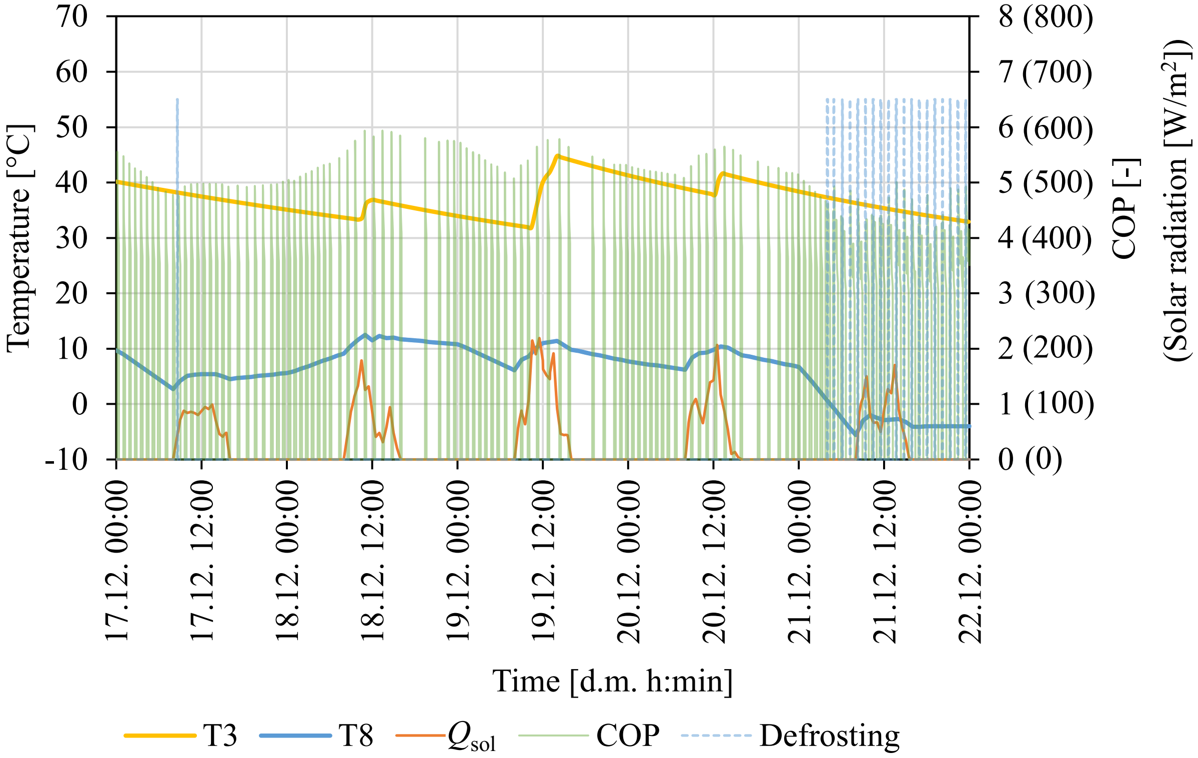

Figure 6 Transient temperature variations of the PCM temperature (T3), outside air temperature (T8), heat pump COP, solar radiation intensity (Q_{Sol}) and periods in which the heat pump works in the defrosting of the dry cooler regime (Defrosting), for the period from December 17 to 22 of the reference year, for System B

