Energy cost reduction by optimal control of ideal sensible thermal energy storage in domestic space heating

Brecht Baeten[1], Frederik Rogiers[2], Lieve Helsen[3]

[1] *KU Leuven, Diepenbeek, Belgium, Phone: +32498537777, Fax: 32 11 23 07 89, e-mail: brecht.baeten@kuleuven.be*

[2] *KU Leuven, Diepenbeek, Belgium*

[3] *KU Leuven, Mechanical Engineering Department, Division Applied Mechanics and Energy Conversion, Heverlee, Belgium*

Abstract

In the light of demand side management, the combination of thermal energy storage and space heating using electricity as energy vector is promising. The environmental gains of the use of heat pumps in buildings increase as the fraction of renewable electricity production rises. When variable electricity prices represent the availability of renewable energy sources, consumer gain can be accompanied by environmental benefits. The aim of this study is to determine the potential in energy cost reduction when using sensible thermal energy storage in a domestic space heating context. To fully investigate the potential of thermal energy storage, an optimal control strategy is applied to two idealized sensible energy storage tanks. The cost for space heating in a single-family dwelling using a sensible thermal energy store for diurnal storage is compared with a reference cost, without storage capacity present. As the cost reduction is dependent on the match between the energy use profile and the energy price profile, two energy pricing schemes are studied: a day-night tariff according to local electricity prices and a quarter-hour energy pricing scheme based on the daily variation of nationwide energy use. The resulting control profiles and variation of storage state of charge are presented for several values of storage capacity. The space heating energy cost is calculated for each case and compared for the stratified and mixed storage tanks and the reference cost. The results indicate a potential for user cost reduction of up to 20% using the perfectly stratified storage model.

Keywords: demand side management, space heating, thermal energy storage, sensible energy, stratification, optimal control

1. Introduction

In the European Union buildings are responsible for 40% of the primary energy consumption. Moreover they deliver the largest contribution to the greenhouse gas emissions [1].

Heat pumps, known as energy efficient technologies for space heating, using electricity, are seen as a valuable alternative for reducing greenhouse gas emissions. As more renewable energy technologies are connected to the electricity grid the environmental benefits of heat pumps rise. However due to the variability of these energy technologies the need for interconnection and energy storage increases to maintain a stable electricity grid [2]. When using electricity driven heat generation in combination with thermal energy storage (TES) the possibility of demand side load management (DSM) is another advantage [3]. The energy tariff structure is of great importance to the economic and environmental viability of demand side management through TES [4].

Sensible thermal energy storage (STES) in buildings can be achieved through the structural mass of the building [5] or through the heating of a separately insulated mass of storage material. The former is referred to as passive storage whereas the latter is referred to as active storage. The benefit of active storage is that the storage is controllable independent of the building thermal comfort.

Active thermal storage in dwellings is most economically accomplished through a hot water buffer [6]. When using a hot water storage tank the distribution of energy throughout the storage is not defined a priori. Andersen and Furbo [7] showed the effect of stratification on the thermal performance of solar combi systems and [8] showed the increase in effectiveness of stratified stores compared to conventional hot water storages used for domestic hot water supply. The degree of stratification is very dependent on the charging and discharging methods [9, 10].

This paper aims at quantifying the cost reduction for space heating in a residential dwelling by optimal control of sensible thermal energy storage, focussing on two extreme types of storage tanks: a perfectly stratified water tank and a perfectly mixed water tank. As such the influence of the water tank model can be investigated. Optimal control is considered in a DSM context with two different energy pricing schemes, and different storage tank capacities. To exclude the impact of badly tuned controllers, optimal control is used. Henze et al. [11] showed the effectiveness of optimal control for residential space heating. Several other authors [12, 13, 14, 15] have also used optimal control in a demand side management context, the influence of the TES model, however, has not yet been determined.

2. Materials and methods

2.1. System overview

The current paper considers space heating of a residential building incorporating the possibility to store thermal energy in a sensible energy buffer. The method of heat generation is currently unspecified but the energy is assumed to be taken from the electricity grid e.g. a heat pump. A schematic representation of the complete system is given in figure 1. The focus of this study however lies with the heating system delineated by the dashed line in figure 1. The interaction of this system with the building is provided by the heat emission system while the interaction with the electricity grid is achieved in the heater.

