Available online at www.sciencedirect.com

ScienceDirect

Energy Procedia 78 (2015) 806 – 811

Energy Procedia

6th International Building Physics Conference, IBPC 2015

An optimization strategy for scheduling various thermal energy storage technologies in office buildings connected to smart grid

Christian Finck[a,*], Rongling Li[a], Wim Zeiler[a]

[a]*Eindhoven University of Technology, de Rondom 70, 5612 AP Eindhoven, The Netherlands*

Abstract

An optimization strategy for scheduling various thermal energy storage capacities in an office building is investigated. An activated building wall (building thermal mass), a phase change material (PCM) tank, a hot water (HW) tank and a thermochemical material (TCM) storage are simulated and their charging and discharging behavior are optimized. Therefore, a case study is performed using a very simplified room model (office) and typical weather data for the Netherlands. To model the storage's scheduling behavior for control and optimization, a resistance capacitance (RC) network is applied. The RC network represents the critical energy storage parameters for optimization and control. The minimization of electricity costs is defined as optimization objective towards the Smart Grid. Cost saving potentials up to 12.5 % are calculated using an electrical heat pump and a solar collector for heating the room and charging the thermal energy storage capacities.

Peer-review under responsibility of the CENTRO CONGRESSI INTERNAZIONALE SRL

Keywords: "Thermal energy storage; optimization; scheduling; office building; smart grid"

1. Introdution

To reduce power peaks in electricity networks and to cover the mismatch between the energy demand of buildings and the supply of (renewable) energy, thermal energy storage (TES) technologies combined with electrical heat pumps (HP) can be applied. The most promising technologies to store thermal energy in buildings are the building thermal mass (BTM), water buffers, ice buffers, phase change material tanks and thermochemical material tanks [1].

* Corresponding author. Tel.:+31(0)402473667
E-mail address: c.j.finck@tue.nl

Peer-review under responsibility of the CENTRO CONGRESSI INTERNAZIONALE SRL
doi:10.1016/j.egypro.2015.11.105

The integration of these technologies in building energy management systems (BEMS) isn't sufficiently investigated. There exists no clear representation of the critical energy storage parameters for the model control and there is no clear structure for the model control & optimization of energy storage capacities.
In this paper, we introduce the most critical energy storage parameters for the model control & optimization. For the representation of these parameters a resistance capacitance network is used to establish an optimization structure for the model control of TES in buildings. The optimization strategy is to minimize the electricity costs of the heat pump that is used for space heating and charging of various thermal energy storages.

Nomenclature

C_{el}	electricity price [Euro/kWh]	Q	heat input to node n [J]
COP	coefficient of performance [-]	$R_{n,n\pm1}$	thermal resistance between node n and node n±1 [K/W]
C_n	capacity of node n [J/K]		
J	total electricity energy costs [Euro]	T_n	temperature node n [K]
P_{HP}	electrical power heat pump [W]	η	energy efficiency [-]

2. Model initiation

The critical control parameters of the storage capacities included in the model, are the state of charge, self-discharge, charging- and discharging energy efficiency, charging and discharging temperature as well as the storage capacity. The aim of the model was to investigate the charging and discharging behavior of the TESs. Therefore, a very simplified room model was used to simulate the energy demand (Figure 1).

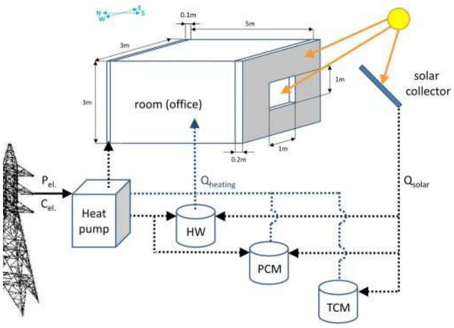

Fig. 1. Simplified room model.

Table 1. parameters of separate TES units.

	HW	PCM	TCM
Mass [kg]	25	25	25
Energy density [kJ/kg]	125	250 [2]	1000 [3]
Charging temp. (in) [°C]	50	50 [2]	80 [4]
Discharging temp. (in/out) [°C]	25/35	25/35	25/35 [4]
Min. charging efficiency	0.87	0.87	0.86 [4]
Min. discharging efficiency	0.87	0.65	0.58 [4]

