KTH Industrial Engineering and Management

Energy Efficiency through Thermal Energy Storage

Possibilities for the Swedish Building Stock

Johan Heier

Licentiate Thesis 2013

KTH School of Industrial Engineering and Management
Department of Energy Technology
Division of Heat and Power Technology
SE-100 44 Stockholm

ISBN 978-91-7501-653-5
Trita KRV Report 13/01
ISSN 1100-7990
ISRN KTH/KRV/13/01-SE

Abstract

The need for heating and cooling in buildings constitutes a considerable part of the total energy use in a country and reducing this need is of outmost importance in order to reach national and international goals for reducing energy use and emissions. One important way of reaching these goals is to increase the proportion of renewable energy used for heating and cooling of buildings. Perhaps the largest obstacle with this is the often occurring mismatch between the availability of renewable energy and the need for heating or cooling, hindering this energy to be used directly. This is one of the problems that can be solved by using thermal energy storage (TES) in order to save the heat or cold from when it is available to when it is needed.

This thesis is focusing on the combination of TES techniques and buildings to achieve increased energy efficiency for heating and cooling. Various techniques used for TES as well as the combination of TES in buildings have been investigated and summarized through an extensive literature review. A survey of the Swedish building stock was also performed in order to define building types common in Sweden. Within the scope of this thesis, the survey resulted in the selection of three building types, two single family houses and one office building, out of which the two residential buildings were used in a simulation case study of passive TES with increased thermal mass (both sensible and latent). The second case study presented in the thesis is an evaluation of an existing seasonal borehole storage of solar heat for a residential community. In this case, real measurement data was used in the evaluation and in comparisons with earlier evaluations.

The literature reviews showed that using TES opens up potential for reduced energy demand and reduced peak heating and cooling loads as well as possibilities for an increased share of renewable energy to cover the energy demand. By using passive storage through increased thermal mass of a building it is also possible to reduce variations in the indoor temperature and especially reduce excess temperatures during warm periods, which could result in avoiding active cooling in a building that would otherwise need it. The analysis of the combination of TES and building types confirmed that TES has a significant potential for increased energy efficiency in buildings but also highlighted the fact that there is still much research required before some of the technologies can become commercially available. In the simulation case study it was concluded that only a small reduction in heating demand is possible with increased thermal mass, but that the time with indoor temperatures above 24 °C can be reduced by up to 20%. The case study of the borehole storage system showed that although the storage system worked as planned, heat losses in the rest of the system as well as some problems with the system operation resulted in a lower solar fraction than projected.

The work presented within this thesis has shown that TES is already used successfully for many building applications (e.g. domestic hot water stores and water tanks for storing solar heat) but that there still is much potential in further use of TES. There are, however, barriers such as a need for more research for some storage technologies as well as storage materials, especially phase change material storage and thermochemical storage.

Keywords: thermal energy storage, buildings, energy efficiency, energy savings, peak load reduction, Swedish building stock

Sammanfattning

Behovet av värme och kyla i byggnader utgör en betydande del av ett lands totala energianvändning och att reducera detta behov är av yttersta vikt för att nå nationella samt internationella mål för minskad energianvändning och minskade utsläpp. En viktig väg för att nå dessa mål är att öka andelen förnyelsebar energi för kylning och uppvärmning av byggnader. Det kanske största hindret med detta är det faktum att det ofta råder obalans mellan tillgången på förnyelsebar energi och behovet av värme och kyla, vilket gör att denna energi inte kan utnyttjas direkt. Detta är ett av problemen som kan lösas genom att använda termisk energilagring (TES) för att lagra värme eller kyla från när det finns tillgängligt till dess att det behövs.

Denna avhandling fokuserar på kombinationen av TES och byggnader för att nå högre energieffektivitet för uppvärmning och kylning. Olika tekniker för energilagring, samt även kombinationen av TES och byggnader, har undersökts och sammanfattats genom en omfattande litteraturstudie. För att kunna identifiera byggnadstyper vanliga i Sverige gjordes även en kartläggning av det svenska byggnadsbeståndet. Inom ramen för denna avhandling resulterade kartläggningen i valet av tre typbyggnader, två småhus samt en kontorsbyggnad, utav vilka de två småhusen användes i en simuleringsfallstudie av passiv TES genom ökad termisk massa (både sensibel och latent). Den andra fallstudien som presenteras i denna avhandling är en utvärdering av ett existerande borrhålslager för säsongslagring av solvärme i ett bostadsområde. I detta fall användes verkliga mätdata i utvärderingen samt i jämförelser med tidigare utvärderingar.

Litteraturstudien visade att användningen av TES öppnar upp möjligheter för minskat energibehov och minskade topplaster för värme och kyla samt även möjligheter till en ökad andel förnyelsebar energi för att täcka energibehovet. Genom att använda passiv lagring genom ökad termisk massa i byggnaden är det även möjligt att minska variationer i inomhustemperaturen och speciellt minska övertemperaturer under varma perioder; något som kan leda till att byggnader som normalt behöver aktiv kylning kan klara sig utan sådan. Analysen av kombinationen av TES och byggnadstyper bekräftade att TES har en betydande potential för ökad energieffektivitet i byggnader, men belyste även det faktum att det fortfarande krävs mycket forskning innan vissa av lagringsteknikerna kan bli kommersiellt tillgängliga. I simuleringsfallstudien drogs slutsatsen att en ökad termisk massa endast kan bidra till en liten minskning i värmebehovet, men att tiden med inomhustemperaturer över 24 °C kan minskas med upp till 20 %. Fallstudien av borrhålslagret visade att även om själva lagringssystemet fungerade som planerat så ledde värmeförluster i resten av systemet, samt vissa problem med driften av systemet, till en lägre solfraktion än beräknat.

Arbetet inom denna avhandling har visat att TES redan används med framgång i många byggnadsapplikationer (t.ex. varmvattenberedare eller ackumulatortankar för lagring av solvärme) men att det fortfarande finns en stor potential i en utökad användning av TES. Det finns dock hinder såsom behovet av mer forskning för både vissa lagringstekniker samt lagringsmaterial, i synnerhet för lagring med fasändringsmaterial och termokemisk lagring.

Nyckelord: termisk energilagring, byggnader, energieffektivisering, energibesparing, toppbelastningsutjämning, Sveriges byggnadsbestånd

Preface

With a steadily increasing use of energy in the world, many researchers are focused on how to reduce energy demand or how to introduce more renewable energy into the energy mix. One specific area that constitutes a large part of the total energy use is the building sector, where energy is used to maintain a comfortable indoor environment through heating and cooling. This licentiate thesis is part of a PhD project in the field of "Thermal Energy Storage", financed by the Swedish Energy Agency ("Termisk energilagring i byggnader", project P31894-1), with the goal of mapping out what technologies are available for thermal energy storage in buildings and how these can be used to increase the energy efficiency in the Swedish building stock. The work is done as a combined effort between Energy and Environmental Technology, School of Technology and Business Studies at Dalarna University and the Department of Energy Technology at KTH Royal Institute of Technology.

Acknowledgements

First and foremost I express my gratitude to my supervisors, Chris Bales and Viktoria Martin, who have been of tremendous help during my PhD studies with their support and fruitful discussions during the research as well as thoroughly reading and commenting on this thesis. I thank everyone in my reference group: Bahram Moshfegh, Linköping University; Conny Ryytty, Swedish Energy Agency; Hans Isaksson, K-Konsult Energi Stockholm AB; Jonas Gräslund, Skanska; Lars-Olof Södergren, K-Konsult Energi Stockholm AB; Martin Bergdahl, Dalarna County Council for contributing with expertise from their respective areas and for all the input and good discussions during our meetings. Special acknowledgements go to Conny Ryytty and the Swedish Energy Agency for the financial support of the project.

I thank Artem Sotnikov and Ganna Ponomarova for their well performed master's thesis work that provided the basis for Paper II and I also want to thank everyone who allowed me to use their artwork in this thesis. I express gratitude to my colleagues, both at Dalarna University and at KTH, for providing a great working environment. Gratitude also goes to Jonn Are Myhren for taking the time and effort to do a quality review of this thesis.

Finally I thank my friends and family for their support during my studies and I especially thank my wife Chie for being with me through this whole period; you are everything to me!

Publications

Papers included

I. Heier, J., Bales, C. and Martin, V. 2010. Energy Efficiency through Thermal Energy Storage - Evaluation of the Possibilities for the Swedish Building Stock, Phase 1. Clima 2010, Antalya, Turkey.

II. Heier, J., Bales, C., Sotnikov, A. and Ponomarova, G. 2011. Evaluation of a High Temperature Solar Thermal Seasonal Borehole Storage. ISES Solar World Congress 2011, Kassel, Germany.

III. Heier, J., Bales, C. and Martin, V. 2012. Thermal energy storage in Swedish single family houses - a case study. Innostock 2012, Lleida, Spain.

IV. Heier, J., Bales C. and Martin, V. 2012. Combining Thermal Energy Storage with Buildings – A review.

Paper IV is submitted to Journal of Renewable & Sustainable Energy Reviews, reference number: RSER-D-12-01363.

Contributions:

The author of this thesis is the first author for all included papers. For Paper I, III and IV the background work, literature review and writing of the paper is to the majority performed by the author of the thesis. For Paper II the first author is responsible for part of the supervision of the master’s thesis work on which the paper is based, as well as some result synthesis and all the writing of the paper. For Paper III, the first author is also responsible for the simulations and analysis of results.

Nomenclature

Abbreviations

AC	Air conditioning
CAV	Constant air volume
COP	Coefficient of performance
CTES	Cold thermal energy storage
DHW	Domestic hot water
DX	Direct expansion
HVAC	Heating ventilation and air conditioning
LHTES	Latent heat thermal energy storage
PCM	Phase change material
TABS	Thermally activated building systems
TES	Thermal energy storage
VAV	Variable air volume

Table of Contents

Index of figures

Index of tables

1 Introduction

In 2008, 141 TWh of energy, or 36% of the total energy used in Sweden, was used in the residential and service sector alone and out of this, 61% was used for heating (Swedish Energy Agency, 2009). Statistics for cooling in buildings is more difficult to find, but district cooling started to be distributed in Sweden in the beginning of the 1990s (Swedish Energy Agency, 2010). In 2000 the supply had increased to slightly over 300 GWh and it reached almost 830 GWh in 2009, with an increase of 7% relative to 2008 (Swedish Energy Agency, 2010). Goals to reduce our impact on the climate have been agreed on for all sectors and for the Swedish building sector, the goal is to reduce the energy use by 20% until 2020 and by 50% until 2050, compared to the year 1995 (Boverket, 2007, Naturvårdsverket, 2012).

An increased use of renewable energy is also important, and as discussed in a recent directive of the European Parliament on the energy performance of buildings (Official Journal of the European Union, 2010), reduced energy consumption and an increased use of energy from renewable sources also play an important role in, among others, the security of energy supply and the technical development. Since there is often a time difference between the availability of renewable energy and the need for the same energy, it is not always easy to take advantage of this energy to a full extent. An example is solar energy, which is available in abundance during the summer months while most of the heating requirement is in the winter. Another example is cold night air whose cooling energy could be used during the day when the cooling demand, in for example an office, is high. For this type of cooling, the term "free cooling" is often used and this is "…understood as a means to store outdoors coolness during the night, to supply indoors cooling during the day" (Zalba et al., 2004).

To use this energy when needed, it is of outmost importance to be able to store it from one time to another. The storage period can be anything from short term storage within a day or from one day to the next, to long term seasonal storage for example from summer to winter. The potential benefit can easily be understood when examining Figure 1.1. Here it is clearly seen that there is a mismatch between the available solar irradiation usable for free solar heating and the heating demand of the building. If the solar energy could be stored from daytime to nighttime, this mismatch would be eliminated.

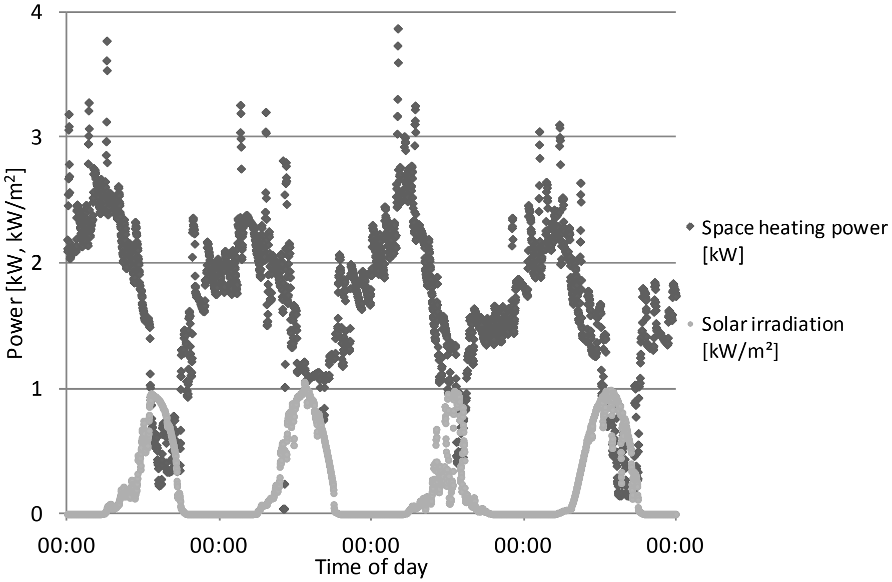

Figure 1.1. The space heating demand for a Swedish single family house together with the solar irradiation during four spring days (data acquired within the project CombiSol (Papillon et al., 2010))

Although various kinds of energy can be stored (electrical, mechanical, thermal etc), here only thermal energy storage (TES) will be discussed. Thermal energy storage is described by Dincer and Rosen (Dincer and Rosen, 2002) as "… an *advanced energy technology* that is attracting increasing interest for thermal applications such as space and water heating, cooling, and air conditioning".

What is discussed above is mainly using TES to reduce the non-renewable primary energy demand by opening up opportunities for renewable sources of energy, which is one important aspect of storage. Another important use of TES is the ability to shift the heating or cooling load in time from peak hours to off peak hours. This is called peak shifting or peak shaving and often three strategies are discussed, as shown in Figure 1.2 and as discussed by Dincer (Dincer, 2002) and He (He, 2004). These strategies are often used for cold storage in building cooling applications, which will also be the example used here. Load leveling is a strategy where the chillers are designed to run at optimal (constant) power the entire day during which they either meet part of the cooling load directly or charge the store. In this case, the peak power reduction is not so large but in return, the chiller power can be kept at a minimum and the chillers can be allowed to work continuously (He, 2004) and efficiency can therefore be maximized. The capacity of the storage required is small compared to the other strategies. When using a demand limiting strategy, a larger storage is required since the store will cover a larger part of the cooling load during peak time. The chillers have to be larger to be able to charge the store during off peak hours but during peak hours the chiller load is reduced significantly. The last strategy is called full storage and as the name suggests, the storage unit covers the entire load during peak hours and the chillers can be shut down during this period. The required chiller power is high and so is the required storage capacity (He, 2004). Which strategy is best in a certain case depend on many factors such as load profile, energy cost differentiation between on and off peak periods, available space for storage and many more. Generally, full storage is only used in special cases due to the requirements on both storage capacity and installed chiller power but can be advantageous in buildings where peak loads are high but short in duration (Dincer, 2002).

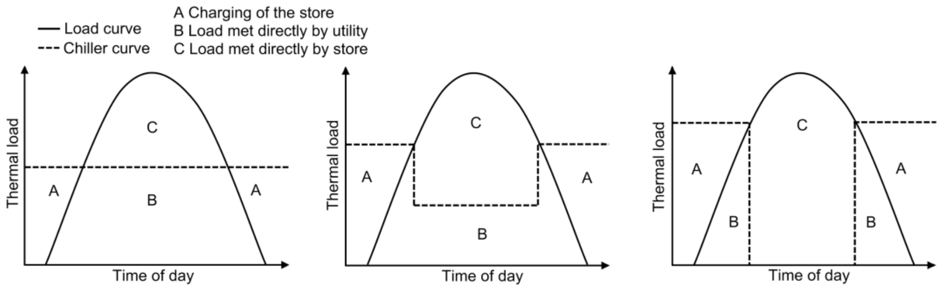

Figure 1.2. Three strategies for peak shifting (from the left: load levelling, demand limiting and full storage)

As was discussed above, it is possible to use TES to increase the efficiency of a chiller by being able to run it continuously on optimal power for most of the time (using the load leveling strategy). The same is also possible for other types of HVAC equipment with another example being biofuel boilers. Win, Persson and Bales (Win et al., 2012) show that a large part of emissions from wood pellet boilers occur during the start and stop period. Further, as shown by Heinz (Heinz, 2007b) in a simulation study, a small tank connected to a boiler can reduce the number of start and stops (Figure 1.3) resulting in reduced emissions.

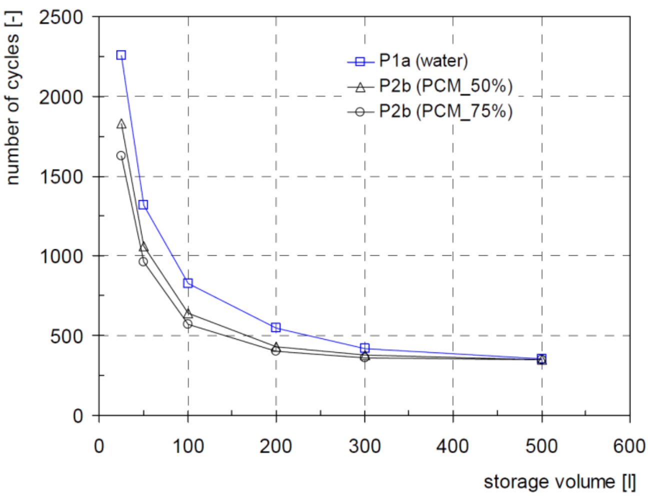

Figure 1.3. Annual number of start and stop cycles for a pellet boiler when using different storage volumes, with water storage and water storage with integrated PCM modules (Heinz, 2007b)

By looking at these examples, it is quite clear that thermal energy storage can play an important role in the heating and cooling systems of buildings, as well as have a large potential for reduction of non-renewable primary energy use and harmful emissions from the building sector.

1.1 Indoor thermal comfort

This section discusses common boundaries for indoor thermal comfort, which in this thesis is centred on indoor temperature. There are also other parameters besides indoor temperature that are important for the indoor comfort, such as humidity, air movement and amount of clothing (Wang, 1993) as well as fresh air and ventilation. Since the choice of indoor temperature is the factor that has the largest influence on most storage systems, especially passive systems as discussed below, the comfort discussion in this paper is limited to this factor.