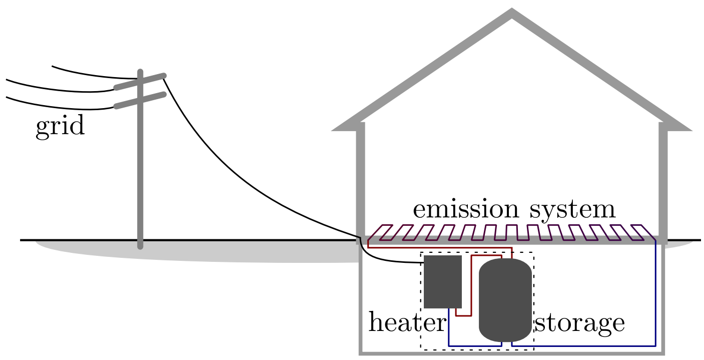


Figure 1: Schematic representation of the assumed system

2.2. Storage system modelling

The heating system with thermal energy storage is shown schematically in figure 2. The heater is assumed to modulate it's power in such a way that the temperature of the fluid at it's exit is constant at $T_{heater,out}$. The fluid entering the heater is at a temperature $T_{heater,in}$. The storage tank receives heat $\dot{Q}_{sup} = \dot{C}_{sup}(T_{heater,out} - T_{heater,in})$ from the heater. The temperature of the fluid entering the emission system is $T_{emission,in}$ while the temperature of the fluid exiting the system is $T_{emission,out}$. The emission system is modelled as having a uniform temperature T_{em} to which a heat flow $\dot{Q}_{em} = \dot{C}_{em}(T_{emission,in} - T_{emission,out})$ is added from the storage tank.

The variation of state of the storage system can now be written as:

$$\frac{\mathrm{d}E}{\mathrm{d}t} = \dot{Q}_{sup} - \dot{Q}_{em} - \dot{Q}_{hl} \tag{1}$$

With E the energy in the storage tank and $\dot{Q}_{hl}$ the heat lost from the storage to the ambient air through heat transfer which can be calculated as:

$$\dot{Q}_{hl} = UA_{sto}(\bar{T}_{sto} - T_{amb}) \tag{2}$$

Here the storage is assumed to be outside of the heated volume, transferring heat losses directly to the ambient temperature (T_{amb}).

To provide for the temperatures exiting the storage, the storage model must be further specified. The simplest choices are the assumptions of known and constant temperature at the top (T_h) and at the bottom of the tank (T_c) or the assumption of a uniform, but variable, temperature throughout the tank. The former represents an ideally stratified storage tank while the latter represents an ideally mixed storage tank. The values for T_h and T_c are determined from the heating system and the emission system. T_h will be equal to the heater outlet temperature while T_c is equal to the average emission system return temperature. For the ideally stratified model the state equation turns into:

$$\frac{\mathrm{d}E}{\mathrm{d}t} = \dot{C}_{sup}(T_h - T_c) - \dot{Q}_{em} - \dot{Q}_{hl} \tag{3}$$

While for the ideally mixed model the state equation becomes:

$$\frac{\mathrm{d}E}{\mathrm{d}t} = \dot{C}_{sup}(T_h - T) - \dot{Q}_{em} - \dot{Q}_{hl} \tag{4}$$

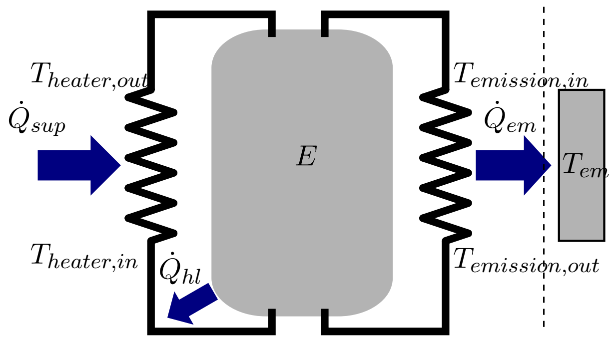


Figure 2: Model of a thermal energy storage tank

2.3. Boundary conditions

The emission system provides the interaction between heating system and building. To obtain a certain level of thermal comfort the heating system needs to supply, at any time, a certain amount of heat to the emission system ($\dot{Q}_{em}$) which needs to be at a certain temperature (T_{em}) to be able to transfer the energy to the entire building. These two values can thus be used to represent the entire building. In this paper the heat demand and temperature will be fixed prior to the optimization. As a consequence the building thermal capacity will not be actively used to store thermal energy.