The room model consists of an outer wall, a volume of air and an inner wall. No further thermal capacities such as the floor, the ceiling or residual walls, have been considered. The outer wall (insulating lightweight concrete, heat conductivity of 0.14 W/(mK), density of 480 kg/m^3, specific heat of 1000 J/(kgK) [5]) is exposed to the ambient air. Incident solar radiation heats up the outer wall as well as the room through the window. The inner wall (structural lightweight concrete, heat conductivity of 0.61 W/(mK), density of 1600 kg/m^3, specific heat of 921 J/(kgK) [5]) can be actively heated at a maximum power of 10 W/m^2. This value is in a good agreement to the standard values of TABS (thermal activated building systems) that are embedded water based surface heating system [6]. The inner wall has been assumed to be a TAB system. Both walls embody the characteristics of a typical BTM storage, the outer wall as a passive thermal storage and the inner wall as an active sensible thermal storage. Additionally, separate units (tanks) of hot water, PCM and TCM were assumed. The basic parameters associated with these thermal energy storage units are specified in Table 1.

3. Model description & optimization strategy

A lumped parameter model was implemented using a resistance capacitance (RC) network as main structure (Figure 2a). RC networks that are based on a system of ordinary differential equations, have been widely used for simplified building modeling offering low computational effort [7]. In this paper, we use a RC network in the general form:

$$\frac{dT_n}{dt} = \sum \frac{\Delta T}{C_n R_{n,n\pm1}} \quad (1)$$

The upper part of figure 2a depicts the room model. The room, the inner wall and the outer wall are represented by temperature nodes that are connected to each other using the thermal resistances R_{wall} = 0.16 K/W and R_{room} = 0.11 K/W. The lower part of figure 2a describes the three different heat storage capacities (HW, PCM, TCM) that can deliver heat to the room. The temperature node of HW, PCM and TCM are theoretical representations of the state of charge in which the specific heat capacity of each storage is adapted to its energy density.

The heat pump can deliver heat to the room, to the inner wall, to the HW tank and to the PCM tank. The resistances of the piping systems between the heat pump and the room, the inner wall, the HW tank and the PCM tank have been assumed to be zero. For heating the room, no additional radiator resistance has been taken into account. For heating the inner wall, no construction of the TAB system such as the dimension of the embedded water pipes has been considered.

The TCM unit cannot be heated by the HP because of a charging temperature of 80 °C (assumption for a closed TC system [4]) that is in general higher than the maximum output temperature of the HP. To charge the TCM tank a flat plate solar collector (collector surface = 2 m^2) was included that can also heat the HW and PCM unit. No additional piping resistances have been assumed between the solar collector and the storage tanks. Depending on the charging temperature, the solar collector efficiency varies between 40 and 55 %. Both tanks HW and PCM are insulated and $R_{insulation}$ is 3.13 K/W. The energy loss of the TCM unit is not considered since the heat is stored in a chemical reaction [8].

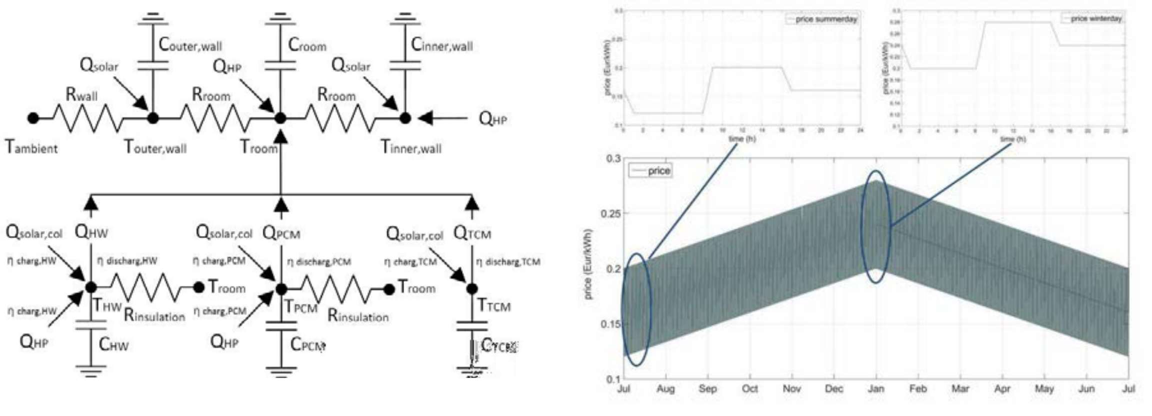

Fig. 2. (a) RC network, room & thermal energy storage capacities; (b) Yearly electricity price function.