For residential buildings, the Swedish National Board of Health and Welfare recommends that the indoor air temperature is above 20 °C for the whole year and does not exceed 24 °C during wintertime or 26 °C during summertime (Socialstyrelsen, 2005). Traditionally, Swedish residential buildings are not equipped with cooling systems, but lately passive houses have started to become more popular which poses a risk for an increased cooling demand. The Swedish demand specifications for passive houses (Erlandsson et al., 2009) now state that the indoor temperature in the warmest part of the building during the period between April and September should not exceed 26 °C for more than 10% of the time. There are also standards and recommendations for the indoor temperature that are dependent on the outdoor temperature, as shown in Figure 1.4. In the European standard EN 15026 (CEN, 2007), there is a linear increase in the recommended indoor temperature between an outdoor temperature of 10-20 °C. For naturally conditioned spaces where occupants control the thermal conditions mainly using opening and closing of windows, ASHRAE standard 55-2004 (ASHRAE, 2004) provides a recommended interval for the operative indoor temperature that also increases linearly for a monthly mean outdoor temperature between 10 °C and 33.5 °C. This optional method is only valid under certain conditions as discussed in the ASHRAE standard (ASHRAE, 2004) and also not outside the given mean outdoor temperature range.

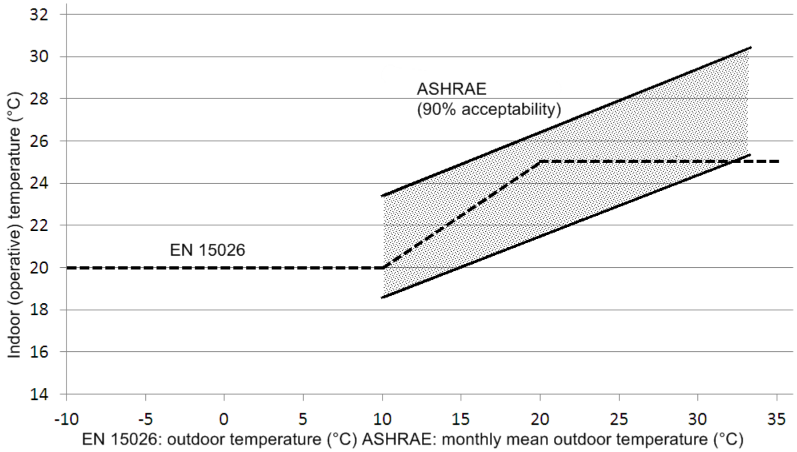

Figure 1.4. Recommended indoor temperature depending on the outdoor temperature according to European standard EN 15026 (CEN, 2007) (dashed line) as well as recommended operative indoor temperature interval for 90% acceptance depending on monthly average outdoor temperature according to ASHRAE standard 55-2004 (ASHRAE, 2004)

The often narrow indoor climate recommendations mean that a thermal energy storage system often needs to operate within rather strict temperature intervals, which may limit the possibilities or effectiveness of the system. This is especially true for passive systems trying to achieve a reduced energy demand, since they are relying on swings in the indoor temperature, and the performance might be hindered due to strict comfort intervals as discussed by Ståhl (Ståhl, 2009). This makes the allowable indoor temperature range one of the more important boundary conditions when discussing thermal energy storage in general and passive TES in particular.

For commercial buildings, a large driving force for improved indoor comfort is the increased productivity that comes with a good indoor environment. Earlier studies on productivity and error rates of workers, students etc. has helped in the development of modern standards for indoor comfort. Fisk and Rosenfeld (Fisk and Rosenfeld, 1997) have made a literature review on relevant papers showing the impact of indoor environments (often indoor temperature) on human performance. Although the performance is said to be hard to quantify in many cases, many papers come to the conclusion that the indoor temperature is very important for good productivity.

1.2 Aims and scope

This thesis is written as part of project P31894-1 financed by the Swedish Energy Agency titled "Termisk energilagring i byggnader" (Thermal Energy Storage in Buildings). The main aim of the project is to map the possibilities for using thermal energy storage in buildings as well as show the possibilities for increased energy efficiency and reduced heating and cooling peak loads through the use of thermal energy storage. The focus is mostly on the use of TES in Nordic climates and more specifically, on identifying thermal energy storage technologies and system solutions that are of particular interest for the Swedish building stock. In this licentiate thesis, the aim is focused on showing a comprehensive summary of available technologies for TES in buildings as well as assessing the possibilities for increased energy efficiency. This is an important part since there are numerous TES technologies either available on the market or currently being researched. The combination of TES systems in various building types, including both residential and commercial buildings, is also investigated in order to find system solutions with a potential for increased energy efficiency. The goal is that the research presented in this thesis can be used to evaluate which combinations of TES and building type that show promise enough to be investigated further.

The main focus is on the need to keep a certain indoor temperature range in a building with the help of thermal energy storage, which makes for a very broad starting point. All buildings where heat and cold is used to maintain a comfortable indoor climate are included, both residential and commercial buildings. In a first stage, all types of TES, both short and long term, active and passive are considered. There are also some limitations; process heat or cold is not considered, and the relevant temperature range is that of human comfort levels meaning that cold rooms etc. are also excluded. As for storage, only TES inside or in direct vicinity to the building(s) is studied, and not centralized TES in a large system, for example a district heating or cooling system.

1.3 Methodology

This thesis is focused on a background literature study on TES for use in buildings, as well as case studies on the implementation of certain storage techniques. Since the starting point is so wide, involving many storage technologies, the literature study is centred on how these technologies have been used or can be used in buildings, without going into too much detail on each technology. A description of various thermal energy storage technologies together with conclusions from the main literature review is presented in chapter 2. The selection of storage techniques to be included to this chapter is partly based on Paper I while the main conclusions and literature review is based on Paper IV. A majority of the material of which both Paper I and Paper IV are based on is derived from scientific publications discovered through Science Direct, Google Scholar, Web of Knowledge (among others) by using combinations of key words such as “thermal energy storage”, “thermal storage”, “building” as well as key words related to specific storage techniques. The reference group in the project has also been a valuable asset, especially in identifying relevant Swedish TES projects and literature. Based on the available literature and through discussions together with the reference group, a list of key figures designed to assist in the selection of TES technologies that were deemed promising enough for further studies was produced. The conclusion was, however, that this selection could not be made in an objective way and therefore this process is not included in this thesis. Instead, further literature review (resulting in Paper IV) and case studies (discussed below) were used as means to help in the identification of promising TES techniques.

Following, in chapter 3, is a discussion on the composition and energy use in the Swedish building stock together with a selection of building types. Statistics on the Swedish building stock available through Statistics Sweden (SCB) is used to describe the Swedish building stock and two typical buildings (one single family house and one office building) are chosen as being representative for a large number of existing buildings. A third typical building, also a single family house, is selected to represent new buildings with better insulation standard. Chapter 3 is to some extent based on Paper I.

Two case studies have been performed in order to evaluate the potential of selected TES systems. The first case study is an evaluation of an existing seasonal borehole storage for residential buildings (presented in section 4.1 which is a summary of Paper II). In this case study, measurement data was used to calculate defined key figures in order to evaluate both the performance and the function of the system. The key figures are compared to both the design values as well as values from an earlier evaluation. The second case study is a dynamic building energy simulation study of passive TES in two single family houses using the software TRNSYS 17 (presented in section 4.2; a summary of Paper III). The buildings are simulated using the IEA SHC Task 32 Reference Heating System (Heimrath and Haller, 2007) as a base and the climate used is that of Stockholm. The two buildings simulated are fictive representations of a 1940 single family house and a modern single family house fulfilling the passive house recommendations given by FEBY (Erlandsson et al., 2009). The buildings are simplified to single zone models, but with realistic internal gain profiles and weather data. For the simulations with phase change materials (PCM), a PCM model released by TESS (TESS Libraries) is used. This model simulates an ideal PCM meaning a constant phase change temperature as well as negligible resistance between the PCM and the surrounding wall layers.

The methods presented above are used in combination to support a discussion around the current and future use of TES in buildings and what the benefits can be from an energy efficiency perspective.

2 TES Used in Buildings

In this chapter, the technologies and systems for TES that are used in buildings are described. This chapter is mainly based on the review in Paper IV which in turn to some degree is based on the literature review done for Paper I. In the first part of this section storage technologies are described in general. A more detailed review with additional references is available in Paper IV. In the second part of this chapter, the main results from Paper IV are presented together with a table summary of available articles with research on combinations of TES and specific building types.

Thermal energy storage can have many purposes, but for residential and commercial buildings, the core purpose discussed here is the use of thermal storage to keep the indoor temperature within specified comfort limits. As mentioned in the introduction, energy storage is required to make the most of many renewable energy sources available, both for heating and cooling purposes, and can therefore contribute to current goals of increasing the share of renewable energy in the building sector.

TES in buildings can be divided into two major categories, passive and active storage, but there are also combinations of the two where the charging is active and the discharging is passive or vice versa. For a passive storage, the driving force for charging and discharging the store is only the temperature difference between the store and the surroundings. In the case of an active storage, the charging and discharging occurs with active help from pumps or fans. Most of the techniques used for TES in buildings are active and only two passive techniques will be discussed; sensible storage in building elements with high thermal mass and latent storage using phase change materials (PCM) in the building walls, ceiling or floor. The categorization of TES in buildings suggested and used in Paper IV is shown in Figure 2.1.

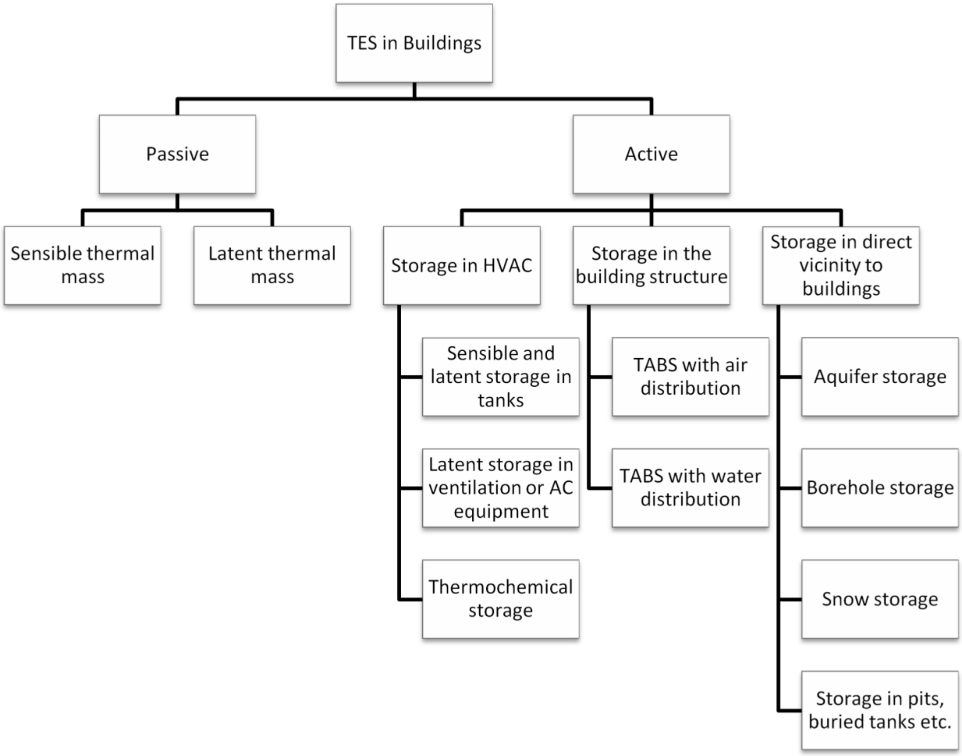

Figure 2.1. Categorization of techniques for thermal energy storage used in Buildings

Due to the research field of TES in buildings being both wide and popular, a summary of available review articles was done in order to determine the focus of this field. A table summarizing these review articles, mainly since the year 2000 and later, is presented in the Appendix. The summary shows that research on phase change materials and their applications is a very popular research field with a majority of the available reviews focused on this subject. Reviews not focused on PCM tend to be focused on a single technique for thermal energy storage or a small group of similar techniques. The aim in Paper IV is therefore to present a broader review on the techniques available and also focus on the research where these storage techniques have actually been used in real buildings.

Much work on thermal energy storage has also been carried out within the International Energy Agency (IEA) and a review report on this work, written within IEA ECES Annex 23, is due for publication in the first half of 2013 (Basecq et al., 2013).

2.1 Passive storage techniques

Passive storage treated here includes storage in the building structure such as walls, ceiling and floor. The main difference between an active and a passive system is that a passive system uses temperature differences over time in the building for storing and releasing of heat. This means that the occupants in the building need to accept temperature variations over the day, and the larger the temperature variation is the larger is also the potential for passive heat storage. This is especially true for sensible storage but passive storage is also possible using latent storage in PCM. Using the latent energy of a phase change in a material means that the energy can be stored in a smaller temperature interval around the melting point of the phase change material. Temperature variations are still necessary, but the same amount of energy can potentially be stored within a smaller temperature range if PCM is used. It is, however, important to make sure that the temperature variation is large enough so that the PCM can actually melt and solidify again. One important parameter for both sensible and latent passive storage is the amount of heat or cold that can be stored in the material. For sensible storage this is generally referred to as "thermal mass" and there is often a distinction between light and heavy construction materials. For PCM the corresponding important parameter is the heat of fusion which tells how much energy can be stored in the phase change of the material. Taking a building wall as an example, a schematic picture illustrating the difference between a light, heavy and phase change material wall is shown in Figure 2.2. The figure shows that the PCM can store a large amount of energy in a small temperature range around its phase change temperature. If the temperature difference is very large or the temperature changes outside of the phase change range of the PCM, however, a heavy sensible material may have better storage potential. Besides the temperature difference between the wall and surrounding air, the heat transfer to, from or within the thermal mass also has an important role and can influence the heat transfer rate as well as how much energy can be stored in practice.

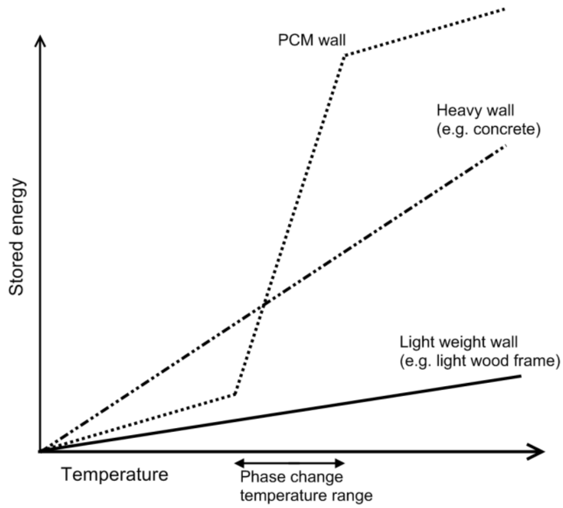

Figure 2.2. A schematic picture showing the difference between a light weight, heavy weight and PCM wall for passive storage in buildings

2.2 Active storage techniques

If a deliberate energy input is required to make the storage system work as intended, it is considered here to be an active storage. This can for example be electricity to pumps or fans. As was shown in Figure 2.1 active storage is divided here into three groups: storage in the HVAC system, storage in the building structure and storage in direct vicinity to buildings. Storage in HVAC systems include storage both for heating and cooling purposes that are more or less integrated with either the heating, ventilation or air conditioning system of the building. Storage in the building structure with active charging, discharging or both is often referred to as TABS (thermally activated building systems) and is divided here into TABS with air distribution or with water distribution. Storage in direct vicinity to buildings includes aquifer, borehole and snow storage as well as storage in pits or buried tanks. Since many of the storage techniques used in vicinity to buildings are designed for larger systems, they fall outside the scope of this project but the technologies themselves are still briefly described.

2.2.1 Storage in the HVAC system

Sensible and latent storage in tanks

One of the most common ways to store thermal energy is in tanks, which is used in a wide range of applications both for residential and commercial buildings. One of the simplest and also by far the most common is a small domestic hot water (DHW) tank which can be heated by for example solar energy, gas boiler or electricity. The main reason for DHW storage being so widely used is the large hot water discharge powers required for e.g. showers and baths. If no store is available, the heating power required would be very high and the store therefore works as a peak shaving device. A more advanced system is a so called combisystem, a system providing both DHW and space heating, which is common in many countries in the world. An example is the solar combisystem and a schematic of a common Swedish solar combisystem is shown in Figure 2.3. Here the store is charged with solar collectors and a second source, for example a biofuel boiler, and heat is extracted to both domestic hot water and space heating. Combistores are discussed by Streicher and Bales (Hadorn, 2005), showing several storage designs and pointing out the importance of stratification. Some examples of solar and pellet combisystems are shown by Persson (Persson, 2004). Solar combisystems including combistores was also the topic of the European project CombiSol, whose goal was the promotion and standardization of solar combisystems in Europe (Papillon et al., 2010).

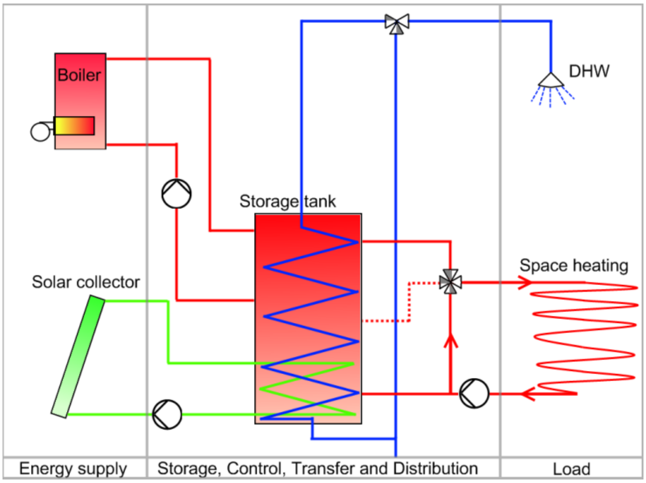

Figure 2.3. A schematic diagram of a typical Swedish solar combisystem with solar collectors and a boiler charging the water storage tank, to which both domestic hot water and space heating is connected (based on (Papillon et al., 2010))

Active storage in tanks can be both sensible and latent, where sensible storage in tanks using water as heat storage medium is the most used storage type today. Storage with PCM is beneficial in that the storage density is higher, at least for relatively small temperature ranges, resulting in potentially smaller storage volumes for the same amount of stored energy. Although storage of hot water might be common in residential buildings, cold storage in tanks is widely used in commercial buildings. For cold storage water is often used, both sensible at low temperatures but also as a PCM through ice storage.

Latent storage in ventilation or AC equipment

It is also possible to add a TES directly into the ventilation or air conditioning of a building and in some cases also use the storage medium as heat transfer medium in the system, as will be discussed in this section. Since there are often limitations of space when storage is to be integrated into the ventilation system, the focus is on using latent storage to increase the energy storage density. Although most storage in this category is used for space cooling, there are also examples for space heating.

One example used for free cooling in buildings is shown in Figure 2.4. In this case, addition of a PCM store to the ventilation system of a school for free cooling was investigated (Ning-Wei Chiu et al., 2012). The figure shows three operating modes for the system when the store is either charged with cold air, in standby while the ventilation air is taken directly from the outside or discharged to cool the building.

