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Thermal energy autonomy study for a reference house equipped with PV panels, a heat pump and PCM storage elements

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Abstract. Despite their rapid growth, renewable energies cannot provide energy on demand, which is an essential requirement for heating buildings. To this end, we developed heat exchangers with Phase Change Materials that allow the on-demand charge, storage and discharge of thermal energy. In this paper we evaluate the storage capacities needed to achieve thermal energy autonomy. An existing reference house, meteorological data from MeteoSwiss and solar radiation intensity were used to evaluate the thermal needs and the solar power production for the year 2019. To heat the building an air-water heat pump is preferably powered by solar energy. The calculations have been performed from October to March. Using 1200 litres of PCM, a thermal autonomy of 100% was achieved for March and October. In February, November and December, 24 days could not reach a thermal autonomy. For the month of January that was studied in detail 15 days are self-sufficient. By increasing the PCM volume to 2'600 litres 5 more days become self-sufficient. To achieve total building heating autonomy, seasonal storage is necessary.

Keywords. Phase Change Material, building application, energy autonomy, thermal storage, active discharge, comfort temperature, thermal simulations

1. Introduction

Reducing the use of fossil fuels is one of the biggest challenges of the current energy transition. Since thermal needs correspond to up to 80% of the building energy consumption, using solar energy to heat buildings could provide key improvements in energy efficiency. However, while PhotoVoltaic (PV) panels can provide a high average power, their power is too low during high thermal demands, which makes energy storage essential. We propose to use Phase Change Materials (PCM) [1, 2, 3, 4] to store thermal energy during periods of high solar power and reuse it when the renewable power becomes insufficient.

The aim of this work is to assess the thermal energy autonomy of buildings equipped with this type of storage. We based ourselves on an existing building with 3 flats and calculated the heating needs according to the weather data of 2019. Renewable energy production was calculated for 74 m^2 of PV panels on the basis of data from the Swiss Federal Office of Energy for solar radiation power in 2019. The heating of the building preferentially uses this renewable energy and is provided by an air-water heat pump with a Coefficient of Performance (COP) of 3.

2. Thermal storage system

The thermal storage is provided by a PCM heat exchanger, shown in Figure 1, which consists of two fluid circuits and a PCM container located between them. Such a system has been built with micronal [5, 6] and recently with CrodaTherm24W PCMs. A fusion temperature (T_f) of 23°C was chosen to allow the storage of heat in winter and cold in summer. Each fluid has its particular function: in our case, hot water can circulate in the primary circuit and transfer its energy to a solid PCM by melting it. Since the container is isolated from the environment, thermal energy is stored in the liquid PCM. A circulation of air or water in the second circuit with a temperature lower than T_f causes the solidification of the PCM which releases its latent energy.

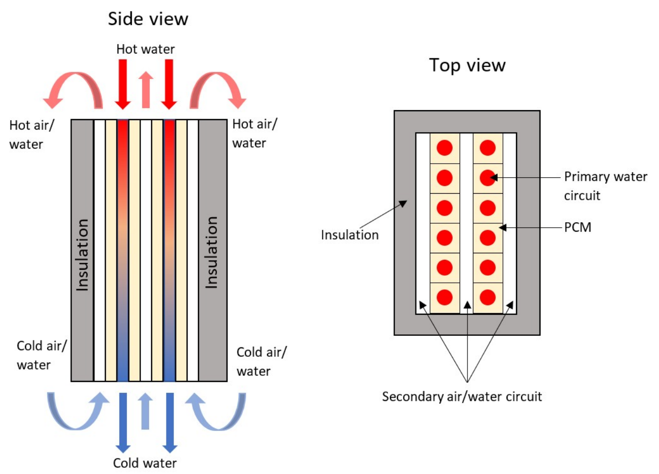

Figure 1. Side and top views of a PCM heat exchanger: the PCM container in yellow is located between the primary charge circuit (red) and the secondary discharge circuit (white). The charge/discharge processes are driven by the fluid (water or air) circulation in both circuits and the storage is assured by the presence of an insulation layer between the heat exchanger and the environment.