The second boundary condition to the heat supply system involves the electricity grid side. The demand side management aspect of the problem will be accounted for by using a time varying energy price $p(t)$.

2.4. Optimal control problem formulation

In an optimal control problem the profile of a controlled variable will be varied to obtain an optimal value of a cost function. The controlled variable and all state variables influenced by this control are given appropriate constraints. In the system formulation described above $\dot{C}_{sup}$ is the controlled variable and E is a dependent state variable. As the building energy demand, and thus it's thermal comfort are fixed prior to optimization the cost function can be defined as the total energy cost during the optimization period:

$$J = \int_0^{t_f} \dot{C}_{sup}(T_{heater,out} - T_{heater,in})p(t)\mathrm{d}t \tag{5}$$

This implies the inclusion of the heater efficiency in the energy price signal and the independence of the efficiency of everything but time. An outside temperature dependent efficiency is however still possible as the outside temperature itself is only time dependent.

To avoid transient conditions, a periodic operation with relative period t_f is assumed and periodic boundary conditions are applied:

$$\begin{aligned} E(0) &= E(t_f) \\ \dot{C}_{sup}(0) &= \dot{C}_{sup}(t_f) \end{aligned} \tag{6}$$

The problem is constrained by the maximum amount of energy that can be stored, the maximum power of the heat supply and the maximum heater capacity flow rate:

$$\begin{aligned} 0 \leq \quad & E && \leq E_{max} \\ 0 \leq \quad & \dot{Q}_{sup} && \leq \dot{Q}_{max} \\ 0 \leq \quad & \dot{C}_{sup} && \leq \dot{C}_{max} \end{aligned} \tag{7}$$

In the perfectly stratified model the second and third constraint are equivalent while in the perfectly mixed model they differ as the heat flow depends on the state of the storage tank.

For the perfectly mixed model an additional constraint needs to be added ensuring sufficient energy can be transferred through a finite heat exchanger to the emission system:

$$\dot{Q}_{em} \leq (\varepsilon\dot{C})_{max}(T - T_{em}) \tag{8}$$

Where ε is the effectiveness of the heat exchange to the emission system.

2.5. Solution of the optimal control problem

To solve the discussed optimization problems the Acado Toolkit [16] and Matlab interface was used. The control profile is discretized in 48 time steps. A sequential quadratic programming approach with exact Hessian calculation is used.

To address numerical scale issues and to extend the applicability the model is nondimensionalized using reference quantities derived from the boundary conditions. The period of simulation (t_f)

is taken as the reference time, in this paper this will be one day. As a reference for energy the total demanded energy is used.

$$\begin{aligned} t_{ref} &= t_f \\ E_{ref} &= \int_0^{t_f} \dot{Q}_{em} \mathrm{d}t \end{aligned} \tag{9}$$

From these quantities a reference value for heat flow rate can be determined as the average heat flow rate:

$$\dot{Q}_{ref} = \frac{E_{ref}}{t_{ref}} \tag{10}$$

The energy price is nondimensionalized using the average energy price for heating the dwelling when no energy buffer is present.

$$p_{ref} = \frac{1}{t_f} \int_0^{t_f} \dot{Q}_{em} p(t) \mathrm{d}t \tag{11}$$

In subsequent sections quantities divided by their reference quantity will be denoted with * as a superscript.