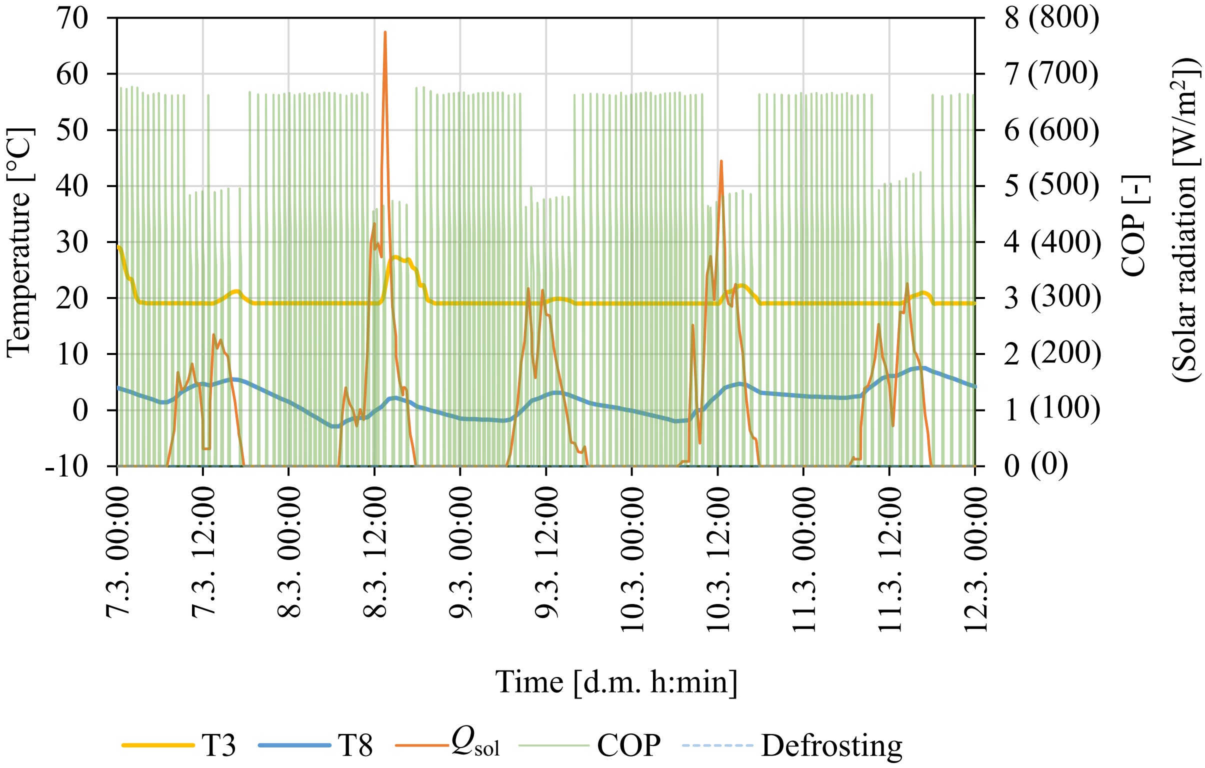

Figure 7 Transient temperature variations of the PCM temperature (T3), outside air temperature (T8), heat pump COP, solar radiation intensity (Q_{Sol}) and periods in which the heat pump works in the defrosting of the dry cooler regime (Defrosting), for the period from March 7 to 12 of the reference year, for System A