This method allows to store thermal energy from a renewable energy source by using a heat pump to heat the primary circuit and the PCM. The secondary circuit circulation is activated when the building needs to be heated and the container is loaded. Note that although the system can be used to store cold in the summer, this article focuses solely on storing heat to maintain a comfortable temperature during the cold seasons.

Figure 2 describes the overall system with the solar panels on the roof, an air-water heat pump and a PCM heat exchanger-accumulator. The latter can be placed as shown in the figure in the technical room with a water secondary circuit for underfloor heating. It can also be distributed in the building rooms with secondary air circuits, illustrated in Figure 1, allowing direct air heating in the rooms. The system has three operating modes:

1. PCM charge with a hot flow in the primary circuit melting the PCM.
2: thermal storage when no fluid is circulating in both circuits and $T_{PCM}>T_f$
3: PCM discharge caused by a flow with $T<T_f$ in the secondary circuit.

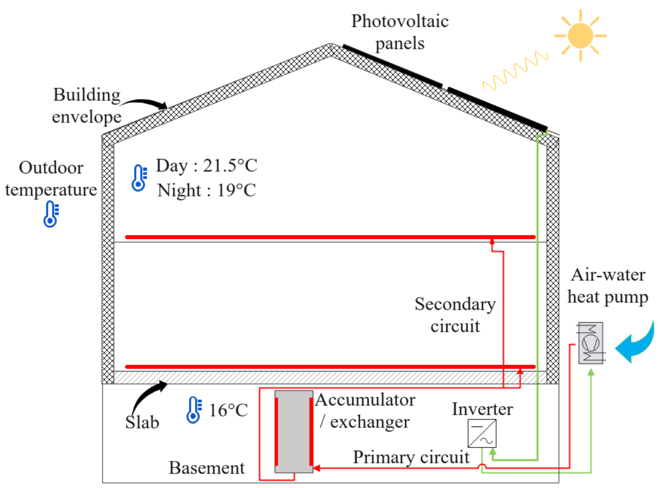

Figure 2. Schematic view of the building's heating and thermal storage. The solar panels feed a heat pump which allows the storage of thermal energy in a PCM heat exchanger. The secondary circuit is used to heat the building. The chosen comfort temperatures are 21°C during the day and 19.5°C at night.

3. Simulation

3.1. Simulated building

The building chosen for the simulation (Figure 3) is a Swiss Minergie standard certified house of 3 apartments located in Epagny in the canton of Fribourg. It was built in 2009 and houses a 5.5 room duplex with a living area of 123m^2 and two other 3.5 room apartments with a living area of 74m^2 each. The house has a semi-buried basement containing the technical room, the atomic shelters and the cellar. The building is constructed with triple glazed windows and 20 cm of perimeter insulation.
For this simulation, the heating system corresponds to an air-water heat pump with a COP of 3 powered by 74 m^2 of PV panels via an inverter with 90% efficiency. The panels are placed on the south side of the roof with a slope of 20°. As first approach, the COP of the heat pump was kept constant at 3, regardless of the outdoor temperature.

Figure 3. Reference building taken for the simulation.

3.2. Key factors of the simulation

We list here the value of the most important factors used for the simulation. Thermal transmittance U-factors of 0.18, 0.19, 0.2, 0.5 and 1.0 W/m^{2}K has been used for the building's façades, roof, ground floor slab, roller blind boxes and windows, respectively. Note that the basement is counted as an unheated room with a constant temperature of 16°C. The indoor temperature was considered to be 21.5°C during the day and 19°C at night. Daytime periods were defined as being between 6am and 6pm and night-time periods as between 6pm and 6am. Averages of the daytime and night-time temperatures was used to calculate the thermal requirements.

3.3. Weather data for the year 2019

The weather data used for this simulation come from two sources:

- the MeteoSwiss weather station located in Marsens, 7 km from the building. It indicates the temperature every three hours, which allowed us to calculate the day and night thermal needs.