3. Results and discussion

3.1. Boundary conditions

To determine the heat demand and emission system temperature a linear optimal control problem similar to the one described in [17] was solved. The model consists of an RC-network with states for a single thermal zone, the emission system, internal walls and outer walls. Solar heat gains are added to the internal walls while internal gains are added directly to the thermal zone capacity. In this paper the internal heat gains are calculated from measurement data from [18]. The ambient temperature profile is calculated as a November design day in Belgian climate according to [19].

The total amount of energy supplied to the building is minimized while a minimum zone temperature of 20°C is maintained. In the period from 23h in the evening to 16h in the afternoon the minimum temperature is decreased to 18°C.

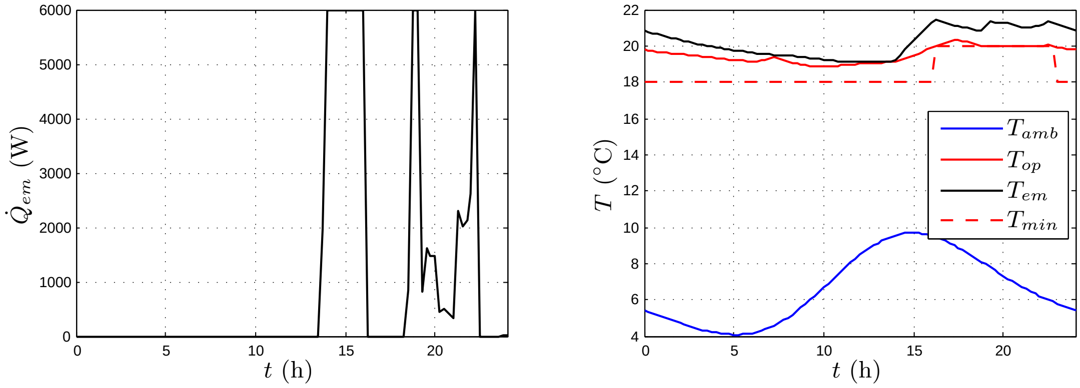
The resulting optimal control problem is easily solved and the emission temperature T_{em} and heat demand $\dot{Q}_{em}$ are extracted and given in Figure 3.

Two price profiles were investigated, one corresponds to a general day night tariff as is common in Belgium (Figure 4(a)). The energy price reduction during off peak hours is 30%. The second pricing scheme is a time of use scheme where the price variation is determined by the variations of the nationwide energy use on a representative day according to [20] (Figure 4(b)).

3.2. Parameters of interest

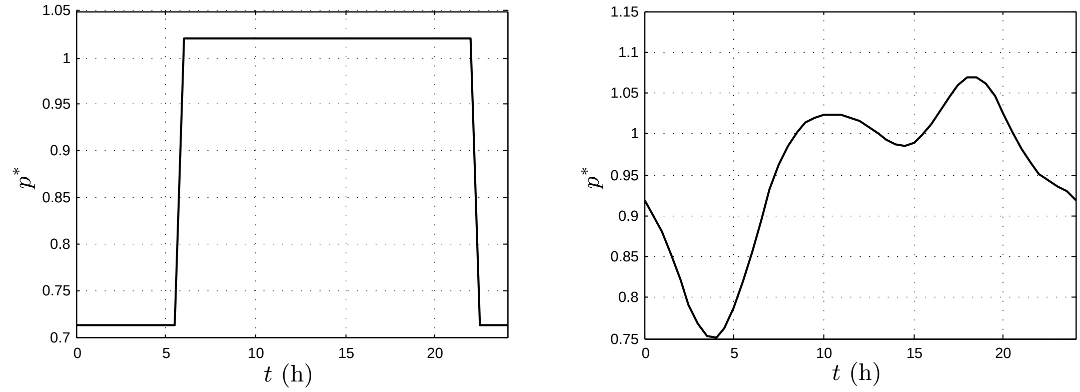
The parameters $\dot{Q}_{max}$ and $\dot{C}_{max}$ are both determined by the heat supply system. A maximum heater power of 6000 W was determined to be sufficient for a single family dwelling complying with Belgian regulations. The maximum heater capacity flow rate depends on it's maximum power and was chosen to be 2100 W/K.