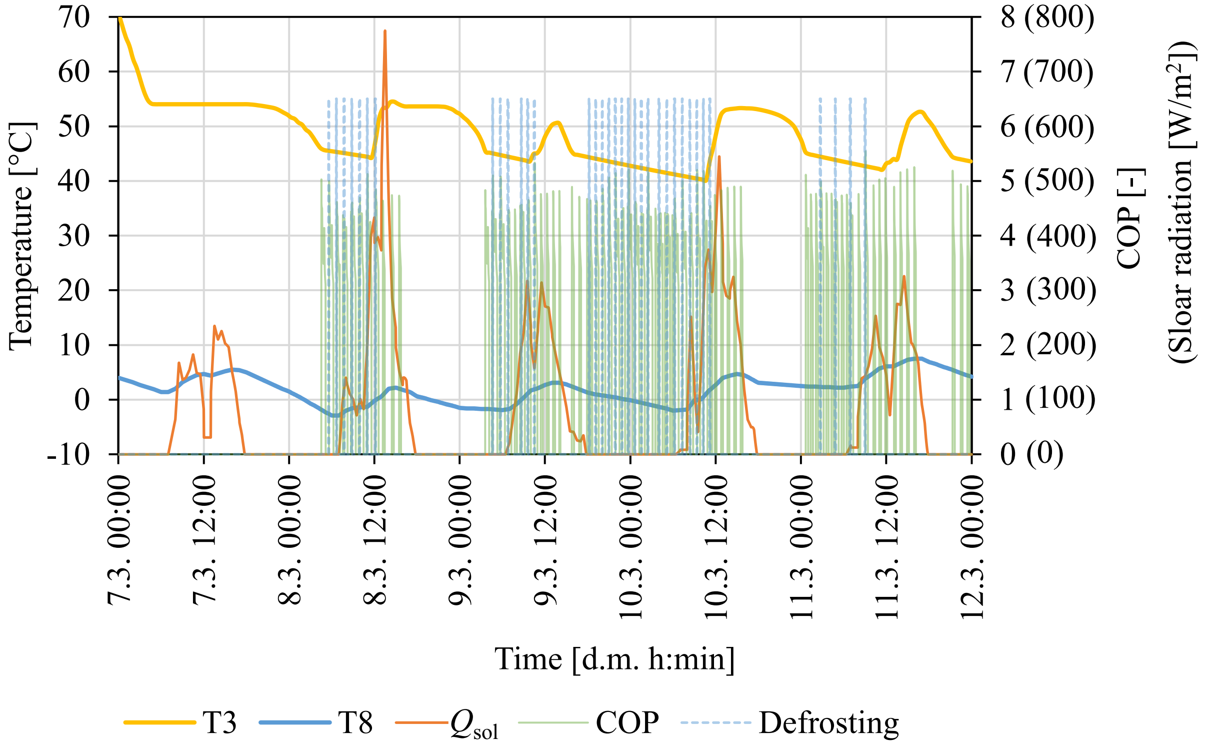

Figure 8 Transient temperature variations of the PCM temperature (T3), outside air temperature (T8), heat pump COP, solar radiation intensity (Q_{Sol}) and periods in which the heat pump works in the defrosting of the dry cooler regime (Defrosting), for the period from March 7 to 12 of the reference year, for System B

In the period from March 7 to 12 of the reference year, the average temperature of the ambient air was 1.9 °C, and the total radiated energy of solar radiation at horizontal surface was 34.2 MJ/m^2.

The heat pump power was defined in a way that its heating power in the conditions of the highest heat load will be sufficient to maintain the desired thermal condition in the building. However, when the heat pump switches to the defrost mode, it may happen that the energy required for heating must be met by the auxiliary heater. Figure 7 shows that for System A, during periods of low temperatures of outside air but with available solar radiation, the occurrence of defrost cycles can be completely avoided. However, as can be seen in Figure 8, during the entire first day and during half of the second day in the selected period from March 7 to 12, the use of the heat pump in System B was avoided, reducing the amount of consumed electricity. From the transient temperature variations of the PCM and transient variation of the solar radiation intensity, showed in Figure 8, it can be observed that during those days the amount of stored energy was large enough to maintain the desired thermal state in the building by only using the heat stored in the LTES. Due to low outside air temperatures in the period from March 7 to 12 of the reference year, the occurrence of defrost cycles can be observed for System B.

3.2. Performance criteria

Thermal performance of heating systems which use renewable energy sources was assessed with the following performance criteria:

1) The share of renewable energy in total delivered energy which is defined as

$$\varepsilon = \frac{E_{\text{renewable}}}{E_{\text{total}}} = \frac{E_{\text{total}} - E_{\text{non-renewable}}}{E_{\text{total}}} \quad (1)$$

where E_{total} is the total delivered energy, required to maintain the desired thermal stare inside the building and $E_{\text{non-renewable}}$ is the non-renewable used energy such as the electricity for operating the heat pump, auxiliary heater, circulation pumps and fans.