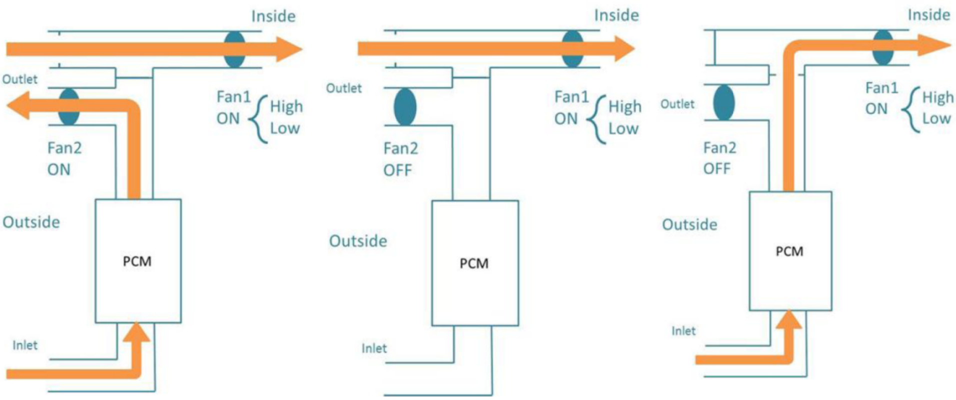

Figure 2.4. Operating modes for a ventilation system with PCM store (from the left: charging of the store, standby with outside air direct ventilation and discharging of the store to cool the building) (Ning-Wei Chiu et al., 2012)

In the solution presented above, ventilation air is passing through a store that can be filled with for example encapsulated PCM. Another solution without adding an actual store, is to put PCM directly into the ventilation air duct to, more or less, increase the thermal mass of the air ducts. This is simpler to do in an existing ventilation system but the downside with this simpler solution is the lack of additional control that is possible with a system designed with storage in mind. In both these cases, air (which is used as the heat transfer medium) is in direct contact with the PCM. Another solution is to use PCM both as a storage medium and the heat transfer medium in the ventilation system, which can be achieved by using a PCM slurry (either using ice or a different PCM which then usually is microencapsulated). The PCM slurry is used as heat transfer medium, delivering cold from the central cooling system to local heat exchangers from which chilled air is used as normal. One advantage with this solution is that the electricity consumption for pumping the slurry is significantly lower than the required electricity for other more common solutions (Hayashi et al., 2000).

Thermochemical storage

In thermochemical storage, reversible chemical reactions are used to store heat. The basic principle, as shown in Figure 2.5, is fairly simple. During the charging process, heat is added to a chemical compound causing it to react and produce two components. The two components are put into separate storage units and can be stored in a stable condition until needed. When the heat is needed, the store is discharged by mixing the two components resulting in an exothermic reaction to form the original compound and at the same time release heat. Thermochemical storage is divided in two different types: open and closed. The main difference between these two types is that an open system has both heat and mass exchange with the surrounding environment, while a closed system only has heat exchange. In practice, this means that water is the only possible working fluid in an open system. One of the most promising aspects of thermochemical storage is that when separated (in the storage phase) the two components can be stored without any heat losses. This is of great importance for long term storage, since low heat loss is a necessity for long term storage to work at all. This type of storage is an emerging technology where many problems still have to be solved through research but there are numerous more or less promising technologies, many of which are presented in the final report of IEA Solar Heating and Cooling Task 32 (Hadorn, 2005). One of the important aspects of a thermochemical storage is that both heat and mass transfer occurs simultaneously, which means that both heat and mass transfer limits can reduce the achievable heating or cooling power (Lahmidi et al., 2006, Mauran et al., 2008). A second common problem is that a low grade heat source is required during the discharge process (in closed systems) in order to evaporate the working fluid. As the most common working fluid is water the temperature of this heat source commonly needs to be at least 5 °C in order to evaporate water under vacuum conditions (Hadorn, 2005).

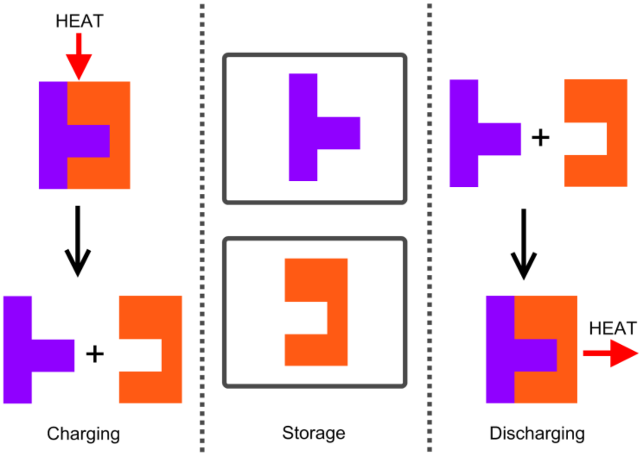

Figure 2.5. The basic principle behind thermochemical storage

2.2.2 Storage in the building structure

Active storage in the building structure is often referred to as thermally activated building systems, or TABS. Unlike passive storage discussed in section 2.1, the walls, floor or ceiling of a building is made active through the incorporation of pipes or hollow cores. Here either a liquid, commonly water, or air can be circulated to help in the charging and/or discharging of thermal energy in the building elements (direct electricity can also be used for heating purposes). The most common use of this technology (although it may more often than not be regarded simply as a heating system more than a storage system) is through floor heating, where water pipes (or electric heating cables) are embedded in the floor. An example of this, where the storage aspect is considered, is the direct solar floor which was one of the systems discussed in IEA Solar Heating and Cooling Task 26 (Weiss et al., 2003, Chèze and Papillon, 2002). For cooling purposes active ceiling panels with embedded water pipes are often used. Ventilated hollow core slabs (Figure 2.6) is a specific group of TABS where concrete slabs used for construction of the building is also used to transport ventilation air through hollow cores in the slabs to provide both heating and cooling of the building. Since TABS can provide active charging or discharging (or both) it can provide better control possibilities than passive storage in the building structure, but having a high thermal mass closely integrated in for example the ventilation system can also make the system difficult to operate. An example of this is a simulation study of an office building with TABS + VAV (variable air volume) ventilation is used, where the authors conclude that the coordination between the TABS and VAV-system is crucial to reach a high system efficiency (Henze et al., 2008).

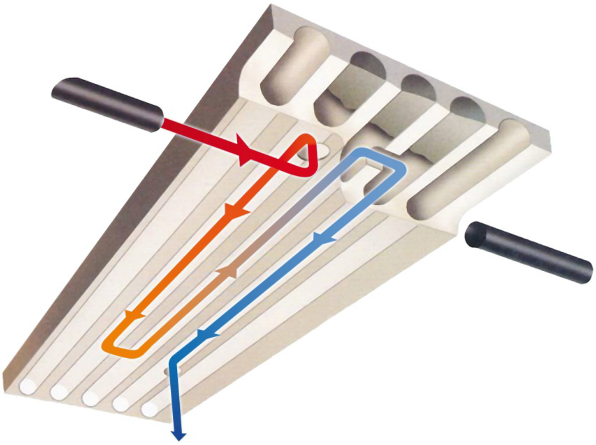

Figure 2.6. The principle of a ventilated hollow core slab, showing the air flowing through the slab (Strängbetong)

2.2.3 Storage in direct vicinity to buildings

This kind of TES is usually intended for larger areas including many buildings (where local district heating or cooling systems are used) and would, as such, in many cases fall outside of the scope of this thesis. There is, however, a large "gray area" which is why also these technologies are included and discussed briefly. One of the case studies included in this thesis (chapter 4.1) treat a TES system of this kind.

Aquifer storage

Aquifer storage is a rather limited technology since there has to be a suitable aquifer in close vicinity to the building(s). To be able to make full use of an aquifer storage it is also important that the heating and cooling loads are somewhat balanced using both warm and cold wells in the aquifer, as can be seen in Figure 2.7. If these conditions are met, there are several advantages to aquifer storage as compared to for example borehole storage. The most important advantage is the possibility to achieve very high heating and cooling power rates from an aquifer since water can be pumped at a high rate (Paksoy et al., 2009). If the temperature in the aquifer is sufficient, this means that direct heating and cooling can be used without the need for heat pumps or some type of short term high power storage. Due to the nature of aquifer storage, it is only suitable for buildings (or groups of buildings) with a high heating and cooling demand.

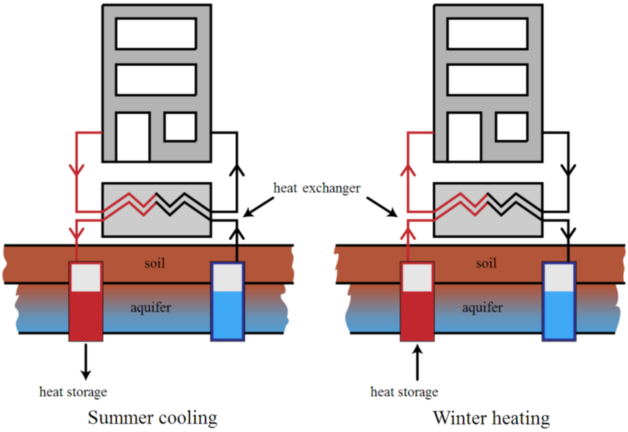

Figure 2.7. Schematic picture showing storage in warm and cold wells of an aquifer (Wikipedia Commons)

Borehole storage

Many might associate borehole storage with the increasingly popular ground source heat pumps for single family houses. In most cases, however, since no heat is deliberately put into the borehole in these single borehole applications it should not be considered a TES. Instead, borehole storage refers to larger systems where many boreholes (tens or several hundred) are drilled in close proximity, creating a large "storage volume" of rock. The store can then be charged during summer from solar collectors or from cooling buildings and discharged during winter to heat buildings. A schematic picture is shown in Figure 2.8. As seen in the figure, the core of the borehole storage volume has the highest temperature in order to minimize heat losses to the surrounding ground. For borehole storage systems it is common to use heat pumps during the discharge but there are also examples of systems with high temperature storage without using heat pumps, such as the system described in 4.1. In the described system, water tank storage is used in combination with the borehole storage system in order to achieve a more efficient short-term performance (higher heating rates), i.e. peak shaving.

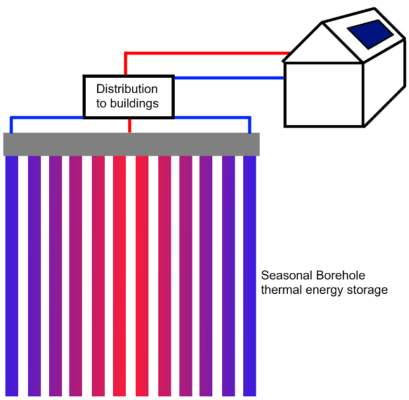

Figure 2.8. Schematic picture of a seasonal borehole thermal energy storage system

Snow storage

In cold climates seasonal storage of snow can be a good way to cover cooling demands during the summer for buildings with a large cooling demand. This kind of system has proven to be both reliable and cost effective, as shown by Skogsberg and Nordell (Skogsberg and Nordell, 2001, Skogsberg, 2002), where a snow storage system for a hospital in Sweden is described, see illustration in Figure 2.9. One negative aspect is, however, that a large area is required for storing the snow (8400 m^2 for the Swedish hospital in the study).

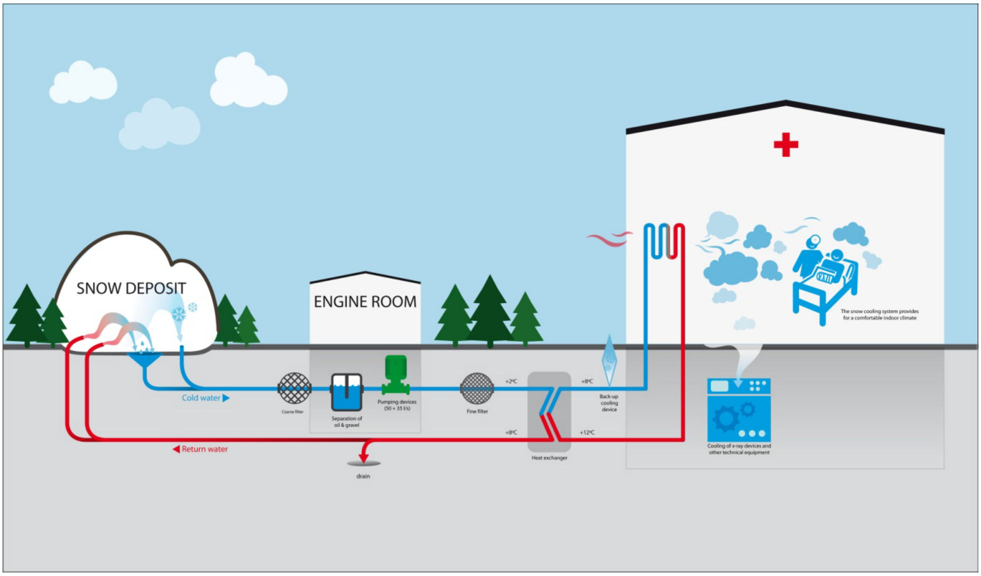

Figure 2.9. Illustration of the snow storage system at Sundsvall hospital (IDAG Designbyrå)

2.3 Combining thermal energy storage with buildings

Apart from reviewing available TES techniques, one of the main aims with Paper IV was to highlight available literature on the combinations of TES and building types (residential and commercial) and discuss benefits and difficulties with these combinations. This resulted in two tables showing available literature as well as some information and results on combinations of TES techniques and residential buildings (Table 2.1) as well as commercial buildings (Table 2.2). These two tables show the availability of papers (almost exclusively journal papers) that specifically treat the use of thermal energy storage in buildings. This means that studies for example on the storage technology itself or more general studies are not included in the tables. As for the main results presented in the tables, all listed references do not necessarily agree with all results listed.

Table 2.1 shows that a large part of the studies in residential buildings is done through simulations. This is not so surprising considering the complications of doing research and measurements in people's homes, but it is important to remember that theoretical studies such as simulations always involve simplifications and might not always behave as actual systems. The studies in Table 2.1 and Table 2.2 show many possible improvements through using TES in buildings, some examples being reduced need for purchased energy (often by introducing alternative energy sources such as solar heat or free cooling), reduction in heating or cooling peak power and smaller variations in the indoor temperature. Passive storage (sensible or latent thermal mass) often show a reduced heating and/or cooling demand, but most papers reach the conclusion that only a small reduction is possible (Ståhl, 2009, Hagentoft and Svensson, 2000, Heier et al., 2012). Instead there is a larger possibility for reduction in excess temperatures and lower swings in indoor temperature (Ståhl, 2009, Peippo et al., 1991, C. Castellón, 2006, Heier et al., 2012). As already mentioned earlier, proven storage techniques such as water storage tanks are already used successfully to a large extent for short term storage but long term storage in residential buildings still proves to be difficult, at least in single family houses. This is because the heating load is too small for successfully introducing a seasonal storage such as borehole or aquifer storage (especially since the the cooling load is more or less non-existent). It is however possible to introduce seasonal storage in larger residential complexes or in small communities where the store is used by several buildings, such as the borehole storage system described in section 4.1. More advanced storage using thermochemical reactions for seasonal storage in smaller residential buildings is receiving research attention but the road is still long before such techniques are commercially available.

Similar to residential buildings, using passive TES in commercial buildings (Table 2.2) only shows a small reduction in the heating or cooling demand. Contrary to residential buildings, cooling is often required in commercial buildings and research on TES is to a large extent focused on reducing either the amount of purchased cooling or reducing the required peak cooling power. Storage in the ventilation system or active storage in the building construction shows promise for short term storage. For long term storage there are more options since the heating and cooling demands generally are large in commercial buildings and using borehole, aquifer or even snow storage can be very beneficial.

Table 2.1. Literature summary for thermal energy storage in residential buildings

Storage technique	Studied buildings	Methodology	Focus of studies	Main results	References
Passive sensible storage	Single and multifamily buildings	Almost exclusively simulations.	Majority on energy savings, but also comfort and peak reduction	Most studies report small energy saving potential but more stable indoor temperature.	(Ståhl, 2009), (Zhu et al., 2009a), (Hagentoft and Svensson, 2000), (Norén et al., 1999), (Heier et al., 2012)
Passive latent storage	Single and multifamily buildings, test cubicles	Simulation and experiments	Majority on comfort, but also for energy savings and peak reduction	Reduction of excess temperatures and cooling demand, small reduction in heating demand.	(Peippo et al., 1991), (C. Castellón, 2006), (Heier et al., 2012), (Yahay and Ahmad, 2011),
Sensible storage in tanks	Single and multifamily buildings	Simulation and experiments	Emission reduction, system evaluation, peak reduction	Emission reduction from boilers and heating peak load reduction possible.	(Johansson et al., 2004), (Papillon et al., 2010), (Arteconi et al., 2013), (Schmidt et al., 2004)
Latent storage in tanks	Solar low energy buildings	Simulation	Energy savings	No significant improvement of PCM compared to water for heating applications.	(Streicher et al., 2008)
Latent storage in ventilation or AC equipment	Single family houses	Simulations	Improved indoor climate, energy savings	Considerable reduction of excess temperatures. Reduced ventilation load.	(Arkar and Medved, 2007), (Takeda et al., 2004), (Persson and Westermark, 2012)

Table 2.1 cont.

Storage technique	Studied buildings	Methodology	Focus of studies	Main results	References
Thermo-chemical storage	Single family houses	Simulation and prototypes	Switch in energy source	Long term storage with minimum losses is possible. Storage capacity often close to theoretical. Problems with low heat transfer and high temperature. Much R&D is still needed.	(Lahmidi et al., 2006), (Mauran et al., 2008),(Bales et al., 2008), (Gartler et al., 2004), (Caliskan et al., 2012a), (Caliskan et al., 2012b)
TABS with water distribution	Test cubicle, passive house, low energy house	Simulations, real building	Energy savings and peak reduction	Control optimization necessary, significant peak shaving and auxiliary energy use	(Mazo et al., 2012), (Kalz et al., 2010), (Pahud, 2002), (Chèze and Papillon, 2002), (Weiss et al., 2003)
Borehole storage	Single family houses, residential complex	Studies on both real buildings as well as simulations	Evaluation of existing systems, switch in energy source	A seasonal borehole storage system is capable of meeting the heating demand also in severely cold areas. Cooling with or without heat pumps is possible. Important to consider losses in system.	(Nordell and Hellström, 2000), (Lundh and Dalenbäck, 2008), (Heier et al., 2011), (Wang and Qi, 2008), (Wang et al., 2009)
Storage in pits, buried tanks etc.	Apartment complexes	Studies on real buildings	Switch in energy source	Possible to reach a high solar fraction. Heat losses from stores are fairly high.	(Schmidt et al., 2004), (Bauer et al., 2010)

Table 2.2. Literature summary for thermal energy storage in commercial buildings

Storage technique	Studied buildings	Methodology	Focus of studies	Main results	References
Passive sensible storage	Small office building (4 floors), school	Simulation	Energy savings, improved comfort	Small reduction in heating and cooling demand.	(Ståhl, 2009)
Passive latent storage	Single office	Simulation	Reduction of excess temperatures	Operative temperature can be reduced summertime but results show high dependence on climate and PCM properties.	(Evola et al., 2013)
Sensible storage in tanks	University	Case study on existing building	Peak reduction	Significant peak demand reduction	(Boonnasa and Namprakai, 2010)
Latent storage in tanks (ice storage)	Small and large office buildings	Case study of existing buildings, simulation	Energy savings, peak reduction, exergy evaluation	Efficiency of cooling system improved, large peak reductions. Benefits depend on climate and many other factors.	(Rismanchi et al., 2012), (Sehar et al., 2012), (Henze et al., 2003)
Latent storage in ventilation or AC equipment	Small office building, single offices, commercial complex, school	Experiments in real building, simulation, prototype testing	Heat transfer improvement of store, switch in energy source, excess temperature reduction	Cost and space reduction possible if heat transfer can be improved. CO_2-emissions can be reduced and so can excess temperatures.	(Hamada and Fukai, 2005), (Turnpenny et al., 2000), (Turnpenny et al., 2001), (Bellas and Tassou, 2005), (Ning-Wei Chiu et al., 2012)

Table 2.2 cont.