The effectiveness of the emission system at the maximum capacity flow rate is assumed to be 0.6. As the hot zone of the storage receives energy from the heater it will be at the temperature of the heater outlet which is assumed constant at 35°C. The temperature at the bottom of the



(a) heat load (b) emission and zone temperature

Figure 3: Building side boundary conditions



(a) day-night tariff (b) time of use scheme

Figure 4: Grid side boundary conditions

storage is determined by the temperature of the flow returning from the emission system. This temperature can be calculated as $T_c = T_h - \varepsilon(T_h - \bar{T}_{em})$. Here the same effectiveness $\varepsilon = 0.6$ is used.

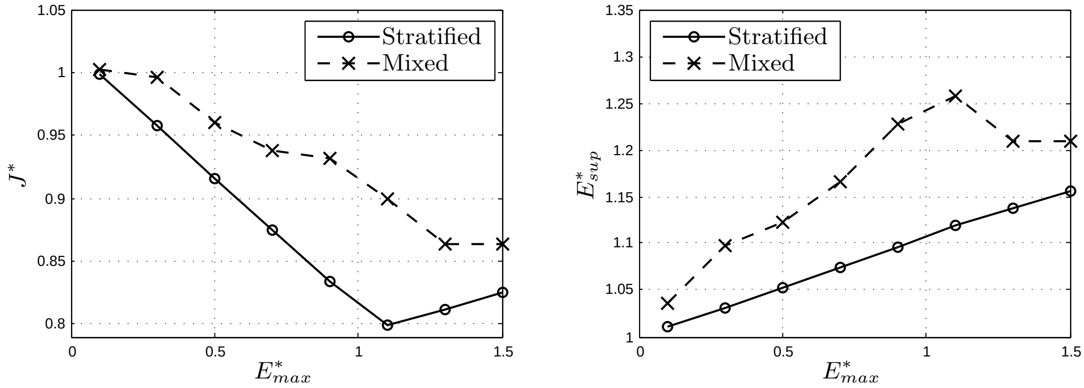
The rate at which heat is lost from the thermal energy storage to the surroundings is determined by the UA value. This value is assumed to be linearly dependent on the storage capacity. This assumption is justified by the observation of several commercially available tanks. The proportionality factor is chosen to be 3500s^{-1}.

The only variable parameter is E_{max}, representing the maximum storage energy capacity. This parameter is varied from 0.1 to 1.5 times the total building energy demand to represent small and large storages.

3.3. Comparison of stratified and mixed storage

3.3.1. Day-night energy tariff

In figure 5(a) the optimized total energy cost assuming the day-night energy price tariff is presented for several storage sizes for both the stratified and mixed storage model. A minimum relative energy cost of 0.80 is obtained for the stratified model when the storage capacity is 1.1 times the energy demand. For the mixed model no minimum in energy cost is obtained within the calculated range. The total energy use is presented in figure 5(b). The rise in energy use for both models is explained by increasing heat losses with storage size, this also explains the rise in energy cost seen in the stratified storage model.

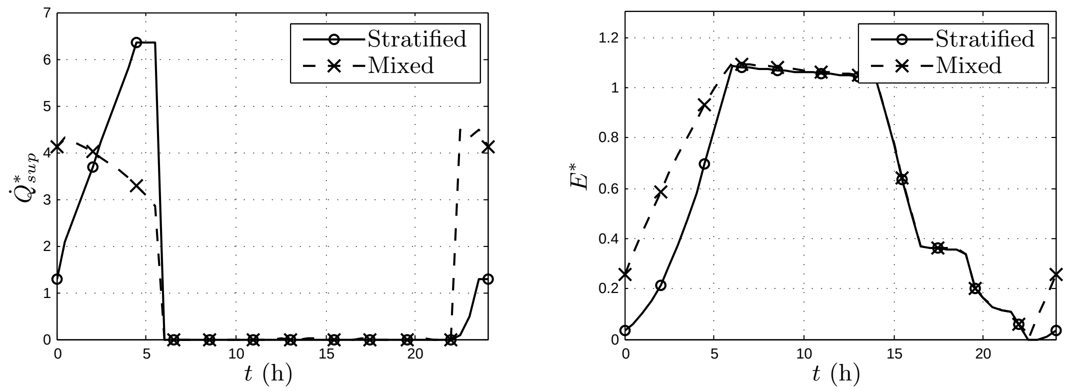


(a) Energy cost (b) Total supplied energy

Figure 5: Relative total energy cost assuming the day-night tariff for several storage sizes.

