Heat storage in building mass and shifting potential of electricity demand in buildings with heat pumps

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Abstract. This study evaluates the potential of typical building structures to store heat and supply flexibility for electricity consumption by heat pumps. The theoretical potential of a hydronic underfloor heating to store heat and supply flexibility for electricity consumption by heat pumps is 0.16 kWh/m² at 4 K temperature swing. In real operation with a realistic controller, about 50% of this potential can be activated even during daytime with solar gains. For all cases the overall heat demand and the thermal comfort stay equal. A simple but universal rule could be: Independent from the insulation quality of the building, an intermittent increased heating control could merge two heating cycles of the demand-controlled mode to one, where the following waiting time increases by factor 1.5 to 2.

1. Introduction
Increasing use of heat pumps in buildings causes an additional load on electric grids. With a view to optimizing the management of their grid, the city of Zurich has therefore commissioned a study of the potential of heat storage in building mass and corresponding time management of the electricity demand of heat pumps. Typical building structures are investigated for their capacity to store heat and supply flexibility for electricity consumption by heat pumps. Therein, only buildings are evaluated in detail with a heat emission system that activates a part of the building structure. These are underfloor heating systems or thermally activated building structures (TABS). Radiator systems are excluded from detailed consideration, because relevant storage capacity is mostly not accessible due to manually set thermostatic valves and limited room temperature range. This paper gives an excerpt of a more comprehensive study report published in German. [1].

2. Methods
In the first part, a theoretical analysis shows the ability of building structures to store heat and summarises the physical principles involved. In the second part, detailed annual dynamic simulations with realistic controller operation show how much heat can be additionally stored or shifted under the constraint that the room temperatures are still within the same comfort band and also energy consumption stays equal. The paper finalises with an estimation of the heat storage potential for buildings owned by the city of Zürich on a daily basis.
3. Results of theoretical analysis

The first part of the results depict basic physical principles of heat storage in the activated building structure and their mathematical description. The increase or decrease of heat stored in a building element depends on the specific heat storage capacity and the temperature difference $\Delta \theta$. The change of stored heat $Q_i$ caused by an impressed temperature difference can be calculated as shown in equation (1). For the transient case, the temperature differences $\Delta \theta$ and the heat flows $q$ are variable. Hence, also the stored heat is temporally variable. The periodic penetration depth $\sigma$ according to equation (2) is a measure of the range of temperature fluctuations (heat waves) into a material layer with a periodic excitation of the period $T$. $\sigma$ corresponds to the depth in an infinite homogeneous building material at which the amplitude of the sinusoidal temperature fluctuation on the surface is reduced by the factor $e$ ($e = 2.817$) [2] [3].

$$Q_i = c \cdot \rho \cdot V \cdot \Delta \theta \quad (1)$$

$$\sigma = \frac{\lambda \cdot T}{\sqrt{\pi \cdot \rho \cdot c}} \quad (2)$$

with: $Q_i$ inner heat (kJ) $c$ specific heat capacity (kJ kg$^{-1}$K$^{-1}$)
$\rho$ density (kg m$^{-3}$) $\Delta \theta$ temperature difference (K)
$V$ volume ($m^3$) $\sigma$ periodic penetration depth (m)
$T$ period of oscillation (s) $\lambda$ heat conductivity (kWm$^{-1}$K$^{-1}$)

3.1. Underfloor hydronic heating

The construction of an underfloor hydronic heating is assumed as a reinforced concrete floor with a floor screed with underfloor hydronic heating. Only the floor screed is considered as an activated storage element, since it is thermally insulated from the concrete structure by the impact sound insulation. The pipes of the underfloor heating are laid in the center of the floor screed. Table 1 shows the element structure [2]:

| Element                     | thickness | heat conductivity $\lambda$ (Wm$^{-1}$K$^{-1}$) | spec. heat capacity $c$ (J kg$^{-1}$K$^{-1}$) | density $\rho$ (kg m$^{-3}$) |
|-----------------------------|-----------|-----------------------------------------------|-----------------------------------------------|-----------------------------|
| carpet                      | 0.012     | 0.08                                          | 1000                                          | 300                         |
| floor screed                | 0.080     | 0.87                                          | 1100                                          | 1800                        |
| impact sound insulation     | 0.030     | 0.05                                          | 1500                                          | 150                         |
| concrete                    | 0.240     | 1.80                                          | 1100                                          | 2400                        |

Since the pipes of the underfloor hydronic heating are placed in the middle of the floor screed, heat distributes equally to both sides and material thickness to one side is 40 mm. The periodic penetration depth according to equation (3) is bigger than the activated material layer. Hence, the specific transient heat capacity can be calculated as shown in equation (4).

