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On the thermal inertia and time constant of single-family houses

Johan Hedbrant

INSTITUTE OF TECHNOLOGY
LINKÖPINGS UNIVERSITET

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Division of Energy Systems
Department of Mechanical Engineering
Linköpings universitet, SE-581 83 Linköping, Sweden.
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Abstract

Since the nineteen-seventies, electricity has become a common heating source in Swedish single-family houses. About one million smallhouses can use electricity for heating, about 600.000 have electricity as the only heating source.

A liberalised European electricity market would most likely raise the Swedish electricity prices during daytime on weekdays and lower it at other times. In the long run, electrical heating of houses would be replaced by fuels, but in the shorter perspective, other strategies may be considered. This report evaluates the use of electricity for heating a dwelling, or part of it, at night when both the demand and the price are low. The stored heat is utilised in the daytime some hours later, when the electricity price is high.

Essential for heat storage is the thermal time constant. The report gives a simple theoretical framework for the calculation of the time constant for a single-family house with furniture. Furthermore the “comfort” time constant, that is, the time for a house to cool down from a maximum to a minimum acceptable temperature, is derived. Two theoretical model houses are calculated, and the results are compared to data from empirical studies in three inhabited test houses.

The results show that it was possible to store about 8 kWh/K in a house from the seventies and about 5 kWh/K in a house from the eighties. The time constants were 34 h and 53 h, respectively. During winter conditions with 0°C outdoor, the “comfort” time constants with maximum and minimum indoor temperatures of 23 and 20°C were 6 h and 10 h.

The results indicate that the maximum load-shifting potential of an average single family house is about 1 kW during 16 daytime hours shifted into 2 kW during 8 night hours. Up-scaled to the one million Swedish single-family houses that *can* use electricity as a heating source, the maximum potential is 1000 MW daytime time-shifted into 2000 MW at night.

Acknowledgements

This work started as a project support for the energy evaluation of Bo92, a Swedish housing exhibition in 1992. The work expanded and over the years, it has given me a unique view, spanning from technical details in building construction to European energy policy, including social and behavioural aspects on houses and dwellings. I now want to express my gratitude to those I have met.

Professor Björn Karlsson, one of the driving forces behind the development of single-family houses during the eighties, is one of the few who actually accepts the challenge of technical science and makes new, different things happen. Dr Mats Söderström and Dr Stig-Inge Gustafsson, have both done a skilful work in guiding me through the project work and the documentation. During Bo92 Peter Karlsson was invaluable, solving all problems with technical maintenance and data collection. All my colleagues at the Division of Energy Systems should be acknowledged for support and vivid discussions.

I also want to express my gratitude to some people outside this university. The scientific council and my colleagues involved in the Bo92 project for sharing information, experience, and ideas. The families and tenants of the test houses for taking the trouble of our experiments and our occasional messing with the technical equipment. Dr Bengt Bengtsson, SECTRA AB, for introducing me to the data from the Övertorneå test-house.

My colleagues at the Commissioned R&D department at Linköping University, especially Carola Holmér and Sten Trolle, who managed the EU-project IDEM, which was run together with Bo92, should be acknowledged. The discussions with the partners from the UK, Switzerland, Italy and Greece gave me a useful view of cultural aspects of domestic energy use.

Also the partners in the EU-project MACTEMPO on environmental policy formulation should be acknowledged. It was during the discussion of resource optimisation, that the idea came up that it could be worthwhile to formulate a more general framework around thermal inertia in single-family houses.

To all of you not mentioned here, who have contributed — thank you all!

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Contents

1 Introduction

Short-time heat storing is an important part of the challenge to make buildings more energy-efficient. Heat may be stored when available and utilised some hours later. This report is intended to cover some aspects of heat storing in single-family houses.

The reader may wonder why heat storage in single-family houses is important. The answer is found in the Swedish' custom to use electricity as a heating source. If electrically heated houses could use electricity at night instead of in the daytime, additional capacity would be set free in the production plants and distribution grid. This would have large benefits.

Electrical resistant heating is used in Sweden and a few countries where electricity is cheap and easily available. In the rest of the world, electricity is complicated to produce, expensive and the production is detrimental to the environment. The rest of the world therefore only uses electricity for specific purposes, such as running electrical motors and lights. This load is largest in the daytime since it is driven by human activities.

If the conditions for international electricity business are right, a large share of the Swedish electricity could be exported. Since most of the Swedish electricity is produced by hydropower and nuclear power, exported electricity can reduce emissions of greenhouse gasses by replacing electricity produced in Danish' and continental coal condensing plants. The European society — of which Sweden is a part — would gain more from using the electricity for electricity-specific purposes than from making Swedish homes lukewarm. Thus, in a closed, national, perspective, Swedish' electrical heating may have advantages. In an international perspective with a liberalised electricity market, electrical heating is a waste with a valuable resource.

On the European electricity market, customers may be willing to pay more for daytime electricity than Swedish house-owners do today. Swedish electricity would therefore be more expensive in the daytime. In the short run, Swedish house-owners must stick to electrical heating since it is a major heating source. In the long run, Swedish house-owners may have to heat the houses in other ways. For some decade, the house-owners should consider how to prepare for a changing situation. Hence the idea of using electricity for heating in the night when the demand, and hopefully the price, is low. The stored heat is utilised in the daytime some hours later when the price is high. The potential for this, from the perspective of a single-family house, is elaborated in this report.

The first part of the Introduction is a short historical background to the development of Swedish single-family houses, and a presentation of some political trends influencing the Swedish energy use. It is not intended to be scientific, rather to give a brief and comprehensive historical background to Sweden's use of electrical resistant heating and the present energy debate.

References that describe specific Swedish conditions are mostly written in Swedish. The interested reader may enjoy some of the non-scientific sources I have referred to. The book ”Tetra”, by the journalist Peter Andersson and the business economist Tommy Larsson, tells the thrilling story of how Tetra Pak grow from one man's vision to an international business empire. The book ”IKEA”, by Bertil Torekull, is not less exciting. Torekull is one of the pioneers of Swedish economic press and the founder of ”Dagens Industri”, a major Swedish business journal. Both books tells the story of a Swedish entrepreneur who surfed on the wave of the social and industrial welfare development after the Second World War, and whose companies grew to multinational sizes. The values and visions of the Swedish society during these decades expressed in the books would be highly relevant also for the development of the Swedish energy system and single-family houses.

The science journalist Birgitta Johansson has worked at Sveriges Radios scientific editorial office. She is the author of the book ”Stadens tekniska system”, which gives a rich outline of the development of the urban infrastructure, including the electrical power system. Professionals from scientific, political and municipal institutes reviewed the book. Stefan Edman, the author of ”Världens chans” became an honorary doctor at Chalmers' institute of technology. He has worked with environmental issues for more than two decades and became environmental advisor to Sweden's Prime Minister Göran Persson. In his books he gives a view of present international trends and possibilities in making Sweden a leading nation in the work for a sustainable development. Both Johansson and Edman provide references for further reading.

Is there a science where the insulation of houses' walls and international energy business meet, really? If there are important issues with problems and possible solutions, there *should* be a such a science: The second part of the introduction is a short note on the science of technology, systems analysis and the Division of Energy Systems at Linköping University.

The third part is some words about Bo92, the housing exhibition where some of the ideas of single-family houses were tested. The three parts of the introduction are intended to give a view of the prerequisites for the work.

The second chapter is a description of the anticipated result of the work, and the limitations for it. The third chapter, State of the art, is some highlights from related works, internationally and nationally, where storing or thermal time constants[1] have been investigated.

The fourth chapter is a text with a short theoretical background for thermal storing. It describes the house as a thermal storage with flows of heat through walls and ventilation to charge or discharge it. Two theoretical example houses are evaluated, and as validation and reasonability check there is also a short calculation of the annual energy use. Hopefully, the discussion and mathematics would be possible to use for simple theoretical calculations also of other single-family houses.

The fifth chapter is a description of three different experiments with heat storing in single-family houses. Each experiment had its own prerequisites — different house design, different storage methods and different evaluations. In one of the houses a more detailed analysis were made.

The results are evaluated in the sixth chapter. The agreement between theory and practice is discussed, as well as comfort aspects and some ”softer” issues around the results. Shortly, the potential in the national perspective is referred to. This part must be read with some distance, since the numbers are based only on a few experiments. A short review of the Bo92 visions is also made here, what did come true, what did not come true, and what has not yet come true?

The seventh chapter is the conclusions, the results in a short form. The eighth chapter shows some areas for future works.

The author wishes you a pleasant hour!

[1] The Time constant is the time needed for e.g. a building to adjust to the surrounding temperature. See definition in Chapter 4.2.

1.1 Energy in a developing Sweden

1.1.1 Housing in Sweden

During the 20th century there was an unprecedented political effort to improve the Swedish social welfare. In the century's first decades the social project ”Den hela och rena människan” was launched, focusing on rationalised food supply and improved education. Several of Sweden's large companies grew out of the emerging markets of energy and information infrastructure, of vehicles for transportation of people and goods, of food supply and pharmaceuticals [1, 2].

After the Second World War, light was put on Swedish homes. Housing became an important aspect of the Swedish' lifestyle. In the project ”Miljon-programmet”, the goal of building one million modern dwellings during ten years was fulfilled. The technical standard of Swedish homes reached an international state-of-the-art. New easily maintained materials and technical equipment for cooking and cleaning were part of this. The project ”Folkhemmet” gathered societal attention and even more companies were founded to provide goods to be used in homes [3, 4].

In the mid-sixties and seventies, there was a large movement towards single-family houses. An expanding economy and subsidiaries allowed several hundred thousands of new towards single-family houses to be built. People moved from rented dwellings in apartment houses into their own house [5].

1.1.2 Energy for heating

During history, the conditions for energy supply have changed several times [6]. The Swedish society experienced its first energy crisis already during the 18th century, namely lack of wood fuel. Initially, methods to increase efficiency were developed, e.g. the improved tiled stove. When the wood prices slowly increased, so did also the coal import from England. Then the central heating system was developed. A central heating system means that each house had one stove and a closed water-loop distributed the heat to the radiators.

The change from wood fuel to coal implied a change from self-support and local production to an organised distribution with few large coal providers. The apartment-house owners and later the cities overtook from the tenants the responsibility for heating the dwellings.

The transfer from coal to oil in the fifties did not imply any large changes. Oil was popular because it was cheap, easy to distribute and useful for several purposes. The production chain was then as well as now controlled by a small amount of very large companies. The responsibility for the Swedish energy supply was gradually transferred to the international oil industry, which to a large extent co-operated with the motor industry[2].

1.1.3 Electricity

In 1890, the three-phase, high-voltage technology for long-distance distribution of electrical power was developed and the use of electricity was then diffused over the country. Easily available electrical energy has been one of the driving forces behind the Swedish welfare. Sweden has no fossil fuels, but large resources of hydropower. The electricity had a larger impact in Sweden than in most other countries.

Both in the thirties and in the end of the fifties the Swedish utility Vattenfall had excess production capacity. This opened the markets for white goods and other electrical household equipment and later resistant heating[3].

There had been attempts to reduce the energy use. The Swedish Fuel commission (1941) gave several directions of energy savings. Also in the Fuel savings report of 1951 measures to reduce energy use (insulation, heat pumps etc) were suggested, with the aim to reduce a threatening oil dependence. But when the final report was published 1956, all thoughts of limiting the energy use had disappeared.

During the sixties and seventies, producers and distributors worked intensively to make the consumers increase their electricity use. The expansion of resistant heating was an important part of this strategy. When the crucial decisions were made about nuclear power, the decision-makers made very optimistic predictions about increased electricity use[4].

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[2] Johansson B. Stadens..., p 167.
[3] Johansson B. Stadens..., p 168.
[4] Johansson B. Stadens..., p 169.

1.1.4 The oil crisis

In the mid-seventies, the first oil crisis made ”Folkhemmet” realise it was vulnerable to energy shortage. This increased even more the motivation to move into nuclear power.

The years that followed redirected the domestic energy use from oil to electricity. Cities and communities were challenged with oil replacement targets for the heating sector. Tax-free electrical power was sold on separate contracts to so-called disconnectable electrical heaters used in industry and district heating.

The electricity use for heating increased from 5 TWh 1970 to about 29 TWh in 1993. Including heat pumps and disconnectable electrical heaters in district heating it was 42 TWh. Of this almost 14 TWh, about a third, was resistant heating[5].

After the oil crises of the seventies and the referendum 1980 about the nuclear power, the Swedish parliament (Riksdagen) 1981 decided that the future Swedish energy system to the largest possible extent should be based on national, renewable, energy sources with low environmental impact. The nuclear energy should be phased out to the year 2010, and be replaced by energy savings and more sustainable energy sources.

A manager at a Swedish utility stated that it was easy to expand the energy system with 70 TWh — ”twelve decisions in five board-rooms”. To replace it, e.g. by converting electrical heating, millions of decisions around kitchen tables are needed[6].

1.1.5 The Sick-Building Syndrome

Energy aspects grew important after the oil crises. Increasing energy prices, or risk for it, made house owners look at their houses as energy-using systems.

Occasionally, house owners tried to reduce the energy use by reducing the ventilation rate. In the late seventies, a backlash was emerging. Problems with moisture, mould and so-called ”sick buildings” began to appear in large scale, both in single-family houses and apartment houses [7, 8, 9]. Many tenants

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5 Johansson B. Stadens..., p 169.
6 Johansson B. Stadens..., p 166.

experienced different symptoms of impaired health. Not only moisture problems were believed to contribute to the health impact. Emissions from many ”modern” materials such as floor levelling putty, plastic wallpapers and floors, paint and surface protection of furniture etc were suspected to influence the indoor air when ventilation was reduced.

Beside moisture due to too low ventilation rates, ”built-in” moisture from the construction of the houses also appeared. Unlucky circumstances with e.g. rain during the construction period and diffusion-proof materials were also believed to have causes problems.

The sick-building syndrome put a finger at the complexity of the house as a socio-technical system. A large share of the single-family houses were built and used by people who had lived in apartment houses. They may occasionally have had a lack of knowledge of how to maintain a single-family house. The solution with reduced ventilation flow to improve energy efficiency was most likely efficient and seemed to be a good idea from an energy perspective. A short and intensive construction period also saved resources. But the house was not only a building. It was a dwelling for human beings, in which built-in wet construction materials could be detrimental, and moisture and chemical emissions from surfaces had to be removed and replaced with fresh air. Some aspects of a building for human beings were not possible to compromise with.

1.1.6 The liberalisation of the electricity market

The Swedish electricity market was deregulated in January 1996. The market has gradually opened for any customer to buy power from any producer. As a first step, the larger customers were allowed to buy power on an hour-to-hour basis. The original plan was that also smaller customers should be given the same possibility. The smaller customers however also needed electricity meters that could register the power use on an hourly basis. The relatively high price of these meters made the market penetration low.

From November 1999, the Swedish electricity market followed Norway’s example and used template load profiles for single-family houses. By using a template load profile together with the monthly energy consumption of the individual single-family house, the hourly electricity use could be approximated. Hence also smaller customers could benefit from the liberalised electricity market.

1.1.7 Important international trends

The World Commission for Sustainable Development, also called the Brundtland commission, was 1983 challenged by the UN to develop a global agenda for change. It was presented in the report Our Common Future 1987, and formed a basis for issues of environment, economic growth and social development [10, 11].

In the UN conference in Rio 1992, environmental issues were for the first time brought up on the international political agenda. The Rio declaration stated that the right to development for present generations must be satisfied in a way that does not harm the environment and does not compromise the ability of future generations to satisfy their own needs.

The most important message from the Rio conference was stated in Agenda 21, the survival program for the 21st century. Agenda 21 not only stated the problems but also pointed at solutions and discussed timelines and resources. It concluded that the power for changes could only come from below, from individuals with knowledge and inspiration. From households, working-sites, villages and cities.

In the autumn 1997 the Factor 10 initiative was launched by a group of politicians, researchers, business managers and environmental experts, supported by analyses from the Wupperthal institute. It stated that in a few generations, 30-50 years, may and must the rich countries of the world reduce the use of natural resources in average ten times — a factor 10 — and share the welfare with the rest of the world.

Experiences indicate that a factor 4 in increased efficiency is possible to achieve with traditional engineering methodologies. This was often reached by doubling the performance and halving the resource use. What also happens when less resource per unit is used is that the price drops and the demand increases. This increases sales and increases welfare, but does not necessarily reduce resource use.

A factor 10 in average reduction in resource use at a maintained level of welfare is a gigantic challenge for the western society. The strategies to reach the goal are not known to us at present, but there are no indications that it is not possible.

The reactions to collective challenges have also been studied [11, 12], and may be appropriate to mention here. An important dimension is the individual's choice between actions gaining the collective or gaining the individual himself (Tragedy of the Commons). Three groups are possible to distinguish. The first is idealistic and does what is of advantage to the whole, regardless of other's behaviour. The second has a responsible realism, will act in accordance with other but only if other also does it. The third group has a more individualistic approach, acting in accordance with its own interests and does not support initiatives for a collective action. Motivations for the last group may be that it has its own more optimistic judgements of the future, or that the group (individual, company, country) is too small to have any real influence.

Agenda 21 was evaluated after five years at the UNGASS meeting 1997. EU suggested a goal with a factor 10 in the long run, but also a milestone with an improvement with a factor 4 over the next 20-30 years [13].

1.2 The research landscape

This chapter describes one of the research perspectives at the Division of Energy systems. It is a view of the fundamentals that influence our scientific work, our choices of methods, our surroundings and our scientific judgements.

The purpose with this chapter is twofold. The reader already familiar with the research landscape can easier understand our position in the landscape, the reader not familiar with the landscape can learn about it from our point of view.

1.2.1 Systems analysis and science

A comment regarding research methodologies can be made here. ”Traditional” science (e.g. physics, chemistry) is reductionistic to its nature in the sense that it aims at reducing research problems into parts that are limited enough to study [14]. This has been the carrying idea of science since the 17^{th} century, and has led to a successive refining of the disciplines (e.g. physics has been divided mechanical physics and electrical physics, and so on). The mission of science was to find a ”Truth”. This Truth was objective, stable, independent of time and space, and could be found by any researcher looking for it.

However, during the 20^{th} century it turned out that some problems were not possible to divide without losing its intrinsic qualities (Figure 1.1) [15]. These problems occasionally consisted of sets of related ”components”, as in e.g. economy, ecology, health sciences and social sciences.

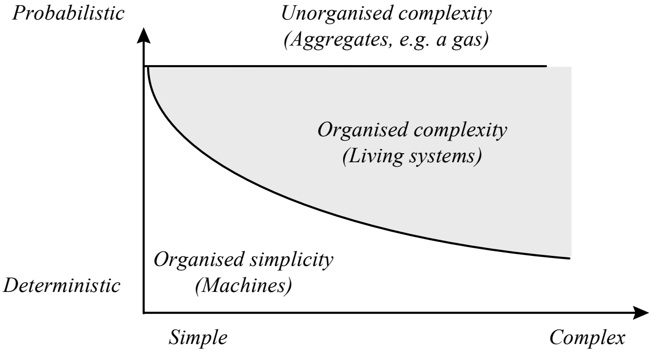

Figure 1.1. Research domain for systems analysis [15].

The problems appeared because a system was too complex to be studied in its full context. But when it was reduced, it was deprived of its relations and crucial aspects disappeared. As a reaction, the systems analysis emerged during the first half of the 20th century. Systems analysis is occasionally regarded as a scientific discipline, but in fact it is not. The systems analysis did not formulate any solutions, it rather pointed at the limitations of traditional scientific methods.

The systems analysis offers an alternative way to reduce the problem, a way to focus a more limited part of the problem but without having to study each individual component separately. Here is where the scientific conflict arises — there is no evident choice of method for how the reduction should be made. One way to cut out a representative system from a complex reality may be as appropriate as the other may.

Traditional science has grown more humble considering the richness in systemic phenomena. A wider definition of the mission of science is occasionally used — not to ”Find a Truth” but to ”Find a Way to view” [16, 17]. Instead of a theoretical validity with a quantitative value, a practical validity with qualitative values may be used when appropriate.

Any system model used in systems analysis should therefore not be regarded as a Truth, rather as a Way to view, one of an infinite set. If it is good or bad should be decided from the research context in which is used.

1.2.2 The philosophy of technology

The natural science is limited to study things that exist. The technical science is not, rather it is designed to create. In science philosophy the definition of technology has been discussed. One important demarcation is that (traditional) science wants to know *why*, and technology wants to know *how* (to act) [18, 19]. There is no evident connection between these two knowledge forms — knowledge *may* lead to a correct or efficient action, action *may* lead to increased knowledge, at least if the sequels of the action are analysed.

Since science and technology have different purposes — true explanations and practical usefulness — their common methodology should be different. One difference is that verification of usefulness is crucial in technology. Hence the experiments are designed for the usefulness to be decided, rather than for the cause of the phenomena to be analysed.

The method of technology may be separated in three factors [20].

Most technology is extremely complicated in a scientific sense. Everything may not be predicted beforehand. The aim is to <u>produce practical, useful, results telling *that* something works</u>, rather than *why* it does it.

Since the technology is expected to work in a natural and socio-economic environment, such <u>an environment must exist</u>, or at least some rough approximations of it. Evidently, there are no methods to describe all aspects included in the environment. Assumptions have to be made, and the most rational choice is to use the best knowledge available.

Furthermore there must <u>exist a value system</u>, which can decide the usefulness when the result is applied in the environment. This is a question of norms. But norms are generally not a scientific issue. They are rather decided by other factors, e.g. traditional and social conventions. Often economical success is one of the criteria for a good result.

Besides from the primary results, which the experiment was designed to yield, secondary effects may be analysed. These can be both side effects, e.g. waste or emissions from the use, or attendant effects, e.g. a changed market situation. Since successful results of technology, primary or secondary, tend to reach far, attitudes from those influenced by the results show large variations.

1.2.3 The Division of Energy Systems

The intersection of the local and global, of short and long time-horizons, of components and systems, of technical and political sciences is the research field of the Division of Energy Systems. The division was established in 1980 and the research idea is ”Resource-efficient Energy Systems”. During the years, five research domains have emerged. The theses referred to are presented in Appendix A.

- An early task was to develop measurement and control equipment to be used in industrial and building applications to collect data and evaluate control strategies [A1, A2].

- Optimisation of energy systems has been a challenge throughout the years. Some efforts have been put in to develop general optimisation software for energy systems, e.g. MIND [A3] which has been used most with industrial systems and MODEST [A4, A5, A6] used with municipal, regional and national systems.

- The lion part of the dissertations have been to perform cost-efficiency analyses of real world problems, occasionally with the use of the MIND and MODEST optimisation tools, but also with other methods [A7, A8, A9, A10, A11, A12, A13, A14, A15, A16, A17, A18, A19, A20]. Optimisation generally means to find the system that generates the lowest system cost, i.e. the lowest sum of all running and fixed costs during a specified time frame in all possible and potential configurations of producers, distributors and consumers.

- Some researches have focused buildings and houses, both energy aspects [A21, A22, A23] and the quality of indoor climate [A24].

- In the last research domain, individual components and characteristics in certain energy systems have been studied, e.g. thermal storage, insulation, as well as aspects of nuclear reactors [A25, A26, A27, A28, A29].

Projects have been run together with both industrial and public partners, financed as commissioned R&D or scientific research.

1.3 Bo92 — A view of the future

The initiating project behind this report was the housing exhibition Bo92 in Örebro, a city situated 150 km west of Stockholm. The ideas behind Bo92 emerged from the history of the Swedish society during the 20th century — the improving of the Swedish welfare, the increased availability of energy and electricity, the movement of single-family houses, the oil crisis and the sick-building syndrome.

From there, the ideas also considered a future with increasing electricity prices, demand for construction materials with low chemical emissions, as well as for a construction technology with low environmental load and low life-cycle costs.

The R&D of small-houses started 1985 together with the single-family house construction company Boro. The plans for the housing exhibition Bo92 emerged in the late eighties, about the same time the Brundtland commission finished their report. The UN conference in Rio had not been held yet and the Agenda 21, the Factor 10 initiatives, the UNGASS and Kyoto conferences were far off in the future. So was also the liberalised electricity market. This chapter is a short summary of the visions of the project, as viewed from back then.

1.3.1 Air-borne heating

In the Sick-Building syndrome, moisture, construction materials and insufficient ventilation were assumed to play a key role [7, 8, 9]. Furthermore, there had been indications (the oil crises and the referendum about nuclear power) that energy would not be as cheap in future as it had been. Hence Boro designed a single-family house with features to secure ventilation and energy efficiency. The houses were well-insulated (245 mm glass wool), had triple-glazed windows and used airborne heating with heat recovery.

Airborne heating was a method to use the indoor air as heat-carrying medium. The heated fresh air was circulated through the house, then passed through a heat exchanger that pre-heated the incoming fresh-air.

With airborne heating, the ventilation rate of the house was decided from the heater and could not be accidentally reduced by the user. The house construction was a commercial success for Boro. During the eighties, the company grew to be Sweden’s biggest single-family producer. Some ten thousands of houses with airborne heating were produced [21].

1.3.2 Adaptation to the national power grid

In the Bo92 vision, the houses should fit in a liberalised electricity market.

Industry and household were substantially relying on electricity. Both used more electricity daytime, and the use of electricity as a heating source made the demand as largest during winter. The load profile was therefore largest during daytime weekdays in winters (Figure 1.2). The electricity at the power peaks was occasionally produced with oil condensing power and even gas turbine powered generators, at a low efficiency and with high environmental load.