Storage technique	Studied buildings	Methodology	Focus of studies	Main results	References
TABS with air distribution	Small office building	Simulation	Switch in energy source, improved comfort	Control system is crucial. Possible to reduce primary energy demand and increase comfort.	(Henze et al., 2008), (Gwerder et al., 2008)
TABS with water distribution	Single office, office building	Simulation	Switch in energy source	Significant reduction in mean cooling power. Control strategy has large impact on results.	(Lehmann et al., 2007), (Lehmann et al., 2011)
Aquifer storage	Hospital	Case study of existing building	Switch in energy source	Considerable reduction in use of fissile fuels as compared to a reference system.	(Vanhoudt et al., 2011)
Borehole storage	University complex	Case study of existing buildings	Switch in energy source, exergy evaluation	Potential for large reduction in purchased energy if exergy efficiency is evaluated for all system components.	(Kizilkan and Dincer, 2012)
Snow storage	Office building, hospital	Prototype testing, case study of existing building	Switch in energy source	Significant primary energy reduction. Construction cost reductions necessary. Large space requirement.	(Skogsberg and Nordell, 2001), (Skogsberg, 2002), (Hamada et al., 2010)

2.4 Review summary and discussion

After an extensive literature review, not only on the storage techniques themselves but also on their combination with buildings, there are many conclusions and points of discussion to be made. A more detailed background for many of the discussions in this section is presented in Paper IV, which should be used as a reference for the conclusions here.

From the review it is clear that thermal energy storage already is an important part of the building sector. Water tank storage for domestic hot water or coupled with solar collectors and/or boilers is actively used with great success in almost all buildings and large thermal mass as passive storage (at least sensible thermal mass) is an important part of many buildings (although not always consciously used as thermal energy storage). One problem with using the thermal mass as thermal energy storage is, however, that the only driving force for charging and discharging the "store" is the temperature difference between the thermal mass (for example in the wall) and the rest of the room. Since a large temperature difference intrudes on the thermal comfort, there is a limit to the amount of thermal energy that can be stored before inhabitants/tenants start to complain. Using phase change materials to increase the thermal mass of buildings has become a very popular research field and today there are commercial products available, for example in the form of PCM plaster boards. The theory behind using the latent heat of a material to increase the thermal mass in a small temperature range is indeed interesting; if PCM with a phase change temperature within the building comfort temperature is used, a larger amount of energy can be stored within the comfort range as compared to sensible storage in a normal wall. In reality however, there are still many problems with PCM such as the melting/freezing range not being as narrow as would be required or problems with for example subcooling, hindering the PCM to freeze properly within the required temperature interval and losing its effect. Much research is therefore still required, perhaps mainly on phase change materials themselves.

Using PCM instead of or in combination with water in active tank storage, such as the above mentioned domestic hot water tanks or larger stores, is also a current topic for research. Conclusions from several sources however, indicate that normal water is often a better choice for many reasons. One of the main issues discussed is the poor heat transfer properties in PCM making it difficult to achieve desired heating or cooling power (Martin et al., 2010, Heinz, 2007a, Martin and Setterwall, 2009, Hamada and Fukai, 2005). Water as PCM is, however, successfully used commercially in especially one specific application, which is peak shifting of the cooling in commercial buildings using ice storage to be able to take advantage of off-peak energy tariffs.

Actively using the building thermal mass for storage can be done by "activating" parts of the building (ceiling, walls or floor) either with hollow cores where air can flow or with pipes for fluid (water). If air is used, normally the building ventilation is routed through the hollow cores in the building structure (concrete slabs with large thermal mass). This kind of slabs are marketed as giving large reductions in heating and cooling demands at the same time as improving the indoor temperature levels in buildings. Discussions on 10 October 2010 with Jonas Gräslund, representing a large construction company, and Martin Bergdahl, representing a County Council, show a different opinion based on experience in actual buildings equipped with such TABS. Gräslund comments on the rough surface of both the hollow cores and the slab, mentioning air leakage between the concrete slab and the ventilation duct system as well as questioning the cleanability of the hollow cores. He also mentions that the system is slow to react on control input, and this is also mentioned by Bergdahl, pointing out that the control system is extremely important. Gräslund also exemplifies with a building where the ventilation system had to run on full power during both nights and weekends to heat the building, when the ventilation normally is turned off, resulting in higher electricity consumption especially as the electricity required for energy transport is much higher in air than in water. The required difference in indoor temperature over the day is also questioned by Gräslund and he speaks of cases where the tenants often complain about cold mornings and warm evenings. Using a fluid instead of the ventilation air will remove some of the problems highlighted above, but not all. Conventional floor heating is, however, an adaptation of this technology that is widely used, although there is seldom a conscious choice as a thermal energy storage technique and therefore not optimized as one in most cases (one exception being the "direct solar floor" system mentioned in 2.2.2).

TES using thermochemical reactions has, in the review, shown interesting potential for seasonal storage in buildings mainly for two reasons; the thermal energy can be stored with little to no heat losses even seasonally and the technique can also be used in buildings where the heating requirement is low (single family houses). It needs to be pointed out however, that thermochemical storage is an advanced and emerging technology that still has many problems that need to be solved before the technique can be used with reliability. A couple of points that are especially important should be noted. First, a thermochemical storage system not only needs heat during charging but commonly also a low temperature heating source is required during discharge. This is required to obtain water vapor, which is often used as a reactant. One solution is to use indoor air as water vapor source but this is problematic since it requires large airflows (Hadorn, 2005). A second problem is the power at which the stored energy can be discharged. In thermochemical storage not only heat transfer but also mass transfer needs to be considered and both transfer rates need to be high enough for the store to be useful. One way to reduce this problem is to combine the thermochemical store with a water tank which can significantly reduce the power requirements from the thermochemical store (Bales et al., 2008), since heat can be extracted from the water tank at high rates which in turn can be charged over a longer duration. There is still much research required on materials however, as identified within IEA Solar Heating and Cooling Task 32 (Hadorn, 2005).

More proven and also commercially available techniques for seasonal TES, such as aquifer, borehole and snow storage, can reduce the amount of purchased energy significantly by taking advantage of solar energy (common with borehole storage), balancing heating and cooling demands over the year (aquifer and borehole) or storing snow from winter for cooling in the summer. These techniques also have their difficulties, but the problems are not so much related to the technologies themselves but rather to system design (for example making sure heat losses are minimized), placement of the building (Are the ground conditions for a borehole storage sufficient? Is there an aquifer nearby that can be used? Is there enough space to store the snow?) as well as other building requirements (Is the heating/cooling demand large enough for this kind of seasonal storage to be cost efficient?).

Finally, it can be concluded that thermal energy storage is already used today in many building applications, although not always consciously as a storage technique. New novel solutions, often using PCM or thermochemical technologies, are emerging but in order for these technologies to become commercially viable, much research is still required both on materials themselves and on storage systems. The literature shows a large potential for using thermal energy storage in buildings but the fact that all buildings are different makes it difficult to find standard solutions, and storage systems often need to be designed and optimized on a building to building basis. The available building stock is therefore an important factor when evaluating TES in buildings on a larger scale, which leads to the next chapter (chapter 3) where the Swedish building stock is discussed.

3 Identification and selection of building types

This chapter focuses on the identification and selection of building types representative of the Swedish building stock. The heating and cooling systems common in these buildings are also discussed and exemplified. The chapter is partly based on the literature study done in Paper I, but also on the work done in Paper III.

3.1 The Swedish building stock

To get a good overview of the building stock in Sweden and to get a basis for selection of building types, national statistics from Statistics Sweden were used (SCB, 2009c, SCB, 2009a, SCB, 2009b). Statistical data on average energy use, heated floor area and construction year for one and two family buildings, multifamily buildings and premises was compiled. This is also the method used by SP (Technical research institute of Sweden) when mapping the building stock (Haglund Stignor et al., 2009). Nygren (Nygren, 2003) used a similar method when mapping Swedish one- and two family residential buildings using electricity for heating. It is important to note, however, that figures for average energy use provided by Statistics Sweden are based on purchased energy, and not the actual energy use. Figures showing the average purchased energy and the percentage of total heated floor area for different construction years are shown as follows for one- and two-dwelling buildings (Figure 3.1), multi-dwelling buildings (Figure 3.2) and premises (Figure 3.3). Figure 3.4 shows the average purchased energy for premises broken down by premises type. For the residential buildings, the use of cooling is not large enough to even be included in the statistical figures and is therefore not shown here. For premises (Figure 3.3 and Figure 3.4) a combined figure on cooling from district and comfort cooling is also included. Both figures are for purchased energy (district cooling or electricity for comfort cooling) based on surveys to building owners/occupants but according to SCB (SCB, 2009b) the response rate was low, giving the figures on cooling a high uncertainty.

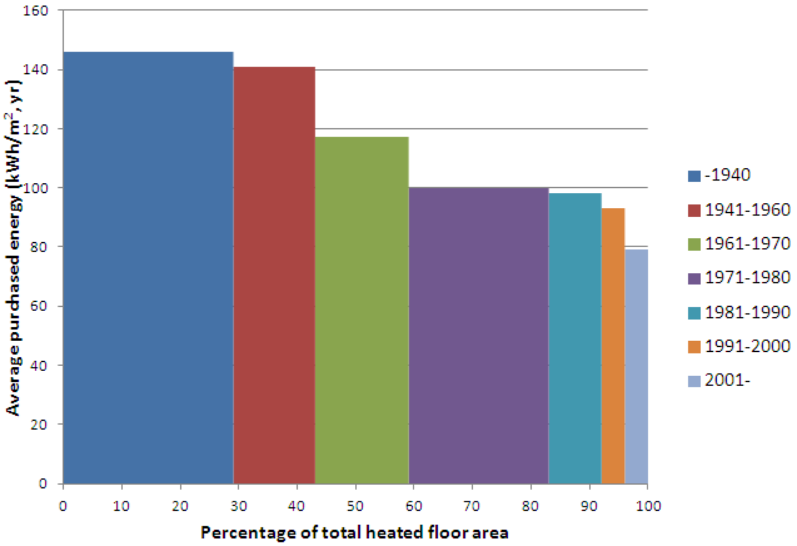

Figure 3.1. Use of purchased energy in one- and two-dwelling buildings in 2008 for heating and domestic hot water broken down by construction year, pictured as a surface with the average purchased on the y-axis, and the percentage of the total heated floor area on the x-axis

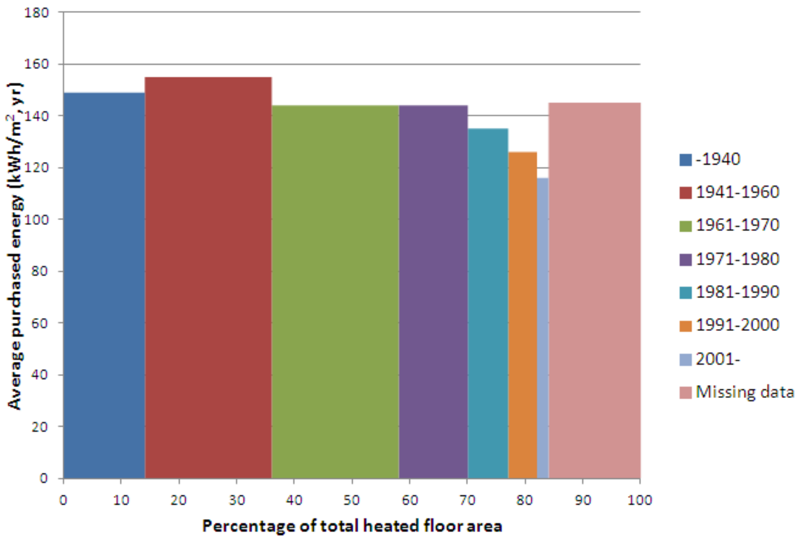

Figure 3.2. Use of purchased energy in multi-dwelling buildings in 2008 for heating and domestic hot water broken down by construction year, pictured as a surface with the average purchased energy on the y-axis, and the percentage of the total heated floor area on the x-axis

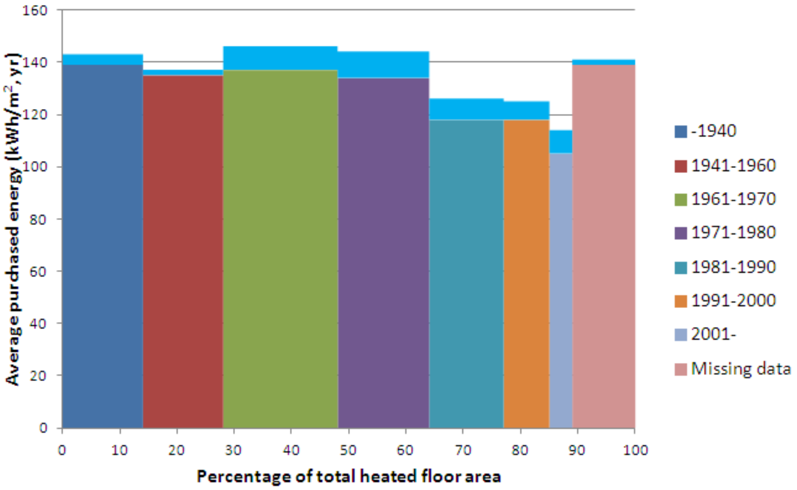

Figure 3.3. Use of purchased energy in premises in 2007 for heating, domestic hot water and cooling broken down by construction year, pictured as a surface with the average purchased energy on the y-axis, and the percentage of the total heated floor area on the x-axis. The cooling (purchased energy for district and comfort cooling) is shown separately at the top of each column

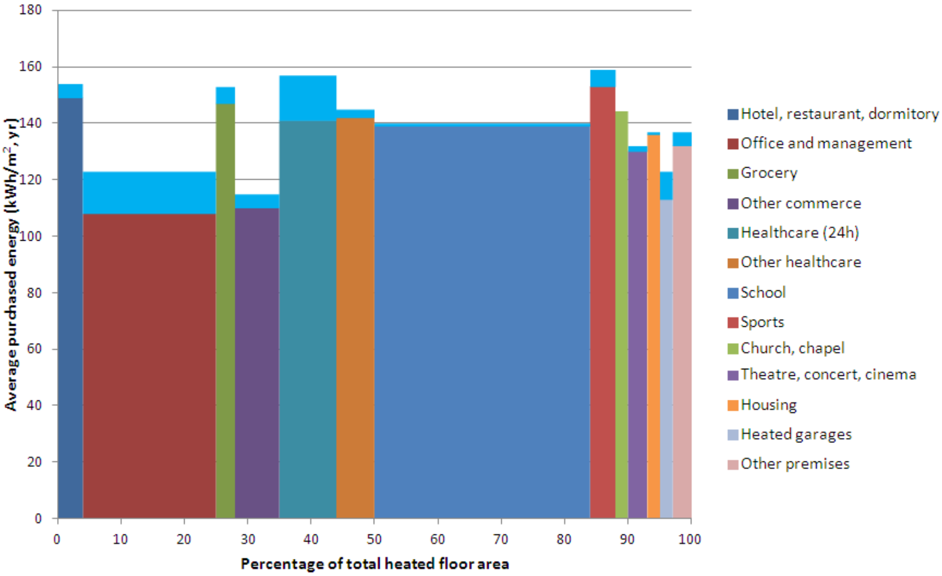

Figure 3.4. Use of purchased energy use in premises in 2007 for heating, domestic hot water and cooling broken down by premises type, pictured as a surface with the average purchased energy on the y-axis, and the percentage of the total heated floor area on the x-axis. The cooling (purchased energy for district and comfort cooling) is shown separately at the top of each column

3.2 Selecting building types for evaluation of TES concepts

To create clear and meaningful boundary conditions for comparison of techniques for thermal energy storage, it is necessary to define building types within the different sectors of residential and commercial buildings. The defined buildings need to be typical for each sector in order to represent as many existing buildings as possible. The method for selecting building types used in this study is based on the same approach used by SP (Haglund Stignor et al., 2009) for single family houses, multifamily buildings and premises, and by Nygren (Nygren, 2003) for single family houses. This method involves using the available national building statistics to find what types of buildings are most common in the existing building stock. Building types representing a large part of the building stock are then chosen as typical buildings. In this case, however, it is also important to consider new buildings, since many storage techniques might be difficult to incorporate in existing buildings. For the scope of this thesis, the building type selection is limited to two single family houses and one commercial building, but only the single family houses are used beyond the selection process (in section 4.2).

By looking at Figure 3.1 it is evident that the oldest buildings (constructed up until 1940) compromise the largest part of the single family houses existing today. This group of buildings also has the highest average energy demand. To represent this large part of the building stock, one of the single family houses chosen is therefore a 1940 single family house. Even though the construction rate of new buildings is low compared to the existing building stock, it is also important to include new buildings as well; partly because these buildings also will be in use for a very long time and partly because the choice of TES system might differ between a new and an existing building. It was therefore decided to also include a modern single family house to highlight the differences between the two very different buildings. The two buildings are shortly described below.

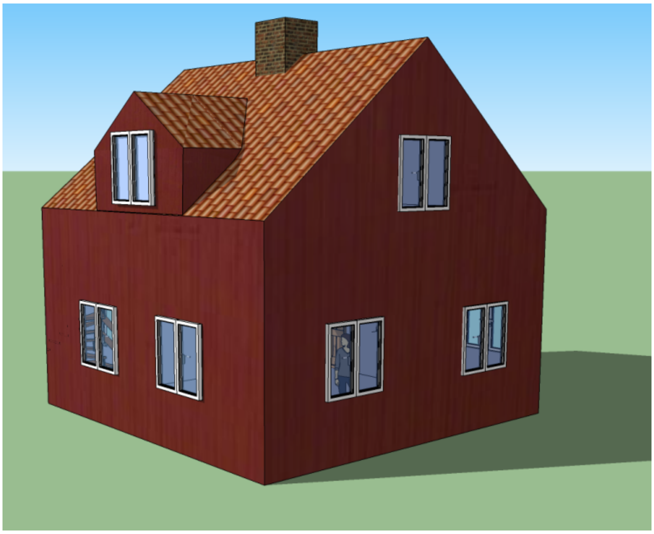
Figure 3.5. An approximate representation of the 1940 single family house modelled in chapter 4.2

One of the typical buildings chosen is a fictive representation of a 1940 single family house, which visual approximation is shown in Figure 3.5. The building is mainly based on the 1940 house described by Haglund Stignor et al. (Haglund Stignor et al., 2009) and a table showing some of the key values used in the simulation (chapter 4.2) is shown in Table 3.1.