- the PhotoVoltaic Geographical Information System (PVGIS) for the Solar irradiation data.

3.4. Hypothetical self-sufficiency based on monthly thermal needs and solar power production

The energy produced during a year is sufficient to ensure a heating energy autonomy. The renewable heating energy and the heating needs are shown in Figure 4 for each month. The thermal energy produced is higher than the monthly needs for all months except for January where it is slightly lower. As the calculations are carried out on a monthly total basis, strong disparities between days are not taken into account. These disparities increase the number of days with production lower than the thermal needs and reduce the energy autonomy. A daily based study of thermal needs and thermal energy production is necessary to have a precise vision of the potential for energy autonomy.

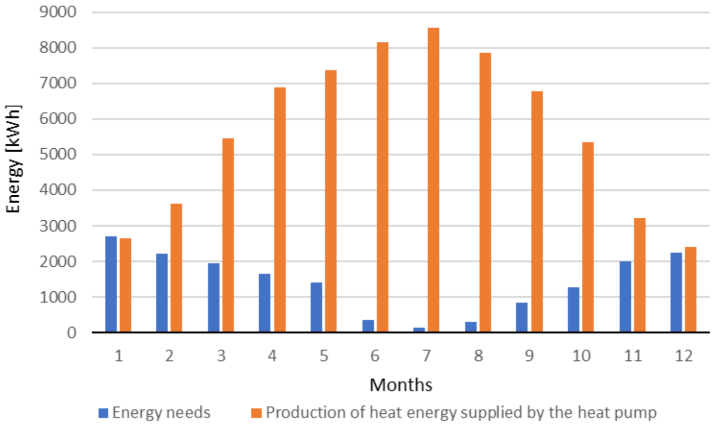

Figure 4. Monthly thermal needs and thermal energy production by means of a heat pump powered by PV panels.

4. Daily winter thermal analysis

December and January are the most critical months with the lowest solar production and highest thermal requirements. The daily thermal energy production and heating demand of January 2019 is shown in Figure 5.

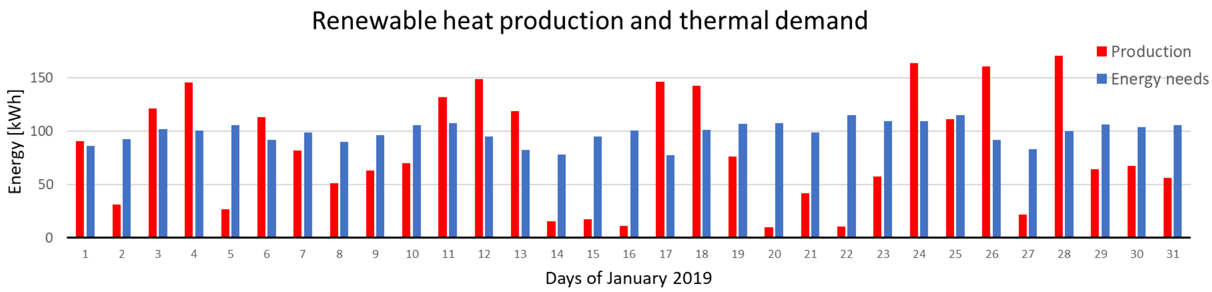

Figure 5. Daily heating energy production in red and thermal needs in blue for January 2019.

We notice that there are days when the thermal energy production is insufficient to guarantee the target temperature inside the building, such as from January 14 to the 16 and from January 19 to 23. Note that there is a phase shift of about 8 hours between the hours of high energy production and high energy consumption. This implies that for the night and early morning, thermal autonomy can only be ensured by the heat exchanger-accumulator. The heat exchanger must therefore store at least the nightly energy needs.