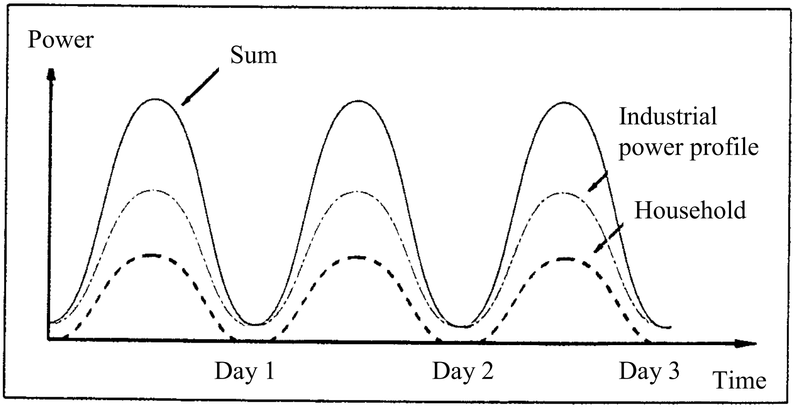

Figure 1.2. Electrical load from industry and household in phase. (Figure from Bo92 information material [22]. Translated.)

If the household load could be time-shifted in a way that compensated the industrial load, a smoother load profile occurs (Figure 1.3).

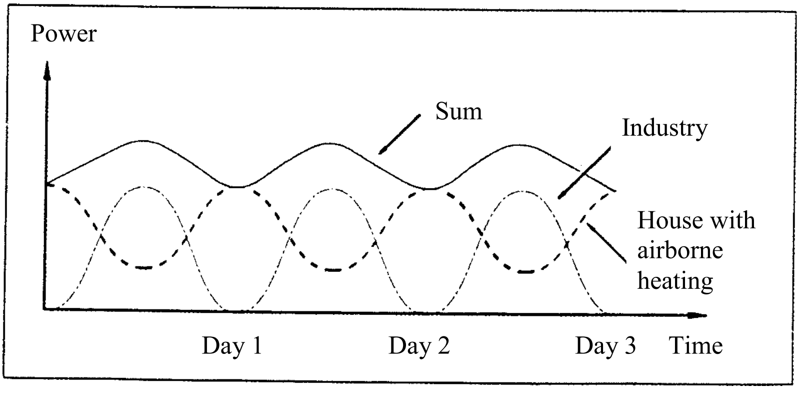

Figure 1.3. Electrical load from industry and household in opposite phase. (Figure from Bo92 information material [22]. Translated.)

Buying ”off-peak” electricity may also be good business. In a balanced market, the electricity price covers a producer’s short run marginal cost for production and maybe also a premium which may or may not provide an incentive for new facilities [23, 24].

If there is a pronounced electricity surplus, i.e. too much electricity chases too little demand, the result would be an auction among producers. The price then reduces to the short run marginal costs (and occasionally below, at cut-throat auctions). If there is pronounced electricity deficit, i.e. the demand chases the production, the result would be an auction among customers. The price increases, panic bids and speculative bubbles may occur [23].

The risk of shortage during nighttime and weekends is virtually zero, the right price during nighttime is hence close to the short run marginal cost.

1.3.3 Load management

To evaluate the potential of equalising the national load profile as well as reducing heating costs, load-management in single-family houses was suggested. The need for expensive, inefficient and ”dirty” peak production might be avoided, a better utilisation of the electricity production plants might be achieved and the electricity might be bought at prices near the running cost for production.

Load management can be performed in several ways [25]. The strategy for single-family houses was to use time-shifting and storing; i.e. to heat the houses during the nights and use the stored heat during the days.

With successful load shifting it was assumed that, in a time perspective of some decades, a large part of the national nuclear power production capacity could be released. Either the released capacity could be phased out according to the referendum 1980 or be used for export of CO_2-free electricity, improving the national trade balance.

In both cases, higher electricity prices daytime was to be expected. If electricity were exported to the European continent, the continental market would influence the Swedish prices. For instance, on the European continent electricity is not used as a major heating source in winters, rather for cooling purposes daytime in summers. Increased demand would lead to higher prices during daytime in summers.

1.3.4 Thermal inertia

With load shifting and storing, Swedish houses could use electricity during the off-peak periods when the industry didn't use it. In some early evaluation projects[7] and occasional applications[8], separate heat storing devices had been used. These were hot-water tanks of about 10 m^3 volume. They were quite expensive and spacious, and hence not easily used in single family houses.

The airborne heated house was designed to have a large thermal inertia, that is, it kept the heat inside the house for a long time after the heater was switched off. If the house had a large thermal inertia, the house itself could be used as the storage.

1.3.5 Houses and electricity as future export products

An extended vision for Bo92 included a Swedish role in a future integrated Europe. In the time horizon of some decades, and by means of houses with large thermal inertia, it might be possible to aim towards an energy system where industry and houses live in an energy synergy. The electricity would be produced in combined heat and power plants, fuelled with CO_2-free biomass fuels. Heat from the co-generation would be used in district heating systems in cities. Electricity would be used in industry during daytime and for houses in areas without district heating during nighttime.

A simple calculation[9] indicated that if, say, 25 TWh electricity could be exported instead of being used for heating Swedish houses, the use of about 8 Mton coal could be avoided. This would reduce the emission of CO_2 with 30 Mton. (The total CO_2-emissions, including the transport sector, in Sweden during the nineties have been around 60 Mton). The value of the electricity export will be in the magnitude of 2 500 - 5 000 MSEK annually at 100-200 SEK/MWh.

The need for export capacity will be in the size of ten cables of the size of Baltic Cable, that is, in total about 5 000 MW. These cables will then be used to the equivalent of full power during 5 000 daytime hours each year[10].

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[7] Göteborg Energi, pers. comm.
[8] Wahlbin, single-family house owner in Borensberg
[9] 1 Mton coal = 3 TWh electricity and 3.7 Mton CO_2
[10] About 14 hours per day each day of the year. There are 8 760 h per year.

1.3.6 Bo92 energy projects

A number of projects were formulated, with the aim to study energy use in the single-family houses at Bo92, as well as different alternatives for heating [26]. Some issues were:

Energy supplies systems. Alternative heating sources at peak load, such as gas, biomass fuel or local combined heat and power generation.

Energy storage. The heating system should be designed to use the electricity spot price to give the lowest life cycle cost and best cost-effectiveness.

Floor heating. Features of a heating system were secured ventilation, warm floors, cooler bedrooms, foundation without moisture and a good economy.

Tenant's influence. With the user-friendly Miniwatt computer controller for the heating system [22], the tenant should get more comfort out of less money.

Flexible pricing. If the electricity spot price reflecting the current production costs is available at the house, the customer may reduce the energy use when price is high and producers may sell more when price is low.

With a system installed at the utility (Örebro Energi) allowing for updated electricity prices to be transmitted on the same cables as the electricity (power line carrier), some equipment in the house could be controlled via the electricity price.

Unfortunately Boro together with several major construction companies went bankrupt during the large recession in the beginning of the nineties. The construction of the single-family houses was stopped for several months. When the houses were finally built, it was in a large hurry and the original plans for construction and quality assurance were not followed.

During the first heating season, winter 92/93, the houses were not inhabited. The second heating season, winter 93/94, it turned out that occasional houses had construction flaws that made our measurements unsuitable to evaluate [26]. Out of the experiments planned in the Bo92 houses, we however managed to carry out a few. Among these was the experiment in Hus 15, described in Chapter 5.3.

2 Scope

This chapter describes the anticipated *results* (aim), the *environment* in which the result is anticipated to work (limitations) and the *value system* that is used for the evaluation.

2.1 Aim

- This work will provide a simple theoretical framework for energy storage in the structure of a typical Swedish single-family house. The analysis will use information about house design, construction materials and furniture.

- This work will comprise the storage capacity and time constant related to thermal storage in the structure of the house.

- The theoretical framework will be illustrated by calculations on relevant examples of single-family houses.

- The theoretical result will be verified by measurements in some few single-family houses of different types and design.

2.2 Limitations

- The purpose of the storage is to reduce the electrical load for space heating during the 16 daytime hours, weekdays in winter. The storing of heat is time-shifted to the previous 8 nighttime hours.

- The incentive for storing is to use lower electricity prices during the 8 night hours, and thus lower the heating costs for tenants.

- The high and low temperature in the storage regimen should in future be chosen by the tenants, thus assuring the appropriate trade-off between comfort reduction and cost savings. This work will therefore discuss stored energy per degree (kWh/°C) and not stored energy as such (kWh), since this depends on the tenants' preferences.

- The storage strategies should be simple and portable to any type of heating system. Typical storage strategies would be to run the heating system on/off, or run it more/less.

- The influence of shorter time constants (e.g. heat storage in indoor air) is not within the scoop of this work.

- The storage analysis methods should be independent of outdoor temperature.

- Evident comfort experiences (positive or negative) by tenants will be briefly discussed, but a detailed evaluation of subjective matters is not in the scoop of this work.

2.3 Evaluation

- A successful result should have a correspondence between the theoretical framework and empirical validation within ±10 %.

- A successful storage regimen should have an acceptable comfort level for the tenants.

- The storage methods suggested should, up-scaled to all Swedish single-family houses, have a technical potential of the same magnitude as the Swedish condensing power capacity or the Swedish gas turbine capacity, that is, about 1000 MW.

3 State of the art

Thermal storage in building constructions has been evaluated in a variety of contexts. A common research field on the European continent and in the USA is cooling. Eaton et al. [27] looked at nighttime cooling of commercial buildings and refers to an evaluation of four different types of constructions. They discuss the difference between thermal mass and physical mass, that is, that thermally heavyweight buildings (large storage capacity) can be structurally lightweight. Eaton also discusses heat transport in voids or channels under the floor. The aim of the work was to minimise the incidence of high temperatures, i.e. the number of hours per year when the temperature exceeds the maximum comfort level of 24°C.

Penman [28] studied a working school with respect to the thermal response, and formulated a second order RC (resistance-capacitance) network model in which the parameters were identified by means of empirical data. The aim of Penman's work was to evaluate if simple models could capture essential elements of observed behaviour of a building. Loss coefficients and storage capacities were thoroughly discussed in the work, time constants were only indirectly mentioned.

Nighttime cooling was also studied by Roucault et al. [29] where the aim of the study was to consider thermal inertia when installing ventilation systems in buildings. Roucault had a more theoretical approach based on so-called modal analysis, but concluded that for studying the nighttime ventilation problem, it was sufficient to use only the building's main time constant, and supply a parameter that describes also the rapid dynamics of the air temperature.

A research team from Canada, Bailey et al. [30], used a climate chamber and studied heat storage in a number of building materials and furnishings. Also this work focused on nighttime cooling loads. Since nighttime air has a high moisture content, the hygroscopic storage in the materials was of large importance besides the time constant.

For the Nordic climate and single-family houses, several studies are of interest for this work. An early Swedish study on intermittent heating and nighttime temperature reduction was made by Dafgård [31]. The work presented time constants for a number of buildings — apartments houses and single-family houses as well as public and industrial buildings. Dafgård also made several experiments with nighttime temperature reduction and studied the energy savings.

A second study was made in 1983 on sixteen single-family houses in Gränna, east of the lake Vättern between Stockholm and Gothenburg [32]. Eight of the houses had a heavy construction and air-borne heating, four had a heavy construction and resistant heating and four had a light construction and airborne heating.

It turned out that all houses used about the same amount of energy per year, but the light construction used more electricity during daytime, and the house with the heavy construction and airborne heating used less electricity during daytime compared to the heavy construction and resistant heating. The time constant for one of the heavyweight houses was calculated to 184 h.

The third study was made by Södergren et al. [33] 1985. They studied the heat capacity of building structures and the availability for heat storage. The analysis was made on two building models (not necessarily domestic houses) with the computer program BRIS. One model had a light construction, the other a heavy one. The main time constants were 20 h and 147 h, respectively.

The fourth work of interest was made by Vattenfall, in a typical family house from the seventies representative for about 200 000 Swedish single-family houses [34, 35]. The house was unoccupied and used for several experiments to study strategies and costs for converting from resistant heating to water-borne heating. The time constant was measured to 27 h.

4 A theoretical study of thermal storage

The purpose of this chapter is to introduce the theory used in the discussion on thermal storage, and also to present the approximations used in this work. At first ‘thermal storage’ is discussed, showing that the potential depends on ‘thermal capacity’ in relation to ‘thermal losses’.

The following step discusses thermal capacity and losses. This is done ”bottom-up”, from materials to construction elements.

The discussion ends with an analysis of two examples of small-houses with furniture (one traditional house and one modern house). The results from these will later be compared with the experiment data from test houses.

4.1 Fundamental conceptions

The theory of heat storage is possible to relate to the general systems analysis and to discussions on flows and stocks. The main conceptions are the *thermal energy flow*, or heat flow, transferred through a specified area. This flow enters a specified volume of mass, where it is stored as *thermal energy*, or heat. The thermal energy is experienced as *temperature*, which is depending on the *specific heat capacity* of the mass. The storing mass has a *heat conductance*, which allows the thermal energy to diffuse inside the mass. From the envelope, the enclosing surface, there may be a *heat transfer* to the surrounding environment of the mass.

Usually some approximations are made. The important characteristics of the heat storing mass are assumed to be linear and homogenous, as well as the heat transfer characteristics of the envelopes of the mass. Under these circumstances, one may consider the thermal energy in a heat storage as e.g. the water in a glass or the electric charge in a capacitor (Figure 4.1).

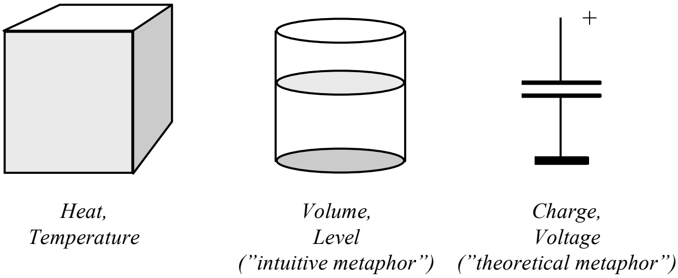

Figure 4.1. A heated body, a glass with water and a charged capacitor.

Occasionally, it is of interest to study temporal aspects of a storage, e.g. the time required for a flow to charge or discharge a storage. This time is often described by the time constant, which is calculated as follows:

If a step change is made in the level outside the storage, the flow makes the charge of the storage adjust asymptotically to the new level. A convenient measure is the time to fulfil 63 % of the step. The value is calculated from the expression 1-1/e. This time is called the time constant, denoted τ.

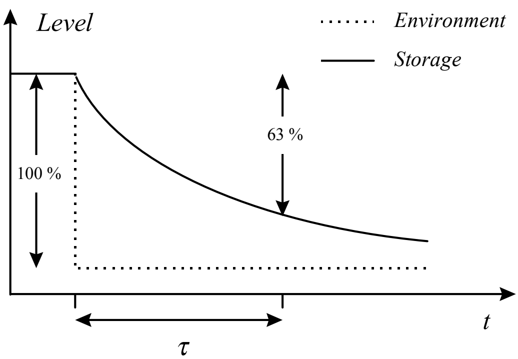

Figure 4.2. The time constant, τ, is the time to fulfil 63 % of a step change.

4.2 Thermal storage

Here, the time constant of a thermal storage is derived and expanded to be used on a building.

4.2.1 Time constant of a thermal storage

Consider a simple thermal storage, with a flow and temperature related according to Figure 4.3 [36]. It consists of a heat flow modelled as a current, q, through a resistance, R, discharging a storage mass, modelled as a capacitor, C (electrical analogies are frequently used, since several methods for analysing heat transfer problems then can be found in electric circuit theory).

Figure 4.3. Electronic circuit analogy for thermal storage.

The heat storing capacity C, and the stored energy W, may be calculated as

$$C = c_p \cdot m \qquad \text{[J/K]} \qquad (4.1)$$

$$W = C \cdot T \qquad \text{[J]} \qquad (4.2)$$

where c_p is the specific heat capacity [J/kgK]
m is the mass [kg]
T is the excess temperature [K]

At steady state, the heat flow q, is determined from

$$q = \frac{1}{R} \cdot T \qquad \text{[J/s or W]} \qquad (4.3)$$

$$R = \frac{R_a}{A} \qquad (4.4)$$

where R is the thermal resistance [K/W]
R_a is the thermal surface resistance [m^2 K/W]
A is the area [m^2]

The heat transfer across a surface is influenced by the conditions for convection, i.e. the air movements. Also, there is a part of the transfer that depends on thermal radiation. Therefore *R* is dependent on the physical conditions for the heat transfer.

To calculate the thermal time constant τ, the relation between *q* and *C* is needed. From the electronic circuit theory we have

$$q = C \cdot \frac{dT}{dt} \tag{4.5}$$

$$T = R \cdot q \tag{4.6}$$

Combining (4.5) and (4.6) gives:

$$\frac{dT}{dt} = \frac{1}{RC} \cdot T \tag{4.7}$$

with the solution:

$$T(t) = e^{\frac{1}{RC} \cdot t} \tag{4.8}$$

Comparing (4.8) with the solution of a first order differential equation shows that:

$$\tau = RC \tag{4.9}$$

Formula (4.9) gives the thermal time constant τ

where	*C*	is the heat storing capacity of the storage mass	[J/K]
	R	is the thermal resistance of the envelope of the mass	[K/W]

Formula (4.9) can be applied on any mass in which heat is stored as long as the diffusion of heat inside the mass is large compared to the heat diffusion across the envelope of the mass.

4.2.2 Time constant of a building

It is now possible to make a simple first order model of a house as a heat storage. As for storing capacity, all masses participating in storage have to be considered and for losses, the transmission losses through the walls, ceiling and foundation have to be considered, as well as the ventilation loss for the house.

The thermal resistance *R* in Formula (4.9) must be expanded. The resistance should relate to transmission losses, i.e. heat conducted through the building materials, as well as ventilation losses, i.e. heat carried by with the ventilation air. *R* can be written as:

$$R = \frac{1}{G_{tr} + G_v} \tag{4.10}$$

where G_{tr} is the thermal conductance from transmission [W/K]
G_v is the thermal conductance from ventilation [W/K]

The time constant, τ, may hence be expressed as

$$\tau = \frac{\sum (m \cdot c_p)}{G_{tr} + G_v} \tag{4.11}$$

where $\Sigma\,(m \cdot c_p)$ is heat storing capacity of all masses in the storage [J/K]

The time constant, τ, can be thus influenced through the heat storing masses, the transmission loss and the ventilation loss.

Generally, when speaking of increasing the heat storage capacity of a house, one usually means making the heat last longer, that is, increasing the thermal time constant. Formula (4.11) states that this does not necessarily require a larger heat storing mass. An increased thermal time constant may also be achieved by reducing the heat losses.

4.2.3 ”Comfort” time constant

The time constant, τ, is a convenient mathematical measure to describe *one* thermal property of a building. However, if the building is used to support comfort to tenants, as a single-family house, consideration has to be taken to the maximum and minimum indoor temperature accepted by the tenants. An adjustment of the time constant, τ, is therefore useful (Figure 4.4).

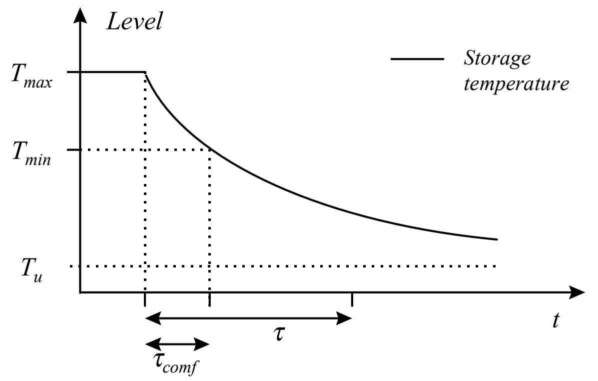

Figure 4.4. The ”comfort” time constant, τ_{comf}, is the time to reach the minimum accepted temperature from the maximum accepted temperature.

From Figure 4.4 it follows that

$$T_{\min} = \left(T_{\max} - T_u\right) \cdot e^{-\frac{\tau_{comf}}{\tau}} + T_u \qquad (4.12)$$

where τ is the time constant [s]
T_{min} is the minimum accepted temperature [°C]
T_{max} is the maximum accepted temperature [°C]
T_u is the uncompensated indoor temperature [°C]

Hence the ”comfort” time constant, τ_{comf}, can be calculated as

$$\tau_{comf} = -\tau \cdot \ln\left(\frac{T_{\min} - T_u}{T_{\max} - T_u}\right) \qquad (4.13)$$

4.3 Superposition of thermal flows

For heated houses, there is a thermal flow from the climate compensation during the heating season. When using the walls, ceiling and foundation constructions as heat storage, also a thermal flow related to this process will occur. Therefore, the relation between storage flows and steady-state flows for climate compensation is discussed here.

In this situation, the idea of superposition is useful. If the thermal characteristics of the walls, ceiling and foundation constructions are linear, as assumed, it is possible to subtract the flow for climate compensation and study the storage flow separately (Figure 4.5). That is, in the analyses and discussions of heat storage, the climate compensation flow may be left out and only the flow charging and discharging the thermal storage is studied.

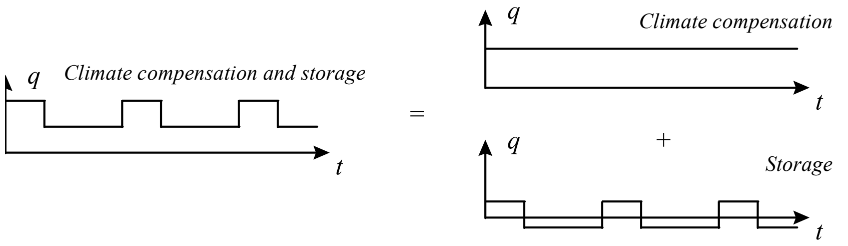

Figure 4.5. Heat transfer for climate compensation and storage may be split up and treated separately.

If the thermal resistance related to the transmission and ventilation losses is constant, the outdoor temperature only influences the climate compensation flow. The process of charging and discharging a storage or the amount of energy stored will not depend on the outdoor temperature.

However, if the stored energy would be used to replace a climate compensating flow, the heat would last shorter at colder outdoor temperature. Furthermore, the climate compensation flow could be of importance for the storage flows in other ways, e.g. occupy power resources during extremely cold periods.

4.4 Heat transfer through building materials

Heat can be transferred by conduction, convection and radiation. Inside a solid material the heat is conducted. From the surface it is transferred by convection and radiation. Formulas and material properties are discussed in this chapter.

4.4.1 Thermal conductivity in a material

Consider the construction materials in Table 4.1. The materials were chosen to illustrate differences in heat conductance and heat capacity [36, 37]. The values might vary with the producer, local conditions, moisture content etc.

Material	Specific Heat Conductivity W/(mK)	Specific Heat Capacity MJ/(m^{3}K)
Brick	0.45	1.49
Concrete	2.7	1.83
Concrete, lightweight	0.13	0.4
Gypsum board	0.1	0.88
Wood (oak)	0.19	1.7
Wood (pine)	0.14	1.5
Glass-wool	0.045	0.062
Insulation (styrofoam)	0.035	0.01
Cork floor	0.1	0.36
Air, 0°C	0.024	0.0013

Table 4.1. Material properties for some construction materials.

The heat flow through a wall segment is expressed by Formula (4.14).

$$q = \frac{k \cdot A}{x} \cdot \left(T_i - T_o\right) \tag{4.14}$$

where k is the specific heat conductivity, A is the area of the wall segment, x is the thickness of the wall, T_i and T_o are indoor and outdoor temperatures.

A material with low thermal conductivity is useful for insulation. A material with high specific heat capacity is useful as thermal storage. Since both qualities is desirable in e.g. a wall construction in a house with large thermal inertia, there are conflicting demands on the construction materials. Often a wall is made of several materials, e.g. wood for the structural qualities, glass wool for the insulation, and on the outside brick for the esthetical appearance and low demands for maintenance.

4.4.2 Heat transfer from a surface

Heat can be transferred from a surface by means of convection. The heat transfer depends on the surface temperature of the hot body, T_w, the temperature of the air, T_∞, the area of the body, A, and the convection heat-transfer coefficient, h_c, according to Formula (4.15).

$$q = h_c \cdot A \cdot (T_w - T_\infty) \tag{4.15}$$

Heat is also transferred from the surface of a hot body by means of radiation. The heat transfer depends on the temperature of the body, T_w, the temperature of the environment, T_∞ the area of the body, A_w, according to Formula (4.16).

$$q = \varepsilon_w \cdot \sigma \cdot A_w \cdot (T_w{}^4 - T_\infty{}^4) \tag{4.16}$$

where σ_w is the Stefan-Bolzmann's constant, 5.669 10^{-8} W/m^2K^4
ε_w is the emission coefficient of the body surface

If the emission coefficient is 1, all the heat is radiated according to the T^4-law. The body is then called a "black" body because black surfaces approximate this behaviour. Other types of surfaces still follow the T^4-proportionality but do not emit the same amount of radiation. They have emission coefficients less than 1.

For practical reasons, e.g. in construction engineering, the conduction and radiation heat transfers are lumped together and Formula (4.17) is used.

$$q = h \cdot A \cdot (T_w - T_\infty) \tag{4.17}$$

where h is the heat-transfer coefficient including both convection and radiation, and valid only in specified circumstances. The construction engineering literature frequently uses the inverse value, the heat transfer resistance $m = 1/h$. In the following calculations, h and m have the values suggested by the Swedish construction standard SS 02 42 02 [38] (Table 4.2).

Surface	h W/m^2K	m $m^2 \cdot K/W$
Indoor and outdoor (wind shielded)	7.7	0.13
Outdoor (exposed to wind)	25	0.04

Table 4.2. Heat transfer coefficient, *h*, and heat transfer resistance, *m*.