Table 3.1. Selected key values for the two typical single family buildings

	1940 building	Passive house
Total heated area [m^2]	98	146
Number of floors	1.5	1
U-value façade [W/(m^{2}K)]	0.5	0.1
U-value roof [W/(m^{2}K)]	0.4	0.05
U-value floor slab	0.6	0.1
U-value windows	3	0.8
Heating system	Water radiators	Heating of ventilation air
Ventilation	Natural ventilation	Heat recovery ventilation
Air exchange rate [h^{-1}]	0.4	0.5
Number of inhabitants	3	4
DHW use [l/day]	200	200

The second typical building chosen is a modern single family house insulated to passive house standards. The passive house is a single floor building and is, same as the 1940 house, simulated in the case study presented in chapter 4.2. The house used as reference is shown in Figure 3.6. The data for the building are mainly based on the building used by Persson and Heier (Persson and Heier, 2010) where the same building has been used as basis for a simulation model. Selected key values used for the passive house are shown in Table 3.1.

Figure 3.6 A picture of the house used as basis for the passive house modelled in 4.2 (Fiskarhedenvillan)

Looking at the construction year distribution for premises in Figure 3.3, it is more equally distributed than the single family houses with many buildings constructed between 1960 and 1990. Looking closer in Figure 3.4 at what kind of premises that are most common, schools have the largest heated floor area followed by offices in second place. Even though schools are not in operation the entire year, the average purchased energy is among the highest of all premises. One explanation for this could be high ventilation airflows without heat recovery (Swedish Energy Agency, 2007). Since office buildings have a larger cooling demand, however, an office building is deemed to be the more interesting choice when evaluating techniques for thermal energy storage since the cooling aspect also becomes important. The choice for a typical commercial building was therefore an office building with a construction year around 1980. The main key values for the office building itself, presented in Table 3.2, are to a large extent based on the typical office building used by Haglund Stignor et al. (Haglund Stignor et al., 2009). As already mentioned, the office building is not used within this thesis beyond the typical building selection process.

Table 3.2, Selected key values for the typical office building

	1980 office building
Total heated area [m²]	2500
Number of floors	5
U-value façade [W/(m²K)]	0.25
U-value roof [W/(m²K)]	0.25
U-value floor slab [W/(m²K)]	0.4
U-value windows [W/(m²K)]	1
Ventilation	Heat recovery ventilation

3.3 Systems used for heating and cooling in buildings

This section will shortly describe some of the systems for heating and cooling used in buildings to uphold the indoor temperature within comfort limits. The aim here is to give an overview of the types of systems used and not to go into details on specific systems. First residential buildings will be treated followed by commercial buildings where office buildings will be the building type used as reference for discussions. The focus is on buildings in cold climates and Sweden in particular. In general, there are three kinds of equipment to consider (Bradshaw, 2006): equipment to generate heat or cold, equipment for distribution to the space where heat or cold is needed and finally equipment to deliver heat or cold into the space. Often, these three parts are more or less integrated.

Residential buildings

In residential buildings in Sweden, cooling is seldom used and therefore, only heating will be discussed. For generation of heat there are mainly three possibilities (not counting renewable sources such as solar heating): heat generation in a boiler, stove or similar (bio fuel, oil), heat from electricity (direct or via heat pumps) or central production of heat (district heating). When using a boiler, for example a pellet boiler, the heat is commonly distributed via pipes in a water system to the rooms in the building where it is released through water radiators or floor heating. It is also possible, but uncommon in Sweden, to use a water to air heat exchanger in the ventilation air and distribute the heat through the ventilation system. If using a stove, heat is transferred directly from the stove to the room air making the stove a combination of all three parts mentioned above (there are also water jacketed stoves which are basically a combination of a boiler and a traditional stove). For boilers (and water jacketed stoves) a storage tank is often used to store the heat up to a few days while for stoves, other storage solutions are required such as large thermal mass of the building or the stove.

Using electricity to generate heat can be done in many ways. One way is using direct electricity in electric radiators or electric floor heating, requiring no other distribution system. Electricity can also be used for heating of fresh air in the ventilation system to be delivered to the rooms in the building or for heating of the water in a storage tank to be distributed to water radiators or floor heating. Electric heating with heat pumps comes in many varieties and can be divided into four categories: air-air, air-water, fluid-water and exhaust air heat pumps. In new single family houses, it is very common that an exhaust air heat pump is recommended by the house manufacturer (Henning et al., 2010). An air-water heat pump can be used if the building is already equipped with a water based distribution system, such as water radiators, while an air-air heat pump can be an alternative in buildings where direct electricity is being replaced.

With district heating the heat generation takes place outside of the building boundaries while distribution in the building is commonly done in the same way as for a boiler. With the help of a spreadsheet tool (Westerlund et al., 2007) using Swedish statistics for single family buildings (SCB, 2006c) it can be calculated that 18% of the single family houses use biofuel boilers with a water distribution system, 31% and 29% use electricity with and without water distribution system respectively (including heat pumps) and 10% use district heating. For multifamily buildings (SCB, 2006a), the same tool shows that the majority use district heating (81%) while 9% use electricity with or without water distribution system (including heat pumps) and only a small amount use biofuels in any combination.

One conclusion that can be drawn from this is that TES in the HVAC system can have a larger potential in single family houses due to heating systems that better benefit from storage while multifamily buildings are mainly heated by district heating where local storage may be of less importance. On the other hand, storage in the form of water storage tanks is already installed in most single family houses with the appropriate heating systems.

Commercial buildings

The use of energy in commercial buildings is completely different from residential buildings and in many buildings a large part of the energy demand is accounted to cooling due to high occupancy and high internal heat gains. During off hours, most internal gain sources are removed resulting in large differences in the heating and cooling demand over the day. This is one reason why passive TES can provide larger benefits in commercial buildings, such as offices as shown by Ståhl (Ståhl, 2009). A problem can, however, be the allowed temperature interval that is usually very strict in commercial buildings to avoid complaints from customers and tenants which is a point also highlighted by Gräslund as discussed in section 2.4.

The same spreadsheet tool used for residential buildings was also used for commercial buildings, using Swedish statistics (SCB, 2006b). Although, as mentioned before, cooling is important in many commercial buildings the Swedish statistics on cooling in buildings is very limited and the spreadsheet tool was only used to show the proportion of different heating sources. The statistics show that half of the commercial buildings are heated by district heating, 31% are heated with electricity (including heat pumps), 17% are heated with fossil fuels (oil or gas boilers) and finally 2% are heated with biofuel boilers. In Swedish commercial buildings, the most common distribution system for heat is water radiators, although it is also common that part of the heat is supplied with the ventilation air through pre-heating of the air (Jardeby et al., 2009).

For cooling there are several technologies that can be used and although these will not be described in detail, the following section will give a brief description of the types of cooling generation and distribution used, with a focus on what is used in Sweden. Not only the indoor temperature, but also the humidity, air velocity etc. are important factors for a good indoor comfort but the discussion regarding that is in this work limited to the section on indoor comfort in Paper IV.

The generation of cold can either be local in a single room or centrally in the building with distribution to the rooms. For local cold production a vapor-compression cycle using direct expansion, a so called DX system, can be used to cool the indoor air directly over the evaporator (see Figure 3.7 showing the vapour-compression cycle, where the indoor air is the heat source in a DX system and the work is electricity). DX systems can also be used centrally with the cold air being distributed in air ducts to where it is needed. Cooling equipment using the same refrigeration cycle as the DX system but cooling water instead of air are often simply called chillers. The cold water that is produced centrally is distributed in pipes to be used locally, either directly in chilled ceilings, water cooled baffles etc. or in a combined duct and pipe system via an air handling unit in which the cold water is heat exchanged with air which in turn is distributed into the rooms. Another type of chiller is the absorption chiller, which uses a different thermodynamic cycle (usually the lithium bromide-water cycle) to generate cold from heat (for example from solar collectors) instead of from electricity.

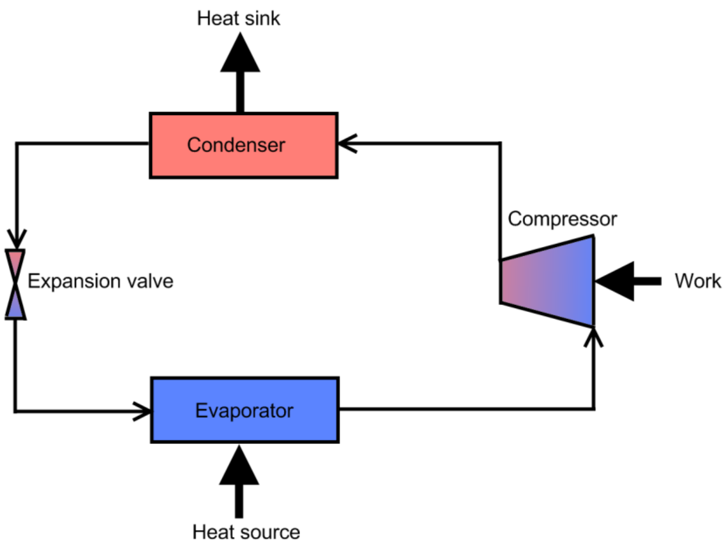

Figure 3.7. The standard vapour-compression refrigeration cycle

Ground source heat pumps (borehole systems in particular) can be used for cooling of buildings, since the ground temperature during the summer is lower than the air temperature. If the ground temperature is low enough and the cooling demand of the building is not too large, the ground heat exchangers can be used for free cooling without using the heat pump resulting in a very high COP for cooling. If this for some reason is not possible, the heat pump can be used in "reverse mode" to generate cold in a similar way as a chiller but using the colder ground temperature for the heat sink.

In order to identify what types of cooling systems have been and are used in Swedish commercial buildings, a representative from a large construction company (J Gräslund 2012, e-mail conversation, 16 October) having extensive experience in the construction of commercial buildings was contacted. The discussion indicated that in many Swedish commercial buildings it used to be very common with central generation of cold which was distributed with a constant air volume (CAV) duct system. In buildings with a smaller cooling load, DX systems were common while other chillers were used for larger cooling loads. For some larger projects also variable air volume (VAV) systems were used but this required complicated VAV boxes with advanced control in several places of the building, increasing the complexity of the system. Around 20 years ago water distributed cooling started to increase in popularity using fan coil units and water cooled baffles and as of now, water distributed cooling is the most commonly used cold distribution solution, at least in normal to large sized projects (this is also confirmed by Jardeby et al. (Jardeby et al., 2009)). Air based VAV cooling is however said to be increasing again over the last few years due to the introduction of good motorized diffusers.

Summarizing, older commercial buildings are likely to be equipped with a duct system for air distribution of cold while newer buildings, especially large buildings, are more likely to be equipped with a water distribution system. This can have an impact on what kind of TES systems that would be considered either for renovation or for a new building.

3.4 Concluding remarks from the selection of building types

Statistics of the Swedish building stock shows that, especially for single family houses, old buildings have a high purchased energy demand while at the same time constituting a large part of the total heated floor area. TES systems, as well as other energy efficiency measures, that can be applied to existing buildings are therefore just as important as those intended for new buildings. To reflect this, both an old and a new single family house were the chosen building types for the simulation case study presented in the next chapter (chapter 4.2). It is also important to consider that many older buildings are in need of renovation and that it, during the renovation planning, might be a good opportunity to consider energy efficiency measures including TES. A TES system can then be planned and evaluated together with other energy efficiency measures, such as additional insulation or changing the whole HVAC system.

Regarding the systems used for heating and cooling in Sweden, chapter 3.3 has shown that there is a large diversity of heating systems used in single family houses while district heating is used in a majority of the multifamily houses. This may lead to more difficulties in finding standardized TES solutions for single family houses as compared to multifamily buildings. Due to the large share of district heating used in multifamily buildings, a question that rises, although answering it lies outside the boundaries of this thesis, is if the best solution for TES in multifamily buildings is distributed storage (in each buildings) or larger storage integrated into the district heating network. In commercial buildings there is, similar to single family houses, a large variety in the heating systems used. For cooling in commercial buildings there is a clear difference in older and newer buildings, where older buildings tend to have air distributed cooling through duct systems while newer buildings are equipped with a water distributed cooling system. This is something that can affect the choice of storage system differently in old and new commercial buildings.

4 Case studies of TES systems

In order to evaluate the potential of some selected TES systems, two case studies were performed. The first case study is a follow-up evaluation of a high temperature solar thermal seasonal borehole storage for a residential area (presented in Paper II). The second case study presented is a simulation study on passive TES in single family houses using the software TRNSYS 17 (presented in Paper III).

4.1 High temperature solar thermal seasonal borehole TES

In late 2002, operation of a solar thermal system with seasonal borehole storage started for a residential area in Anneberg in Sweden. The system was the first system in Europe with seasonal solar storage in rock not utilizing a heat pump during discharge. The system has been evaluated twice earlier (Bernestål and Nilsson, 2007, Sweco Theorells, 2007) with one conclusion being that the borehole storage still was increasing in temperature and had therefore not yet reached steady state or its full potential. It was therefore decided to do a case study to confirm that the store had reached steady state and also evaluate the system according to several key figures including the solar fraction and borehole storage losses.

4.1.1 System description

The whole residential area (shown in Figure 4.1) compromises 50 residential units with a total yearly design heating demand, including DHW, of 565 MWh. There are three ways in which heating can be supplied: directly from the flat plate solar collectors (2400 m^2 in total), from the 60,000 m^3 solar charged borehole storage or from individual electrical boosters when the first two options are not enough. In the system there is a main unit distributing heat to 13 sub units, each equipped with one or two 750 litre DHW stores depending on the number of residential units connected.

Measurement data is logged by the system in 4 minute intervals but due to storage space restrictions when the system was built, data is only saved for a limited number of sensors resulting in some estimation being required when calculating the key figures for the system.

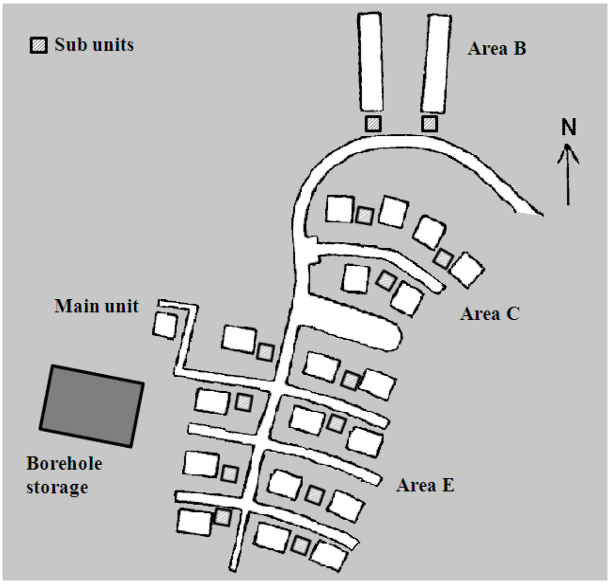

Figure 4.1. An overview of the residential area showing the borehole storage, main unit and the 13 sub units in the three areas B, C and E (Heier et al., 2011)

4.1.2 Method

The work was focused on doing an evaluation of the current system and for this, measurement data for 2010-2011 was used. Key figures were chosen and defined to assist in evaluating both the system performance as well as the system function. For a thorough definition as well as a complete list of key figures, see Paper III. As mentioned earlier, due to restrictions in the measurement system, only selected data was logged and available. This resulted in that some key figures related to the sub units and apartments had to be extrapolated to the whole residential area. Measured data was available for the main unit, 3 sub units (out of 13) and 4 apartments (out of 50). The assumptions used during extrapolation of the data are the following:

- All sub units in one area have the same relative location to the main unit (influences pipe system heat losses).
- In one area, all energy related values (loads, solar gains and energy transported to/from the borehole storage) for a sub unit only depend on the number of buildings, their living area and collector area. The values are considered to be independent of building location relative to the sub unit, shading effects, building orientation, building geometry and number of inhabitants.
- Sub unit losses were assumed to be equal for all sub units.

4.1.3 Results from evaluation

Although the current evaluation was focused on data for 2010-2011, the key figures used were also calculated where possible for both the design values based on earlier works related to the system (Lundh and Dalenbäck, 2008, Dalenbäck et al., 2000, Nordell and Hellström, 2000) as well as for the system evaluation in 2006 (Bernestål and Nilsson, 2007). Results are presented in Table 4.1 and the most noteworthy figure is probably the solar fraction, since it shows how good the system is working overall. Here there is a clear difference between the design value of 80% and the actual values calculated from the system operation of only around 40 percent. Looking at the other key figures, it can be noted that the reason for the low solar fraction is a combination of an overestimation of the collector efficiency in the design and an underestimation of the heat losses in the distribution system (including the sub units). The total heat demand as presented in Table 4.1 is significantly larger in the most recent evaluation but this is mainly due to the large heat losses in the sub-units. Without taking the sub-unit losses into consideration, the difference in total heat demand between design values and 2010 evaluation is much lower and can be accounted to the lower winter temperature of 2010.

Table 4.1. Key figure comparison between design values, values calculated for 2006 and values calculated for 2010

Key figures	Design values	2006 evaluation	2010 evaluation
Solar fraction [%]	80	42	40
Borehole storage efficiency [%]	50-55	35	46
Borehole storage losses [MWh]	500	527	387
Losses in distribution system [MWh]	100	163	267
Losses in sub-units [MWh]	30	NA	85
Total heat demand (including sub-unit losses) [MWh]	565	574	631
Total auxiliary use [MWh]	120	334	379
Solar energy from collectors [MWh]	1075	980	906
Energy supplied to borehole storage (measured at main unit) [MWh]	NA	809	720
Energy taken out from borehole storage (measured at main unit) [MWh]	NA	232	333
Average winter temperature [°C]	-0.3	1.9	-3.8
Annual horizontal solar radiation [kWh/year]	922	1020	992
Collector efficiency [%]	49	40	38

One of the questions before the evaluation was if the borehole storage had reached steady state or not. The evaluation in 2006 showed a temperature increase of 1 °C in the borehole storage over the measured year, indicating that the storage was still charging (the charged energy was calculated to 50 MWh). The evaluation for 2010-2011 however showed that the storage temperature was the same at the beginning and end of the measurement period, as shown in Figure 4.2. This is a confirmation that the borehole storage has indeed reached what can be called a steady state.