The optimal energy flow profile to the storage tank and the energy content of the storage for the optimal storage sizes is shown in figure 6. The sizes shown are 1.1 times the energy demand for the stratified storage tank and 1.5 times the energy demand for the mixed storage tank. In figure 6(a) the load shift away from the high price period towards the low price period is clearly seen. As in this figure the storage is large enough the entire production of energy is shifted to the low price period. However, in figure 6(b) can be seen that the maximum amount of stored energy is almost equal for both models. A mixed storage will thus have to be larger than a stratified storage in order to be able to receive an equal amount of energy due to limited capacity flow rates.

Due to heat losses it is most efficient to add the energy to the storage as close to the time of discharge as possible. Due to the rising inlet temperature of the heater and the constrained mass flow in the mixed model, the deliverable power decreases as the storage charges. The energy will thus be added at earlier times which deteriorates the cost reduction.

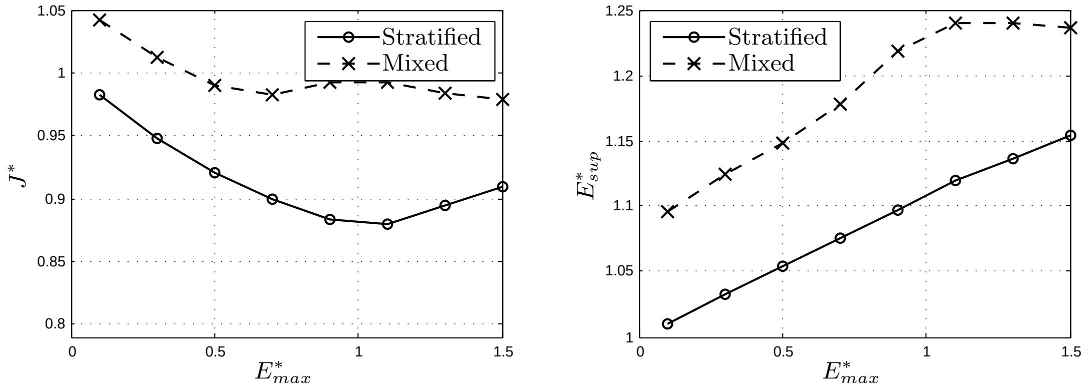


(a) Storage energy flow (b) Storage energy content

Figure 6: Optimized energy flow profile and storage energy content assuming day-night energy price tariff for the optimal storage size, 1.1 times the energy demand for the stratified storage tank and 1.5 times the energy demand for the mixed storage tank

3.3.2. Variable energy tariff

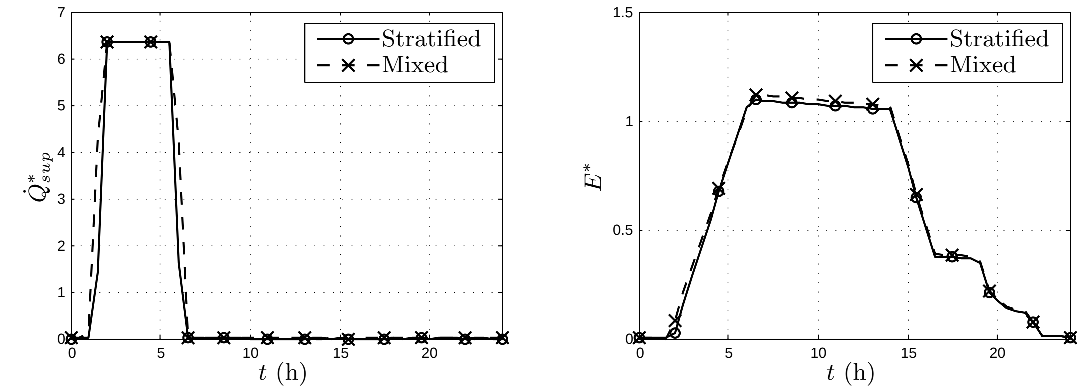
In figure 7(a) the total energy cost is given for several storage sizes for both the stratified and mixed model. In the case of variable energy prices, the optimal storage size using the stratified model remains 1.1 times the total energy demand as in the case of the day-night tariff. The minimum relative energy cost rises to 0.88. The mixed model however shows a local minimal cost at 0.7 times the energy demand. The minimal cost is however still obtained with the largest storage size and has a value of 0.98. This increase in cost relative to the day-night pricing scheme is caused by the smaller variation of the energy prices. Although both control profiles (figure 8(a)) look very similar the mixed model uses more energy and thus has a higher cost.