$$\sigma = 0.11 \ m \quad \frac{\sigma}{\sqrt{2}} = 0.08 \ m \ > \ 0.04 \ m \quad (3)$$

$$C_{F,24h} = c \cdot \rho \cdot d = 1100 \frac{J}{kg \cdot K} \cdot 1800 \frac{kg}{m^3} \cdot 0.08 \ m = 158400 \frac{J}{m^2 \cdot K} = 0.04 \frac{kWh}{m^2 \cdot K} \quad (4)$$

The conditions for compliance with the thermal comfort according to SIA 180:2004 [4] allow a maximum temperature difference of 4 K in the comfort range where not more than 10% of the persons are allowed to be dissatisfied. Using this temperature difference, the specific daily stored energy in the floor screed can be calculated as:
3.2. Conclusion of theoretical analysis

Static calculations based on a day cycle result in a specific dynamic heat storage capacity of 0.04 kWh/m²/K for underfloor heating and 0.28 kWh/m²/K for TABS. Considered are the heat capacity and conductivity of the building elements and the periodic penetration depth for a daily temperature swing. A simplified dynamic simulation with repetitive boundaries results in a comparable value of 0.50 kWh/m² for TABS at a 2 K temperature oscillation and for underfloor heating of 0.16 kWh/m² at 4 K temperature oscillation. Hence, the heat stored in the floor of a detached house with 200 m² and underfloor hydronic heating with a temperature oscillation of 4 K corresponds to a technical storage with a volume of 2.76 m³ with a temperature lift of 10 K.

4. Detailed simulation results

Aim of the detailed simulations is to evaluate the heat storage potential of building elements in real operation with realistic controller operation and under realistic boundaries. The objective here was not to evaluate different control strategies like in [5], but to estimate a realistic heat storage potential and derive boundaries under which thermal comfort and heat demand stay equal. These boundaries are to be described in a way that it is easily understood by the all people involved in the building process – from heat pump manufacturer to the installer. Furthermore, a simple but as far as possible general rule should be derived that characterises the potential usage of the building mass with respect to classical heat pump operation. Hence, detailed annual simulations were carried out for a reference building with three insulation qualities, with two heat transfer systems (floor heating & TABS) and two control strategies (outside temperature-controlled return flow temperature heating curve & flow temperature heating curve with zone temperature control). This paper presents only the results for the new building.

The building model consists of four thermal zones with 25 m² floor area each. Figure 1 shows the arrangement of the thermal zones on the left side and the construction of the floor elements with the two different heat emission systems on the right side.

![Figure 1. Left: 4-zone building model, right: construction of ceiling element with underfloor hydronic heating and with TABS](image_url)
temperature heating curve with closed-loop room temperature control (cl-ctrl). The second hydraulic concept is a simplification of this system, where the closed-loop room temperature control and hydraulic storage are cut out. This second system uses only an open-loop room temperature control (ol-ctrl) via return flow heating curve. For all simulations average climate data for Zürich are used.

In the system with the controller with outside temperature-controlled return flow heating curve (ol-ctrl), a hydraulic adjustment is made so that the same temperatures prevail in all four zones. For time intervals with increased heating mode (building structure charging process), the heating curve of the building is increased in the control logic so that additional heating operation takes place (ol-ctrl-inc). The control logic sets a negative off-set to the heating curve if the heating should be reduced.

If the heating power is set via closed-loop room temperature control (cl-ctrl), the room temperatures must also be measured and fed back into the control. In order to achieve the desired set point temperatures in the zones, the four mass flows of the zones are controlled individually. A hydraulic storage separates the heat generation circuit with the heat pump from the heat distribution in the four zones. The flow temperature is controlled as a function of the outside temperature and defined by the heating curve. For the increased thermal loading of the building structure (cl-ctrl-inc), the increased heating operation is achieved by increasing the set room temperature and raising the heating curve.

Figure 2. Schematic principle for the heating system with room temperature control

The activation time for an increased heating operation is set between 10:00 - 17:00 o'clock. This means that the increased heating mode is unblocked at 10:00 and additional heat can be buffered in the building structure. On the one hand, the largest PV yield for possible own use occurs during this period; on the other hand, passive gains from solar irradiation are to be expected during this period. Since the thermal comfort must always be fulfilled, the choice of this time interval will result in a conservative estimation of the potential amount of heat buffered in the building structure. Activation of the boosted heating operation at another time during the day, e.g. in the late evening, would be under more favorable conditions and allow for a bigger amount of stored heat.