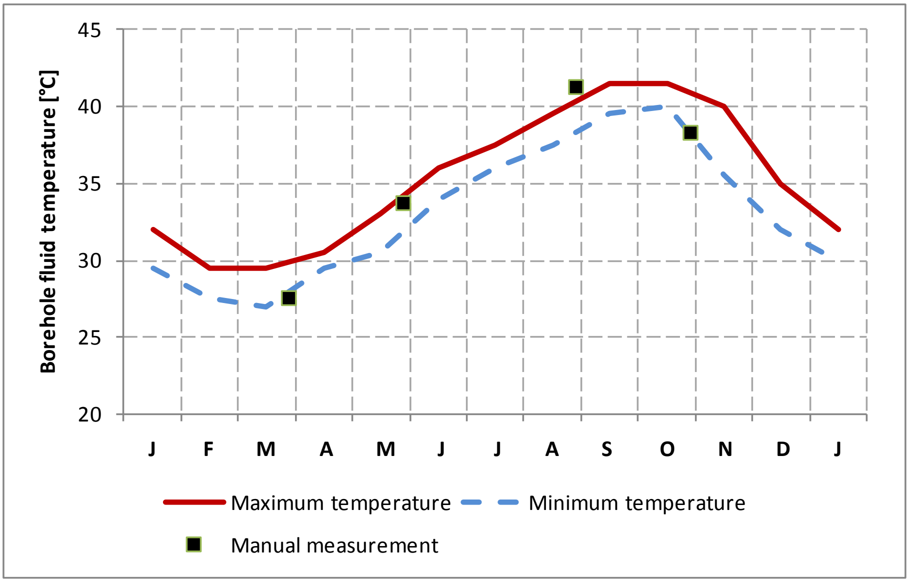

Figure 4.2. Maximum and minimum temperatures for the borehole storage core between January 2010 and January 2011 estimated from the outlet temperature, as well as manual measurements at one point in the store (Heier et al., 2011)

4.1.4 Conclusions – High temperature seasonal TES

The main conclusion from the evaluation is that although the borehole storage itself works as intended with a relatively similar borehole storage efficiency for both the design case and the 2010 evaluation, high heat losses in the distribution system and some problems in the system operation (this is described in paper III) results in a solar fraction that is much lower than the original design values. It was also concluded that the borehole storage has indeed reached a steady state with the surrounding rock and has therefore reached its maximum performance. There are, however, high uncertainties in some of the results, since data was only available for a limited number of sensors and many assumptions and extrapolations had to be made.

4.2 Passive TES in Swedish single family houses

For single family houses, large storage systems can be difficult to find the space for, and are also expensive to install. Complex active control systems that require constant monitoring or technical expertise are also often out of the question depending on who occupies the building. It is therefore of interest to investigate the potential of using passive TES; storage that doesn't need maintenance and doesn't necessarily have a large space requirement. Two building types were used in the simulations, an old 1940 house and a modern single family house with passive house standard, from here called the passive house. A short description of the two buildings is given in chapter 3.2.

4.2.1 TRNSYS model description

The model used to simulate the reference buildings is based on the Task 32 Reference Heating System (Heimrath and Haller, 2007), where a detailed explanation of the model is available. For the 1940 building, the heating system used is radiators controlled by a PID-regulator, where the convective and radiative gains are used as inputs to the building model. The passive house uses a heating battery in the ventilation system for heating and the required heating enters the building with the fresh ventilation air. For the reference case, the set point temperature is 20 °C.

Although there is no cooling system for the buildings, there are however other means of keeping the indoor temperature down below the desired temperature (24 °C for the base reference case). Two methods are implemented in the model: shading through internal venetian blinds and night ventilation through opening of windows. Both methods are described in more detail in the Task 32 Reference Heating System report (Heimrath and Haller, 2007), but are described shortly below, including some changes made.

For the shading to be activated there are three conditions that must be fulfilled: a total global solar irradiation on the horizontal of above 300 W/m^2, a room temperature of above 23.8 °C and an average ambient temperature for the last 24 hours of above 12 °C. If these are fulfilled, the south facing windows are shaded to 70%, corresponding to a blind tilt angle of around 45° for flat slates with negligible thickness according to Athanassios (Athanassios, 2008).

Free night ventilation through opening of windows can be used during the summer time when the following conditions are met:

- The time has to be between 21:00 and 08:00
- The daily average temperature is above 12 °C
- The room temperature is above 24 °C
- Ambient temperature is at least 2 K below the room temperature

If all the above conditions are met, three windows of 1.25x1.25 m are opened with a tilt angle of 10°.

The passive house was also simulated with PCM wallboards and the model used for this was Type 1270, released by TESS (TESS Libraries). Three phase change temperatures were investigated: 21.0, 21.7 and 23.5 °C.

4.2.2 Simulation results and discussion

For the reference case, the two buildings were simulated without using any window shading or passive night ventilation. A summary of the results is shown in Table 4.2. Results for the 1940 building show a high heating demand but also many hours with indoor temperatures above desired. As expected, the passive house has larger problems with overheating and the number of hours above 24 °C is more than four times that of the 1940 house. The solar contribution was determined by running all simulations twice: one time with normal solar irradiation and one time with solar radiation disabled. This made sure that the entire useful solar gain but nothing more is included in this figure.

Table 4.2. Yearly figures for the reference buildings taken or calculated from simulation results

	1940 building	Passive house
Total backup energy used [kWh] (kWh/m²,yr)	19950 (204)	5660 (39)
Space heating demand (tank drawout) [kWh] (kWh/m²,yr)	16020 (163)	2320 (16)
Solar gain contribution [kWh/m²,yr]	63	21
Maximum space heating power [kW]	5.9	1.8
Time with indoor temperature over 24 °C [hr]	600	2700

To evaluate the impact of an increased thermal mass, concrete (mainly due to its high density adding thermal mass) was added to the external wall in several variations which are shown in Table 4.3. The insulation and the thickness of other layers were adjusted to make sure that the U-value of the wall was equal for all walls (and equal to the reference building). A value for the wall capacitance, C_w, (as an indication to the thermal mass) is also shown in Table 4.3. The wall capacitance is calculated for the external wall containing *i* number of layers according to Eq. 1, where C_w is the wall capacitance and A_w is the wall area (excluding windows).

$$C_w = \sum (Cp_i \rho_i d_i)\, A_w \qquad \textit{Eq. 1}$$

Table 4.3 U-value and wall capacitance for the external walls and maximum heat load for the buildings with different external wall construction

1940 building	U-value [W/m²K]	C_w [MJ/K]
1940 reference	0.513	36
5 cm concrete on inside	0.513	47
10 cm concrete on inside	0.513	60
10 cm concrete on outside	0.513	58
All concrete construction	0.513	71
Passive house		
Passive reference	0.103	15
Passive concrete	0.103	97

For the 1940 building the various wall constructions were simulated with all the other parameters as the base reference case (no shading, no night ventilation and a desired temperature range of 20-24 °C) and the results are presented below in Table 4.4. It is clearly shown that just using concrete on the outside of the external wall has little to no effect, both on the energy demand and the indoor temperatures, which are all very close to the reference case.

As for concrete on the inside of the external wall, there is only a slight difference in the yearly energy demand and the solar contribution, although both in favour of the higher thermal mass. The yearly energy demand is, however, only lowered by less than 1% and this difference could just as well be explained by other differences in the wall construction (such as a slightly different U-value). The main difference, however, is in the times with excess temperatures. When comparing the case with 10 cm concrete on the inside with the reference case, the number of hours with temperatures exceeding 26 °C is lowered by a third.

Table 4.4. Simulation results for different external wall constructions using 5 or 10 cm concrete on the inside (5/10cmi), 10 cm concrete on the outside (10cmo) or an all concrete construction

1940 building	Yearly energy demand [kWh/m^2,yr]	Solar contribution [kWh]	Max. SH power [kW]	Time with temp. above 24 °C [hr]	Time with temp. above 26 °C [hr]
Reference	204	6180	6.4	600	156
5cmi	203	6250	6.1	537	119
10cmi	202	6290	6.1	492	103
10cmo	204	6170	6.4	601	156
Concrete	203	6310	6.1	499	103

It is apparent that increased thermal mass through a concrete layer on the inside of the external wall will result in less time with overheating. To further investigate how shading and passive night ventilation affect the result, the building was simulated with night ventilation, a combination of night ventilation and 10 cm added concrete on the inside and with shading using internal blinds. The results presented in Figure 4.3 show that just using night ventilation has almost the same reduction in excess temperatures as an increased thermal mass, however combining night ventilation with high thermal mass results in a much larger reduction. Still, it is clear that the most important factor is the shading and just by using shading with internal blinds, the excess temperatures can almost be eliminated in the 1940 house.

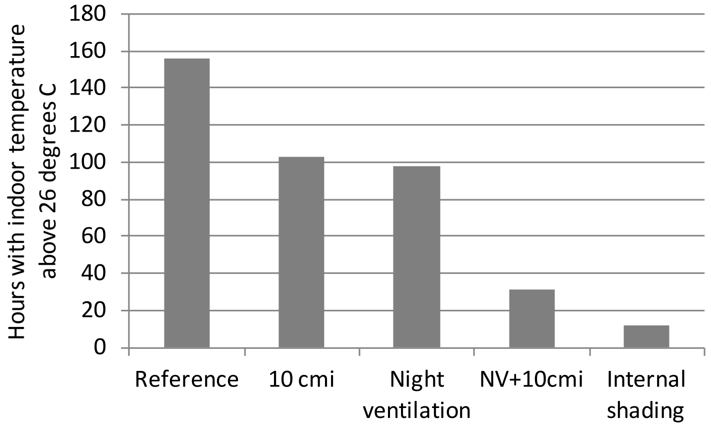

Figure 4.3. Time with excess temperatures for different variations of the 1940 house

As could be seen in Table 4.2, the number of hours with excess temperatures is much higher in the reference passive house. Similar to the 1940 house, several combinations of measures for lowering the indoor temperature were simulated. The results are presented in Figure 4.4 and show that only using internal blinds for shading is not enough to keep the indoor temperature down during the summer. Introducing external blinds for shading has a much larger impact, but still result in a large number of hours with excess temperatures. Only with a combination of external shading, passive night ventilation and large thermal mass can the indoor temperature be kept below 26 °C for the entire year.

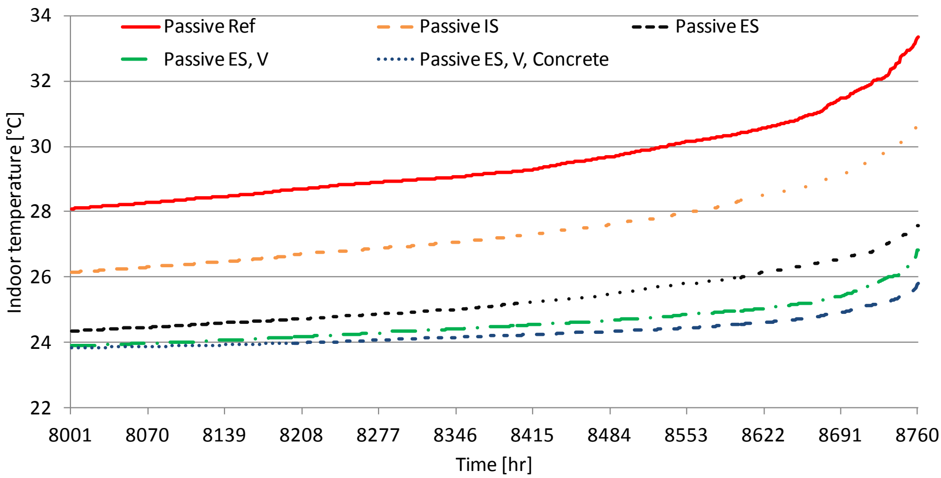

Figure 4.4. Duration curve of the 760 hours with highest indoor temperature for the reference passive house as well as several combinations with internal shading (IS), external shading (ES) and night ventilation (V)

As described earlier, the passive house was also simulated with PCM wallboards added to the light weight construction to see differences between sensible (concrete) and latent thermal mass. Three phase change temperatures were used and the results are displayed in Figure 4.5. The figure shows the percentage change for space heating demand and time with temperatures above 24 °C when comparing a "thermally heavy" building to the corresponding light weight building. For the 1940 house, the building with internal shading and 10 cm concrete on the inside is compared to the building with internal shading but without added concrete. It is clear that the reduction in space heating demand is very small (less than one percent) while the time with excess temperatures can be reduced by almost 12 percent. For the passive house, there is a larger percentage change when comparing the light weight and the concrete construction with a 4-5 percent decrease in space heating demand and almost a 20 percent decrease in excess temperatures. When comparing the light weight passive house and the light weight house with added PCM wallboard panels, the phase change temperature makes a large difference in the results. The reduction in space heating demand is comparable to the concrete building for a PCM with phase change temperature close to the heating system set point, but much lower if the phase change temperature is higher. The opposite is true for excess temperatures, where a phase change temperature close to the upper allowable indoor temperature was shown to reduce excess temperatures more than sensible thermal mass in concrete.

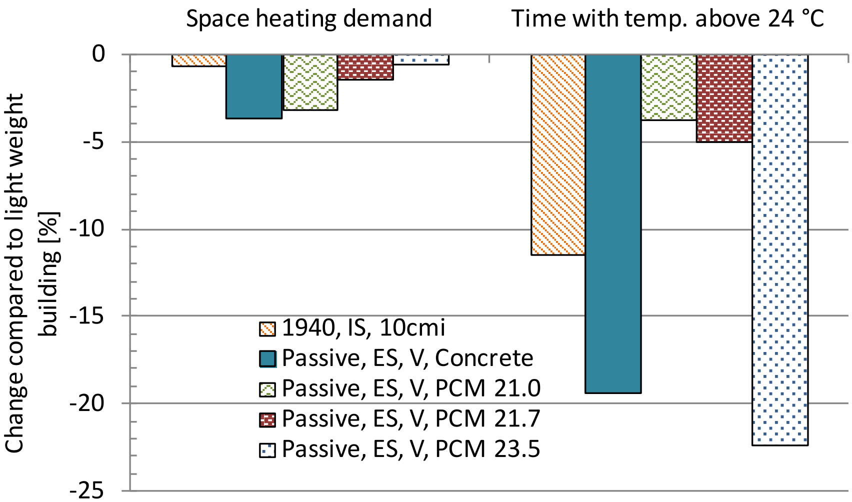

Figure 4.5. Change (in percent) in space heating demand and time with indoor temperature above 24 °C when comparing buildings with increased thermal mass to the corresponding building with low thermal mass

4.2.3 Conclusions – Passive TES integrated in buildings

The simulation case study shows that there is only a small benefit on the space heating demand and space heating power for a single family house with a high thermal mass, as compared to a light weight building. No special control algorithms for the heating system were used however, and it is possible that actively making use of the thermal mass through an optimized control system might yield more promising results. Larger benefits can be seen in reduction of excess temperatures, but using proper shading is still better by far. When using PCM wallboards it could be observed that the phase change temperature is of great importance for the results. It is however important to remember that an ideal PCM model was used in this study and for a real PCM material, phase change temperature range, sub cooling effects etc. will have a negative impact on the benefits shown.

5 Discussion and Conclusions

The main objective of this thesis has been to highlight the area of thermal energy storage and map available technologies as well as the possibilities for increased energy efficiency in buildings through the use of thermal energy storage. A description of available storage techniques as well as an extensive literature review on the subject shows that thermal energy storage is already used in almost every building. Primarily two storage techniques dominate: domestic hot water storage tanks and passive thermal mass. These two techniques differ in the sense that tank storage of domestic hot water is a deliberate choice that is used to reduce the heating peak load that would otherwise be required for hot water discharges (for example a shower or a bath), while thermal mass in building materials (concrete, brick etc.) is seldom chosen solely due to its thermal storage capabilities (and therefore often is an unconscious way of storing thermal energy in buildings). Although passive storage with thermal mass in most of the studied cases does not lead to a large reduction in the heating or cooling demand, a significant reduction in excess indoor temperatures is often noted. This result is something that can become more and more important with the increasing amount of passive houses or other low energy buildings since these buildings can experience problems with excess temperatures during summer. Where it would normally be required to install active cooling to keep the indoor temperature on a comfortable level, a high thermal mass might be enough to avoid an active cooling system altogether. Aside from the two very common storage techniques mentioned above there are, as has been shown in this thesis, many more ways of storing thermal energy in buildings; some already commercially available for many years and some emerging technologies where research is still required.

The literature reviews presented have shown that a large part of the knowledge in this field is based on simulations or limited experiments, and not so much on studies in real buildings. This is not surprising since long term measurement in a real building can be a difficult task for several reasons including economic reasons and difficulty actually getting access to buildings for measurements. It is however important to remember that a thermal energy storage system in many cases is an advanced system depending on many factors such as building design, occupant behaviour, location (weather conditions) and more. This means that there are not two buildings that are exactly the same and the benefits of a TES system can differ greatly from building to building; something that also can be seen in the varying results of available literature. The design and sizing phase of the TES system therefore becomes a critical part, where correct assumptions on the building and its use can be deciding factors if the system is successful or not. One difficulty worth mentioning is that standards or clear sizing guidelines are lacking for many types of TES systems. This means that even more effort and time is required when a more advanced storage system is to be tailored for a specific building, something that probably causes many building owners to rethink and install more standardized HVAC systems. When a storage system finally has been installed in a building, due to the many variables often involved, it is important to do follow up studies after installation, at least for a more advanced storage system. Such follow up studies would not only increase the probability for a well working HVAC system including TES but would also greatly contribute to the knowledge base of TES in buildings if made available to researchers in the field. An example of this is shown in chapter 4.1 of this thesis where a follow up study of a seasonal borehole TES system for a residential area is presented. The results shown there can serve as important information for future similar projects and highlight that not only the TES itself but also the surrounding system and control has a large influence on the long term outcome.

One of the main results presented within this thesis is the literature summary of combination of TES in various building types as shown in Table 2.1 and Table 2.2. These two tables give a good idea of what studies have been made on specific combinations of TES and building type as well as some basic information of the nature of the studies. The tables show that TES can be beneficial in many ways, both for heating and cooling of buildings. In order to evaluate what combinations to focus on for Sweden it's also important to take the Swedish building stock into account. Studying the available statistics for Swedish buildings has resulted in the definition of several typical buildings that represent a significant part of the Swedish building stock. Two of these typical buildings have been used in a case study in this thesis (section 4.2) but in order to estimate the potential for TES in Swedish buildings in general, additional typical buildings that represent the Swedish building stock should be identified (also see the section on Future work). Something that is quite clear, however, is that most of the buildings that exist today, will still remain standing for a foreseeable future. This together with the fact that the production rate of new buildings is fairly small show that increasing the energy efficiency in existing buildings is at least as important as making sure our new buildings are as energy efficient as possible, and developing TES systems that can be used in existing buildings should therefore have a high priority.