Based on Figure 5, we can see that the daytime energy production of January 1, 3, 4, 6, 11, 12, 13, 17, 18, 24, 26 and 28 is sufficient to cover the night-time needs which must be stored in the PCM. If the night-time needs correspond on average to 900 litres, 1050 litres of PCM are necessary to ensure an autonomy for the 14 days. For the other days, the renewable energy of several days is necessary. If the night-time needs can be obtained from two consecutive days, the storage capacity requirements slightly increase as for January 7 where 1150 litres PCM are required. If more days are needed, the storage capacity requirements increase sharply as for January 29 with a PCM requirement of 2600 litres. The graph in Figure 6 illustrates the number of autonomous days as a function of PCM volume. The red curve showing the number of autonomous days per litre of PCM indicates an optimum at 1050 litres, which corresponds exactly to the 14 days when the daily overproduction is greater than the night-time requirements.

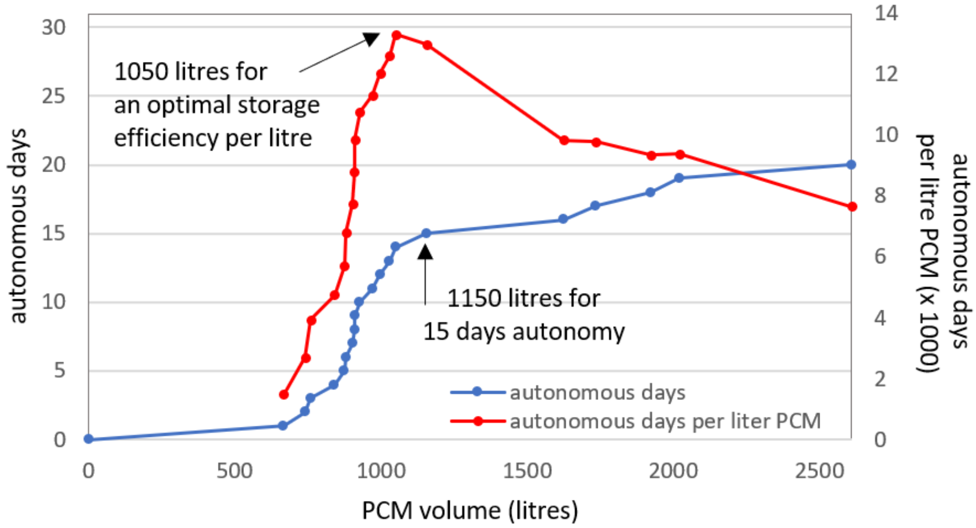

Figure 6. Thermal energy autonomy dependence on the PCM storage capacity in January 2019. The number of autonomous days is shown in blue and this number per litre PCM in red. A saturation of the storage efficiency is observed above 1150 litres.

For the month of January, a maximum of 20 days of thermal autonomy can be reached but this requires 2600 litres of PCM. For the remaining 11 days, the lack of photovoltaic production is too important and could only be filled by a seasonal energy storage. For the month of January, this storage corresponds to 500 kWh. For cost reasons, the simplest solution is to have a backup heating system for the critical days and this can be done by using energy from the grid to power the heat pump.

A less detailed analysis was undertaken for the other winter months. While March and October can achieve full thermal autonomy with PCM storage, a total of 24 days during November, December and February require external supply to ensure a comfortable temperature.

Note that we did not consider the thermal energy passing through the windows on the building south side. However, if this contribution is important for days with high photovoltaic production, it is limited on the critical days when the solar power is low. It should also be noted that the thermal inertia of the building has not been taken into account, it could reduce the thermal needs when a cold day follows a hotter day. This contribution would however be limited for the cold periods lasting several days.

5. Conclusion

We found that thermal autonomy can be achieved from March to October. In February and December, production is higher than demand, but due to the large variation in daily solar energy production, thermal energy autonomy cannot be ensured for each day. January displays an energy production slightly lower than the demand. For these last 3 months seasonal storage or backup heating is needed.

We found that by using 1000 litres of PCM with a latent heat of about 200 KJ/l, a large number of winter days become thermally self-sufficient. Due to very little autonomy improvement, adding extra litres of PCM is economically not interesting.

The simulations presented could be improved by adding the energy gain from radiation through the windows and by considering the total inertia of the building.

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