(a) Energy cost (b) Total supplied energy

Figure 7: Relative total energy cost assuming the variable energy price tariff for several storage sizes.

The optimized energy flow to the storage tank and the energy content of the storage assuming the variable energy price tariff for the optimal storage size is presented in figure 8. As the energy tariff has a distinct minimum the optimization attempts to concentrate the charging around this minimum. The reduction in maximum heater power observed under the day-night tariff assumption for the mixed storage model is thereby eliminated.



(a) Storage energy flow (b) Storage energy content

Figure 8: Optimized energy flow profile and storage energy content assuming a variable energy price tariff for the optimal storage size 1.1 times the energy demand for the stratified storage tank and 1.5 times the energy demand for the mixed storage tank

In both the stratified and mixed tank optimizations the load peaks present in the situation without energy storage will be shifted to other periods but will not diminish in size. When the penetration of demand side management is large the effect of this load shift on the grid (and the energy price) needs to be investigated and integrated demand side-supply side simulations are necessary [21].

From figures 5(b) and 7(b) an increase in total energy use due to storage heat losses can be seen for all storage sizes and configurations. To obtain an environmental benefit the increase in energy use must be supplied by renewable energy sources. This can be obtained as the storage is charged at times different from the time of use if the energy price represents the availability of renewable energy sources which would otherwise be wasted.

4. Conclusions

The effect of the active thermal energy storage model in an optimal control environment for demand side management has been investigated under different price scenarios. A reduction in consumer energy cost up to 20% was calculated for a dwelling conform with Belgian regulations on an average November day. This value however is valid with perfect weather and occupancy predictions and without model mismatch, and assuming constant heat production efficiency.

For a price signal with a long period of constant minimal energy prices, such as the day-night tariff in Belgium, a significant difference in control profiles between the ideally stratified and the ideally mixed storage tank model is obtained. The storage size for which minimal energy cost is obtained was also calculated and was found to be larger for the ideally mixed model. From the optimisations using the time-of-use energy price less consumer benefit was obtained. Moreover due to the distinct short minimum cost period peak loads are not diminished but are likely to be more concentrated.

The difference between the ideally stratified model and the ideally mixed model has also been evaluated. The stratified model outperforms the mixed model in all simulated cases. Only when the energy storage capacity is oversized significantly a comparable performance is expected. This raises issues for the implementation of model predictive control algorithms in real situations using sensible thermal energy storage since an actual storage in this configuration will have a behaviour in between the two ideal cases. The required storage control model will have to account for the imperfect stratification leading to non-convex optimization problems which are difficult to solve.

5. Acknowledgements

This research was funded from the academisation of the study of industrial engineering at the catholic university college Limburg, KHLim.

Nomenclature

A	Area [m^2]
C	Heat capacity[J/K]
$\dot{C}$	Heat capacity flow rate [W/K]
DSM	Demand side management
E	Energy [J]
J	Cost [€]
p	price of heat [€ /J]
$\dot{Q}$	Heat flow rate [W]
STES	Sensible thermal energy storage
t	Time [s]
T	Temperature [K]
TES	Thermal energy storage
U	Coëfficiënt of heat transfer [W/m^2K]

Greek symbols

ε	Effectiveness [−]

Superscript	
*	Dimensionless variables

Subscript	
amb	Ambient
c	Cold
em	Emission
f	Final
h	Hot
hl	Heat loss
max	Maximum
min	Minimum
ref	Reference
sup	Supply
op	Operational

References

[1] European Commission. http://ec.europa.eu/research, 2013.