4.4.3 Overall heat transfer

Consider the plane wall shown in Figure 4.6 exposed to outdoor air at one side and indoor air at the other side. Since the heat flow, q, is the same through the whole wall segment, the formulas (4.14) and (4.17) can be combined. The heat transfer is expressed by Formula (4.18).

$$q = h_a \cdot A \cdot \left(T_o - T_a\right) = \frac{k_1 A}{x_1} \cdot \left(T_a - T_b\right) = \frac{k_2 A}{x_2} \cdot \left(T_b - T_c\right) = h_c \cdot A \cdot \left(T_c - T_i\right) \quad (4.18)$$

where k_1 is the specific heat conductivity for material 1
k_2 is the specific heat conductivity for material 2

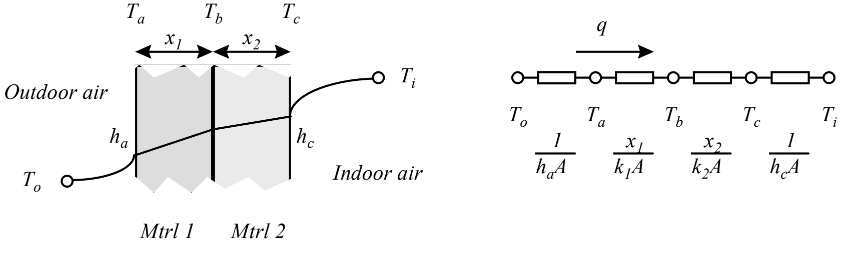

Figure 4.6. Physical model and electronic circuit model of overall heat transfer through a plane wall.

If the equations in Formula (4.18) are solved simultaneously, the heat flow can be expressed by the temperature difference and the resistors, Formula (4.19).

$$q = \frac{T_o - T_i}{\frac{1}{h_a \cdot A} + \frac{x_1}{k_2 A} + \frac{x_2}{k_2 A} + \frac{1}{h_c \cdot A}} \quad (4.19)$$

The overall heat transfer by conduction and convection is frequently expressed by the U-value, Formula (4.20).

$$q = U \cdot A \cdot \left(T_o - T_i\right) \quad (4.20)$$

Combining formula (4.19) and (4.20), the U-value may be written

$$U = \frac{1}{\frac{1}{h_a} + \frac{x_1}{k_2} + \frac{x_2}{k_2} + \frac{1}{h_c}} \quad (4.21)$$

4.5 Modelling of heat storage in the structure

The use of a single-family house as a thermal storage, rises some questions. Which masses can store energy, and how much? To what extent does the structure participate in the storing? How fast can a storage be charged and discharged? How much of the stored heat will be lost?

This chapter is a discussion of the approximations made in the modelling of different wall constructions.

4.5.1 Heat storage in the climate shield

Consider the corresponding electronic circuit for heat transfer and storage in a construction block, e.g. a wall, with several materials (Figure 4.7).

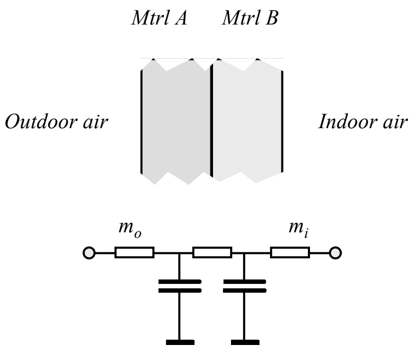

Figure 4.7. Cross-section of a wall with two materials. Heat transfer resistors between wall and air.

This heat storage model is different from the heat transfer model in Figure 4.6. In the heat transfer model, the materials were considered as resistors, with good conduction between them. In the heat storage model, the materials are considered as homogeneous bodies with good inner conductance, possibly with a resistance between them.

As indicated in Chapter 4.4.1, there are conflicting demands on a building material used as heat storage. On one hand, it should be a good insulation material. On the other hand, it should be a good storage.

4.5.2 Wall with several materials

If a wall consists of two materials, it is generally made of materials with opposite thermal characteristics. Then the materials may be idealised to one ”resistance” material, and one ”storage capacity” material (walls with more than two materials can usually be treated similarly).

Consider e.g. brick or concrete with glass wool for insulation. Sometimes, the bricks are used as facade material outside the glass wool (which is integrated in a wooden construction used for structural reasons). Sometimes the opposite is seen; additional insulation outside a brick or concrete wall. In the modelling, the insulation is considered as a pure resistance to be related to the surface heat transfer resistors, while the layer of concrete or brick is considered as a pure capacitor. This model set-up is easy to calculate by hand. The approach is sometimes called the lumped-heat-capacity method [36].

4.5.3 Wall with one homogeneous material

With one homogeneous wall material with both structural and insulating qualities, e.g. a wall made of timber, lightweight or gas concrete, the situation is trickier. Obviously, the ”inner” part of the wall participates more in the storing than the outer part, at least in a short-time storage.

One way to manage the problem is to make an unsteady-state model where the wall is sliced into thin layers. The heating of the wall is then successively calculated by calculating the heating of each wall slice for short periods. There are several formal methods to do this [36] and consequently, there are also several software packages available on the market to support unsteady-state heat transfer analyses.

The comparison of heat storage in some different climate shield constructions presented below was made with one such software, the PC-program HEAT2 [39]. HEAT2 allows several construction components to be thermally interconnected and exposed to different boundary temperatures or thermal energy flows. By dividing each volume of homogeneous material in several interconnected smaller mathematical elements, it allows a non-uniform heat distribution within the same construction component.

Hence the temperature may vary inside a construction component, for instance, be cold near the outer surface and warm near the inner surface and have a changing heat distribution between the surfaces.

4.6 Heat storage, calculation with HEAT2

In this chapter, some calculation experiments were performed with six wall constructions and three floor and ceiling constructions.

The heat storing calculation experiments in HEAT2 were made by letting the ”indoor” temperature vary between +1°C during 8 hours and 0°C during 16 hours. The ”outdoor” temperature was 0°C. By using a temperature change of 1°C, the specific storage capacity is achieved from which any amount of stored energy can be calculated. (2°C will result in twice the energy stored, etc.)

The experiments were intended to reflect only the thermal flow charging and discharging the storage, not a steady state flow possibly superimposed for climate compensation. However, the heat loss caused by the increased average temperature was calculated.

4.6.1 Heat storage in wall constructions

To study the storage characteristics of walls, six example constructions were calculated. The constructions were

Wall construction		U-value W/m^2K
a)	wooden wall with 10 cm glass-wool insulation.	0.42
b)	same as a) but with 10 cm brick on the outside.	0.38
c)	10 cm brick wall with 10 cm glass wool outside.	0.38
d)	30 cm lightweight concrete (gas concrete).	0.40
e)	wooden wall with 24 cm glass-wool insulation.	0.182
f)	same as e) but with 2 cm gypsum board on inside.	0.178

Table 4.3. Six example constructions with U-values.

The U-values were calculated according to Formula (4.21) with thermal properties according to Table 4.1 and Table 4.2.

The walls a) to d) were constructions that had been used in the sixties and seventies. The wall e) was a construction used in the eighties and nineties. It was assumed that the wood studs in the wooden walls did not influence the thermal characteristics as the wood was only used for structural reasons.

The thickness of the materials in the example constructions in Table 4.3 should be considered as magnitudes rather than exact values, since deviations occur due to design, site, local tradition etc.

The result is presented in Table 4.4. Some temperature profiles related to the charging and discharging of the wall segments are found in Appendix B.

Wall construction (materials specified from cold to warm surface)	Stored energy* Wh/m^2K	Energy loss* Wh/m^2K
a) 10 cm glass-wool	0.52	3.3
b) 10 cm brick, 10 cm glass-wool	0.69	3.1
c) 10 cm glass wool, 10 cm brick	21	3.1
d) 30 cm lightweight (gas) concrete	6.7	3.2
e) 24 cm glass-wool	1.29	1.45
f) 24 cm glass-wool, 2 cm gypsum board	5.6	1.40

* Stored energy and Energy loss per °C increased temperature during 8 hours.

Table 4.4. Thermal properties of the six example wall constructions.

The energy loss in Table 4.4 was caused by the additional heating during the storing cycle. If heat storage is used with the purpose to equalise the national load profile on the electrical power net, the additional energy losses caused by the storage regimen should not be too large. Therefore, it is important to keep track also of the losses.

The losses were calculated by HEAT2, but may as well be calculated by hand:

The average temperature during the storing cycle was
$(8 \text{ h} \cdot 1°\text{C} + 16 \text{ h} \cdot 0°\text{C}) / 24 \text{ h} = 0.33°\text{C}$.

The energy loss for e.g. wall a) with a U-value of 0.42 W/m^2K was
$0.33°\text{C} \cdot 0.42 \text{ W/m}^2\text{K} \cdot 24 \text{ h} = 3.3 \text{ Wh/m}^2\text{K}$.

4.6.2 Heat storage in ceiling and floor

Using the same calculation procedure as in Chapter 4.6.1, three example constructions of floor and ceiling were studied. The construction h) may be valid both as a ceiling construction and a floor construction. It was assumed that the outer concrete surface of the floor construction in case i) was facing air (wind shielded, m = 0.13 $m^2 \cdot K/W$), for instance a basement ceiling, or the ceiling of a crawl space foundation. Case j) and k) are variants of the "slab-on-the-ground" foundation. See Table 4.5. Some temperature profiles related to the charging and discharging of the floor segments are found in Appendix B.

Floor and ceiling construction (materials specified from cold to warm surface)	Stored energy* Wh/m^2K	Energy loss* Wh/m^2K
g) 20 cm glass-wool, 2 cm gypsum board	5.4	1.63
h) 20 cm glass-wool, 2 cm wood	9.6	1.66
i) 10 cm concrete, 0.5 cm cork floor	8.1	23.1
j) 10 cm insulation, 10 cm concrete, 0.5 cm cork fl	23.3	2.60
k) 10 cm insulation, 10 cm concrete	29.5	2.64

* Stored energy and energy loss per °C increased temperature during 8 hours.

Table 4.5. Thermal properties of the six example floor and ceiling constructions.

Some observations can be made from the results:

- To store heat in the climate shield, it is not enough with good insulation. There must also be mass to store the thermal energy. For instance cases a) and e) have less stored energy than most of the others.

- The storage capacity increases drastically if the storing mass is placed inside the insulation. For instance, case c) stores 30 times more energy than does case b) with the same construction materials, but in the opposite order.

- A well insulated house has a large benefit even from small additional storage masses indoor. For instance, case f) stores four times more than e) with a thin gypsum board added.

- The storing capacity of the structure is impaired even by small amounts of surface-covering materials (e.g. soft floor materials for comfort reasons). For instance, the thin cork floor in case j) reduces the storage capacity of the "slab-on-the-ground" in case k) with more than 20 %.

4.6.3 Heat storage in furniture

In addition to heat storing in walls, ceiling and floor, heat is also stored in furniture and the internal walls of houses.

Furniture from a typical Swedish single family house was idealised to be designed from 3 cm flat wooden boards (oak). One type of furniture (tables, chairs, empty shelves, doors etc) had both sides of the wooden board exposed to the indoor air, while the other type had only one side (padded chairs, sofas, beds, cupboards, drawer etc.). See Figure 4.8.

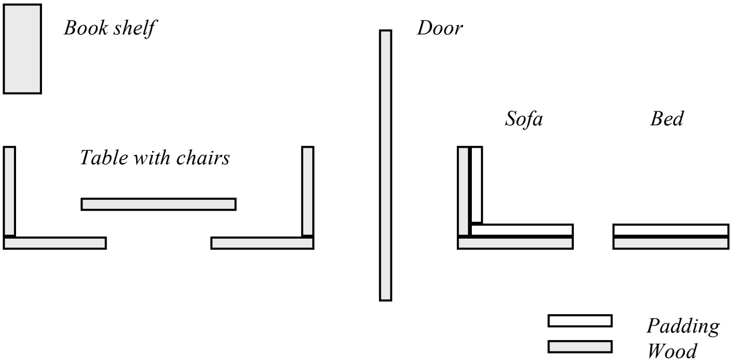

Figure 4.8. Furniture, ”double-sided” and ”single-sided”.

Other kinds of furniture were either considered too small to contribute to heat storing, or too padded to contribute (textile objects).

To study the heat storage capacity in 1 m^2 furniture of each type, the HEAT2 program was used. The calculations with HEAT2 indicated that approximately 14 Wh/m^2K could be stored in the double-sided furniture and 9 Wh/m^2K in single-sided furniture (Table 4.6).

	Double-sided furniture Wh/m^2K	Single-sided furniture Wh/m^2K
Storage capacity	14	9

Table 4.6. Storage capacity of 1 m^2, 3 cm thick furniture.

Comparison with by-hand calculation shows that double-sided furniture is almost completely uniformly heated:

Oak: $1.7\ MJ/m^3K \cdot 0{,}03\ m \cdot 1/3600\ h/s = 14.2\ Wh/m^2K$

4.7 Storage calculations in two example houses

The important question is how much energy could be stored in an average single-family house under good circumstances. From some key data, the time constants can be calculated: From the heat storage capacity and the power need per °C lower outdoor temperature the ”structure” time constant (Formula 4.11) can be calculated. From the energy stored by increased indoor temperature and the uncompensated indoor temperature, the ”comfort” time constant (Formula 4.13) can be calculated.

It is evident from earlier chapters that the lower limit of stored energy in practice would be close to zero, if the heat storing surfaces have low mass, are thermally insulated or have their surfaces covered with insulating materials which reduce the thermal coupling.

To address the question of the time constant, the heat storage capacity and the power need of two example single-family houses were analysed. Both had the size of 9 x 14 m (126 m^2). See Figure 4.9.

The first example house was assumed to be a traditional single-family house, built with 100 mm brick and additionally insulated with 100 mm glass wool as in case c) above. The second example house was assumed to be a modern single-family house with 240 mm glass-wool walls behind gypsum boards as in case f) above.

In the first house, the interior walls were assumed to be of 100 mm brick. In the second house, they were assumed to be made of 20 mm gypsum board with glass-wool behind.

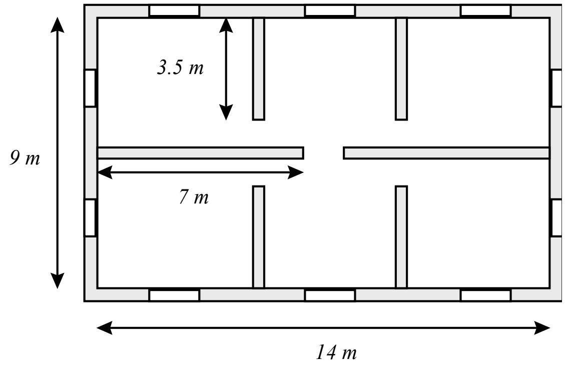

Figure 4.9. Example single-family house.

Some more details were provided for the calculations:

- **Walls.** The length of the walls of the house were 46 m and the height 2.4 m. The total area of walls and windows was 110 m^2.

- **Windows.** The window area was assumed to be 17 m^2 (this corresponded to 15 % of the ”walls-and-windows” area of the climate shield).

- **Ceiling and floor.** The ceiling and floor were assumed to be of wood with glass-wool behind, as case h) above. Each one had an area of 126 m^2.

- **Interior walls.** The houses were assumed to have interior walls, separating the dwelling into rooms. It was assumed that there was one 13-meter supporting wall through the entire house. This wall had an area of 62 m^2 (including both sides of the wall). Additionally, there were four walls of 3.5 m with an area of 67 m^2 (including both sides of the wall). For the calculations to be consistent, the internal brick wall was considered to have only half the thickness, that is, 5 cm.

- **Furniture.** The example houses were furnished according to Table 4.6 and Figure 4.10. In all, the double-sided furniture (of 14 Wh/m^2K) had an area of 43 m^2. The single-sided furniture (of 9 Wh/m^2K) had an area of 16 m^2.

- **Indoor air.** The volume of the dwelling is 302 m^3.

”Double-sided” furniture	m^2	”Single-sided” furniture	m^2
3 writing tables	6	4 beds	8
1 dining table	2	2 dining room sofas	8
1 living room table	2		
7 book shelves	7		
5 doors	10		
10 chairs	10		
6 cupboards	6		
Total	**43**	**Total**	**16**

Table 4.6. Amount of furniture in the example single-family houses.

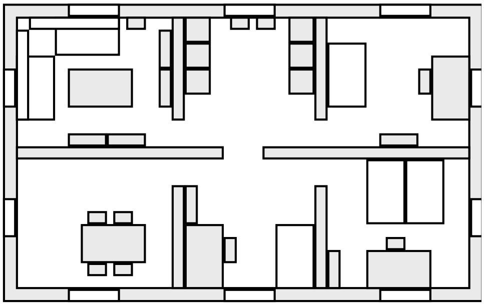

Figure 4.10. Furniture arrangement in example house.

4.7.1 Storage capacity

The total storage capacity for each example single-family house was calculated. Properties for materials and construction components were collected from Table 4.4, Table 4.5 and Table 4.6.

Total. The total specific storage capacity (i.e. storage capacity per °C increased indoor temperature) of the example houses is seen in Table 4.7.

Storage	Traditional house (brick + add. insulation) Wh/K	Modern house (24 cm glass-wool) Wh/K
Walls	2 340	629
Ceiling	1 361	1 361
Floor	1 361	1 361
Interior walls	2 395	726
”Double-sided” furniture	602	602
”Single-sided” furniture	144	144
Indoor air	109	109
Total	**8 312**	**4 932**

Table 4.7. Total storage capacity per K of the example single-family houses.

4.7.2 Power need per °C

The power need was calculated for the two example single-family houses. In Table 4.8, the U-values and heat transfer for different parts of the building are presented, as well as the ventilation losses.

Loss	Traditional house (brick + add. insulation)		Modern house (24 cm glass-wool)	
Transmission	U-value W/m^2K	Power need W/K	U-value W/m^2K	Power need W/K
Walls (without windows)	0.38	36	0.17	16
Ceiling	0.21	26	0.09	11
Floor	0.21	26	0.09	11
Windows	6	102	1.65	28
Ventilation	Exchange rate 1/h		Exchange rate 1/h	
	0.5	55	0.5	27*
Total		**245**		**93**

* The house was assumed to be equipped with a heat exchanger, which re-uses 50 % of the thermal energy in the ventilation air.

Table 4.8. Heating power demand per K during the heating season.

The specific heating power demand in Table 4.8 indicates the extra power needed from the heating system if the outdoor temperature drops 1°C during the heating season.

Heat from the sun, heat contribution from tenants, household equipment etc contribute to the heating. Therefore, the heating system generally doesn’t have to be used until the outdoor temperature has dropped to several degrees below the desired indoor temperature. The better insulated the house, the lower outdoor temperature can be compensated by other sources than the heating system. As a rule of thumb, it is considered that heating is needed for outdoor temperatures lower than +15°C.

As a reflection, the U-values in Table 4.8 can be related to U-values for walls and ceilings from the ERBOL study of Swedish buildings in Table 4.9 [40].

Construction year	U-value, walls W/m^{2}K	U-value, ceiling incl. roof W/m^{2}K
- 1940	0.55	0.36
1941 - 1960	0.52	0.33
1961 - 1975	0.37	0.24
1976 - 1981	0.28	0.18

Table 4.9. U-value, walls and ceiling including roof (ERBOL-study [40]).

4.7.3 Time constant

The time constants of the building structure, Formula 4.11, of the two example houses were calculated by dividing the specific storage capacity (Table 4.7) with the specific heating power demand (Table 4.8). See Table 4.10.

	Traditional house H	Modern house h
Time constant	33.9	53.0

Table 4.10. Time constant of example houses.

4.7.4 ”Comfort” time constant

The ”structure” time constant is a property of the building only. Calculating the ”comfort” time constant, the indoor temperatures (maximum, minimum and uncompensated) must have realistic temperatures to give a credible result.

The ”comfort” time constant was calculated according to Formula (4.13). The indoor temperature was allowed to cool from 23°C to 20°C, towards a +5°C uncompensated temperature (an outdoor temperature of 0°C and a 5°C contribution from other indoor heat sources was assumed.). See Table 4.11.

	Traditional house h	Modern house h
”Comfort” time constant	6.2	9.7

Table 4.11. ”Comfort” time constant of example houses.

4.7.5 Annual energy use

As a reflection, the total energy use of the two example houses was calculated. Both the example single-family houses were assumed to be situated in Örebro, with an annual heating need of 3 375 degree-days [41, 42]

The energy use (in kWh) for the *daily* household and hot-water energy use was calculated from Formula 4.22 and 4.23. [43]

$$hot\_water = 5 \cdot no\_of\_dwellings + 0.05 \cdot heated\_area \tag{4.22}$$

$$household = 4.5 \cdot no\_of\_dwellings + 0.045 \cdot heated\_area \tag{4.23}$$

The annual energy demand is presented in Table 4.12.

	Traditional house (brick + add. insulation)	Modern house (24 cm glass-wool)
Energy use	kWh/year	kWh/year
Heating	19 820	7 590
Hot water	4 120	4 120
Household equipment	3 710	3 710
Total	**27 650**	**15 420**
Energy use / m^2 heated area	kWh/(m^2·year)	kWh/(m^2·year)
Heating	157	60
Hot water	33	33
Household equipment	29	29
Total	**219**	**122**

Table 4.12. Annual energy use in the two example single-family houses.

4.7.6 Indoor temperature intervals during storage

To evaluate the potential for heat storage, this chapter discusses how to calculate the maximum indoor temperature required for the heat, which is stored during 8 h, to cover the climate compensation during the remaining 16 h.

Formula (4.24) for the maximum temperature is derived from Formula (4.13).

$$T_{\max} = \left(T_{\min} - T_u\right) \cdot e^{\frac{\tau_{comf}}{\tau}} + T_u \tag{4.24}$$

where τ is the time constant of the house
τ_{comf} is the "comfort" time constant of the house
T_{max} is the maximum accepted temperature
T_{min} is the minimum accepted temperature
T_u is the uncompensated indoor temperature

Formula (4.11) is rewritten to Formula (4.25).

$$\tau = \frac{C_{house}}{P_{comp}} \tag{4.25}$$

where C_{house} is the heat storage capacity of the house. [Wh/K]
P_{comp} is the power need to compensate 1°C. [W/K]

In Formula (4.13) and (4.24), the temperatures T_{max}, T_{min} and T_u are "absolute" temperatures. These are convenient when discussing temperature levels, relating to tenants and the outdoor climate. In the discussion of storage properties of the house, however, "relative" temperatures are convenient. Consider the substitutions in Formula (4.26) and (4.27).

$$T_{comp} = T_{\min} - T_u \tag{4.26}$$

$$T_{sto} = T_{\max} - T_{\min} \tag{4.27}$$

The temperature T_{comp} is the temperature difference to be compensated by the heater, and the temperature T_{sto} is the storage temperature, i.e. the additional temperature required to store the energy.

Table 4.13 presents some values of storage temperature T_{sto} as a function of compensation temperature T_{comp} with the assumption that the stored heat should last for 16 h (that is, τ_{comf} = 16 h).

Climate compensation	Traditional house (brick + add. insulation)		Modern house (24 cm glass-wool)	
	heat need kWh/day	add indoor temp °C	heat need kWh/day	add indoor temp °C
1°C	5.88	0.60	2.23	0.35
5°C	29.3	3.0	11.2	1.8
10°C	58.8	6.0	22.3	3.5
15°C	88.2	9.0	33.4	5.3
20°C	117.6	12.0	44.6	7.0

Table 4.13. Storage heat needed for 16 h climate compensation.

As shown from Table 4.13, there is a constant ratio between T_{sto} and T_{comp}. By using Formula (4.24), (4.26) and (4.27) it is easy to show Formula (4.28).

$$\frac{T_{sto}}{T_{comp}} = \left(e^{\frac{\tau_{comf}}{\tau}} - 1 \right) \tag{4.28}$$

4.7.7 Loss caused by storage

The increased indoor temperature causes an increased loss. This is shown by the following example: Assume an outdoor temperature of +5°C. Assume also that the minimum indoor temperature is 20°C, and that there is a 5°C contribution from indoor heat sources other than the heating system. The need for climate compensation is then 10°C. According to Table 4.13, this requires 58.8 kWh and 22.3 kWh during 24 h for the houses.

To perform the climate compensation with stored energy for 16 h, that is, with 39.2 kWh and 14.9 kWh, it is necessary to increase the indoor temperature with 6.0°C and 3.5°C for the traditional and the modern house, respectively.

However, increasing the indoor temperature with 6.0°C and 3.5°C requires 8 312 Wh/K · 6.0°C = 49.8 kWh and 4 932 Wh/K · 3.5°C = 17.3 kWh Formula (4.2). The difference, 10.6 kWh and 2.4 kWh, is the loss caused by the higher indoor temperature during storing.

The result is generalised in the following derivation of the loss.

The energy demand, W_{16}, for 16 h climate compensation is expressed by Formula (4.29).

$$W_{16} = T_{comp} \cdot P_{comp} \cdot 16 \tag{4.29}$$

Formula (4.30) expresses the stored energy, W_{sto}, at the storage temperature T_{sto}.

$$W_{sto} = T_{sto} \cdot C_{house} \tag{4.30}$$

The difference is the loss caused by storage. Combining Formula (4.29), (4.30) and (4.28) yields Formula (4.31) showing that the loss is proportional to T_{comp}.

$$W_{loss} = W_{sto} - W_{16} = T_{sto} \cdot C_{house} - T_{comp} \cdot P_{comp} \cdot 16 =$$

$$= \left(\left(e^{\frac{\tau_{comf}}{\tau}} - 1 \right) \cdot T_{comp} \cdot C_{house} - T_{comp} \cdot P_{comp} \cdot 16 \right)$$

$$W_{loss} = \left(\left(e^{\frac{\tau_{comf}}{\tau}} - 1 \right) \cdot C_{house} - \cdot P_{comp} \cdot 16 \right) \cdot T_{comp} \tag{4.31}$$

For the traditional house and the modern house, the daily losses are 1 090 kWh/°C and 249 kWh/°C, respectively. This equals 19 % and 11 %.