Figure 3 shows the simulation results for the new building with hydronic underfloor heating. It can be seen for both hydraulic concepts that the energy demand stays nearly equal for both control strategies, the demand control (cl-ctrl & ol-ctrl) as well as the intermittent increased heating control (cl-ctrl-inc & ol-ctrl-inc). Furthermore, also the thermal comfort is equal for both control strategies. In one case, the annual performance factor of the heat pump JAZ can even be increased for the intermittent increased heating control. These results show that heat generation is only shifted while energy demand and thermal comfort remain equal.
Figure 3. Simulation results for the new building with hydronic underfloor heating

Figure 4 shows the dynamic evolution of the heat stored in the floor element, the thermal state of charge. During the three days shown, the heat pump runs 4-6 times a day to heat up the floor, while the outside temperature is in a range around 0°C. In this case, the amount of heat transferred to the floor screed during one heating cycle in demand control mode (ol-ctrl) is about 4 kWh. In the intermittent increased control mode (ol-ctrl-inc), the amount of heat transferred to the floor screed can be increased to 6 - 7 kWh. But as consequence to the increased heat transfer, also the waiting time for the next heat up cycle is increased from about 5 hours to 7 – 10 hours.

Figure 4. Comparison of stored heat in the floor for newBldg: ol-ctrl versus ol-ctrl-inc

A charging cycle that occurs at the same time as in a continuous but with increased operation may only lead to a 50% increase in electricity consumption and heat load. However, if the component structure cools down to such an extent that one charging cycle is skipped and made up for in the next one, which is possible in the new building, the increase of electricity consumption for one cycle is significantly greater.
In the renewed building with floor heating (renBldg), the amount of heat released (3 to 6 kWh\textsubscript{th}) and the electricity consumption (0.9 to 1.8 kWh\textsubscript{el}) of one cycle can be roughly doubled. Here, the waiting time for the next possible charging cycle is relatively short with about two hours. Also for the well-insulated building (ecoBldg) with TABS, the amount of heat stored during one cycle can be doubled (4 to 9 kWh\textsubscript{th}), but here the waiting time and increase of waiting time is significantly longer with 8 hours to 14.5 hours.

Generally it can be said that, independent from the insulation quality of the building, an intermittent increased heating control could merge two heating cycles of the demand controlled mode to one and as consequence, the waiting time after this increased heating cycle is then also increased by factor 1.5 to 2. If the flow or return flow temperatures stay in the range of ± 2 K, then also the overall heat demand and the thermal comfort can be expected to stay equal.

5. Estimation of heat storage potential

Mainly massive buildings with heavy, thermally activated floors and ceilings are suitable for the managed buffering of heat in the building structure. This requires a strong thermal coupling between building mass and room air. The heat is stored mainly in the floor and in the ceiling. Buildings with beamed ceilings, suspended ceilings or raised floors are therefore less suitable for heat buffering.

Based on these assumptions, the building park owned by the city of Zurich has a total heat storage potential of about 690 MWh\textsubscript{heat}/d, of which around 500 MWh\textsubscript{heat}/d is accounted for by office buildings with TABS and around 190 MWh\textsubscript{heat}/d by residential buildings with underfloor heating. If one assumes that this daily displaceable heat potential of 690 MWh\textsubscript{heat} would be generated by heat pumps only, then (by the division with a typical seasonal performance factor of four) one would get a displaceable electrical energy of 172 MWh/d.

6. Conclusion

The study estimates the potential of typical building structures to store heat and supply flexibility for electricity consumption by heat pumps. The theoretical analysis depicts the specific dynamic heat storage capacity of floor constructions, whereas the simulation study elaborates basic control requirements for heat shifting without increasing the overall heat demand or generating discomfort. It is demonstrated that massive buildings with thermally activated floors and ceilings may effectively be suitable for managed buffering of heat in the building structure. The study shows results for on/off controlled heat pumps, but the results can also be applied to continuously capacity controlled heat pumps.

References

[1] Müller A., Bichsel J., Afjei T., Dott R., Gebäude als Wärmespeicher – Nutzung der thermischen Speicherfähigkeit von Gebäuden zum Lastmanagement von Elektrizitätsnetzen, Stadt Zürich Amt für Hochbauten, Zürich, 03-2018
[2] B. Keller und S. Rutz, Fakten der Bauphysik zu nachhaltigem Bauen, Zürich: vdf Hochschulverlag AG an der ETH Zürich, 2011.
[3] Wärmetechnisches Verhalten von Bauteilen - Dynamisch-thermische Kenngrössen - Berechnungsverfahren (ISO 13786:2007), Zürich: Schweizerischer Ingenieur- und Architektenverein, 2007.
[4] SIA180 Wärmeschutz, Feuchteschutz und Raumklima in Gebäuden, Zürich: Schweizerischer Ingenieur und Architekten Verein SIA, 2014
[5] Fischer D., Bernhardt J., Madani H., Wittwer C., Comparison of control approaches for variable speed air source heat pumps considering time variable electricity prices and PV, Applied Energy, October 2017, DOI: 10.2016/j.apenergy.2017.06.110