To summarize, some of the more important conclusions reached within this thesis are listed below:

- An extensive literature review and state-of-the art assessment has shown that TES is already implemented in buildings to a large extent, but that the benefit to energy efficiency and thermal comfort seldom is quantified. Where it is quantified it is often done so through simulations and seldom through measurements in actual buildings.
- High thermal mass can be used to reduce excess temperatures in buildings and possibly be used to avoid addition of active cooling systems in well insulated residential buildings.

- Combinations of TES techniques can be used to increase the overall system performance. This is especially important in storage systems (often seasonal) where, by themselves, a high enough discharge power cannot be achieved (e.g. in some cases for borehole storage systems or thermochemical systems). If combined with a short term storage system, such as a water storage tank, the system can provide the required discharge power.
- A case study on a high temperature seasonal borehole TES has shown that even if the TES itself works as designed, the function of the surrounding system is very important for the total outcome. In particular, avoiding unnecessary heat loss in the entire system should be prioritized.
- More studies on TES systems in actual buildings and follow up evaluations of built systems are required to quantify the real benefits of many storage systems.
- When considering TES for increasing the energy efficiency in Swedish buildings, it is important to include the existing buildings. A large part of the buildings are old and in need of renovation and evaluating a TES system together with other necessary renovations can potentially lead to a more energy efficient end result. It is also important to consider what heating and cooling systems are used, since this can influence the choice of storage system.
- There are several interesting emerging technologies for TES, such as phase change materials and thermochemical storage, but research is still required in many areas before commercial systems can be introduced to the market.

Finally, this thesis has contributed to the research field of thermal energy storage in buildings with a comprehensive overview of available TES techniques and especially on the combination of TES and building. This thesis has shown that implementing thermal energy storage in buildings can have a positive effect on the energy efficiency and/or thermal comfort of a building through one or a combination of: reduction in heating or cooling demand, peak load reduction for heating or cooling, CO_2 emission reduction and reduction in excess indoor temperatures. TES should therefore be viewed as a technology that both is and will be playing an important role in our buildings and as a technology that is necessary to help in increasing the share of renewable energy used for heating and cooling of buildings.

5.1 Future work

This licentiate thesis has been the first part of a project with an ultimate goal of evaluating the potential for increased energy efficiency in the Swedish building stock through the use of thermal energy storage. In this thesis, the techniques used for TES have been reviewed and so has the Swedish building stock, as well as the combination of storage techniques and various buildings. The next step is to, based on the work presented in this thesis, choose a small number of storage techniques and system concepts which can be considered to be of special interest for the Swedish building stock. Combinations of these storage techniques together with selected building types can then be chosen for more detailed studies in order to assess the potential for increased energy efficiency by introducing TES to a building. Additional typical buildings (mainly commercial buildings) that can represent the Swedish building stock should be defined in order to choose relevant buildings for more detailed studies. The result from the more detailed studies can then be extrapolated to the whole Swedish building stock in order to show the benefits of a widespread implementation of thermal energy storage in Swedish buildings.

The work in the project and especially related to the literature review for Paper IV has shown that studies on thermal energy storage in real buildings, showing the operation over a longer period of time, are few. More studies on TES systems in real buildings, or perhaps more importantly follow-up studies on new systems installed in buildings, are therefore an important way to obtain valuable data on how TES works in real buildings during dynamic conditions. This work is not likely something that can be accomplished within the boundaries of this PhD project and should instead be considered an important area for future projects in order to move the knowledge boundaries of TES forward.

Appendix

Summary of review articles on TES in buildings

Review articles mainly on PCM applications	**Year**	**Short summary**
Al-Abidi et al., *Review of thermal energy storage for air conditioning systems.* (Al-Abidi et al., 2012)	2012	A review concentrating on latent cool storage applications for use in building HVAC system. Many PCMs that could potentially be used for this application are listed with their properties and also heat exchanger configurations and heat transfer enhancements are discussed. Many storage and ventilation combinations are discussed, including the use of PCM directly in the ventilation system to take advantage of nighttime cold air, latent heat TES (LHTES) with a chilled water distribution circuit, LHTES with a heat pump system and AC systems using phase change slurries.
Parameshwaran et al., *Sustainable thermal energy storage technologies for buildings: A review.* (Parameshwaran et al., 2012)	2012	Review with focus on latent heat storage, both passive and active. Based on the papers included in the review, the authors estimate that 10-15% of space conditioning energy can be saved in passively designed buildings using LHTES and 45-55% in buildings with active cool thermal energy storage (CTES).
Tyagi et al., *Review on solar air heating system with and without thermal energy storage system.* (Tyagi et al., 2012)	2012	Energy and exergy analysis of solar air heaters with much focus on construction/types of solar collectors. The storage discussion part is almost exclusively on PCM. The article ia mainly focused on drying and agriculture and not so much on buildings.
Yau and Rismanchi, *A review on cool thermal storage technologies and operating strategies.* (Yau and Rismanchi, 2012)	2012	A fairly short review of chilled water storage followed by a more extensive review of ice storage techniques, including ice harvesters, ice slurry, encapsulated ice and ice on coil. Also several case studies are presented. The concluding remark is that ice storage systems have advantages of larger storage volume capability but instead a lower COP than other cool storage techniques. Storage type should therefore be selected on a case-by-case basis.
Zhou, Zhao and Tian, *Review on thermal energy storage with phase change materials (PCMs) in building applications. (Zhou et al., 2012)*	2012	Applications discussed in this review are wallboards with PCM (including a list of available literature), PCM walls, PCM floors and ceilings for passive solar heating, PCM shutters and PCM ceilings with active heating and cooling. Also a section on simulation of buildings with PCM including a table with reviewed

		papers. After the review, the authors conclude that more research is needed on the inclusion of PCM into the building structure, with regards to long term stability and other safety and reliability issues.
Alkilani et al., *Review of solar air collectors with thermal storage units.* (Alkilani et al., 2011)	2011	Review solar air collector systems with thermal energy storage used for space heating of buildings as well as in greenhouses. Collectors integrated with storage materials as well as heat transfer problems with PCM are also discussed. Storage discussion includes water storage, rock bed storage and PCM storage, with the focus on PCM. The authors conclude that to increase the thermal performance of solar air heaters, PCM with high latent heat and large surface area for heat transfer is required.
Jegadheeswaran, Pohekar and Kousksou, *Exergy based performance evaluation of latent heat thermal storage system: A review.* (Jegadheeswaran et al., 2010)	2010	Description of energy and exergy analysis and a review of methods used for exergy based performance evaluation of LHTES systems. Also methods used for thermoeconomic analysis of LHTES systems are presented.
Shukla, Buddhi and Sawhney, *Solar water heaters with phase change material thermal energy storage medium: A review.* (Shukla et al., 2009)	2009	A historical review of sensible water heaters and their transition to include PCM. The focus is on simpler water heaters and one main conclusion is that there are many designs with PCM but still no international commercial design.
Zhu, Ma and Wang, *Dynamic characteristics and energy performance of buildings using phase change materials: A review.* (Zhu et al., 2009b)	2009	An overview of previous studies divided into free cooling applications in buildings with PCM (active/passive), PCM in buildings for peak load shifting (active/passive) and PCM in active building systems (solar heat pump systems, heat recovery systems etc.). Some of the main conclusions are that PCM can have a positive effect on building thermal and energy performance, but that the results often come from simulations or prototype experiments and more studies on the energy performance of actual buildings are required.
Verma, Varun and Singal, *Review of mathematical modeling on latent heat thermal energy storage systems using phase-change material.* (Verma et al., 2008)	2008	Discussion around assumptions made in different calculation methods/models with focus on the difference between ising the first and second law of thermodynamics (energy vs. exergy) as basis when creating simulation models of LHTES systems. The review shows that the first law of thermodynamics is videly used, with much of the results verified by experimantal work. Although an exergy approach could help in understanding thermodynamic behaviour and efficiency of a TES system, little work is done and more experimental work is required increase acceptability.

Tyagi and Buddhi, *PCM thermal storage in buildings: A state of art.* (Tyagi and Buddhi, 2007)	2007	Lists desired properties for PCM materials. Review of both passive and active PCM storage systems but mostly systems directly integrated into the building (trombe walls, wallboards, PCM shutters, building blocks, floor heating, ceiling boards etc.).
Khudhair and Farid, *A review on energy conservation in building applications with thermal storage by latent heat using phase change materials.* (Khudhair and Farid, 2004)	2004	Review with large sections on encapsulated PCM in buildings, including available materials and products as well as methods for micro and macro encapsulation. Also PCM impregnated building blocks are discussed, together with a section on fire retardation in PCM-treated building blocks. The authors conclude that PCM walls can help in reducing indoor temperature fluctuations as well as enabling off peak cooling of buildings.
Review articles mainly on PCM		
Cabeza et al., *Materials used as PCM in thermal energy storage in buildings: A review.* (Cabeza et al., 2011)	2011	Similar to the review by Zalba et al. (Zalba et al., 2003) but with more focus on buildings. Also some more focus on phase segregation, subcooling and fire retardation in construction materials.
Dutil et al., *A review on phase-change materials: Mathematical modeling and simulations.* (Dutil et al., 2011)	2011	The authors present a PCM model collection sorted by geometrical configuration and applications. The main conclusion is that there are models established for most applications of PCM but these are in many cases simplified, analythical expressions or correlations.
Baetens, Jelle and Gustavsen *Phase change materials for building applications: A state-of-the-art review.* (Baetens et al., 2010)	2010	Introduction to PCM materials with more detailed information on phase change range and latent heat for many PCMs. Manufacturing methods, design methodology and possible PCMs for wallboards and enhanced concrete are discussed. The authors conclude that high energy savings are often reported in the literature but that that properties of current PCMs are not optimal for building applications. One reason mentioned is the low number of PCMs around comfort temperature and the low heat of fusion of those that exist.
Zhang, Ma, and Wang, *An overview of phase change material slurries: MPCS and CHS.* (Zhang et al., 2010)	2010	Introduction to slurries with material examples looking at thermal properties and flow characteristics. Applications in thermal systems.
Ning-Wei Chiu, Martin, and Setterwall, *A review of thermal energy storage systems with salt hydrate phase change materials for comfort cooling.* (Ning-Wei Chiu et al., 2009)	2009	Much on materials, heat transfer enhancement and discussion around minimizing problems like phase separation and subcooling. Also a short section on control systems with a review of available studies.

Zalba et al., *Review on thermal energy storage with phase change: materials, heat transfer analysis and applications.* (Zalba et al., 2003)	2003	The main aim of the review is to bring information and properties on many PCM materials together. The result is a classification of PCMs, listing many materials and their properties as well as discussion around problems such as long term stability of PCMs and PCM containers.
Reviews not focusing on PCM		
Ding and Riffat, *Thermochemical energy storage technologies for building applications: a state-of-the-art review.* (Ding and Riffat, 2012)	2012	Includes an introduction to TES and especially thermochemical energy storage. The review includes some properties of materials used in thermochemical storage and is split up into reviewing open, closed and chemical heat pump systems separately. The conclusion from the authors is that although thermochemical energy storage has many advantages over other types of TES, the technology is still in the experimental stage and there are both technocal and economical questions to be answered before thermochemical energy storage can prove long term viability.
Chidambaram et al., *Review of solar cooling methods and thermal storage options.* (Chidambaram et al., 2011)	2011	Includes a short review of solar collector types (flat plate, concentrating etc.). The absorption cooling technique is discussed in detail and also the use of PCM is discussed to a large extent. The authors conclude absorption chillers has gained attention among researchers but also that more research and development on simpler and cost effective storage systems is needed for increased market impact.
Pinel et al., *A review of available methods for seasonal storage of solar thermal energy in residential applications.* (Pinel et al., 2011)	2011	In this review, three storage principles for seasonal storage of solar thermal energy are discussed: sensible, latent and thermochemical. Most of the review is focused on larger systems, which is said to be more efficient, but a section on seasonal storage for single buildings is also included. Conclusions are that chemical storage has many promising technologies but more research is needed (mainly on materials) and that PCM storage has small possibilities for seasonal storage (only intentional subcooling is said to have some potential but this is expensive and complicated). For sensible storage, space requirement is one of the main obstructions and one of the main research topics is stratification.
Novo et al., *Review of seasonal heat storage in large basins: Water tanks and gravel-water pits.* (Novo et al., 2010)	2010	Focus on seasonal storage of solar energy in central heating systems comparing storage in water tanks vs. gravel-water pits with technical data for many demonstration plants. A conclusion is that generally, water-gravel pits have a lower cost since an expensive tank construction is not necessary but on the other hand, larger volumes are necessary (although it is

		possible to use the ground above a water-gravel pit for car parks or residential areas).
Xu et al., *Active pipe-embedded structures in buildings for utilizing low-grade energy sources: A review.* (Xu et al., 2010)	2010	Mainly a review on active pipe embedded slabs (water) but also mentioning of ventilated hollow cores. Calculation models for pipe embedded structures are reviewed and the authors also discuss around practical applications and performance evaluation.
N'Tsoukpoe et al., *A review on long-term sorption solar energy storage.* (N'Tsoukpoe et al., 2009)	2009	A presentation of the main challenges and selection criteria for thermochemical storage as well as selection criteria for materials, together with information on used and researched materials at the time of writing. Research projects on the subjects are also presented.
Hasnain, *Review on sustainable thermal energy storage technologies, Part I: heat storage materials and techniques.* (Hasnain, 1998a)	1998	A review comparing sensible storage in rock and water with PCM (organic/inorganic). Sensible heat storage include liquid media storage (water, salty water, other fluids) and solid media storage (rocks, building fabric, metals). The conclusion here is that PCM is in the development phase and more research is needed before PCM can be a viable option.
Hasnain, *Review on sustainable thermal energy storage technologies, Part II: cool thermal storage.* (Hasnain, 1998b)	1998	Review on chilled water storage and ice storage (also to some degree eutectic salt storage) mainly as demand side management tool for load management. Office buildings are concluded to be ideal for cool storage due to the narrow cooling loads. Difficulties using cool thermal storage are also discussed. There is much focus on costs, some on operation strategies and also a review of case studies done, with focus on prospects for cool storage in Saudi Arabia.

6 References

Al-Abidi, A. A., Bin Mat, S., Sopian, K., Sulaiman, M. Y., Lim, C. H. & Th, A. 2012. Review of thermal energy storage for air conditioning systems. *Renewable and Sustainable Energy Reviews,* 16**,** 5802-5819.

Alkilani, M. M., Sopian, K., Alghoul, M. A., Sohif, M. & Ruslan, M. H. 2011. Review of solar air collectors with thermal storage units. *Renewable and Sustainable Energy Reviews,* 15**,** 1476-1490.

Arkar, C. & Medved, S. 2007. Free cooling of a building using PCM heat storage integrated into the ventilation system. *Solar Energy,* 81**,** 1078-1087.

Arteconi, A., Hewitt, N. J. & Polonara, F. 2013. Domestic demand-side management (DSM): Role of heat pumps and thermal energy storage (TES) systems. *Applied Thermal Engineering,* 51**,** 155-165.

ASHRAE 2004. ANSI/ASHRAE Standard 55-2004: Thermal environmental conditions for human occupancy. Atlanta, Georgia.

Athanassios, T. 2008. The impact of venetian blind geometry and tilt angle on view, direct light transmission and interior illuminance. *Solar Energy,* 82**,** 1172-1191.

Baetens, R., Jelle, B. P. & Gustavsen, A. 2010. Phase change materials for building applications: A state-of-the-art review. *Energy and Buildings,* 42**,** 1361-1368.

Bales, C., Gantenbin, P., Jaenig, D., Kerskes, H., van Essen, M. & Weber, R. 2008. *Final report of Subtask B "Chemical and Sorption Storage" The overview - A Report of IEA Solar Heating and Cooling programme - Task 32.*

Basecq, V., Michaux, G. & Inard, C. 2013. *A review of energy storage in buildings - Annex 23 "Applying Energy Storage in Buildings of the Future".*

Bauer, D., Marx, R., Nußbicker-Lux, J., Ochs, F., Heidemann, W. & Müller-Steinhagen, H. 2010. German central solar heating plants with seasonal heat storage. *Solar Energy,* 84**,** 612-623.

Bellas, I. & Tassou, S. A. 2005. Present and future applications of ice slurries. *International Journal of Refrigeration,* 28**,** 115-121.

Bernestål, A. & Nilsson, J. 2007. *Brf Anneberg Utvärdering av Energianvändning.* Andersson & Hultmark AB, Gothenburg.

Boonnasa, S. & Namprakai, P. 2010. The chilled water storage analysis for a university building cooling system. *Applied Thermal Engineering,* 30**,** 1396-1408.

Boverket 2007. *God bebyggd miljö - fördjupad utvärdering av miljömålsarbetet.* ISBN: 978-91-85751-77-8

Bradshaw, V. 2006. *The Building Environment: Active and Passive Control Systems*, Wiley.

C. Castellón, M. N., J. Roca, M. Medrano and L.F. Cabeza. Year. Microencapsulated phase changing materials (PCM) for building applications. *In:* STILES, L., ed. Proceedings of the 10th International Conference on Thermal Energy Storage Stockton, 2006 Yersey. 1-9.

Cabeza, L. F., Castell, A., Barreneche, C., de Gracia, A. & Fernández, A. I. 2011. Materials used as PCM in thermal energy storage in buildings: A review. *Renewable and Sustainable Energy Reviews,* 15**,** 1675-1695.

Caliskan, H., Dincer, I. & Hepbasli, A. 2012a. Energy and exergy analyses of combined thermochemical and sensible thermal energy storage systems for building heating applications. *Energy and Buildings,* 48**,** 103-111.

Caliskan, H., Dincer, I. & Hepbasli, A. 2012b. Thermodynamic analyses and assessments of various thermal energy storage systems for buildings. *Energy Conversion and Management,* 62**,** 109-122.

CEN 2007. EN 15026. Hygrothermal performance of building components and building elements - assessment of moisture transfer by numerical simulation. Brussels, Belgium.

Chèze, D. & Papillon, P. 2002. *Report on Solar Combisystems Modelled in Task 26 - Appendix 2: Generic System #3a: Advanced Direct Solar Floor.*

Chidambaram, L. A., Ramana, A. S., Kamaraj, G. & Velraj, R. 2011. Review of solar cooling methods and thermal storage options. *Renewable and Sustainable Energy Reviews,* 15**,** 3220-3228.

Dalenbäck, J. O., Dahm, J., Lundin, S.-E., Hellström, G. & Nordell, B. 2000. Solar heated residential area Anneberg. In: Proceedings of Eurosun 2000, Copenhagen, Denmark.

Dincer, I. 2002. On thermal energy storage systems and applications in buildings. *Energy and Buildings,* 34**,** 377-388.

Dincer, I. & Rosen, M. A. 2002. *Thermal Energy Storage: Systems and Applications*, John Wiley & Sons, Ltd.

Ding, Y. & Riffat, S. B. 2012. Thermochemical energy storage technologies for building applications: a state-of-the-art review. *International Journal of Low-Carbon Technologies*.