The losses from the traditional house and the modern house for some different compensation temperatures T_{comp} are presented in Table 4.14.

Climate compensation	Traditional house (brick + add. insulation)		Modern house (24 cm glass-wool)	
	heat need kWh/day	loss kWh/day	heat need kWh/day	loss kWh/day
1°C	5.88	1.09	2.23	0.25
5°C	29.3	5.4	11.2	1.2
10°C	58.8	10.8	22.3	2.5
15°C	88.2	16.3	33.4	3.7
20°C	117.6	21.8	44.6	5.0

Table 4.14. Heat losses for 16 h climate compensation.

5 The experiments

Three houses were included in the storage study. The first project was carried out in Övertorneå, north of the polar circle. The second was a traditional house with resistant heating in Ljungsbro, 15 km outside Linköping. The third was Hus 15 at the Bo92 exhibition in Örebro.

The three houses were chosen with the aim to study the influence of outdoor temperature, control strategies, construction materials, temperature zones and ways to provide the heat. The Övertorneå house and Hus 15 were modern houses, well-insulated and equipped with heat recovery from the ventilation air. All three houses were also part of other R&D evaluations.

Since different methods and analyses were used in the test houses, the experiments will be referred to in separate chapters.

The ”on/off” strategy referred to in the experiments means that the heater was run at a near-maximum power during heating hours, and was switched off during (most of) cooling hours.

The ”more/less” strategy means that the heating power was slightly increased during the heating hours, and slightly reduced during the cooling hours.

The ”8/16-hour storage regimen” means that the heating period was eight hours, and the cooling period was 16 hours. Some small deviations from these strategies were allowed if necessary, e.g. for comfort reasons.

A ”day”, a 24-hour period, was in the experiments chosen to start at 10 p.m. the day before, and lasted to 10 p.m. the same day. For instance, the February 18 started at 10 p.m. February 17 and lasted to 10 p.m. February 18. The reason for this was that the time tariffs at most utilities started the low price period at 10 p.m. weekdays.

Tariffs with reduced nighttime prices were not applied at all Swedish utilities at the time of the experiments. Local variations occurred. Most high/low tariffs were, however, designed so that the high price between 6 a.m. and 10.p.m weekdays was twice the low price for the rest of the time, and also designed so that the average price during one week corresponded to the flat tariff.

5.1 The ”Övertorneå” test house

5.1.1 Materials

The Övertorneå test house was a modern single-family house built in the very northern part of Sweden (dimensioning outdoor temperature of -30°C) used for verifying the behaviour of the house in an arctic climate.

In the airborne heating system, the heating and ventilation systems were integrated. Fresh air entered through a heat exchanger where it was preheated by the exhaust air. It was then further heated with electricity and piped in near the ceiling. Thus the warmer air ”floated” on the colder air and did not cause any turbulence. Exhaust air channels were located near floors in rooms with high moisture levels, e.g. bathrooms, toilets and the kitchen. The exhaust air passed through the heat exchanger and preheated the fresh air. To increase heat transport capacity, some indoor air was continuously circulated. Circulating air was mixed with fresh air, electrically heated and then brought in again at the ceiling (Figure 5.1).

The house had a heated area of 135 m^2, triple glazed windows and external walls (Appendix C1) with 340 mm glass-wool insulation. It was equipped with a large baking oven made of stone, which the tenants occasionally used. The thermal time constant for the oven was estimated to 40-50 hours [44].

The Övertorneå house was also used for the technical design of the Miniwatt controller. Sectra, the company in charge of the R&D, first used an industrial control computer (Diana ADP 1000) in the house with a phone connection to read data and adjust controller parameters. The data analysed in this chapter were selected from a data set collected during the controller design.

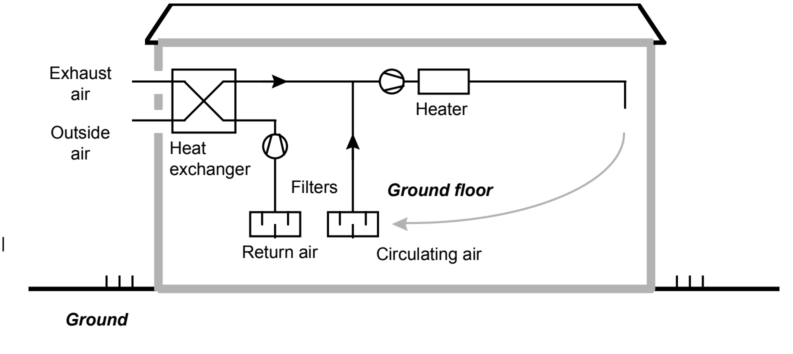

Figure 5.1. Principal diagram of heating and ventilation, Övertorneå test house.

5.1.2 Methods

System. The house was viewed as a system according to Figure 5.2.

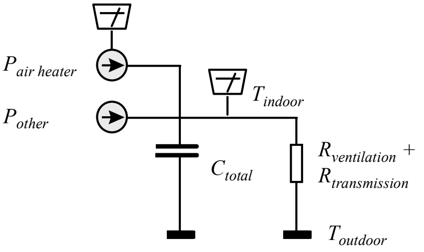

Figure 5.2. Electrical analogy model of the Övertorneå test house.

In this view, the indoor air of the house was heated by the electrical heater and by other sources. The thermal energy was stored in walls, floor, ceiling, furniture and other masses in thermal connection with the indoor air. Heat left the house via ventilation and transmission losses. The power from the air heater and the indoor temperature was measured.

Experiment. The experiment included of a number of changes in indoor temperatures, according to an 8/16-hour schedule used in time-differentiated tariffs by Swedish utilities.

The heating regimen used was an on/off strategy. During the experiment, the heater was run with full power with start from 10 p.m. When the indoor temperature approached the maximum set point, the power was reduced and adjusted to maintain the maximum indoor temperature. At 6 a.m. the power was switched off and the indoor temperature decreased. When approaching the minimum set point, the power was increased and adjusted to maintain the minimum indoor temperature.

This was repeated for five more occasions. During each cycle, the power of the heater and the temperatures were logged. The data were sampled every 15 minutes. See Diagram 5.1 and 5.2.

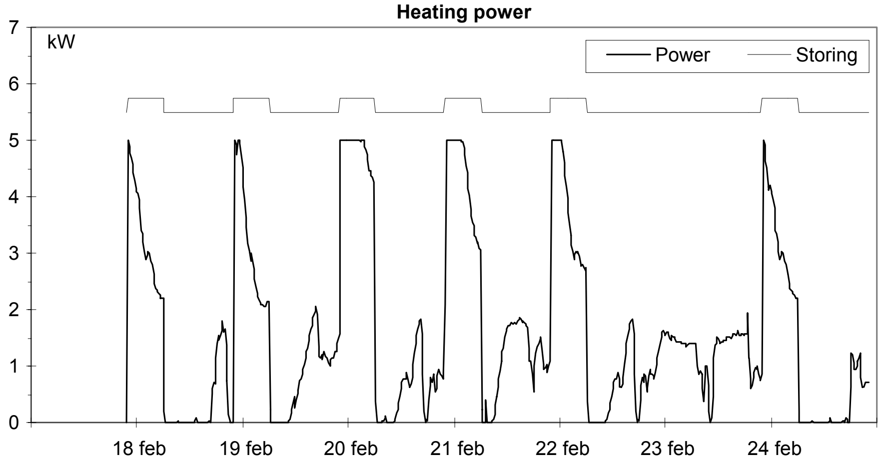

Diagram 5.1. Power used by heater during storage cycles. 15-minute sampling. Heat was stored from 10 p.m. to 6 a.m. according to the line at the top.

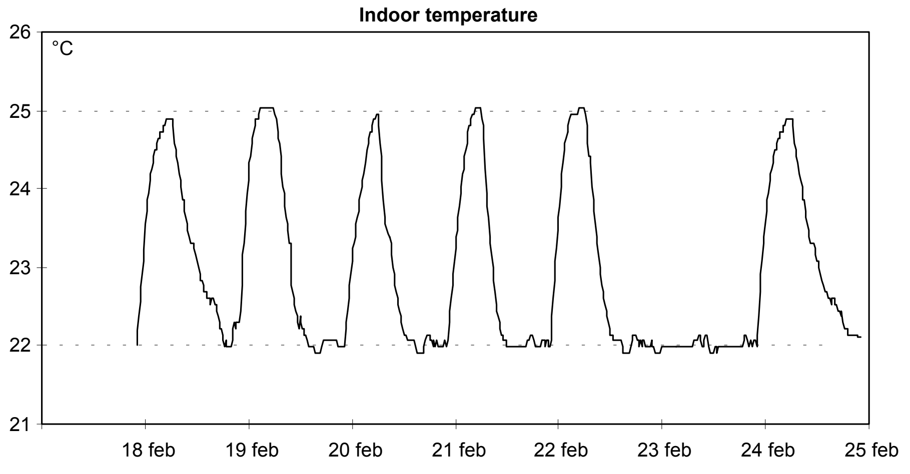

Diagram 5.2. Indoor temperature during storage cycles. Set points for minimum (22°C) and maximum (25°C) temperatures are indicated.

Data interpretation. The energy for climate compensation used by the heater during one day is decided by the outdoor temperature and by heat provided by other sources in the house, e.g. household equipment, tenants, sauna or the baking oven. If the indoor temperature is constant, all climate losses are balanced.

It was assumed (”assumption of superposition”) that heat from other sources and changes in the outdoor temperature were randomly distributed in time or varied slower than one day. By this assumption, and by using the principle of superposition, the power for climate compensation (averaged for 24 h) could be subtracted from the total heating power. The remaining part of the heating power, provided during charging and discharging (bold line, Diagram 5.3) could then be related to temperature changes during the storage cycles (Diagram 5.2). In this way the storage capacity could be calculated. The time-shifted heating energy was calculated for all cycles.

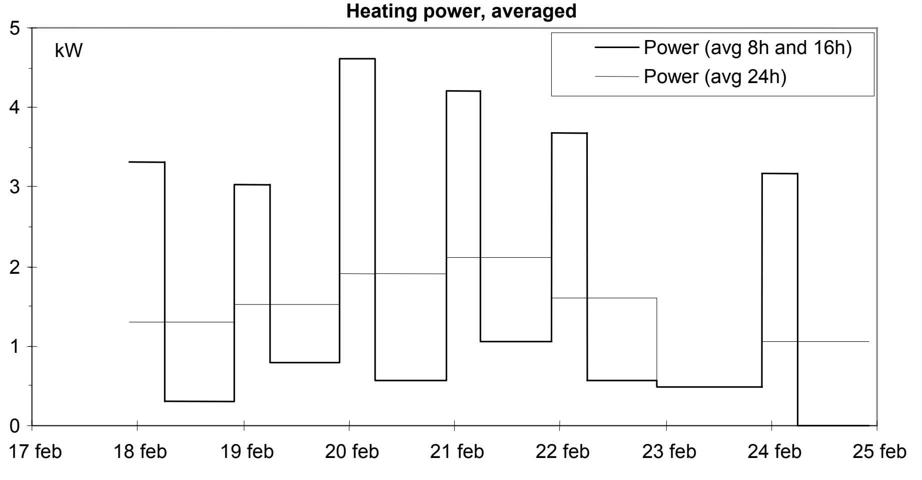

Diagram 5.3. Heating power, averaged for 8 and 16 hours respectively, and averaged for 24 hours.

The stored energy, W_{sto}, for each day was calculated according to Formula 5.1.

$$W_{sto} = \left(P_{sto} - P_{24h}\right) \cdot t_{load} \qquad (5.1)$$

where P_{sto} is the power during storing
P_{24h} is the 24 h power for climate compensation
t_{load} is the duration of storing (in this experiment t_{load} is 8 h)

5.1.3 Results

The result is presented in Diagram 5.4 and Table 5.1. For simplicity, a 24-hour day began at 10 p.m. the day before and ended at 10 p.m. the same day. For instance, the Feb 18 day in Diagram 5.4 began at 10 p.m. February 17 and ended at 10 p.m. February 18.

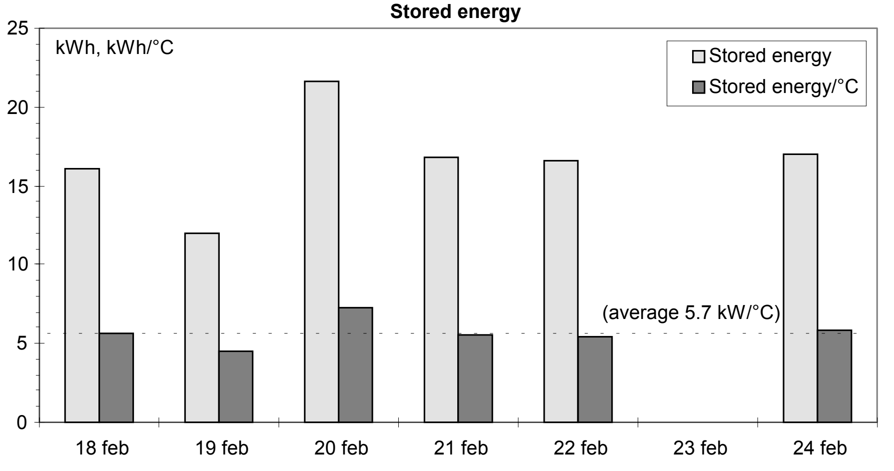

Diagram 5.4. Stored energy, and stored energy per °C increased indoor temperature for the Övertorneå house.

Test house	Heated area m^2	Storage capacity kWh/°C	Temp difference °C
Övertorneå	135	5.7	3.0

Table 5.1. Storage capacity of the Övertorneå house.

The load-shifting experiment resulted in an impaired comfort for the tenants, caused by to the high temperatures in the bedrooms during late night and early morning [44].

5.2 The ”Ljungsbro” test house

5.2.1 Materials

The traditional test house in Ljungsbro was built 1969, with walls of 30 cm lightweight (gas) concrete. Following the standard design for single-family houses in the sixties, the house was built with ventilation air intakes over most of the windows. Exhaust air was discharged through the ceilings in bathroom and toilets (Figure 5.3). The house used for our storage experiment had a ground floor area of 128 m^2 and a basement of the same area. A view of the house is seen in Appendix C2. Baseboards for space heating were heated by electricity, as was also the 300 litre water heater.

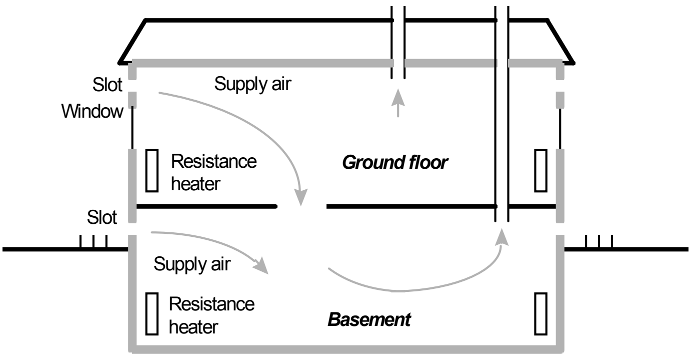

Figure 5.3. Principal diagram of heating and ventilation, Ljungsbro test house.

A baseboard from the sixties and seventies usually used a bi-metallic thermostat, switching it either fully on or fully off. This caused the baseboard to be either hot or cold. The thermostats in the test house had been changed to modern controllers for resistant heating (”soft heating”). They used a strategy where the baseboard was switched on for a fraction of a minute, then off. The fraction depended on the heat need. The surface was therefore normally more or less warm, not hot or cold.

The Ljungsbro house was one of the test houses in the IDEM project [26], an EU project for the development of equipment for integrated domestic energy management.

The house was inhabited by the author of this report, his wife and three children of 8, 6 and 0.5 years.

5.2.2 Methods

System. The house was viewed as a system according to Figure 5.4.

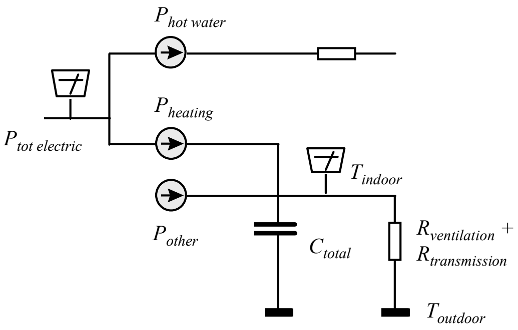

Figure 5.4. Electrical analogy model of the Ljungsbro test house.

The indoor air of the house was heated by the electrical baseboards and by other sources. The thermal energy was stored in walls, floor, ceiling, furniture and other masses in thermal connection with the indoor air. Heat left the house through ventilation and transmission losses.

For technical reasons, it was not possible to separate the power used by the electrical baseboards. The measured total electricity use therefore included the load contributing to the indoor heat but also the hot-water heater.

The indoor temperature was measured in several places. The design of the house didn't support one single measurement point, instead five temperature meters were used on the first floor, and two in the basement. The indoor temperature on each floor was then calculated as the average from all temperature meters, weighted with respect to the area of the room where the meter was installed. The indoor temperature used in the calculations was a weighted average between the temperature on the ground floor and the temperature in the basement, where the ground floor temperature had twice the weight of the basement temperature.

Experiment. The experiment included a number of changes in indoor temperatures, according to the schedule used by utilities in time-differentiated tariffs. The period of 8 hours with a lower cost started at 10 p.m. and ended at 6 a.m. During the rest of the day, the electricity had a higher cost.

For the heating, a ”more/less power” strategy was used. For comfort reasons, it was not possible to turn off the power to the baseboards completely. If the baseboards were cold, a cold draught occurred below the windows. This was both from the incoming ventilation air and from the downward flow of cooled indoor air at the window surface. Therefore, during the 8 hours of nighttime storing the baseboards were run at higher power. During the 16 daytime hours, the baseboards were run at lower power but never shut off, thus utilising the stored heat.

In the ”superposition assumption”, the average climate compensating power can be subtracted from the total power. The remaining part of the power can be assumed to represent the power during charging and discharging of the storage *if influences from other sources are randomly distributed*. This condition was most likely not fulfilled in the Ljungsbro experiment set-up, since the measured power included all electricity use. The household facilities were used according to the habits of the tenants, which were assumed to show periodic variations, repeated day after day, and week after week. Such periodic variations could be that the shower was always used in the mornings, with subsequent hot water heating.

Therefore, the experiment was designed with experiment weeks with storing, to be compared to control weeks without storing. By this technique, the regular influences on the measured power would be compensated.

Equipment. The baseboards were operated by distributed computerised controllers, IQtherm E, manufactured by Cerebel Data AB, Göteborg. The electricity meter was a standard Ferraris type meter with rotating discs. It was supplemented with an optical reader, which gave a pulse each time the marker on the disc passed the reader.

The data recording was made by a Telefrang SIOX system. In this system, the temperature modules and a pulse counting module for the electricity meter were connected to a standard PC by twisted-pair cables. Data were sampled every ten minutes. See Diagram 5.5 and 5.6. ”Total power” in the diagram is $P_{tot\ electric}$ in Figure 5.4.

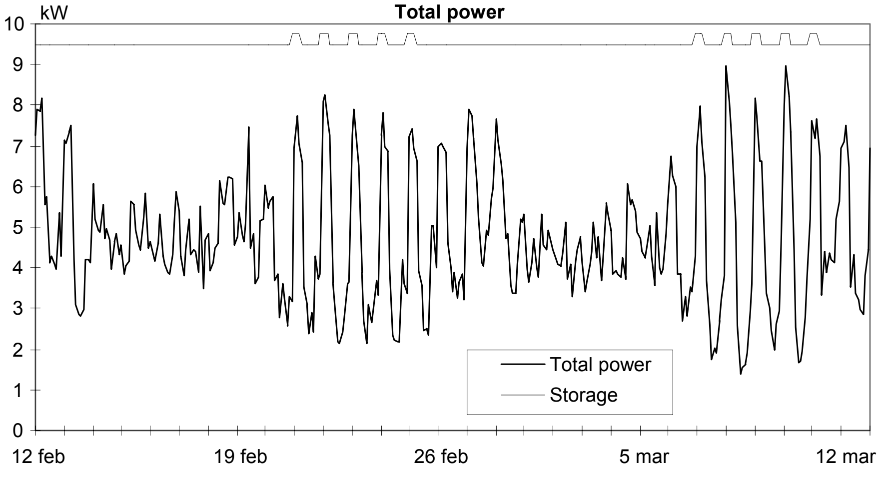

Diagram 5.5. Heating power during control weeks and experiment weeks. 10-minute sampling. Heat was stored from 10 p.m. to 6 a.m. according to the line at the top.

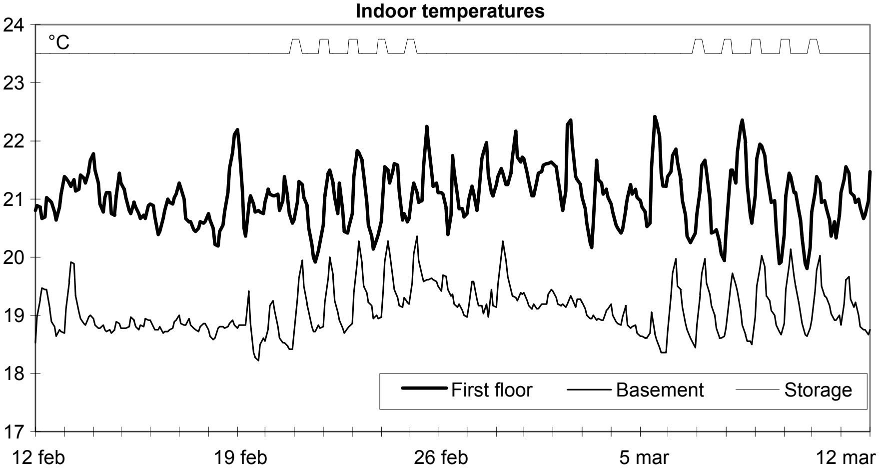

Diagram 5.6. Indoor temperature during control weeks and experiment weeks. Meters for first floor and basement were weighted together. Heat was stored from 10 p.m. to 6 a.m. according to the line at the top.

Data interpretation. The energy for climate compensation during one day is decided by the outdoor temperature and by heat provided by other sources in the house, e.g. household equipment and tenants. However, the measured electricity in the experiment was also used for purposes that did not contribute to indoor heating, e.g. hot water heating.

In the Ljungsbro house, these two sources of influence required two steps of compensation. It was first assumed (”assumption of superposition”) that the power for climate compensation (averaged for 24 h) could be subtracted from the total heating power (Figure 5.7)

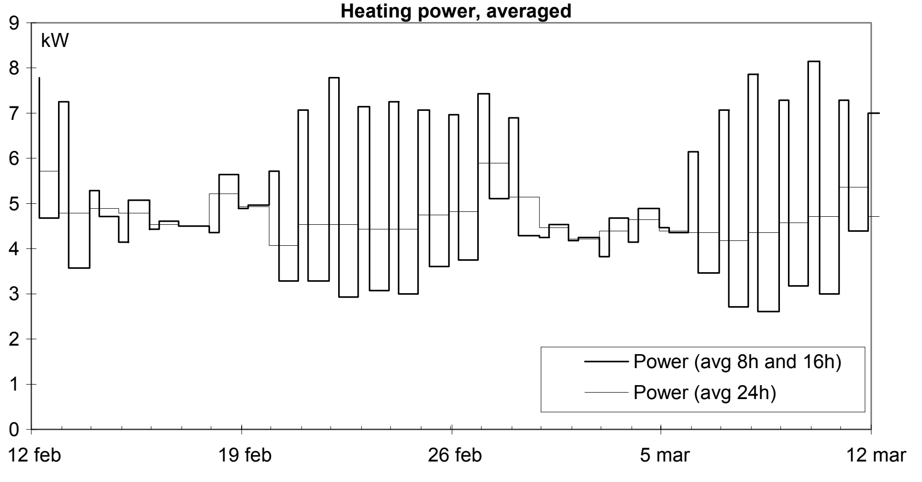

Diagram 5.7. Heating power, averaged during 8 and 16 hours respectively, and for 24 hours.

The remaining part of the heating power included regular and occasional electricity use from e.g. household equipment during *all* weeks. It also included power provided for charging and discharging during *experiment* weeks.

Therefore it was also assumed that the difference in remaining power between the experiment weeks and control weeks compensated regular and occasional electricity use, and provided the power use related to the charging and discharging of the storage.

The same reasoning as for the heating power was applied to the indoor temperature. The change in indoor temperature depended on regular and occasional heat generating activities during *all* weeks. It also depended on the charging and discharging of the storage during *experiment* weeks.

Thus, in the same way as with the power, it was assumed that the difference in temperature changes between the experiment weeks and control weeks compensated regular and occasional temperature changes, leaving the changes related to the charging and discharging of the storage.

The difference was calculated for each pair of days of the experiment and control week. For instance, the temperature difference of the Monday in the first control week was subtracted from temperature difference of the Monday in the first experiment week. See Diagram 5.8. For simplicity, a 24 hour ”day” began at 10 p.m. the day before and ended at 10 p.m. the same day.