The RC model was converted into a linear optimization problem using Matlab. The optimization algorithms that were applied are interior-point and dual-simplex. The objective of the optimization was to minimize the total electricity costs J.

$$min\, J = \sum_{t=1}^{N} (C_{el}(t) \cdot P_{HP}(t) \cdot \Delta t)\,; \quad N = 8760\, h; \quad \Delta t = 1\, h \quad (2)$$

Equation (2) includes a price function (figure 2b) multiplied by the power of the HP. The price function has a daily and a seasonal change representing the Smart grid. The daily change is based on proposed Time-of-Use (TOU) rates [9] with Off-peak, On-peak and Mid-peak energy charge rates. The seasonal electricity price was assumed to increase in winter and decrease in summer.

A whole year simulation was performed starting in summer and using the ambient temperature and the solar radiation from typical Dutch climate (weather data DeBilt from 2010 to 2011). One of the main optimization constraints is the room temperature with a lower bound in the heating period at 21 °C [10] for the working time in the office.

$$T_{lower\ bound,room}(t) = \begin{cases} \geq 21\,°C, & if\ \ 6.00\ \leq\ t\ \leq 18.00; t \neq Sunday; t \neq July; t \neq last\ week\ December \\ < 21\,°C, & elsewhere \end{cases}$$

The maximum temperature for heating the inner wall was set to 28 °C [11]. The maximum electrical power of the HP is 200 W for heating the room (case 1-9), additional 200 W for heating the HW unit (case 3,5) and the PCM unit (case 6,8). The heating of the inner wall (TABS) by the HP was limited to 90 W (9 m² of wall surface, 10 W/m² maximum power). In order to simulate a changing COP of the HP, a function depending on the ambient temperature was implemented.

$$COP_{HP}(T_{ambient}) = \begin{cases} 3, & \max(T_{ambient}) \\ 1.5, & \min(T_{ambient}) \end{cases}$$

4. Simulation results

To compare the optimization results, a reference case was simulated using the HP to heat the room. The upper part of figure 3 depicts the whole year temperature distribution of the ambience, room, inner wall and outer wall. The resulting necessary HP electrical power can be seen in the lower part of figure 3 with a maximum peak of 150 W in the beginning of January just after the Christmas holidays.

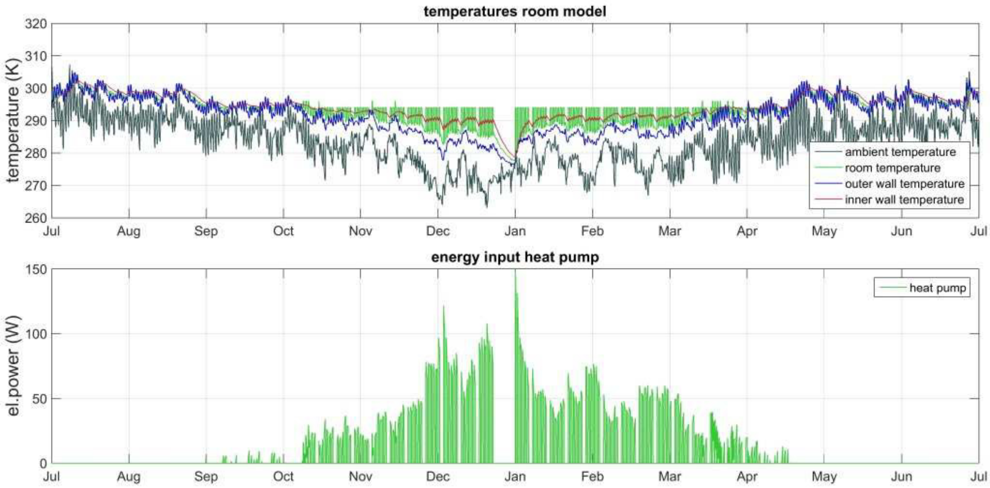

Fig. 3. Results reference case – heat pump is heating the room

All simulated cases are based on the price function from figure 2b. The total electricity costs for the 1st case (reference case) are 19.2 Euro and the total electrical energy consumption is 0.283 GJ (Table 2).

The cases 2 to 9 were optimized in terms of minimizing the electrical input for the HP (Table 2). Heating the inner wall (2nd case) during low cost periods, in this regard, can result in cost savings of 7.9 %, but also leads to an increase of the electrical energy consumption of 12.1 %. This is based on higher energy losses from the room to the ambience that cause from elevated temperature levels of the inner wall and the room during unoccupied periods.

Heating the HW tank during low cost periods (3rd case) shows a similar result with a cost saving of 3.5 % and an increase of electrical energy consumption of 16.5 % compared with the reference case. Because of an assumed charging and discharging efficiency of 0.87, the cost savings are lower than compared with the 2nd case.

The solar energy is free. Connecting a solar collector to the HW unit (4th case) gives a reduction of 7.8 % (ΔE_{el}) and accordingly a cost saving of 7.3 %. The maximum cost saving potential for the HW integrated with HP and solar collector (5th case) is 10 %.