Dutil, Y., Rousse, D. R., Salah, N. B., Lassue, S. & Zalewski, L. 2011. A review on phase-change materials: Mathematical modeling and simulations. *Renewable and Sustainable Energy Reviews,* 15**,** 112-130.

Erlandsson, M., Ruud, S., Sandberg, E., Wall, M., Eek, H. & Wahlström, Å. 2009. *Kravspecifikation för Passivhus*. LTH report EBD-R--09/25, IVL report A1592, ATON report 0902

Evola, G., Marletta, L. & Sicurella, F. 2013. A methodology for investigating the effectiveness of PCM wallboards for summer thermal comfort in buildings. *Building and Environment,* 59**,** 517-527.

Fisk, W. J. & Rosenfeld, A. H. 1997. Estimates of Improved Productivity and Health from Better Indoor Environments. *Indoor Air,* 7**,** 158-172.

Fiskarhedenvillan. *Domherren exteriör 3D* [Online]. Available: http://www.fiskarhedenvillan.se/vara_hus/1-plan/Domherren/ [Accessed 2012-06-08].

Gartler, G., Jähnig, D., Purkarthofer, G. & Wagner, W. Year. Development of a High Energy Density Sorption Storage System. *In:* Eurosun 2004, 2004 Freiburg, Germany.

Gwerder, M., Lehmann, B., Tödtli, J., Dorer, V. & Renggli, F. 2008. Control of thermally-activated building systems (TABS). *Applied Energy,* 85**,** 565-581.

Hadorn, J.-C., editor 2005. *Thermal energy storage for solar and low energy buildings : State of the art by the IEA Solar Heating and Cooling Task 32*.

Hagentoft, C.-E. & Svensson, C. 2000. Energieffektivitet och god termisk komfort genom värmelagring i byggnaden. *Bygg & Teknik,* 5/00.

Haglund Stignor, C., Lindahl, M., Alsbjer, M., Nordman, R., Rolfsman, L. & Axell, M. 2009. *Nästa generations värmepumpssystem i bostäder och lokaler*. SP Arbetsrapport 2009:12

Hamada, Y. & Fukai, J. 2005. Latent heat thermal energy storage tanks for space heating of buildings: Comparison between calculations and experiments. *Energy Conversion and Management,* 46**,** 3221-3235.

Hamada, Y., Kubota, H., Nakamura, M., Kudo, K. & Hashimoto, Y. 2010. Experiments and evaluation of a mobile high-density snow storage system. *Energy and Buildings,* 42**,** 178-182.

Hasnain, S. M. 1998a. Review on sustainable thermal energy storage technologies, Part I: heat storage materials and techniques. *Energy Conversion and Management,* 39**,** 1127-1138.

Hasnain, S. M. 1998b. Review on sustainable thermal energy storage technologies, Part II: cool thermal storage. *Energy Conversion and Management,* 39**,** 1139-1153.

Hayashi, K., Takao, S., Ogoshi, H. & Matsumoto, S. 2000. *Research and Development of High-Density Cold Latent Heat Medium Transportation Technology*. Annex 10 5th Workshop, Tsu, Japan, . Annex 10 5th Workshop, Tsu, Japan

He, B. 2004. 'High-Capacity Cool Thermal Energy Storage for Peak Shaving - A Solution for Energy Challanges in the 21st Century'. PhD thesis, KTH, Stockholm.

Heier, J., Bales, C. & Martin, V. Year. Thermal energy storage in Swedish single family houses - a case study. *In:* Proceedings of Innostock 2012, 2012 Lleida, Spain

Heier, J., Bales, C., Sotnikov, A. & Ponomarova, G. 2011. Evaluation of a High Temperature Solar Thermal Seasonal Borehole Storage. *ISES Solar World Congress 2011*. Kassel, Germany.

Heimrath, R. & Haller, M. 2007. *The Reference Heating System, the Template Solar System of Task 32*.

Heinz, A. 2007a. 'Application of Thermal Energy Storage with Phase Change Materials in Heating Systems'. Technical University of Graz, Graz.

Heinz, A. 2007b. System Simulation Report - PCM storage to reduce cycling rates for boilers, Report C6.3 of Subtask C - A Report of IEA Solar Heating and Cooling programme - Task 32.

Henning, A., Persson, T., Heier, J., Lorentz, K. & Perman, K. 2010. *Klimatsmart villavärme? Solvärme, nya byggregler och möjligheten att förändra,* Falun, Författarna och SERC.

Henze, G. P., Felsmann, C., Kalz, D. E. & Herkel, S. 2008. Primary energy and comfort performance of ventilation assisted thermo-active building systems in continental climates. *Energy and Buildings,* 40**,** 99-111.

Henze, G. P., Krarti, M. & Brandemuehl, M. J. 2003. Guidelines for improved performance of ice storage systems. *Energy and Buildings,* 35**,** 111-127.

Jardeby, Å., Soleimani-Mohseni, M. & Axell, M. 2009. *Distribution av kyla och värme i bostäder och lokaler*. SP Rapport 2009:31

Jegadheeswaran, S., Pohekar, S. D. & Kousksou, T. 2010. Exergy based performance evaluation of latent heat thermal storage system: A review. *Renewable and Sustainable Energy Reviews,* 14**,** 2580-2595.

Johansson, L. S., Leckner, B., Gustavsson, L., Cooper, D., Tullin, C. & Potter, A. 2004. Emission characteristics of modern and old-type residential boilers fired with wood logs and wood pellets. *Atmospheric Environment,* 38**,** 4183-4195.

Kalz, D. E., Wienold, J., Fischer, M. & Cali, D. 2010. Novel heating and cooling concept employing rainwater cisterns and thermo-active building systems for a residential building. *Applied Energy,* 87**,** 650-660.

Khudhair, A. M. & Farid, M. M. 2004. A review on energy conservation in building applications with thermal storage by latent heat using phase change materials. *Energy Conversion and Management,* 45**,** 263-275.

Kizilkan, O. & Dincer, I. 2012. Exergy analysis of borehole thermal energy storage system for building cooling applications. *Energy and Buildings,* 49**,** 568-574.

Lahmidi, H., Mauran, S. & Goetz, V. 2006. Definition, test and simulation of a thermochemical storage process adapted to solar thermal systems. *Solar Energy,* 80**,** 883-893.

Lehmann, B., Dorer, V., Gwerder, M., Renggli, F. & Tödtli, J. 2011. Thermally activated building systems (TABS): Energy efficiency as a function of control strategy, hydronic circuit topology and (cold) generation system. *Applied Energy,* 88**,** 180-191.

Lehmann, B., Dorer, V. & Koschenz, M. 2007. Application range of thermally activated building systems tabs. *Energy and Buildings,* 39**,** 593-598.

Lundh, M. & Dalenbäck, J. O. 2008. Swedish solar heated residential area with seasonal storage in rock: Initial evaluation. *Renewable Energy,* 33**,** 703-711.

Martin, V., He, B. & Setterwall, F. 2010. Direct contact PCM-water cold storage. *Applied Energy,* 87**,** 2652-2659.

Martin, V. & Setterwall, F. 2009. Compact Heat Storage for Solar Heating Systems. *Journal of Solar Energy Engineering,* 131**,** 041011-6.

Mauran, S., Lahmidi, H. & Goetz, V. 2008. Solar heating and cooling by a thermochemical process. First experiments of a prototype storing 60 kWh by a solid/gas reaction. *Solar Energy,* 82**,** 623-636.

Mazo, J., Delgado, M., Marin, J. M. & Zalba, B. 2012. Modeling a radiant floor system with Phase Change Material (PCM) integrated into a building simulation tool: Analysis of a case study of a floor heating system coupled to a heat pump. *Energy and Buildings,* 47**,** 458-466.

N'Tsoukpoe, K. E., Liu, H., Le Pierrès, N. & Luo, L. 2009. A review on long-term sorption solar energy storage. *Renewable and Sustainable Energy Reviews,* 13**,** 2385-2396.

Naturvårdsverket 2012. *Steg på vägen - Fördjupad utvärdering av miljömålen 2012.* ISBN 978-91-620-6500-3

Ning-Wei Chiu, J., Gravoille, P. & Martin, V. 2012. Active Free Cooling Optimization with Thermal Energy Storage in Stockholm. *Innostock 2012.* Lleida, Spain

Ning-Wei Chiu, J., Martin, V. & Setterwall, F. Year. A review of thermal energy storage systems with salt hydrate phase change materials for comfort cooling. *In:* Proceedings of Effstock 2009, 2009 Stockholm, Sweden

Nordell, B. & Hellström, G. 2000. High temperature solar heated seasonal storage system for low temperature heating of buildings. *Solar Energy,* 69**,** 511-523.

Norén, A., Akander, J., Isfält, E. & Söderström, O. 1999. The Effect of Thermal Inertia on Energy requirement in a Swedish Building - Results Obtained with Three Calculation Models. *International Journal of Low Energy and Sustainable Buildings,* 1.

Novo, A. V., Bayon, J. R., Castro-Fresno, D. & Rodriguez-Hernandez, J. 2010. Review of seasonal heat storage in large basins: Water tanks and gravel-water pits. *Applied Energy,* 87**,** 390-397.

Nygren, I. 2003. *Inventering av eluppvärmda småhus i Sverige samt val av typhus.* Borlänge. ISRN DU-SERC--83--SE

Official Journal of the European Union 2010. Directive 2010/31/EU of the European parliament and the council on the energy performance of buildings.

Pahud, D. 2002. Active solar heating system with concrete plate heating analysed with dynamical thermal simulations. *Eurosun 2002.* Bologna, Italy.

Paksoy, H., Snijders, A. & Stiles, L. 2009. State-of-the-Art Review of Aquifer Thermal Energy Storage Systems for Heating and Cooling Buildings. *Effstock.* Stockholm.

Papillon, P., Nielsen, J. E., Cholin, X., Letz, T., Thür, A., Kuhness, G., Bales, C., Albaric, M., Drueck, H., Ullmann, J. & Mette, B. 2010. *Solar Combisystems Promotion and Standardisation Final Report.*

Parameshwaran, R., Kalaiselvam, S., Harikrishnan, S. & Elayaperumal, A. 2012. Sustainable thermal energy storage technologies for buildings: A review. *Renewable and Sustainable Energy Reviews,* 16**,** 2394-2433.

Peippo, K., Kauranen, P. & Lund, P. D. 1991. A multicomponent PCM wall optimized for passive solar heating. *Energy and Buildings,* 17**,** 259-270.

Persson, J. & Westermark, M. 2012. Phase change material cool storage for a Swedish Passive House. *Energy and Buildings,* 54**,** 490-495.

Persson, T. 2004. 'Elbesparing med pelletkaminer och solvärme i direktelvärmda småhus'. Lic. thesis, KTH, Stockholm.

Persson, T. & Heier, J. 2010. *Småhusens framtida utformning : -Hur påverkar Boverkets nya byggregler?* Borlänge. ISRN DU-SERC- -95- -SE

Pinel, P., Cruickshank, C. A., Beausoleil-Morrison, I. & Wills, A. 2011. A review of available methods for seasonal storage of solar thermal energy in residential applications. *Renewable and Sustainable Energy Reviews,* 15**,** 3341-3359.

Rismanchi, B., Saidur, R., Masjuki, H. H. & Mahlia, T. M. I. 2012. Thermodynamic evaluation of utilizing different ice thermal energy storage systems for cooling application in office buildings in Malaysia. *Energy and Buildings,* 53**,** 117-126.

SCB 2006a. *Energistatistik för flerbostadshus 2005*. ISSN: 1654-3769

SCB 2006b. *Energistatistik för lokaler 2005*. ISSN 1654-3769

SCB 2006c. *Energistatistik för småhus 2005*. ISSN: 1654-3769

SCB 2009a. *Energistatistik för flerbostadshus 2008*. ID-no ES2009:08

SCB 2009b. *Energistatistik för lokaler 2007*. ID-no ES2009:05

SCB 2009c. *Energistatistik för småhus 2008*. ID-no ES2009:07

Schmidt, T., Mangold, D. & Müller-Steinhagen, H. 2004. Central solar heating plants with seasonal storage in Germany. *Solar Energy,* 76**,** 165-174.

Sehar, F., Rahman, S. & Pipattanasomporn, M. 2012. Impacts of ice storage on electrical energy consumptions in office buildings. *Energy and Buildings,* 51**,** 255-262.

Shukla, A., Buddhi, D. & Sawhney, R. L. 2009. Solar water heaters with phase change material thermal energy storage medium: A review. *Renewable and Sustainable Energy Reviews,* 13**,** 2119-2125.

Skogsberg, K. 2002. The Sundsvall Regional Hospital snow cooling plant--results from the first year of operation. *Cold Regions Science and Technology,* 34**,** 135-142.

Skogsberg, K. & Nordell, B. 2001. The Sundsvall hospital snow storage. *Cold Regions Science and Technology,* 32**,** 63-70.

Socialstyrelsen 2005. *Allmänna råd om temperatur inomhus*. SOSFS 2005:15

Streicher, W., Schultz, J. M., Solé, C., Cabeza, L. F., Bony, J., Citherlet, S. & Heinz, A. 2008. Final report of Subtask C "Phase Change Materials" The overview - A Report of IEA Solar Heating and Cooling programme - Task 32.

Strängbetong. *Termodeck hollow core concrete slab* [Online]. Available: http://www.strangbetong.se/koncept-komponenter/koncept/termodeck/ [Accessed 2013-01-16].

Ståhl, F. 2009. 'Influence of thermal mass on the heating and cooling demands of a building unit'. PhD thesis, Chalmers tekniska högskola, Gothenburg.

Sweco Theorells 2007. *Brf Anneberg i Enebyberg i Danderyds kommun Utredning SOL/Bergvärmelager*. Stockholm.

Swedish Energy Agency 2007. *Energianvändning och innemiljö i skolor och förskolor - Förbättrad statistik för lokaler, STIL2*. ER2007:11

Swedish Energy Agency 2009. *Energy in Sweden 2009*. ID-no ET2009:30

Swedish Energy Agency 2010. *Energy in Sweden 2010*. ID-no ET2010:47

Takeda, S., Nagano, K., Mochida, T. & Shimakura, K. 2004. Development of a ventilation system utilizing thermal energy storage for granules containing phase change material. *Solar Energy,* 77**,** 329-338.

TESS Libraries. Available: http://www.trnsys.com/tess-libraries/individual-components.php [Accessed 2012-02-17].

Turnpenny, J. R., Etheridge, D. W. & Reay, D. A. 2000. Novel ventilation cooling system for reducing air conditioning in buildings.: Part I: testing and theoretical modelling. *Applied Thermal Engineering,* 20**,** 1019-1037.

Turnpenny, J. R., Etheridge, D. W. & Reay, D. A. 2001. Novel ventilation system for reducing air conditioning in buildings. Part II: testing of prototype. *Applied Thermal Engineering,* 21**,** 1203-1217.

Tyagi, V. V. & Buddhi, D. 2007. PCM thermal storage in buildings: A state of art. *Renewable and Sustainable Energy Reviews,* 11**,** 1146-1166.

Tyagi, V. V., Panwar, N. L., Rahim, N. A. & Kothari, R. 2012. Review on solar air heating system with and without thermal energy storage system. *Renewable and Sustainable Energy Reviews,* 16**,** 2289-2303.

Wang, H. & Qi, C. 2008. Performance study of underground thermal storage in a solar-ground coupled heat pump system for residential buildings. *Energy and Buildings,* 40**,** 1278-1286.

Wang, H., Qi, C., Wang, E. & Zhao, J. 2009. A case study of underground thermal storage in a solar-ground coupled heat pump system for residential buildings. *Renewable Energy,* 34**,** 307-314.

Wang, S. K. 1993. *Handbook of air conditioning and refrigeration*, McGraw-Hill.

Vanhoudt, D., Desmedt, J., Van Bael, J., Robeyn, N. & Hoes, H. 2011. An aquifer thermal storage system in a Belgian hospital: Long-term experimental evaluation of energy and cost savings. *Energy and Buildings,* 43**,** 3657-3665.

Weiss, W. W., Heating, I. E. A. S. & Programme, C. 2003. *Solar Heating Systems for Houses: A Design Handbook for Solar Combisystems*, James & James.

Verma, P., Varun & Singal, S. K. 2008. Review of mathematical modeling on latent heat thermal energy storage systems using phase-change material. *Renewable and Sustainable Energy Reviews,* 12**,** 999-1031.

Westerlund, R., Andersson, C. & Södergren, L.-O. 2007. Modell för energianalys med hjälp av typhus, version 2.01. Stockholm: K-Konsult Energi Stockholm.

Wikipedia Commons. *Heat and cold storage in an aquifer* [Online]. User: Fred the Oyster, Licenced under CC-BY-SA-3.0. Available: http://commons.wikimedia.org/wiki/File:HeatAndColdStorageWithHeatPump.svg [Accessed 2013-01-16].

Win, K. M., Persson, T. & Bales, C. 2012. Particles and gaseous emissions from realistic operation of residential wood pellet heating systems. *Atmospheric Environment,* 59**,** 320-327.

Xu, X., Wang, S., Wang, J. & Xiao, F. 2010. Active pipe-embedded structures in buildings for utilizing low-grade energy sources: A review. *Energy and Buildings,* 42**,** 1567-1581.

Yahay, N. A. & Ahmad, H. 2011. Numerical Investigation of Indoor Air Temperature with the Application of PCM Gypsum Board as Ceiling Panels in Buildings. *Procedia Engineering,* 20**,** 238-248.

Yau, Y. H. & Rismanchi, B. 2012. A review on cool thermal storage technologies and operating strategies. *Renewable and Sustainable Energy Reviews,* 16**,** 787-797.

Zalba, B., Marin, J. M., Cabeza, L. F. & Mehling, H. 2004. Free-cooling of buildings with phase change materials. *International Journal of Refrigeration-Revue Internationale Du Froid,* 27**,** 839-849.

Zalba, B., Marín, J. M., Cabeza, L. F. & Mehling, H. 2003. Review on thermal energy storage with phase change: materials, heat transfer analysis and applications. *Applied Thermal Engineering,* 23**,** 251-283.

Zhang, P., Ma, Z. W. & Wang, R. Z. 2010. An overview of phase change material slurries: MPCS and CHS. *Renewable and Sustainable Energy Reviews,* 14**,** 598-614.

Zhou, D., Zhao, C. Y. & Tian, Y. 2012. Review on thermal energy storage with phase change materials (PCMs) in building applications. *Applied Energy,* 92**,** 593-605.

Zhu, L., Hurt, R., Correia, D. & Boehm, R. 2009a. Detailed energy saving performance analyses on thermal mass walls demonstrated in a zero energy house. *Energy and Buildings,* 41**,** 303-310.

Zhu, N., Ma, Z. & Wang, S. 2009b. Dynamic characteristics and energy performance of buildings using phase change materials: A review. *Energy Conversion and Management,* 50**,** 3169-3181.