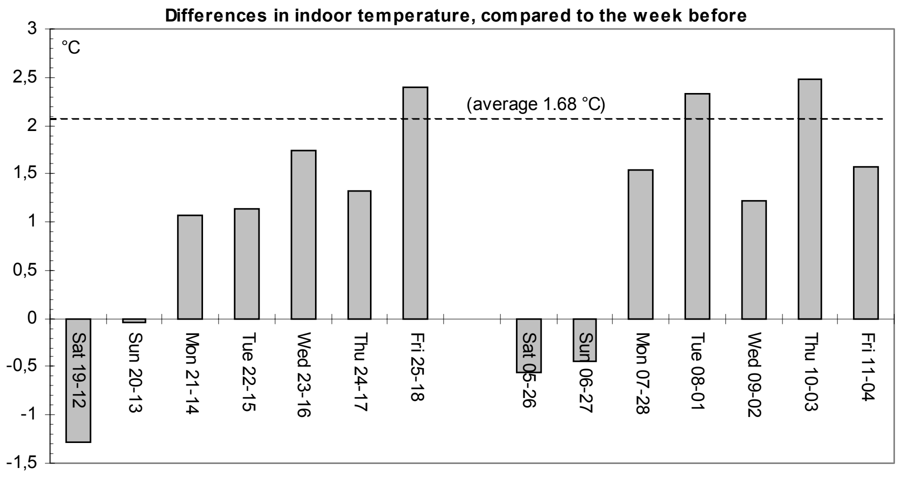

Diagram 5.8. Differences in indoor temperature.

The difference in heating power, provided during charging and discharging, was then related to the difference in temperature changes during the storage cycles. In this way the storage capacity could be calculated.

5.2.3 Results

The result is presented in Diagram 5.9 and Table 5.2. For simplicity, a 24 hour day began at 10 p.m. the day before and ended at 10 p.m. For instance, the Monday 21 day in Diagram 5.9 began at 10 p.m. Sunday 20 and ended at 10 p.m. Monday 21.

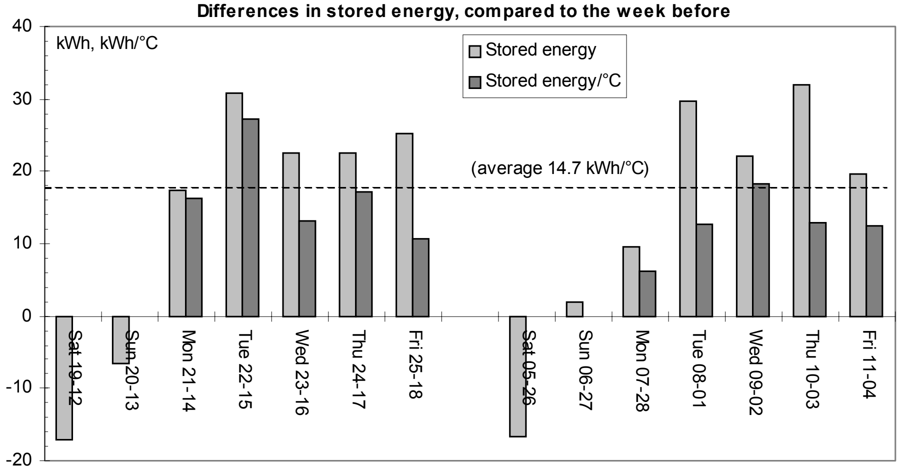

Diagram 5.9. Stored energy, and stored energy per °C increased indoor temperature for the Ljungsbro house.

Test house	Heated area m^2	Storage capacity kWh/°C	Temp difference °C
Ljungsbro	256	14.7	1.7

Table 5.2. Storage capacity of the Ljungsbro house.

The load-shifting experiment resulted in a slightly impaired, but still reasonable, comfort. The utility supplying the Ljungsbro house with electricity did not have a time-differentiated tariff that made it worth-while to use a storage regimen. The storing was therefore ended after the four-week experiment.

5.3 The "Hus 15" test house

Experiences from other test houses [44] indicated that tenants found the high air temperature in the bedrooms inconvenient during nights and early mornings. Furthermore, the construction with piping in the hot air at the ceiling caused a temperature profile with a slightly colder air near the floor.

Therefore a design with an indoor-air ventilated crawl-space was evaluated at the housing exhibition Bo92 in Örebro.

5.3.1 Materials

The Hus 15 test house was single-family house number fifteen at the Bo92 exhibition. It was a wooden house with the inside length of 9.6 m, width of 8.4 m and a total area of 126 m^2 in two floors. A view of the house is seen in Appendix C3. The design included triple-glazed windows, 245 mm wall insulation and airborne heating. The house had an electrical water heater of 300 litres and an occasionally used wood-fuelled tiled stove on the ground floor.

The airborne heating was very much the same as in the Övertorneå house. One difference was that Hus 15 had three temperature zones instead of one. In addition to the temperature zone on the ground floor, the second floor as well as the foundation were separate temperature zones. The air in the foundation was not recirculated, but let out through the heat exchanger. (Figure 5.5).

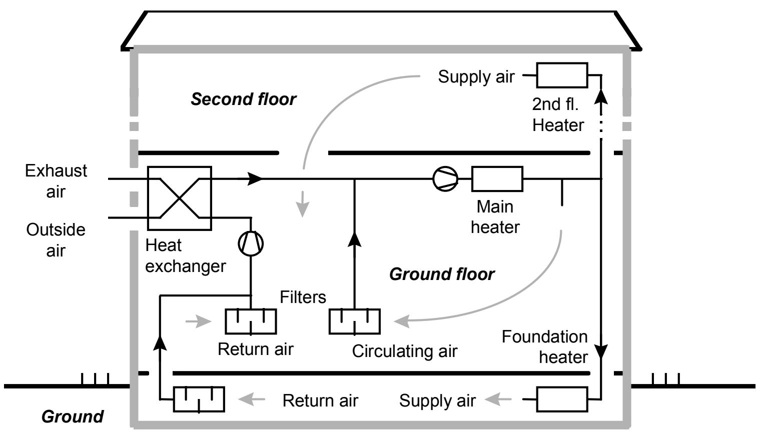

Figure 5.5. Heating and ventilation, Hus 15 test house.

The temperature of each zone could be individually operated. Zone 1 was the ground floor with kitchen and two living rooms, zone 2 was the second floor with bedrooms, and zone 3 was an indoor-air ventilated crawl-space foundation. By this design, the bedrooms could have a slightly lower temperature, which was preferred by the tenants. Furthermore, the insulated crawl-space foundation could be heated without immediately influencing the rest of the house. Since the air in the foundation was both heated and continuously changed, the risk for moisture problems were reduced. The return air from the foundation was let out through the heat exchanger and did not impair the indoor air.

During the load-shifting experiment, two adults lived in the house.

5.3.2 Methods

System. The house was viewed as a system according to Figure 5.6.

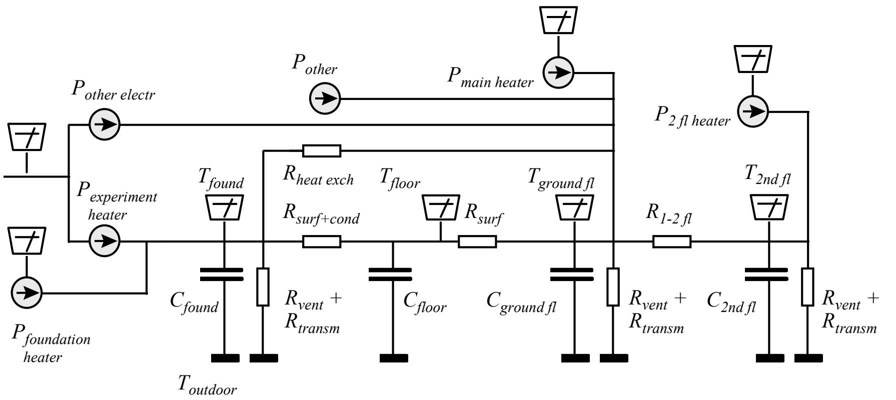

Figure 5.6. Electrical analogy model of the Hus 15 test house.

Figure 5.6 shows four compartments which could be used as heat storage — foundation, floor of the ground floor, ground floor and second floor. There are several power meters, which individually or together could be used to calculate the power contributing to the heating of the different compartments.

The temperature meter of the floor of the ground floor was placed in the entrance hall in the middle of the ground floor. The meter of the indoor air of the ground floor and that of the second floor were placed on internal walls at about 1.6 m above the floor.

Experiment. The experiment was run for several weeks in the late winter and spring. The air in the crawl-space foundation was heated at night. For this purpose a separate heating source, an experiment heater of about 4 kW, was used. The experiment heater was thermally operated not to exceed 34°C.

The experiment was started on January 19, 10 p.m. The experiment heater was run for about 6 hours to 4 a.m., then completely shut off. The ordinary heating sources, i.e. the main heater, the second-floor heater and the foundation heater, were operated by the ordinary heating system. It automatically adjusted the ordinary heating sources to compensate the heat from the experiment heater. This reduced the power from the ordinary heating system. The ordinary system supplied the heat demand that the stored heat didn't cover.

Equipment. Data was recorded on a separate PC-based data acquisition system (MINTOP), which was used during the entire Bo92 evaluation. All data were sampled every 10 minutes and averaged to 1-hour values. See Diagram 5.10.

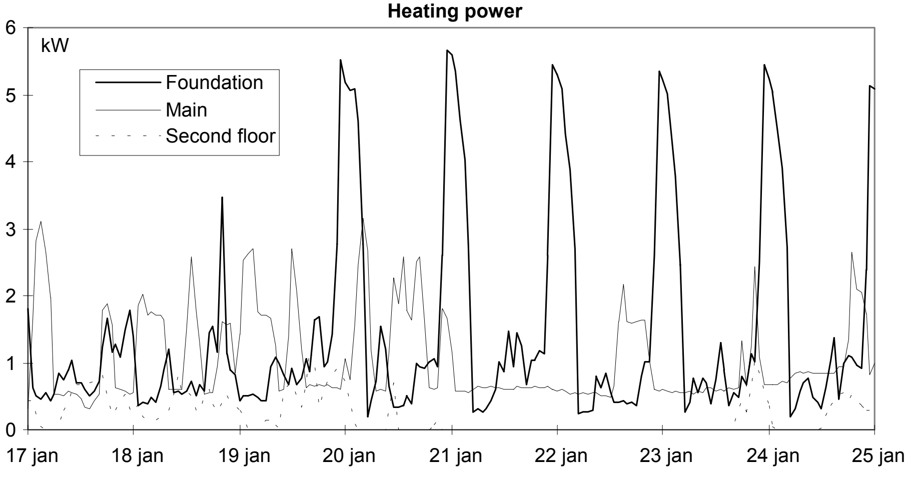

Diagram 5.10. Heating power before and during the load-shifting experiment. When the foundation heating starts, the peaks of both the main heater and second floor heater are reduced.

The temperature profile before and during load-shifting is seen in Diagram 5.11. Before the load-shifting, the floor surface had the lowest temperature, the air on the ground floor was slightly warmer and the air on the second floor had the highest temperature. After the load-shifting the temperature profile was the opposite (Diagram 5.11).

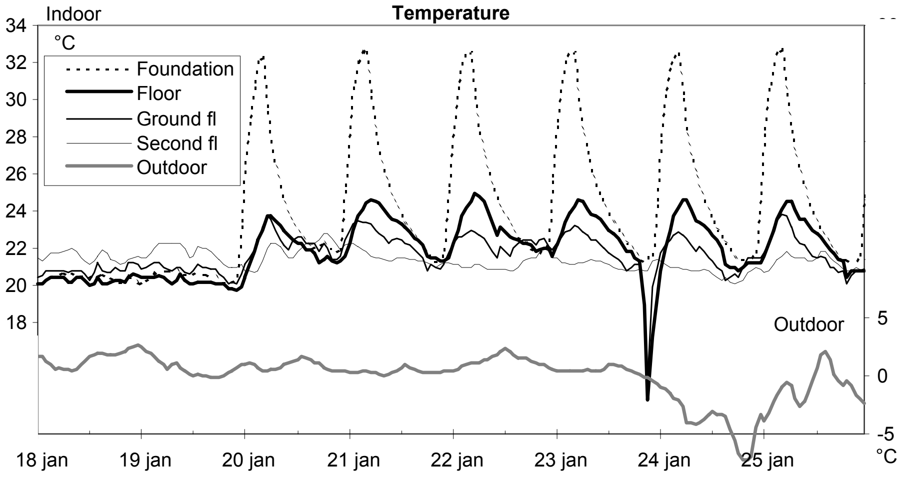

Diagram 5.11. Temperature profile reversed during load-shifting. The foundation heating increased the temperature in the foundation during nights and mornings, which also influenced the temperature of the floor[11]. The temperature of the second floor was not significantly influenced (occasionally slightly decreased) by the storing.

From March 15th, the experiment heater was run for two hours more, that is, from 10 p.m. to 6 a.m. The maximum air temperature of 34°C was maintained.

Data interpretation. As in the Övertorneå experiment, the power contributing to heating could be measured separately. The energy for climate compensation used by the different heaters during one day is decided by the outdoor temperature and by heat provided by other sources in the house, e.g. household equipment, tenants, or the tiled stove. If the indoor temperature is constant, all climate losses are balanced.

It was assumed (”assumption of superposition”) that heat from other sources and changes in outdoor temperature were randomly distributed in time or varied slower than one day. By assuming this, and by using the principle of superposition, the power for climate compensation (averaged for 24 h) could be subtracted from the heating power of all heaters.

[11] The reason for the ”dip” in the temperature of the floor and the air of the ground floor is not known to us. It seems likely that the tenants left the door open for a while. The temperature meters were placed some meters from the door.

5.3.3 Results

The stored energy from the experiment and foundation heaters, the main heater and the second-floor heater was calculated according to Formula 5.1 (Diagram 5.12). The major contribution to storing was from the foundation heater. Neither the main heater nor the second floor contributed significantly to storing.

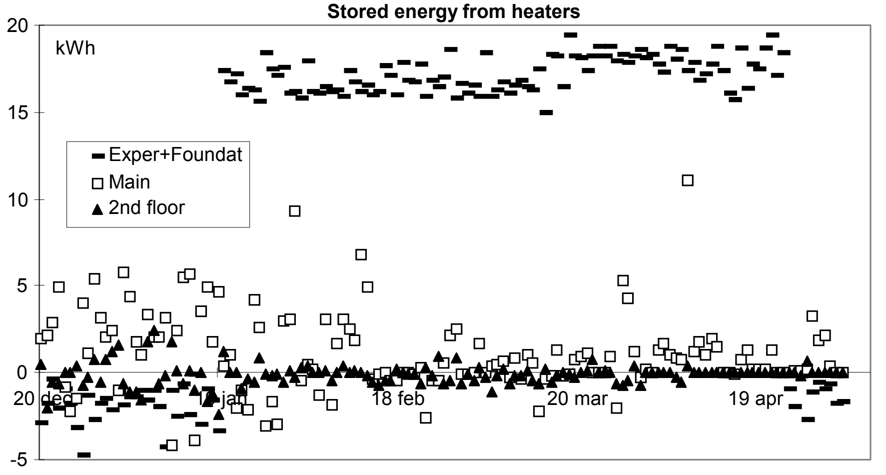

Diagram 5.12. Stored energy from the different heaters during the experiment period.

The resulting temperature differences are presented in Diagram 5.13.

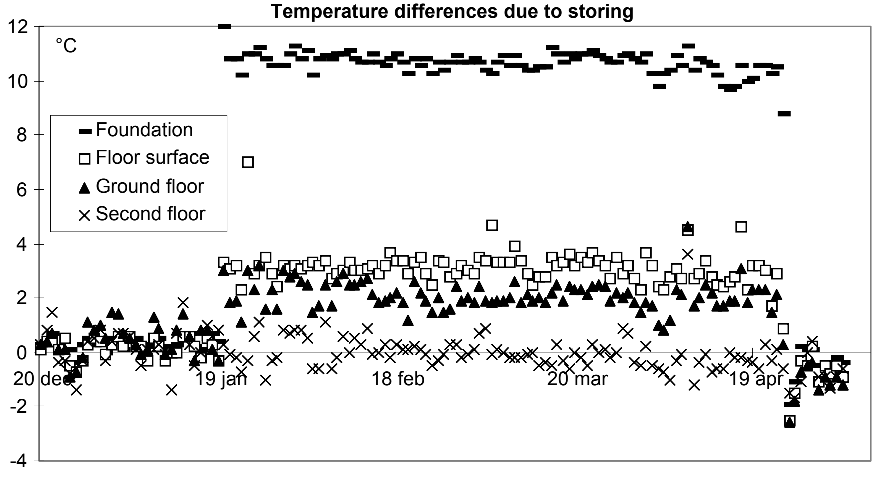

Diagram 5.13. Differences in temperature differences due to storing.

It is evident from Diagram 5.12 that the different heaters contributed to storage to a varying degree. It is also evident from Diagram 5.13 that the storage resulted in a temperature increase in at least three of the four storing compartments (the second floor is not influenced).

It is, however, not evident how to relate the stored energy to the temperature changes in the three compartments. Therefore, averaged values are presented separately for the stored energy and resulting temperature differences from the periods with no storing (Dec 20 - Jan 19), 6 h storing (Jan 20 - Mar 15) and 8 h storing (Mar 16 - Apr 22). (Tables 5.3 and 5.4).

Registration period	Storage time	Energy stored kWh		
	h	Experiment + Foundation	Main	2nd floor
Dec 20 - Jan 19	8*	-1.85	2.22	-0.16
Jan 20 - Mar 15	6	16.67	0.63	-0.10
Mar 16 - Apr 22	8	17.92	1.05	-0.06

* no heating occurred during these 8 hours.

Table 5.3. Average stored energy during periods of no storing, 6 h storing and 8 h storing.

Registration period	Storage time	Temperature difference °C			
	H	Foundation	Floor surface	Ground floor	Second floor
Dec 20 - Jan 19	8	0.3	0.2	0.4	0.2
Jan 20 - Mar 15	6	10.7	3.2	2.1	0.1
Mar 16 - Apr 22	8	10.6	3.0	2.0	-0.2

* no heating occurred during these 8 hours.

Table 5.4. Average temperature difference during periods of no storing, 6 h storing and 8 h storing.

The challenge with indoor heat storing is to store as much energy with the least possible comfort reduction.

One way of calculating a representative value of the storage capacity is therefore to relate the total amount of stored energy in the foundation to the temperature difference in the indoor air. This yields 7.9 kWh/°C in the period with 6 h storing and 9.0 kWh/°C in the period with 8 h storing (Table 5.5).

There is no temperature increase on the second floor with the bedrooms because of the storing, and the floor surface temperature of the ground floor is slightly higher than the indoor air. The heated area of Hus 15 is 126 m^2.

Test house	Heated area m^2	Storage capacity kWh/K	Temp difference °C
Hus 15	126	9.0	2.1

Table 5.5. Storage capacity of Hus 15.

The load-shifting experiment resulted in an improved temperature profile with heated floors in the ground floor, reasonable temperature difference on the ground floor and a negligible reasonable temperature difference on the second floor.

The experiment was appreciated and encouraged by the tenants, which was one of the reasons it was maintained until April 24.

5.4 Detailed analysis of heat storage in "Hus 15"

The storage capacity in Table 5.5 (9.0 kWh/K) was larger than the theoretical estimation for a similar house, Table 4.7, (4.9 kWh/K). Obviously this was because the crawl-space foundation was used as heat storage. The foundation may be considerably warmer than the indoor air since it was not a comfort zone. This chapter is a further analysis of the heat storage in Hus 15. First, there is a theoretical analysis of the structure of foundation, and then a simplified model is presented. Then, data from the experiment are used to find numerical values of the parameters of the simplified model.

5.4.1 Materials

The height of the crawl-space foundation was about 700 mm (Figure 5.7).

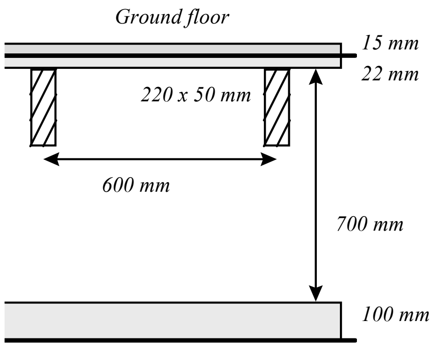

Figure 5.7. Crawl-space foundation.

Walls and floor of the foundation were insulated with 100 mm polystyrene. With this insulation, the foundation had approximately the same insulation standard as the rest of the climate shield. The ceiling of the crawl-space was the joists of the floor of the ground floor. This was constructed with 220 mm standing wooden beams, 600 mm separated.

The floor construction resting on the beams consisted of 22 mm wooden board, 3 mm cardboard and a 15 mm wooden floor. There were 16 beams and the length of each beam was 8.4 m.

5.4.2 Methods

System. It is shown in Table 5.3 and 5.4 that the second floor was not significantly influenced by the heat storing. The electrical analogy model in Figure 5.6 was therefore simplified to the model in Figure 5.8. The heat storing compartments in this model were the foundation (joist, beams), the floor of the ground floor and the rest of the ground floor (walls, ceiling, furniture) etc. The compartments were thermally connected with two heat transfer resistors.

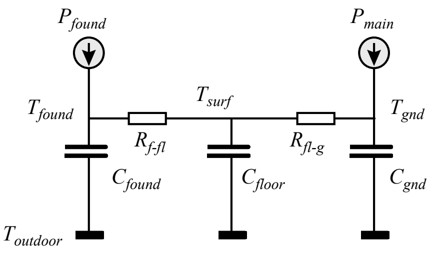

Figure 5.8. Simplified electrical analogy model of the Hus 15 test house.

The challenge is now to find the numerical values of the capacitors and resistors, by using the knowledge of the construction, and data from the Hus 15 experiment.

Analysis. As in the other, Övertorneå, Ljungsbro and the first Hus 15, experiments, the heat flow related to climate compensation was subtracted, and only the heat flow related to the storing was considered.

The model can be described mathematically by three balance equations.

$$C_{found} \cdot \frac{dT_{found}}{dt} = P_{found} - \frac{\left(T_{found} - T_{surf}\right)}{R_{f-fl}} \tag{5.2}$$

$$C_{floor} \cdot \frac{dT_{floor}}{dt} = \frac{\left(T_{found} - T_{surf}\right)}{R_{f-fl}} - \frac{\left(T_{surf} - T_{gnd}\right)}{R_{fl-g}} \tag{5.3}$$

$$C_{gnd} \cdot \frac{dT_{gnd}}{dt} = \frac{\left(T_{surf} - T_{gnd}\right)}{R_{fl-g}} + P_{main} \tag{5.4}$$

This can be rewritten as a system with three first order differential equations. The notation $\dot{T}$ means $\frac{dT}{dt}$, the change in temperature with respect to time.

$$\dot{T}_{found} = -\frac{\left(T_{found} - T_{surf}\right)}{C_{found} \cdot R_{f-fl}} + \frac{P_{found}}{C_{found}} \tag{5.5}$$

$$\dot{T}_{floor} = \frac{\left(T_{found} - T_{surf}\right)}{C_{floor} \cdot R_{f-fl}} - \frac{\left(T_{surf} - T_{gnd}\right)}{C_{floor} \cdot R_{fl-g}} \tag{5.6}$$

$$\dot{T}_{gnd} = \frac{\left(T_{surf} - T_{gnd}\right)}{C_{gnd} \cdot R_{fl-g}} + \frac{P_{main}}{C_{gnd}} \tag{5.7}$$

With vector notation, this is equal to

$$\begin{pmatrix} \dot{T}_{found} \\ \dot{T}_{floor} \\ \dot{T}_{gnd} \end{pmatrix} = \begin{pmatrix} -\frac{1}{C_{found} \cdot R_{f-fl}} & \frac{1}{C_{found} \cdot R_{f-fl}} & 0 \\ \frac{1}{C_{floor} \cdot R_{f-fl}} & -\frac{1}{C_{floor} \cdot R_{f-fl}} - \frac{1}{C_{floor} \cdot R_{fl-g}} & \frac{1}{C_{floor} \cdot R_{fl-g}} \\ 0 & \frac{1}{C_{gnd} \cdot R_{fl-g}} & -\frac{1}{C_{gnd} \cdot R_{fl-g}} \end{pmatrix} \cdot \begin{pmatrix} T_{found} \\ T_{floor} \\ T_{gnd} \end{pmatrix} + \begin{pmatrix} \frac{P_{found}}{C_{found}} \\ 0 \\ \frac{P_{main}}{C_{gnd}} \end{pmatrix} \tag{5.8}$$

or shorter,

$$\dot{\overline{T}} = \overline{A} \cdot \overline{T} + \overline{P} \tag{5.9}$$

With inserted initial values on the temperatures $\overline{T}$ (i.e. T_{found}, T_{floor} and T_{ground}), the differential equation, Formula (5.9) can be solved from $t = 0$ to $t = 6$ h or $t = 8$ h. This means that the temperatures $\overline{T}$ after six or eight hours can be calculated.

Parameters. In the differential equation (5.9), there are seven parameters that influence the solution. By solving three equations, only three variables can be calculated. The variables $P_{found\ heating}$, and $P_{main\ heating}$ were measured in the experiment and are therefore known. The thermal resistors $R_{f\text{-}fl}$ and $R_{fl\text{-}g}$ are unknown, but may be estimated with the values suggested in Table 4.2, or by solving (5.9). The thermal compartments C_{found}, C_{floor} and $C_{ground\ fl}$. are unknown as well, but C_{found} and C_{floor} may quite easily be calculated with Formula (4.1).