Using the heat pump and the solar collector was also applied to charge the PCM tank (6th-8th case). The maximum cost saving potential of the case using the HP and the solar collector (8th case) is 12.5 %.

The capacity of a TCM storage is the highest among the applied heat storage technologies (Table 1). Using the solar collector to charge the TCM unit (9th case) results in a cost saving of 8.1 % (Table 2) and a reduction of electrical energy input for the HP of 8.4 % compared with the reference case.

Table 2. Simulation results – reference case and optimization of various heating cases (one year).

Heating Cases	yearly E_{el} [GJ]	ΔE_{el} [%]	yearly C_{el} [€]	ΔC_{el} [%]
1. HP heating room / reference case	0.283	-	19.2	-
2. HP heating room + HP (pre)heating inner wall (BTM)	0.318	+ 12.1	17.7	- 7.9
3. HP heating room + HP (pre)heating HW	0.330	+ 16.5	18.5	- 3.5
4. HP heating room + solar (pre)heating HW	0.261	- 7.8	17.8	- 7.3
5. HP heating room + HP and Solar (pre)heating HW	0.303	+ 7.2	17.3	- 10.0
6. HP heating room + HP (pre)heating PCM	0.292	+ 3.1	19.1	- 0.4
7. HP heating room + Solar (pre)heating PCM	0.246	- 13.0	16.8	- 12.5
8. HP heating room + HP and Solar (pre)heating PCM	0.249	- 12.2	16.8	- 12.5
9. HP heating room + Solar (pre)heating TCM	0.259	- 8.4	17.6	- 8.1

Gantt charts for the cases 5,8 and 9 were created to show the charging and discharging behavior of the HW, PCM and TCM (Figure 4).

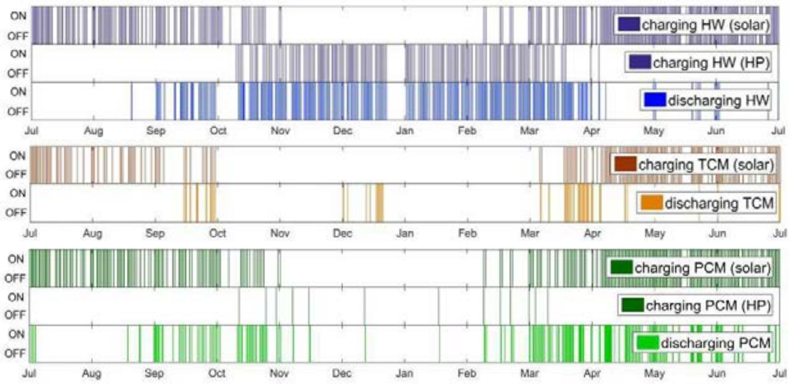

Fig. 4. Gantt chart – results optimization charging and discharging of heating cases 5,8 and 9.

The HW storage (blue bars) is charged by the solar collector during summer and by the HP during the winter. Discharging mainly takes place between September and April.

The PCM storage (green bars) shows a similar solar charging behavior because the charging temperature is the same as for the HW storage at 50 °C. During the cold season the PCM tank is hardly charged by the HP because of a lower discharging efficiency. Discharging of the PCM unit can also be noted during some summer months. This results in an elevation of the room temperature (1 K maximum) that is still within comfort bounds. Thus a comparable maximum cost saving of the PCM optimization might be lower and in the range of the HW storage.

The charging behavior of a TCM unit (brown bars) by the solar collector shifts towards the warmer season. This is based on the charging temperature that is 80 °C. The clear advantage of a TCM storage lies in a seasonal storage that can be seen by the discharge at low ambient peak temperatures during the cold season in December.

5. Discussion

The simulation results for the HW and the PCM tank show that they are mainly used as a short term storage. This is as expected because the heat loss during idle mode does not allow to store heat for a longer term (as of weeks). The charging and discharging energy efficiency, in this regard, strongly influence the scheduling behavior of charging

and discharging and determines whether a short term storage might be heated during the winter time using a HP. The TCM unit can store heat for a longer term (season) by being charged in summer and discharged in winter. Therefore, we need a seasonal price incentive, with higher electricity prices in winter than in summer. The daily price incentive with Off-peak, On-peak and Mid-peak energy charge rates is from main interest for the optimization of the short term storage (HW, PCM, BTM). Only lower electricity prices before periods of presence can result in cost savings. The maximum cost saving potentials, BTM of 7.9 %, HW of 10 %, PCM of 12.5 %, and TCM of 8.1 %, indicate that all these technologies can be a valuable contribution to the energy savings of buildings. The maximum cost savings might change when adding cooling in summer, setting smaller set point boundaries (room temperature – thermal comfort bounds), changing the electricity prices or applying a more advanced building model. The cost savings, however, will give a constraint to investment costs of the thermal energy storage technologies.
Minimizing the electricity costs by heating at low cost periods, on the other hand, can lead to an increase of electricity energy consumption. This might contradict to the general objective of reducing the energy consumption.