2) Total seasonal electricity consumption, calculated as the sum of the used electric energy during the entire heating season.

3) Total energy stored inside LTES, calculated as

$$Q_{\text{LTES}} = \sum_{\text{i}} \dot{m}_{\text{HTF}} \cdot c_{\text{HTF}} \cdot \left(T_{\text{HTF,in,i}} - T_{\text{HTF,out,i}}\right) \cdot \tau \quad (2)$$

where m_{HTF} is the HTF flow rate [kg/s], c_{HTF} is the HTF specific heat capacity [J/kgK], $T_{\text{HTF,in,i}}$ [K] and $T_{\text{HTF,out,i}}$

[K] are the HTF temperatures at the LTES inlet and outlet, and τ [s] is the simulation timestep.

4) Seasonal performance factor of the heat pump system

$$SPF = \frac{E_{\mathrm{total}}}{E_{\mathrm{non\text{-}renewable}}} \tag{3}$$

5) Average solar system efficiency

$$\eta_{\mathrm{sol}} = \frac{Q_{\mathrm{LTES}}}{Q_{\mathrm{sol,total}}} \tag{4}$$

where $Q_{\mathrm{sol,total}}$ is the total solar energy supplied to the solar collectors.

3.3. Comparison of energy efficiency assessment criteria for the two considered system configuration

In order to try to determine which of the two proposed system configurations performed better, a comparison of different energy efficiency assessment criteria was carried out. The results are showed in Table 1.

Table 1. Performance criteria for the two considered systems

Performance criterion	System A	System B
Share of renewable energy in total delivered energy	71.66%	72.89%
Total electricity consumption [GJ]	14.31	13.69
Stored energy inside LTES [GJ]	25.32	19.84
Seasonal performance factor SPF	3.53	3.69
Average solar collector efficiency	41%	32%

The results, given in Table 1, showed that during the selected duration of the heating season, for a location with temperate continental climate, System B, in which the heat from LTES could be used directly for heating, achieved larger share of renewable energy in total delivered energy and consumed less electricity than the System A, in which the heat from the LTES could be used as a heat source for the heat pump. Both stored energy inside LTES and average solar collector efficiency were higher in System A. Finally, the SPF was higher in System B.

4. CONCLUSION

During the two selected 5-days periods with different average outside air temperatures and different amounts of available solar energy, showed in Figures 5 to 8, advantages of both of the considered systems' configurations were observed. In periods with lower available solar energy, the amount of the stored energy was enough to use it as a heat source for the heat pump, enable more favourable operating conditions and increase its efficiency, but it was insufficient to directly use it for heating. On the other hand, during periods with higher available solar energy, the stored energy was enough to use it directly for heating, avoiding the use of the heat pump in System B in those periods, reducing the total electricity consumption and increasing the share of the renewable energy in the total delivered energy.

Finally, the data on the achieved values of the energy efficiency criteria throughout the entire heating season, given in Table 1 suggests that for the selected location with temperate continental climate, System B can achieve a better performance than System A.

AUTHORS' CONTRIBUTIONS

Conceptualization, F.T., K.L., A.T. and I.W.; methodology, F.T., K.L. and A.T.; software, F.T.; validation, F.T., K.L., A.T. and I.W.; formal analysis, F.T., K.L., A.T. and I.W.; investigation, F.T., K.L. and A.T.; resources, K.L., A.T. and I.W.; data curation, F.T.; writing—original draft preparation, F.T.; writing—review and editing, F.T., K.L. and A.T.; visualization, F.T., K.L. and A.T.; supervision, K.L. and A.T.; project administration, A.T.; funding acquisition, A.T. All authors have read and agreed to the published version of the manuscript.

ACKNOWLEDGMENTS

This work was supported in part by the Croatian Science Foundation under the project HEXENER (IP-2016-06-4095) and in part by the University of Rijeka under the project number "uniri-tehnic-18-69".

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