Since the construction of the floor and foundation were known, the storage capacities of foundation and floor were calculated. Thus the differential equation was used to find $R_{f\text{-}fl}$, $R_{fl\text{-}g}$ and $C_{ground\ fl}$.

There are several ways to find the values of $R_{f\text{-}fl}$, $R_{fl\text{-}g}$ and $C_{ground\ fl}$. The most convenient way is to use some standard software package for parameter identification, e.g. Matlab [45]. The parameter identification is generally based on a least-squares method [46].

The reader interested in dynamical modelling may want to find the values of $R_{f\text{-}fl}$, $R_{fl\text{-}g}$ and $C_{ground\ fl}$ ”by hand”. In Appendix D is therefore a more hands-on solution, based on repeated simulations of the system with different values of $R_{f\text{-}fl}$, $R_{fl\text{-}g}$ and $C_{ground\ fl}$. Changing these values in a systematic way will also give the result.

5.4.3 Results

The result for the 8-hour storing is presented in Table 5.6. In the presentation, $R_{f\text{-}fl}$, and $R_{fl\text{-}g}$ is replaced with the corresponding values of the specific surface resistance *m*. These may be compared to the values in Table 4.2.

		6 h data set	8 h data set
$m_{f\text{-}fl}$	[m^2·K/W]	0.295	0.343
$m_{fl\text{-}g}$	[m^2·K/W]	0.058	0.077
$C_{ground\ fl}$	[kWh/K]	2.95	4.40

Table 5.6. Some estimated properties for Hus 15.

The storage capacity of the different compartments are presented in Table 5.7. The results are based on the 8-hour storing.

Hus 15	Heated area m^2	Storage capacity kWh/K	Temp difference °C
Foundation	81	0.62	10.6
Floor of ground floor	81	1.3	3.0
Ground floor	81	4.4	2.0
Second floor	81	(not estimated)	-0.2

Table 5.7. Storage capacity of Hus 15.

6 Discussion

This chapter first discusses the results. The initial question is whether there is a correspondence between the theoretical estimations and practical results from the experiments regarding heat storing capacity, time constants, ”comfort” time constants, energy losses and comfort aspects for tenants. There is not always agreement, and the discussions give some perspective.

The final question is whether load-shifting and storing are of any importance. The national electricity system is briefly discussed, as well as the benefits of load-shifting, and the maximum potential of load-shifting in Swedish single-family houses as estimated from the results in this report.

The discussion also includes some reflections on Bo92. What did we foresee in our visions, and what did we not foresee?

At last, is load-shifting really useful? What values can be expected? Finally, there are some comments about moving electrical load.

6.1 Theoretical and empirical agreement

Considering uncertainties in house constructions, furniture, living habits, outdoor climate etc, there seem to be a reasonable accordance between the theoretical calculations and the experimental results.

The theoretical estimation in Table 4.7 for a 126 m^2 modern house was 4.9 kWh/K, that is, 39 Wh/K·per m^2 heated area. The experiment in the Övertorneå house showed that it was possible to store 5.7 kWh/K (Table 5.1) in the house of 135 m^2, that is, 42 Wh/K per m^2 heated area. The theoretical estimation was thus 7 % lower than the empirical value.

The theoretical estimation for a 126 m^2 traditional house was 8.3 kWh/°C, that is, 66 Wh/K per m^2 heated area. In the Ljungsbro house with 256 m^2 heated area, it was possible to store 14.7 kWh/K, that is, 57 Wh/K per m^2 heated area. The theoretical estimation was thus 16 % higher than the empirical value.

The assumptions made in the theoretical estimations were considerably more uncertain than this deviation. For the traditional house, the house constructions were also different. The theoretical house had brick walls and insulation outside, but the test house had walls of gas concrete.

The conditions of the Hus 15 experiment were slightly more complicated. It had several temperature zones with one zone, the foundation, where the temperature was allowed to exceed the comfortable indoor temperature and another zone, the second floor, which did not participate in the storage.

The experiment showed that it was possible to store about 9 kWh/°C if the temperature of the indoor air of the ground floor was used as reference. Compared to the theoretical estimation, the larger storage capacity in the experiment was explained by the higher-than-comfortable temperature in the foundation.

The detailed analysis in Chapter 5.4 discussed the distribution of the storage capacity between different parts of the house and structure. By calculating the capacities for two of the storing compartments (foundation and floor), a modelling approach could be used to identify the third compartment. Based on these results (Table 5.7), the amount of energy that was possible to store was

$$0.62\ \text{kWh/K} \cdot 10.6°\text{C} + 1.3\ \text{kWh/K} \cdot 3.0°\text{C} + 4.4\ \text{kWh/K} \cdot 2.0°\text{C} = 19.3\ \text{kWh}$$

This should be compared to the stored energy in Table 5.3.

$$17.92\ \text{kWh} + 1.05\ \text{kWh} - 0.06\ \text{kWh} = 18.9\ \text{kWh}.$$

The difference between the results is 2 %.

6.2 Time constants

The correspondence between the theoretically calculated time constants for the traditional and the modern house, as well as the time constants for the houses in Södergren's and Vattenfall's studies are shown in Table 6.1.

House	L m	W m	A m^2	Walls	Heat exch (efficiency)	Time const h
Södergren's (model) [33]	10	10	100	200 mm glass wool 13 mm gypsum	50 %	20
Vattenfall's (Marma) [34]	13.6	7.3	100	(1970's standard)	No	27
Traditional (model)	14	9	126	100 mm glass wool 100 mm brick	No	33.9
Modern (model)	14	9	126	240 mm glass wool 20 mm gypsum (	50 %	53.0
Södergren's (model) [33]	10	10	100	200 mm glass wool 89 mm concrete	50 %	147
Södergren's (Gränna) [32]	11 11	6.5 8.5	(tot) 165	200 mm glass wool 120 mm concrete	Yes	184

Table 6.1. Time constant for the traditional and modern houses, compared to time constants found in other studies.

The values are also well in correspondence with the time constants referred to in Dafgård's report [31].

6.3 ”Comfort” time constants

The time constant is a mathematically convenient measure of the thermal inertia of the house, but it does not say much of the time until the house becomes uncomfortable to live in. Therefore, the cooling of the houses was also discussed in terms of the ”comfort” time constant, the time for the house to cool from a maximum to a minimum acceptable temperature.

6.3.1 The Övertorneå test house

It is seen from Diagram 5.1 that the stored heat in the Övertorneå house was not quite enough to support the house with heat during the entire period from 6 a.m. to 10 p.m. Often the heater started to contribute some time during the afternoon. This is in agreement with the theoretical results in Table 4.11. The theoretical modern house had a ”comfort” time constant of 9.7 hours. In both cases, the difference between maximum and minimum temperature is 3°C.

6.3.2 The Ljungsbro test house

Data from the Ljungsbro test house was not possible to use for deciding the time constant, because the experiment did not involve a complete shut-off of the heaters. A few early trials indicated that this was not realistic due to comfort.

There is however nothing that contradicts the theoretical result in Table 4.11: The ”comfort” time constant of the Ljungsbro test house would most likely be of some few hours.

6.3.3 The Hus 15 test house

The ”comfort” time constant of Hus 15 was not straightforward to decide, because the different temperature zones participated in the storage to varying degrees. Diagram 6.1 presents the power from the different heaters for two periods before and after the storing. The duration of the storing was 6 hours, from 10 p.m. to 4 a.m.

The main heater was not completely shut off during either of the periods. The controller for the main heater used the indoor temperature for deciding the power. Activities in the house then influenced the main heater, which showed an irregular behaviour.

A regular pattern was, however, seen in the ordinary foundation heater. The heater had an average power of 250-300 W before the storing, which was reduced to small occasional peaks during the evenings of the storing period (Diagram 6.1). The foundation heater usually started at about 4-6 p.m. for several weeks of the storing period. If the starting of the foundation heater is the criterion that the house had run out of stored heat, the heat thus lasted from 4 a.m. to 4-6 p.m. The ”comfort” time constant was hence 12-14 hours.

This is more than the theoretically calculated 9.7 hours in Table 4.11, but the theoretical value is calculated from a 3°C difference between the maximum and minimum temperatures. Obviously, the ”comfort” time constant will be longer if a larger temperature difference is allowed, as with part of the storage in the foundation in Hus 15.

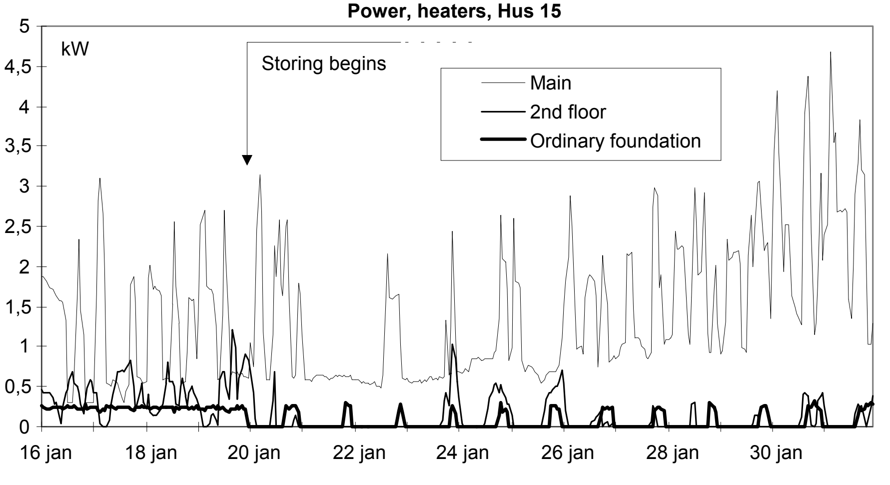

Diagram 6.1. Power of the different heaters in Hus 15 before and after storing. During the storage, the foundation heater starts at about 4-6 p.m. when the foundation is out of stored heat.

6.4 Energy use due to storage

The design of the experiments was intended for throwing light on the charging and discharging of thermal energy in the structure of the house. A question of some interest is whether a single-family house used more energy with or without a storage scheme.

The most important condition is the indoor temperature. If a storage regimen lead to an increased temperature difference between the indoor and outdoor temperatures, the energy use would increase. This could occur if, for instance, the average indoor temperature was 20°C while the storage regimen heated the house to 22°C for 8 hours and let it cool down to 20°C for 16 hours. However, if the house instead was heated to 21°C and cooled to 19°C, the energy loss would be less, maybe zero. It is therefore crucial which temperatures and intervals that are used.

Generally, the indoor temperature is related to the tenants' comfort and economy. It can be assumed that for economic reasons the minimum indoor temperature is set 'reasonably' low, that is, as low as possible without causing any inconvenience. If this temperature is about 20°C, (frequently used as a default value in calculations), it can be assumed that a lower temperature would cause inconvenience. A value slightly higher than 20°C would not. Therefore it is reasonable to assume that storage regimens would have 20°C as the lowest temperature and some few degrees more as the highest temperature.

The two theoretical single family houses, according to Table 4.8, used 93 W and 245 W more if the temperature difference between indoor and outdoor temperature increased with 1°C. A storage regimen that caused a 1°C average indoor temperature increase would therefore result in a 2.2 kWh/day and 5.9 kWh/day additional energy use, respectively.

As stated above, the experiments were performed mainly to evaluate the potential of storing, of course with reasonable conditions for the tenants. Since the tenants' experience of comfort was not evaluated in detail, the issue of comfort in relation to indoor temperature, energy use and economy was not addressed. Data were therefore only analysed in rough outlines to reveal an increase in energy use due to storing.

6.4.1 The Övertorneå test house

The data collected for the experiment in the Övertorneå test house were recorded only for the analysis of the storing regimen. Data of the same resolution before or after the storage period, comparable with respect to heat from other sources than the heating system etc, were not available. Assuming that the Övertorneå house had the same characteristics as the modern theoretical example house (100 W/°C), and that the average indoor temperature increase was 1.5°C (see Diagram 5.2), the additional energy use would be 3.6 kWh/day.

6.4.2 The Ljungsbro test house

The data from the Ljungsbro house included comparable periods with and without storing. The energy use during weekdays with storing was compared to the energy use during weekdays without storing (Table 6.2).

	Without storing	With storing
Max power	7670 W	8970 W
Average power	4680 W	4590 W
Min power	3290 W	1400 W
Max indoor temp	21.4°C	21.4°C
Average indoor temp	20.4°C	20.4°C
Min indoor temp	19.7°C	19.4°C
Average outdoor temp	3.9°C	3.3°C
Average power per temperature difference*	407 W/°C	378 W/°C

* Calculated as Average power / (average indoor temp - average outdoor temp - 5°C) The 5°C is assumed to be contribution from spill heat.

Table 6.2. Some properties from storage experiment in the Ljungsbro house.

More details are shown in Diagram 5.5 (power) and Diagram 5.6 (temperature). The result in Table 6.2 is contra-intuitive, since less power is used to compensate for a higher climate load. This indicates that the variability in power and temperature is so large that the data set is too small to make a statement with decent statistical significance. Rather, with a marginal power need of about 400 W/°C, and an average indoor temperature increase by 1.5°C, the additional energy use would be 14.4 kWh/day.

6.4.3 The Hus 15 test house

The data from the Hus 15 test house included data from a period of one month before the storing started, from the period of 6-hour storing and from the period of 8-hour storing. Therefore, an analysis was made where the energy uses in the different periods were compared. Some key numbers are presented in Table 6.3.

	Dec 20 - Jan 19	Jan 20 - Mar 15	Mar 16 - Apr 22
Max power	6050 W	8780 W	7310 W
Average power	2630 W	2710 W	2330 W
Min power	780 W	413 W	405 W
Max indoor temp	21.7°C	24.7°C	25.0°C
Average indoor temp	20.5°C	22.2°C	22.8°C
Min indoor temp*	17.4°C	18.7°C	20.0°C
Average outdoor temp	0.0°C	0.2°C	3.0°C
Average power per temperature difference**	169 W/°C	159 W/°C	158 W/°C

* The single dip of 14.3°C on the evening 23 January removed. See Diagram 5.11.
** Calculated as Average power / (average indoor temp - average outdoor temp -5°C) The 5°C is assumed to be contribution from spill heat.

Table 6.3. Some properties from a storage experiment in the Hus 15 test house.

Also the results presented in Table 6.3 are contra-intuitive, since the power - climate compensation ratio is lower during storing. Here, the number of samples is greater, so the conditions regarding statistical variability would be better fulfilled. A better explanation would be that the three periods were too different to be compared. The first period included both Christmas and New Year with possible deviations in living habits. During the last period in March and April, the sun began to contribute to the heating.

The same corrective estimation as for the other test houses would yield that Hus 15 with about 160 W/°C and an average indoor temperature increase of 2.5°C (relatively more stored in the foundation compared to the other houses), had an additional energy use of 9.6 kWh/day.

6.5 Comfort aspects

6.5.1 The slow time constant

The most straightforward way to discharge the heat stored in a house is to completely shut off the heating system. In traditional houses this will lead to cold draught which will severely reduce the comfort.

A house where the heating is switched off will turn out to have at least two time constants [29, 34, 35]. The fast time constant is related to the cooling of the indoor air volume. It would not be important for energy storage (indoor air can not store much energy), but rather for discomfort.

The slow time constant is related to the cooling of the structure. This time constant would be important for energy storage. It was calculated by Vattenfall to 27 h in a slightly smaller and unoccupied house [34, 35], and by this report to 34 h and 53 h (Table 4.10). From our experiments, it is obvious that a long time constant is better than a short one, at least for 24-hour heat storage cycles in a cold outdoor climate.

A too long time constant may however make the indoor air temperature hard to control, e.g. if a warm, sunny day follows a night where the storage was fully loaded. Also, during summer, a risk for indoor over-temperature will occur.

6.5.2 The fast time constant

As stated, the most important time constant to indoor comfort is related to the indoor air. When the heating is shut off, the ventilation provides the house with outdoor air. The ventilation rate is usually about 0.5 air exchange per hour. The cool outdoor air mixes with the warm indoor air, and in fractions of an hour the indoor air is considerably cooler than the house structure, surfaces and furniture. Also, in a traditional house a cold draught occurs. The indoor air, chilled by cold surfaces as windows and walls, moves down along the surfaces and out on to the floor.

This colder indoor air has to be heated by the heat stored in the building structure. In Vattenfall's report [34, 35], the short time constant is about 1 h. From diagrams it can be seen that the initial temperature drop is of the magnitude 1-2°C. This is almost the entire comfort temperature span.

The phenomenon with the fast time constant occurred at some early trials in the Ljungsbro house. Slots over the windows provided the ventilation air and if the heating was switched off completely, it resulted in an inconvenient cold draught within a quarter of an hour. This made us consider the conditional ”more/less power” strategy rather than an on/off strategy (see Chapter 5.2.2).

The problem with cold draught is reduced with a ventilation air heat exchanger. This uses the heat of the return air and pre-heats the incoming air. Therefore, the supply air is already somewhat heated when mixing with the indoor air. In a modern house, the windows are also better, which reduces the air movements near cool surfaces.

Both the Övertorneå house and Hus 15 had heat exchangers. It was hence possible to shut off the heating completely for several hours, despite the winter climate.

Increasing the indoor temperature too fast might lead to comfort reduction. During the heating cycle of the Ljungsbro house, the baseboards became inconveniently hot. This caused an increased heat radiation and the air was experienced as ”dry” (which it was not, since neither moisture content nor ventilation was influenced). Over-heated baseboard surfaces may furthermore occasionally increase the risk for burn injuries.

6.5.3 Storage temperature intervals

The temperature intervals should be carefully considered. The inconvenience is related to the temperature interval used in the storage strategy. The specific storage capacity (kWh/K) may be objectively evaluated, but the potential of storing (kWh stored) is not really a technical question since it involves the comfort experience of the tenants. Moreover, it should be evaluated in relation to the economic gains from using a storage regimen. One of the reasons for developing the Miniwatt controller was to allow the tenants to easily influence the average temperature and the storage temperature interval by themselves.

The experiment in Övertorneå resulted in an indoor temperature difference of 3.0°C, also in the bedrooms, which was not appreciated by the tenants. In the Ljungsbro house, the temperature difference was 1.7°C, which led to a slight, but not unreasonable comfort reduction. In the Hus 15, the comfort was increased by the warmer floors of the ground floor together with a negligible temperature difference in the bedrooms, and the experiment was prolonged for several weeks.

The maximum and minimum temperatures do not tell the whole truth. For instance, in the Ljungsbro house, the interval is almost within the normal range of indoor temperature (Table 6.2). Diagram 5.6 shows a better picture — occasional peaks and dips during the non-storing periods explain the extreme values.

Generally, tenants want to have a slightly lower temperature in the bedrooms at night, and higher temperature at breakfast. When the tenants come home in the afternoon, the house should also be comfortably warm, but be cooler at bedtime. Details in data of the Ljungsbro house indicated that these conditions were not quite met.

If a storage strategy for traditional houses is developed, it would probably be useful to allow for slightly different temperatures in different rooms. This condition was, to a large extent, met in Hus 15, by using different temperature zones with the bedrooms in a separate, cooler zone at the second floor.

The construction with a crawl-space foundation of Hus 15, is more expensive compared to a slab on the ground. Still, it was a common construction in single-family houses in the eighties. The modifications for the storage experiment were additional insulation as well as additional ventilation piping from the foundation to the heat exchanger.

6.5.4 Improved temperature profile in Hus 15.

It can be seen in Diagram 5.11 that the temperature profile, after introducing the floor heating, was more in accordance with the tenants' preferences. Before floor heating started, the floor of the first floor had the lowest temperature, about 20°C, in the house. The bedrooms on the second floor had the highest temperature, about 22°C. After a couple of days with floor heating, the profile was the opposite. The floor of the first floor reached a temperature of 24°C in the mornings and 21°C in the evenings. The air of the second floor remained at about 21-22°C, which was the lowest temperature in the house.

The indoor temperature profiles were stable also during the cold evening on the 24th of January when the temperature dropped to -8°C. We do not know the reason for the dip in the air and floor temperature of the first floor in the evening of The 23rd of January. It seems possible that the tenants left the door open for a while.

6.6 The national perspective

6.6.1 The benefits of load-shifting

For one single-family house, it is reasonable to consider an increase in energy use with about 10-15 %, if a storage temperature interval of 3°C is used. Compare Table 4.14. There is then no direct *energy* saving for the house owner — obviously the energy use increases.

However, in a system perspective, there would be large benefits, which can be used as incentives for the house-owner: The Swedish national electricity grid up to the mid 1990's had relied mainly on hydropower and nuclear power. At shortage, there had been fossil condensing power plants for marginal electricity production. These are expensive to run, have a low efficiency and a large environmental load. If the load could be reduced daytime on winter weekdays, the risk for using fossil condensing power plants will also be reduced. Therefore, with a spot market pricing, electricity is cheaper during the night and weekends, and more expensive during daytime on weekdays. For load-shifting to be of interest, the electricity tariffs must compensate for the customers' increased use of energy due to the load-shifting.

A well-developed network for electricity export will also give the same marginal impact. If it is assumed that a liberalised international electricity market will buy electrical power from Sweden daytime when the load is high, the exported Swedish electricity will result in a reduced use of coal condensing plants in Denmark and on the European continent. A saved CO_2-free kWh in Sweden may be exported to save a Danish or German fossil-based kWh and thus approximately 3 kWh of coal. For this to occur, however, the international electricity prices including environmental and other taxes must harmonise.

6.6.2 An estimation of the maximum potential

The following simple approximations based on the results of this work indicates the maximum potential for load-shifting on a national level.

In Sweden there are about 1.9 million small-houses. Most of them are single-family houses. The rest of them are farmhouses, high-standard summer houses etc [21]. About 410.000 of these are heated with resistant heating. There are also about 195.000 houses with water-borne or air-borne electrical heating. In addition, there are 310.000 houses with oil heating or firewood heating, which have been supplied with electrical immersion heaters. Further, there are 140.000

houses with several heat distribution systems, of which one can use electricity as heating source. In all, there are about one million small-houses that might be heated with electricity.

Assume now that the theoretically calculated storage capacity of the traditional house is representative for an average Swedish single-family house (8.3 kWh/K storage capacity, Table 4.7). Assume also that 2°C storage temperature is acceptable for average Swedish tenants without violating a reasonable comfort level (compare Table 5.1, Table 5.2 and Table 5.4). The maximum storage potential in an average Swedish single-family house is then 16 kWh. This indicates that the power at most can be reduced by about 1 kW during 16 daytime hours, and increased by 2 kW during 8 nighttime hours.

The extrapolation of this to one million Swedish single-family houses will yield a maximum of 1 000 MW reduced power during 16 daytime hours, at a cost of 2 000 MW increased power during 8 nighttime hours. The estimation can be compared to the production capacity of condensing power 1999-12-31 which was 452 MW, and of gas turbines etc which was 1 485 MW [47].

In Diagram 6.2, the result is shown together with the estimated national electricity load from the report on the nuclear power phase-out for the Swedish Energy Commission [48]. Compare Figure 1.2 and 1.3.

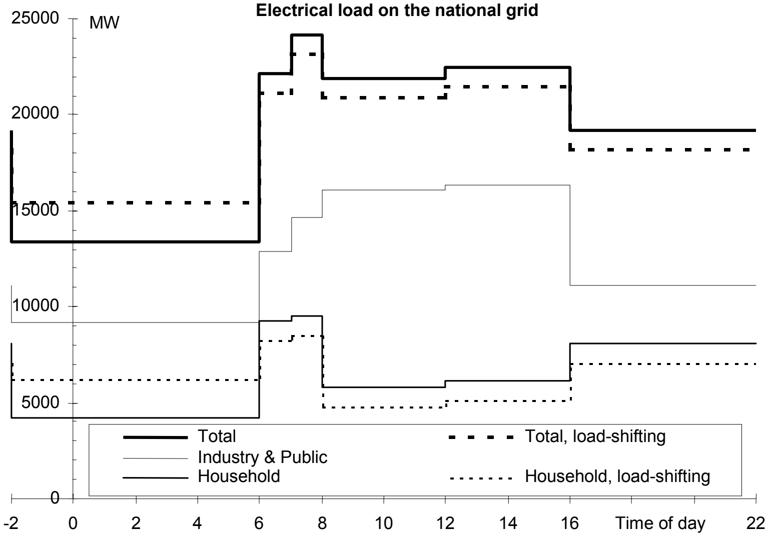

Diagram 6.2. Electrical load on the national grid with and without the maximum potential of 8/16-hour load shifting in single-family houses.

The estimation is based on a *realistic* value of the load-shifting potential in an average traditional single-family house (theoretically calculated and verified with the result from the Ljungsbro test-house). But it is furthermore based on the maximum values of the rest of the factors. It is assumed that all the one million houses that *can* use electricity as a heating source really *do* use it, and that all of them successfully adopt the storing etc.

It is also assumed that the distribution system allows all houses to time-shift their load to nighttime. Since the electricity use is doubled during the night, there may be bottlenecks in the distribution system that set limits.

6.7 Bo 92 — In the rear mirror

A reflection on the Bo92 visions would not be complete without a summing up of what happened and what did not happen to the assumed progress of the surrounding world.

6.7.1 What did come true?

- Global environmental issues, such as emissions of greenhouse gasses and global climate change, got on the international agenda at the Rio conference in 1992. Environmental issues had obviously been discussed before, but this was the first time they were considered of global importance.

- Local environmental issues, such as material efficiency, recycling, moving towards a sustainable society were brought up in the national political debate. A national initiative was Det Naturliga Steget (The natural step), which followed a paper published at a conference on ecological economics in Costa Rica 1994 [49].