6. Conclusion

It has been clearly shown that the assumed critical storage parameters, state of charge, self-discharge, charging- and discharging energy efficiency, charging- and discharging temperature as well as the storage capacity can represent the typical charging and discharging behavior of the BTM, HW, PCM and TCM. It has been further demonstrated that a resistance capacitance network can enable a structure for modeling the control & optimization of various thermal energy storage capacities. So far, we have used a very simplified building model because the focus of the model was set to validate the assumed critical energy storage parameters for the model control. In further steps, it is necessary to include a more advanced building model considering several rooms and floors. This will give a more realistic evaluation of the energy storage potential of the buildings' thermal mass. Besides, additional resistances need to be taken into account representing the heating system such as radiators and piping.
The objective of the simulations was to minimize operational costs for electricity use. It has been found out that in some cases a cost saving results in an increase of electricity energy consumption. Thus, objectives in optimization need to be carefully chosen of whether focusing on cost reduction, decrease of energy consumption or increase of energy efficiency.

References

[1] Arteconi A, Hewitt NJ, Polonara F. State of the art of thermal storage for demand-side management. Appl Energy 2012;93:371–89. doi:10.1016/j.apenergy.2011.12.045.

[2] Cabeza LF, Castell A, Barreneche C, de Gracia A, Fernández AI. Materials used as PCM in thermal energy storage in buildings: A review. Renew Sustain Energy Rev 2011;15:1675–95. doi:10.1016/j.rser.2010.11.018.

[3] Trausel F, de Jong A-J, Cuypers R. A Review on the Properties of Salt Hydrates for Thermochemical Storage. Energy Procedia 2014;48:447–52. doi:10.1016/j.egypro.2014.02.053.

[4] Abedin AH, Rosen MA. Closed and open thermochemical energy storage: Energy- and exergy-based comparisons. Energy 2012;41:83–92. doi:10.1016/j.energy.2011.06.034.

[5] Ma P, Wang L-S. Effective heat capacity of interior planar thermal mass (iPTM) subject to periodic heating and cooling. Energy Build 2012;47:44–52. doi:10.1016/j.enbuild.2011.11.020.

[6] ISO 11855-4:2012 - Building environment design -- Design, dimensioning, installation and control of embedded radiant heating and cooling systems -- Part 4: Dimensioning and calculation of the dynamic heating and cooling capacity of Thermo Active Building Systems (TABS) n.d. http://www.iso.org/iso/home/store/catalogue_tc/catalogue_detail.htm?csnumber=52410 (accessed April 14, 2015).

[7] Kramer R, van Schijndel J, Schellen H. Inverse modeling of simplified hygrothermal building models to predict and characterize indoor climates. Build Environ 2013;68:87–99. doi:10.1016/j.buildenv.2013.06.001.

[8] Finck C, Henquet E, van Soest C, Oversloot H, de Jong A-J, Cuypers R, et al. Experimental Results of a 3 kWh Thermochemical Heat Storage Module for Space Heating Application. Energy Procedia 2014;48:320–6. doi:10.1016/j.egypro.2014.02.037.

[9] Ma J, Qin J, Salsbury T, Xu P. Demand reduction in building energy systems based on economic model predictive control. Chem Eng Sci 2012;67:92–100. doi:10.1016/j.ces.2011.07.052.

[10] DS/EN 15251 : INDOOR ENVIRONMENTAL INPUT PARAMETERS FOR DESIGN AND ASSESSMENT OF ENERGY PERFORMANCE OF BUILDINGS ADDRESSING INDOOR AIR QUALITY, THERMAL ENVIRONMENT, LIGHTING AND ACOUSTICS n.d. https://global.ihs.com/doc_detail.cfm?document_name=DS%2FEN%2015251&item_s_key=00622795#abstract (accessed February 11, 2015).

[11] ISO 11855-1:2012 - Building environment design -- Design, dimensioning, installation and control of embedded radiant heating and cooling systems -- Part 1: Definition, symbols, and comfort criteria n.d. http://www.iso.org/iso/home/store/catalogue_tc/catalogue_detail.htm?csnumber=52407 (accessed February 13, 2015).