[2] Neil J Hewitt. Heat pumps and energy storage - the challenges of implementation. *Applied Energy*, 89(1):37 – 44, 2012.

[3] A. Arteconi, N.J. Hewitt, and F. Polonara. Domestic demand-side management (dsm): Role of heat pumps and thermal energy storage (tes) systems. *Applied Thermal Engineering*, 51(1-2):155 – 165, 2013.

[4] A. Arteconi, N.J. Hewitt, and F. Polonara. State of the art of thermal storage for demand-side management. *Applied Energy*, 93(0):371 – 389, 2012.

[5] G. Reynders, T. Nuytten, and D. Saelens. Potential of structural thermal mass for demand-side management in dwellings. *Building and Environment*, 64(0):187 – 199, 2013.

[6] Marc A. Rosen. The exergy of stratified thermal energy storages. *Solar Energy*, 71(3):173 – 185, 2001.

[7] E. Andersen and S. Furbo. Theoretical comparison of solar water/space-heating combi systems and stratification design options. *JOURNAL OF SOLAR ENERGY ENGINEERING-TRANSACTIONS OF THE ASME*, 129(4):438–448, NOV 2007.

[8] Roman Spur, Dusan Fiala, Dusan Nevrala, and Doug Probert. Performances of modern domestic hot-water stores. *Applied Energy*, 83(8):893 – 910, 2006.

[9] K.G.T. Hollands and M.F. Lightstone. A review of low-flow, stratified-tank solar water heating systems. *Solar Energy*, 43(2):97 – 105, 1989.

[10] Yousef H. Zurigat, Pedro R. Liche, and Afshin J. Ghajar. Influence of inlet geometry on mixing in thermocline thermal energy storage. *International Journal of Heat and Mass Transfer*, 34(1):115 – 125, 1991.

[11] Gregor P. Henze, Clemens Felsmann, and Gottfried Knabe. Evaluation of optimal control for active and passive building thermal storage. *International Journal of Thermal Sciences*, 43(2):173 – 183, 2004.

[12] H. Ren, W. Gao, and Y. Ruan. Optimal sizing for residential chp system. *Applied Thermal Engineering*, 28 (5-6):514–523, 2008.

[13] Phillip Oliver Kriett and Matteo Salani. Optimal control of a residential microgrid. *Energy*, 42(1):321 – 330, 2012.

[14] E.D. Mehleri, H. Sarimveis, N.C. Markatos, and L.G. Papageorgiou. Optimal design and operation of distributed energy systems: Application to greek residential sector. *Renewable Energy*, 51(0):331 – 342, 2013.

[15] Ramanunni P. Menon, Mario Paolone, and Fran çois Maréchal. Study of optimal design of polygeneration systems in optimal control strategies. *Energy*, 55(0):134 – 141, 2013.

[16] D. Ariens, B. Houska, H. Ferreau, and F. Logist. ACADO: Toolkit for Automatic Control and Dynamic Optimization. Optimization in Engineering Center (OPTEC).

[17] Clara Verhelst. *Model predictive control of hybrid ground coupled heat pump systems.* PhD thesis, KULeuven, Leuven, Belgium, 2012.

[18] D.P. Jenkins, S. Patidar, P.F.G. Banfill, and G.J. Gibson. Probabilistic climate projections with dynamic building simulation: Predicting overheating in dwellings. *Energy and Buildings*, 43(7):1723 – 1731, 2011.

[19] *ASHRAE Handbook of Fundamentals*, chapter 14: Climatic design information, page 11. American Society of Heating Refrigeration and Air-Conditioning Engineers, 2009.

[20] Elia. http://www.elia.be/en/grid-data/dashboard, 2014.

[21] K. Bruninx, D. Patteeuw, E. Delarue, L. Helsen, and W. D'haeseleer. Short-term demand response of flexible electric heating systems: The need for integrated simulations. In *European Energy Market (EEM), 2013 10th International Conference on the*, pages 1–10, 2013.