- The national electricity market was liberalised and opened for larger customers in January 1996 and for smaller customers as single-family houses in 1999. The trend by the end of 2000 is an increasing international electricity business, with investments in increased transport capacity.

- The first nuclear reactor, Barsebäck I, was phased out at the end of 1999.

6.7.2 What did not come true?

- The equipment needed for hour-to-hour electricity metering in single-family houses was too expensive to be justified for an average customer. There was hence no potential for demand-side-management, e.g. tariffs based on ”expensive” daytime weekdays during the heating season and ”cheaper” nights, weekends and summer.

  Instead the Swedish electricity market followed Norway and used template load profiles for single-family houses. These template profiles use fixed load profiles for average consumers. The hour-to-hour consumption could thus be calculated from a template profile and the electricity use, which is estimated or measured as usual (monthly or a few times per year).

  By this method, the customer in a single-family house only gets one electricity price during one or several years. Hence the incentive for load-shifting from daytime to nighttime disappeared.

- During the introduction of the liberalised electricity market, the running electricity cost was divided into two components, one for the electrical energy and one for the transportation of the energy on the grid. At the end of the year 2000, the competition lowered the electricity costs for several single-family house customers thanks to the liberalisation of the market, despite increasing electricity taxes.

  The increase in electricity prices following the open international market or nuclear power phase-out has not yet occurred at the end of 2000.

- The environmental taxes on electricity production have not been stable in Sweden, and do not harmonise between Sweden and the rest of the Nordic region [50]. For instance, differences in CO_2-taxes make it more favourable to import electricity from coal condensing production than producing it in Sweden in the end of 2000. On a liberated market, this will obviously lead to increased import.

6.7.3 What might come true?

- Possibly, the Swedish electricity prices will increase. Competition among Swedish electricity producers from 1998 first made electricity prices based on fixed contracts low [47]. During 2000, the electricity production from nuclear power plants was reduced to 55 TWh (from 70 TWh 1999), and the use of hydropower increased to 76 TWh (from 71 TWh 1999) [51].

  At present (April 2001), the water magazines for hydropower are about 10 TWh less than normal and the prices are expected to rise [52]. Electricity spot prices during the first months of 2001 are slightly higher than the years before [53]. The long-term prices of electricity for delivery 2002-2004 are, however, still on the same level as for 2000 [52].

- Possibly, there will be a liberalised European electricity market. The EU directive 96/92/EC establishes common rules for an internal market in electricity [54]. Some of the content is:
  - All consumers in all markets must be free to choose their supplier.
  - Commercial interests of net operators should be fully and effectively separated from the interests of producers.
  - Fair access to the network and undistorted competition would be best achieved through effective regulation, calling for regulatory authorities in all member states.
  - To promote cross-border trade, appropriate mechanisms for tarification and congestion management have to be developed. The interconnecting infrastructure should be reinforced.

  The commission planned to make proposals aimed at completing the electricity market at the Stockholm spring meeting 2001 [55]. The market was suggested to open for large customers in 2003 and households in 2005. But so far, consensus about milestones and goals has not been reached [56].

  Despite the expected delays, increased investments are seen in Swedish and continental utilities. For instance, Vattenfall plans to buy shares in Hamburgische Electricitäts-Werke AG (HEW), previoulsy owned by Sydkraft and e.on Energie [57]. Sydkraft plans to buy shares in MEC Koszalin, a Polish district heating company [58].

6.8 Usefulness of heat storing

In the seventies and eighties, there was a political goal in Sweden to replace fuel with electricity for heating purposes. One reason for this was to be more independent of oil. The political directives were therefore to install more and more electrical heating. This made Sweden rely more and more on nuclear power. The ideas with electrically heated houses whose electricity use was adjusted to the industrial load should be seen in the light of this movement.

During the nineties there were some changes in the perspective. Sweden became more international. Compared to most comparable countries, Sweden has a remarkably high electricity use per capita, to a large extent due to the electrical heating. In a future international perspective it would be more favourable to utilise the higher energy quality of electricity, e.g. by exporting excess electricity and instead use fuels for heating.

Sweden has a simultaneous demand for both electricity and heat during the dark and cold part of the year. In cities, co-generation may be an alternative, using biomass fuels or waste to generate electricity and district heating. Thus, in the long run, buildings in urban areas would regularly not be heated with electricity.

6.8.1 Peak shaving

Heat storing in the way that has been discussed in this report may be an alternative in case of power shortage, either locally (bottlenecks in the distribution system) or nationally (lack of electricity production plants). Good economical incentives would most likely encourage storage to be used.

Occasionally, quite short load reductions may reduce the need for ”peak” power. For instance, if the peak in the national electricity load (see Diagram 6.2) could be reduced the hour between 7 and 8 a.m., with about 2 000 MW, the power equivalent to two nuclear reactors would be superfluous. Occasionally, even shorter incidents may occur, e.g. high load on parts of the distribution system for fractions of an hour. A challenge for the producer would be to avoid the use of peak-load power plants at distribution shortage incidents while still satisfying customer needs. Peak-load plants are expensive and have a greater environmental impact than base-load plants. Load management may be used both to avoid running peak power plants and to avoid building them.

6.8.2 Energy services

Heat storing may be of interest as a business expansion for utilities. As an alternative to sell ”electricity” the utility can sell the energy service ”comfortable indoor climate”. The comfortable indoor climate is then specified as an indoor temperature interval for which the customer (tenant) pays. Added qualities for the customer may be that the utility provides the necessary equipment and has the responsibility for maintenance and replacement. The quality for the utilities is the freedom to provide electricity or fuel in any way it serves them as long as the conditions for the ”comfortable indoor climate” is fulfilled.

6.8.3 ”Competent” load management

Today’s systems are designed for reducing power to selected appliances controlled by the utility, and leave no options for the customers. A drawback is also the ”energy debt” after reduction, requiring additional power when the reduction has ended. This suggests that load reduction is best suited for brief shortages. Load-shifting in single family houses could be performed as suggested in this report by storing before reducing the load, so no energy debts occur.

The equipment for the utility/customer information exchange has so far been too expensive (telephone modems, power line carrier, FM radio paging systems etc). The availability of the Internet and high-speed data communication to every single building may however drastically improve the business opportunities.

Load shifting, with its possible side effect of comfort reduction, may not always be useful. Part of the year, when changes in load profile do not lead to changes in production conditions, there would be no benefit from load shifting. Occasionally individual households would highly appreciate electrical power and would be willing to pay a lot for it. Hence, a system where both customers and the utility can influence the load shifting is preferable. Utilities should use load shifting when it is most beneficial and then compensate the customers. Customers should have full access to power, even at peak load times, but pay the cost for it.

7 Conclusions

This chapter shortly lists some results and highlights.

Theoretical calculations

- The theoretical calculations of two example single family houses showed that it would be possible to store **8.3** kWh/°C in a traditional house from the seventies, and **4.9** kWh/°C in a modern house from the nineties. The power needs per degree reduced outdoor temperature was **245** W/°C for the traditional house, and **93** W/°C for the modern one.

- The theoretical thermal time constant was **33.9** h for the traditional house and **53** h for the modern house.

- When discussing heat storage, it is practical to use the ”comfort” time constant, the time until the indoor temperature had dropped from the maximum comfortable level to the minimum comfortable level. The formula for this is

$$\tau_{comf} = -\tau \cdot \ln\left(\frac{T_{\min} - T_o}{T_{\max} - T_o}\right)$$

For the traditional and modern house, it was **6.2** h and **9.7** h, respectively.

Experiments

- The experiments showed that the storage capacity was **5.7** kWh/°C in a modern test house with one temperature zone (Övertorneå), and **14.7** kWh/°C in a traditional house (Ljungsbro). If relating the results to the heated area, they were in agreement with the theoretical calculations (within ±16 %).

- The experiment in a modern house with multiple temperature zones (Hus 15) resulted in a storage capacity of **9** kWh/°C. Due to heat storage in the crawl-space foundation, a higher-than-comfortable temperature could be used, which increased the capacity.

- The ”comfort” time constant was in accordance with the theoretical results for all test houses, that is, about **10** hours for the one-zone modern house, **some few** hours for the traditional house, and **12-14** hours for the multiple zones modern house.

Comfort

- The indoor thermal climate is important to consider, since tenants live in the heat storage. The **inconvenience** from the experiment was strongly **related to the temperature differences**.

- By heating the crawl-space foundation it was possible **to improve the temperature profile** in the multiple zones modern house, so that the floor temperature on the ground floor was slightly higher than the indoor air, and the air temperature of the second floor with the bedrooms was slightly lower.

Cost/Effectiveness

- Though not supported by the results from this work, it is evident that any storage strategy that uses an increased average indoor temperature would lead to **increased energy use**. For single-family house owners to store heat during nighttime, the increase in energy use must be **compensated** by a lower electricity price at loading time.

Storage regimens

- An **on/off, 8/16-hour** storage regimen in a single-family house with one temperature zone does **not seem realistic** even in a modern house with heat recovery. A necessary temperature interval would be too large to be comfortable for the tenants, and still the stored heat would not be enough to cover the 16 hours without heating.

- An **on/off** storage regimen with a **shorter** cooling period than 16 hours would be realistic in a single-family house with one temperature zone.

- An **8/16-hour, ”more/less”** storage regimen would be useful in **any** house. The temperature interval is chosen with consideration to the tenants’ comfort. The small heating power during the cooling period reduces cold draught.

- An **8/16-hour, on/off** strategy would be realistic in a house with several temperature zones, where one zone is allowed to have a **higher** temperature than the maximum comfortable temperature.

National perspective

- A rough estimate of the *maximum* potential is a load reduction of **1 000** MW during 16 daytime hours shifted into **2 000** MW additional power during 8 nighttime hours. This approximation assumes a storage capacity of 16 kWh in each of the one million houses that can use electricity as heating source.

8 Future work

8.1 Monitoring of energy use

Being in charge of a system, for example a car, a household economy or a house, means taking a lot of decisions about operations (slower/faster, consume/save, warmer/colder) and structure (replacement of worn parts, investments, retrofitting/replacing heating system). All these decisions would be much easier if the right information was available at the right time. Of large importance here, are also historical trends.

Several parameters related to energy use are easy to follow, e.g. electricity use, indoor and outdoor temperature, but it would also be useful if hot water use, the ventilation flow, moisture content and CO2 etc could be monitored. If these parameters were recorded, organised and presented in the right way, it would provide understanding of the house and support decisions in short and long terms. The ideas were discussed already in the IDEM EU-project in the mid-nineties, but then home computers had not yet had their breakthrough.

A suggestion for future work is to study in which way data from energy use and energy related entities could be collected, organised and presented to support understanding and actions to increase comfort and efficiency.

8.2 Process knowledge

During the evaluation of Bo92, we experienced that the tenants' knowledge of their house as an energy system is of large importance for the energy use. So is also their view and expectations of their house.

The discussions before the Bo92 housing exhibition stated that the single-family houses were designed to be energy efficient, relating to the well-insulated walls, the triple-glazed windows and the heat recovery from the ventilation air.

Occasionally, it turned out that the inhabited houses were not *that* energy efficient. Often it was possible to trace the cause of the difference in energy use to actions taken by the tenants. For instance, in one house the tenants had opened the bedroom window to reduce the temperature during the night. This made the fresh air enter the house via the bedroom window and not via the ventilation heat exchanger. The heat in the exhaust air was thus not recovered. Also, tenants occasionally adjusted the indoor temperature to be a bit higher than the 20°C used in the energy calculations, which also increased the energy use.

Of course tenants should be free to open windows and adjust the indoor temperature, as they find best. But not considering the sequels, may give unpleasant surprises and disappointment on the expected energy efficiency.

A suggestion for future work is to study ways to improve system thinking of energy use in a single-family house. Single-house owners, tenants, house designers, energy planners etc should find this useful.

8.3 Values of energy services

The energy use in single-family houses is of course a hot issue for researchers, house constructors and energy engineers and, of course, also for interested tenants. But, occasional tenants have indicated to us researchers that a home can be used for more purposes than energy saving.

Maybe energy use and energy costs are not big issues compared to other domains in life, such as costs for family, travelling, food and pleasure. If a single-family house is presented as a little more energy efficient than the average, this may be good enough — and further efforts to reduce the energy use are not worth while.

A suggestion for future work is to study the values related to energy use in a single-family house. What is the value of slightly increased indoor temperature? What is the value of having light in the house or in the garden when coming home to the house? What is the value of an energy efficient house, compared to one that is beautiful or cheap to produce?

How is it possible to introduce a Factor 10 thinking in the domain of one's home, without introducing the ”increased-efficiency” stress from other parts of society?

8.4 Space-heating in a system perspective

Up to the beginning of the seventies, the average Swedish single-family house used about 300 kWh/m^2 per year for space-heating and hot-water [59]. In 1985, this was reduced to about 200 kWh/m^2 per year. The projected energy use for the single-family houses of Bo92 was about 100 kWh/m^2 per year.

A topic not often discussed is the change from using fossil fuels or firewood for heating and hot-water up to the seventies, to use electricity from the beginning of the nineties. This electricity is produced by nuclear power, which up to 1996 in Sweden was considered to have an efficiency of 100 % [60]. From 1997 and onwards the efficiency was calculated to 34 % in accordance with the international FN/ECE rules [61]. Thus, if also the production losses outside the house are calculated, modern electrically heated houses have about the same efficiency (or slightly worse) as the houses half a century ago. From this distant and somewhat provocative perspective, the design of Swedish single-family houses seems not to have developed in a sustainable way.

A suggestion for future work is a study of the efficiency of heating systems for single-family houses that also considers the outdoor part of the system. In addition to energy use, major material needs and side effects should be included in the study.

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Appendices.

Appendix A. Dissertations, Energy systems.

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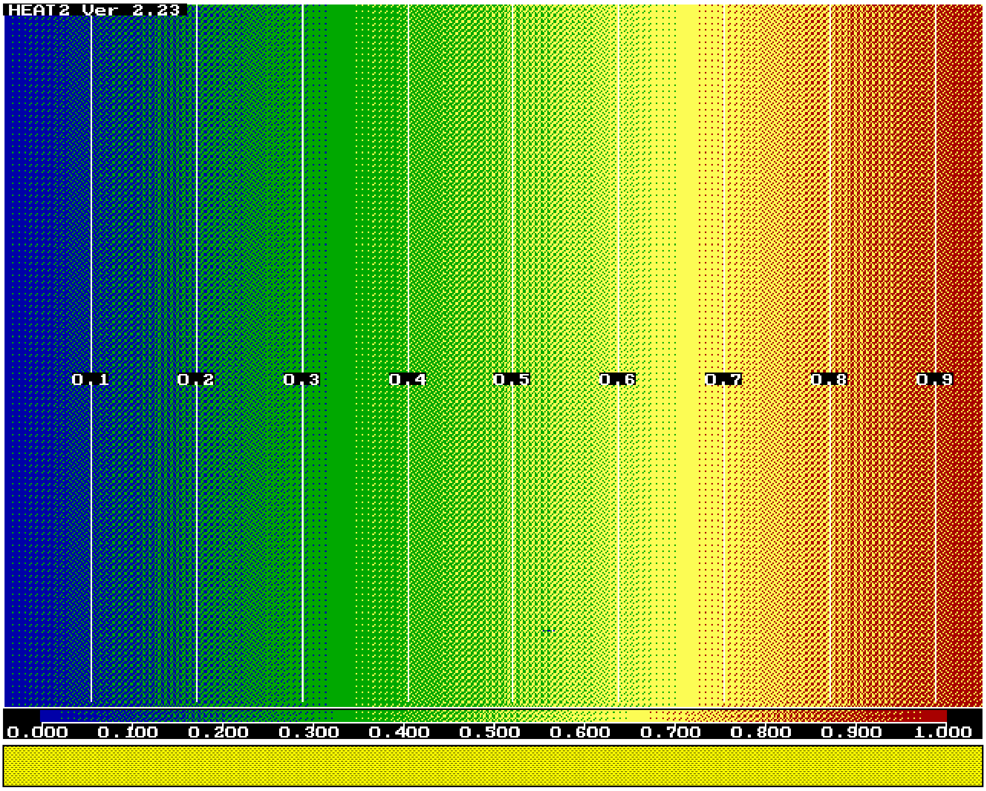
Appendix B. Temperature profiles in materials

B1 Glass-wool insulation



Glass-wool insulation

Figure B1. Temperature profile in a cross-section of wall segment with glass-wool insulation after 8 hours charging with 1°C.

B2 Brick with glass-wool insulation on the inside

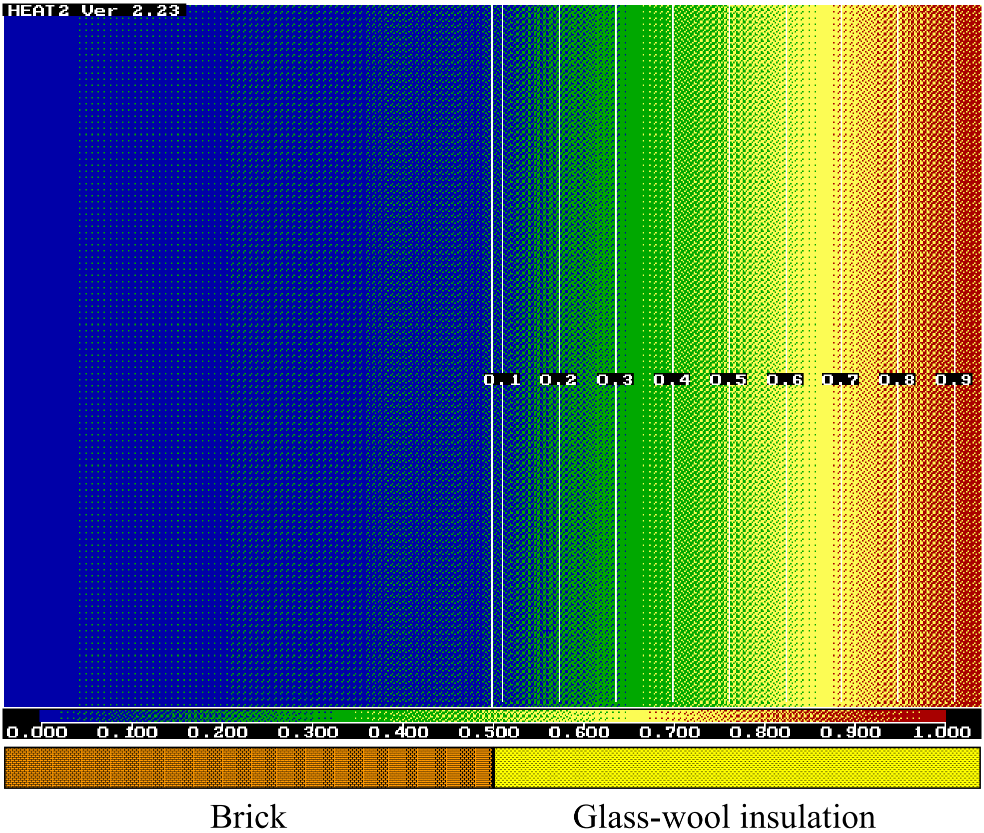


Figure B2. Temperature profile in a cross-section of wall segment with brick and glass-wool insulation on the inside after 8 hours charging with 1°C.

B3 Brick with glass-wool insulation on the outside

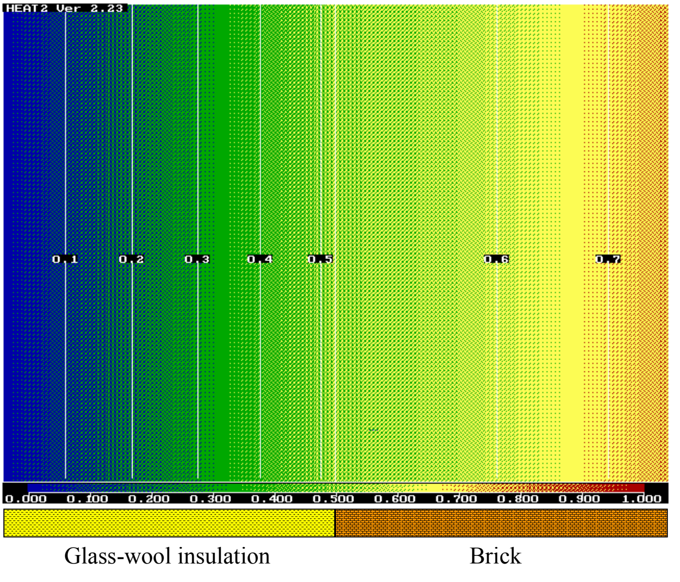


Figure B3a. Temperature profile in a cross-section of wall segment with brick and glass-wool insulation on the outside after 8 hours charging with 1°C.

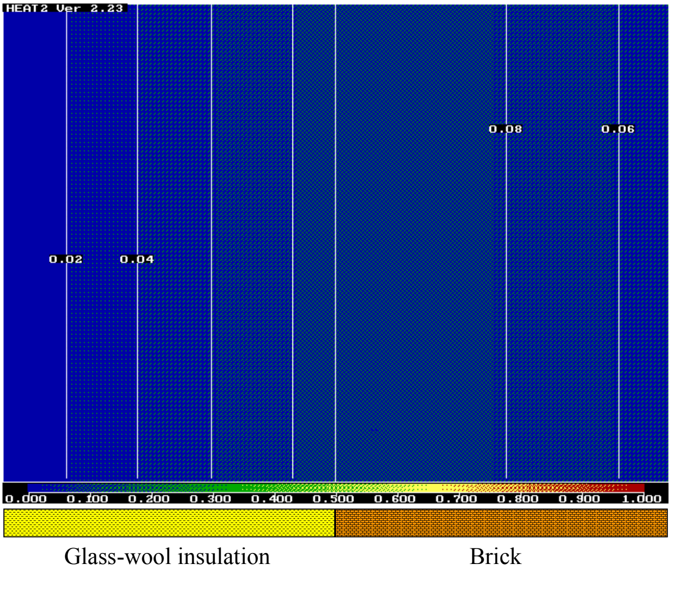
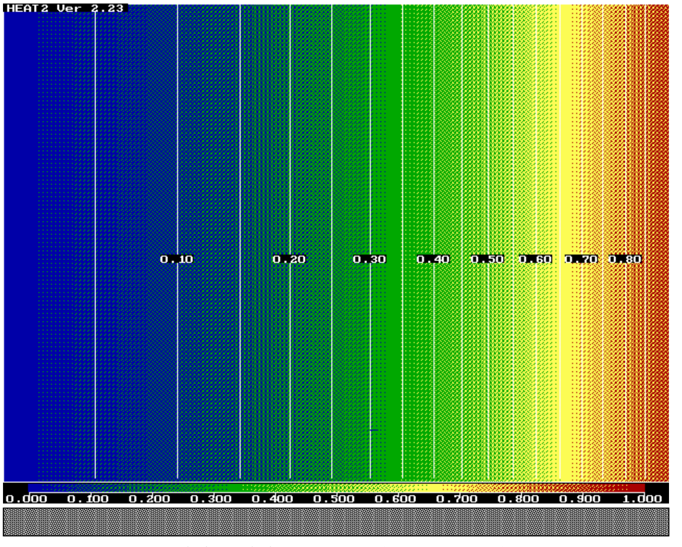


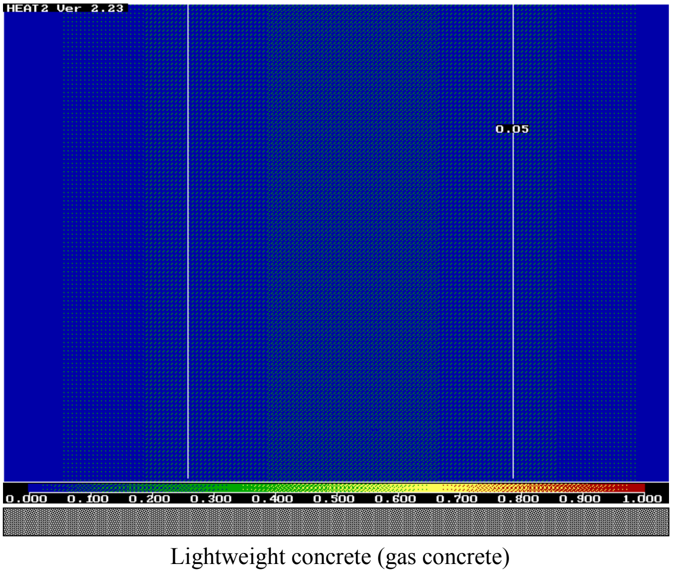
Figure B3b. Temperature profile in a cross-section of wall segment with brick and glass-wool insulation on the outside after 16 hours discharging with 0°C.

B4 Lightweight concrete



Lightweight concrete (gas concrete)

Figure B4a. Temperature profile in a cross-section of wall segment with lightweight concrete after 8 hours charging with 1°C.



Lightweight concrete (gas concrete)

Figure B4b. Temperature profile in a cross-section of wall segment with lightweight concrete after 16 hours discharging with 0°C.

B5 Glass-wool insulation with gypsum board on the inside

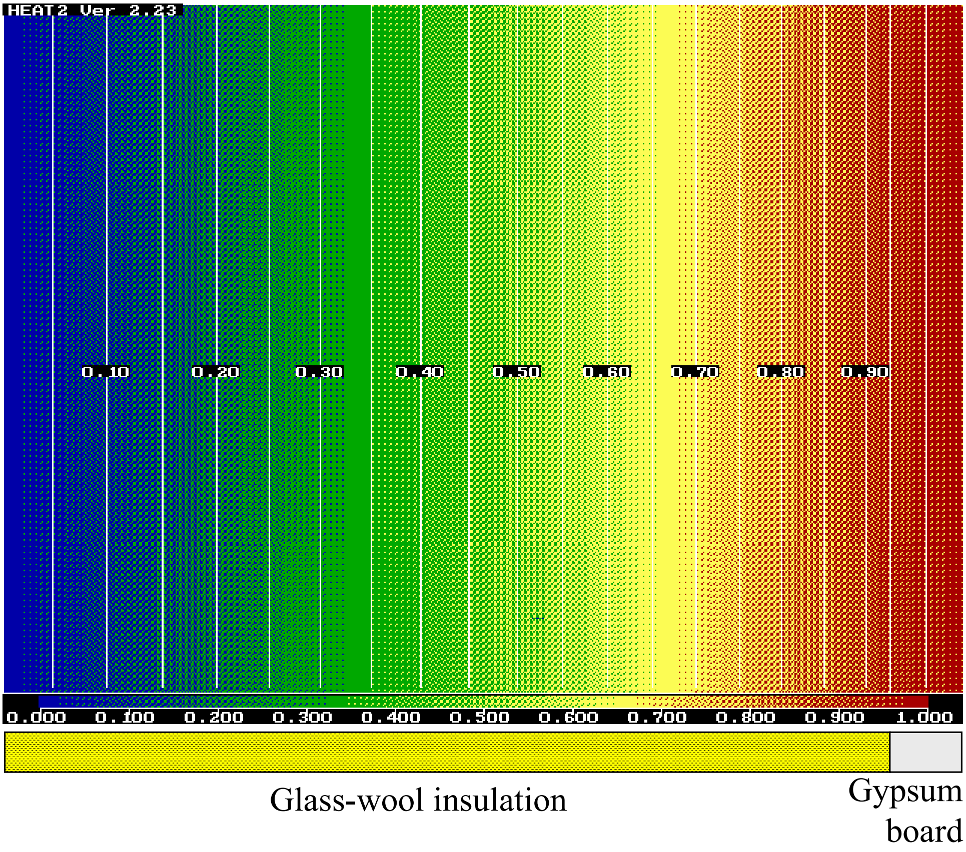


Figure B5. Temperature profile in a cross-section of wall segment with glass-wool insulation and gypsum board on the inside after 8 hours charging with 1°C.

B6 Concrete floor with cork floor on surface

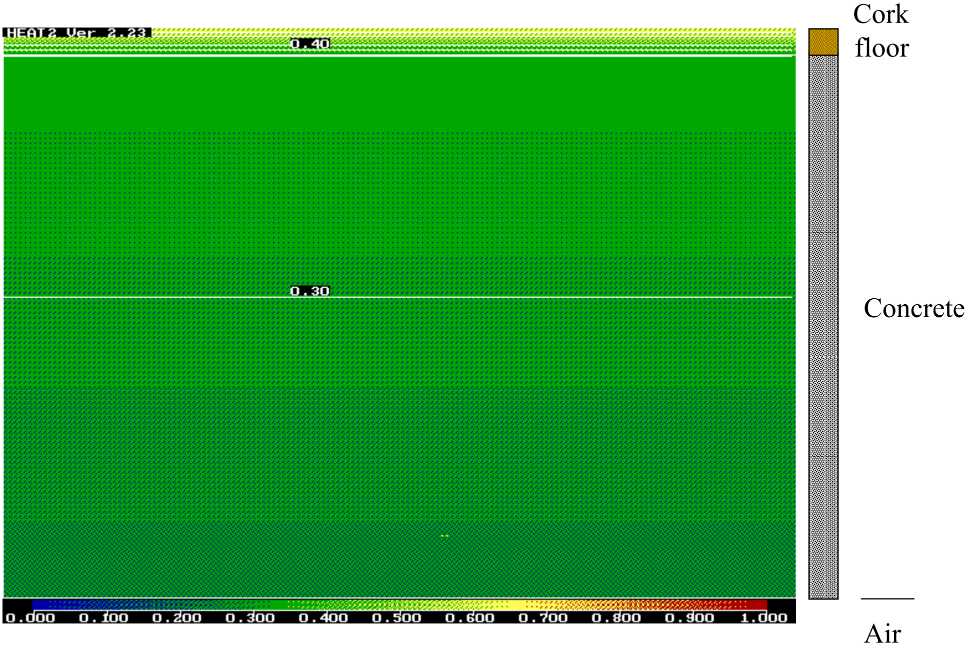


Figure B6. Temperature profile in a cross-section of concrete floor segment with cork floor on the upper surface after 8 hours charging with 1°C.

B7 Insulated concrete floor with cork floor surface

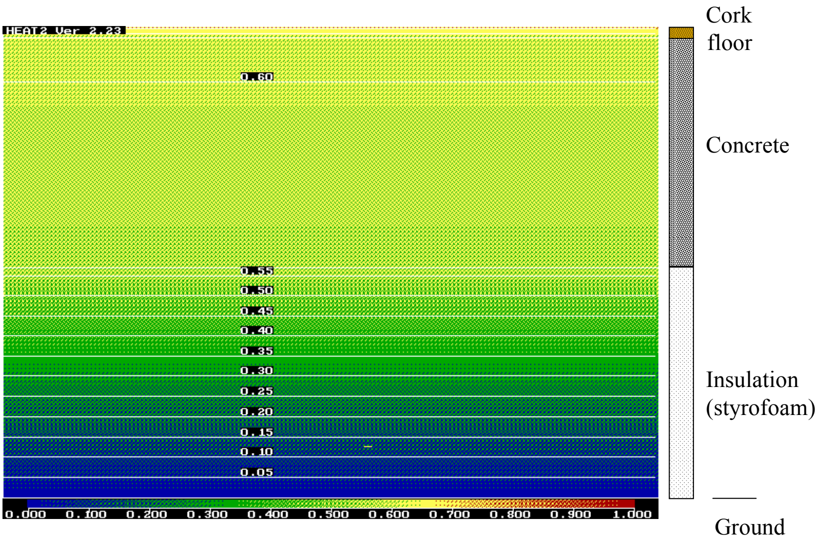


Figure B7a. Temperature profile in a cross-section of insulated concrete slab-on-the-ground segment with cork floor on the upper surface after 8 hours charging with 1°C.

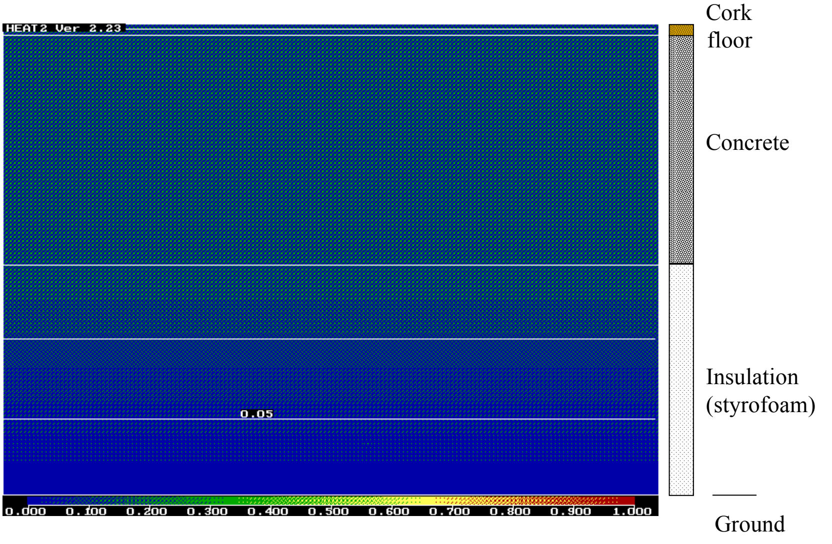


Figure B7b. Temperature profile in a cross-section of insulated concrete slab-on-the-ground segment with cork floor on the upper surface after 8 hours charging with 1°C.

B8 Insulated concrete floor

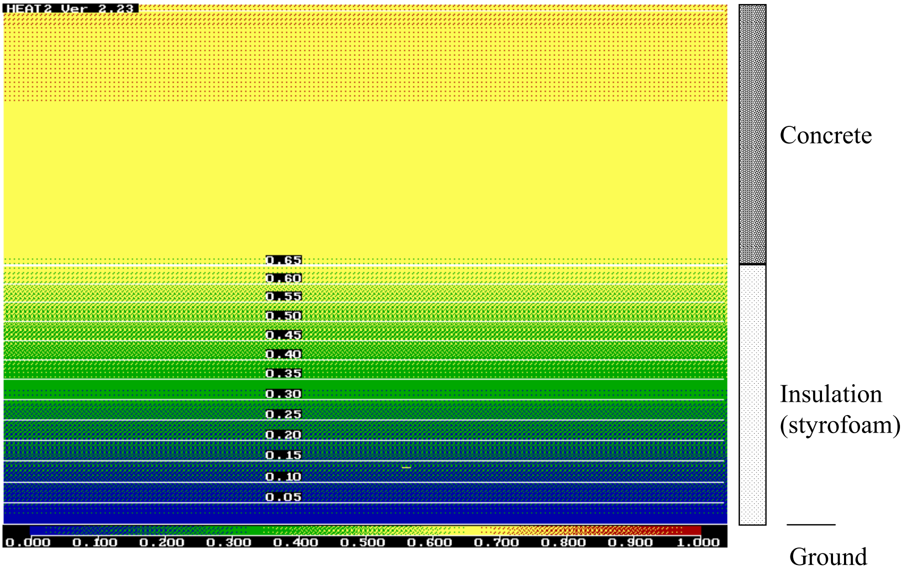


Figure B8a. Temperature profile in a cross-section of insulated concrete slab-on-the-ground segment after 8 hours charging with 1°C.

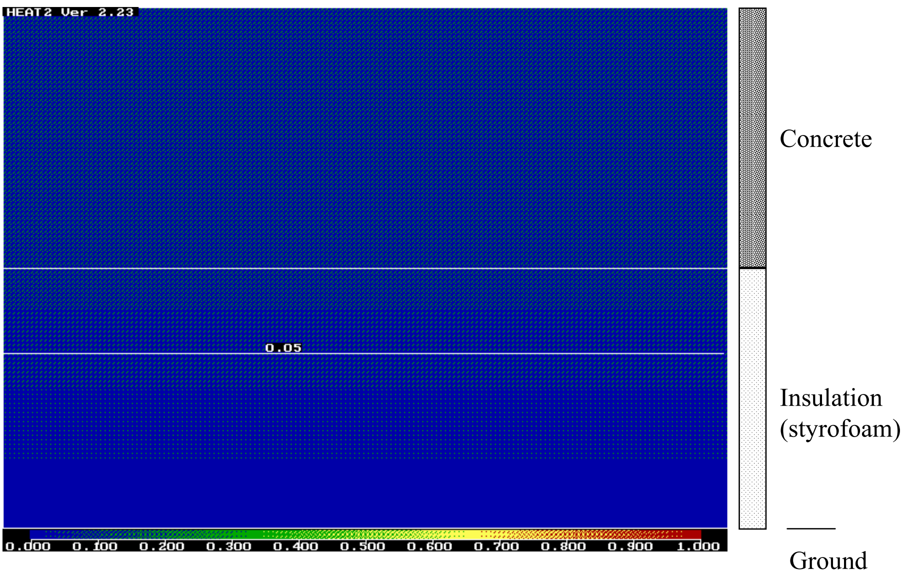


Figure B8b. Temperature profile in a cross-section of insulated concrete slab-on-the-ground segment after 16 hours discharging with 0°C.

Appendix C. Test houses

C1. Övertorneå test house

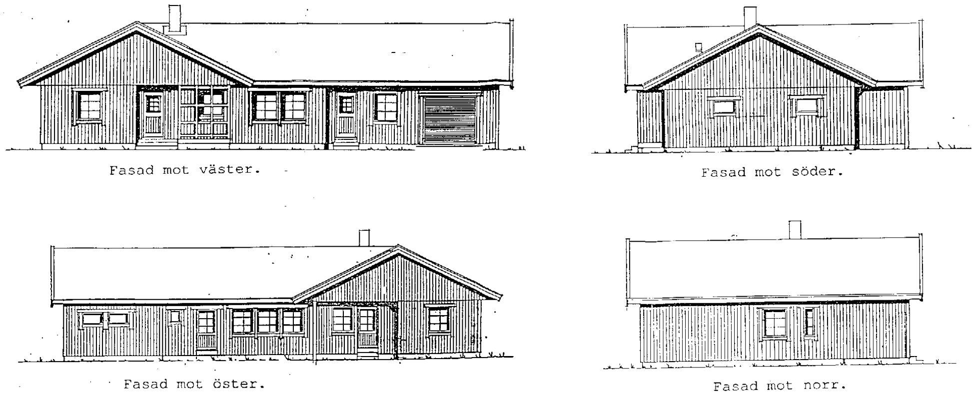


Figure C1a. Face of the Övertorneå test house.

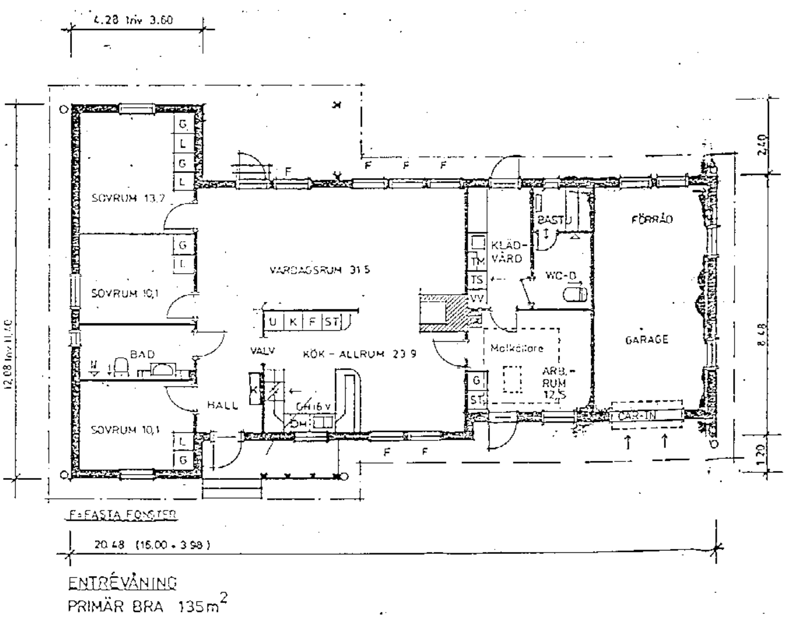


Figure C1b. Plan of the Övertorneå test house.

C2. Ljungsbro test house

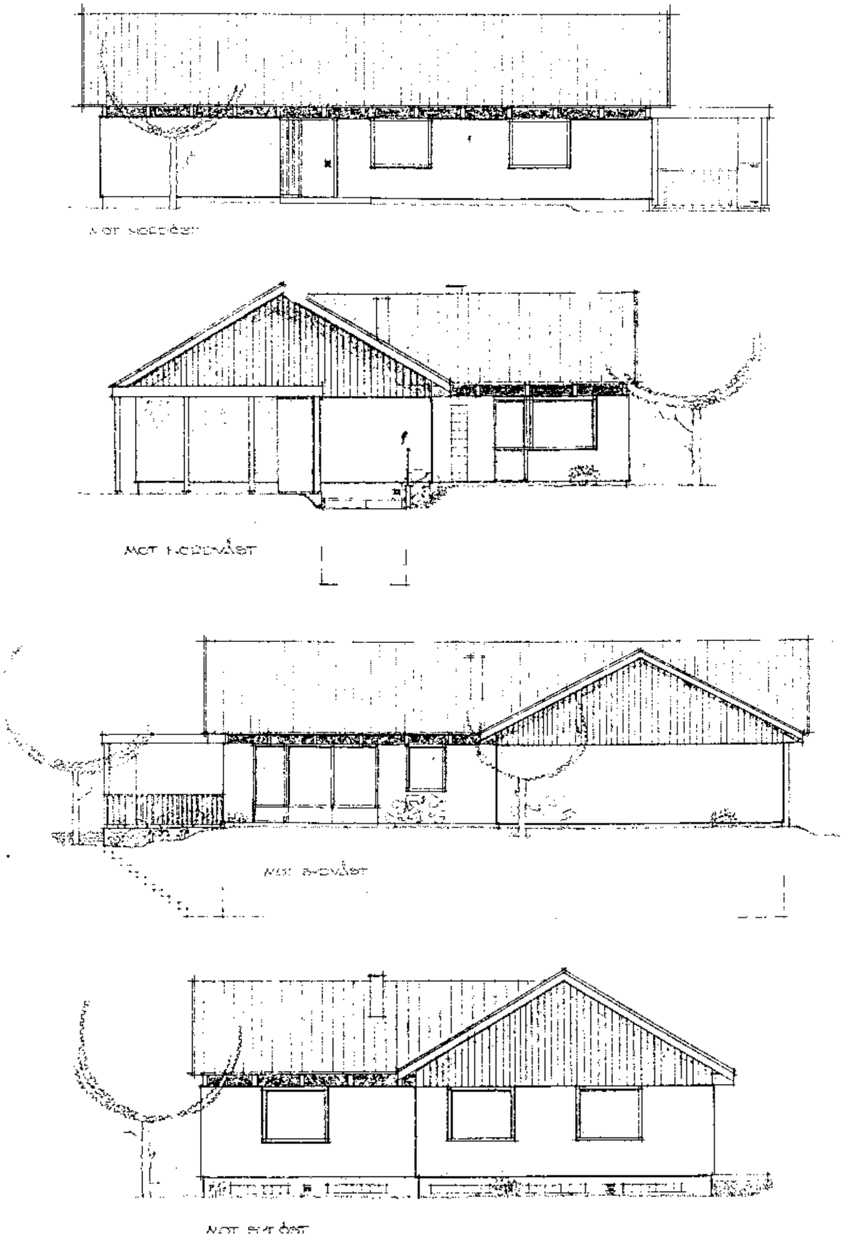


Figure C2a. Face of the Ljungsbro test house.

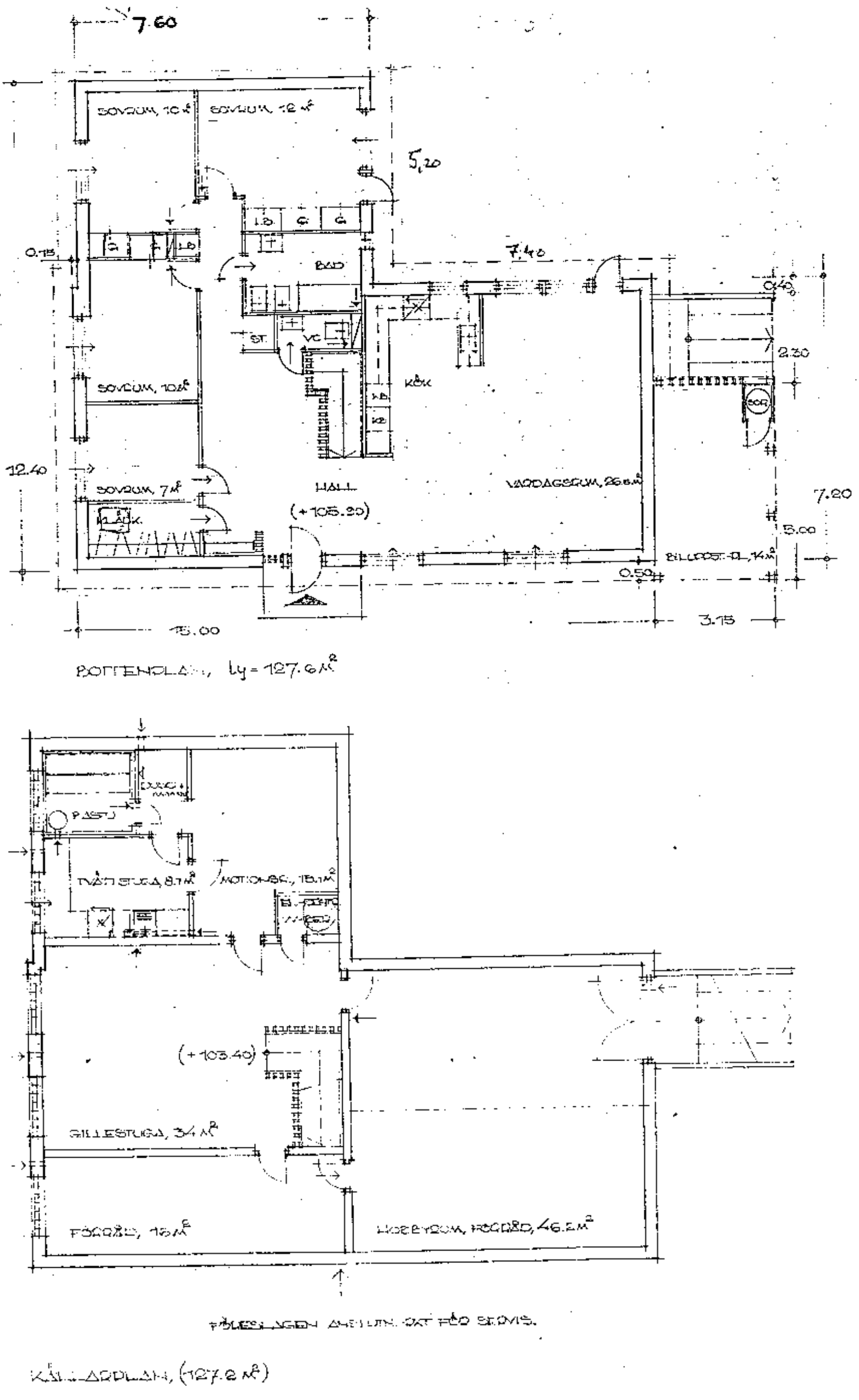


Figure C2b. Plan of the Ljungsbro test house.

C3. Hus 15 test house

Figure C3. Face and plan of the Hus 15 test house.

Appendix D. Simulation based algorithm for Hus 15

If the equation is small, like (5.9), it would also possible to solve it by hand, by using some spreadsheet software, e.g. Excel [62]. The method presented here may not be generally applicable, but has the advantage to be transparent and should be possible to follow. The example is calculated for the 8 h experiment.

<u>Temperature values:</u>

$T_{0\ found}$	= 21.8°C	Values of $\overline{T}_0$ before heating, average of all days of the 8 h experiment period.
$T_{0\ floor}$	= 21.1°C	
$T_{0\ ground}$	= 21.1°C	
$T_{8h\ found}$	= 32.6°C	Values of $\overline{T}_8$ after heating, average of all days of the 8 h experiment period.
$T_{8h\ floor}$	= 24.3°C	
$T_{8h\ ground}$	= 23.2°C	

<u>Parameter values:</u>

C_{found}	= 620 Wh/K	16 beams, 8.4 * 0.22 * 0.05 m3, specific capacity 1.5 MJ/m^{3}K = 2.22 MJ/K = 616 Wh/K.
C_{floor}	= 1 340 Wh/K	80.6 m^2, of wood, 0.04 m, specific capacity 1.5 MJ/m^{3}K = 4.84 MJ/K = 1 343 Wh/K.
$P_{found\ heating}$,	= 2 240 W	17.9 kWh (Table 5.3) / 8 h = 2 240 W
$P_{main\ heating}$.	= 130 W	1.05 kWh (Table 5.3) / 8 h = 130 W

<u>Initial values of parameters to be identified:</u>

$R_{f\text{-}fl}$	= 0.0016 K/W	from Table 4.2; 0.13 m^{2}K/W * 80.6 m^2 floor area
$R_{fl\text{-}g}$	= 0.0016 K/W	from Table 4.2, 0.13 m^{2}K/W * 80.6 m^2 floor area
$C_{ground\ fl}$.	= 4 900 Wh/K	from Table 4.7, storage capacity of modern single-family house (entire house)

First step of the equation.

Use the initial temperatures, $\overline{T}_0$, the values of C_{found} and C_{floor}, as well as of $R_{f\text{-}fl}$, $R_{fl\text{-}g}$ and $C_{ground\,fl}$, and $\overline{P}$. Calculate the changes of the temperatures, $\dot{\overline{T}}_0$, by using (5.5 to 5.7) or, in shorthand

$$\dot{\overline{T}}_0 = \overline{A} \cdot \overline{T}_0 + \overline{P}$$

Calculate the temperatures $\overline{T}_1$, after a small time step Δt. In this solution, 3 minutes was used. This yields 160 steps (n_max = 160).

$$\overline{T}_1 = \Delta t \cdot \overline{T}_0$$

Consequent steps.

Calculate the changes of the temperatures at step n.

$$\dot{\overline{T}}_n = \overline{A} \cdot \overline{T}_n + \overline{P}$$

Calculate the temperatures at the next step, $n+1$.

$$\overline{T}_{n+1} = \Delta t \cdot \dot{\overline{T}}_n$$

Repeat until n = n_max (and t = 8 h)

Adjusting $R_{f\text{-}fl}$, $R_{fl\text{-}g}$ and $C_{ground\,fl}$:

Let $\overline{T}_\varepsilon = \overline{T}_{8h} - \overline{T}_{160}$, that is, subtract the calculated temperatures from the ones given from the experiment. It is desired to make this temperature difference, $\overline{T}_\varepsilon$, as small as possible. This is done by minimising the squares of the components, i.e. minimise

$$\left|\overline{T}_\varepsilon\right|^2 = \left(T_{8h\_found} - T_{160\_found}\right)^2 + \left(T_{8h\_floor} - T_{160\_floor}\right)^2 + \left(T_{8h\_ground} - T_{160\_ground}\right)^2$$

Adjust one of $R_{f\text{-}fl}$, $R_{fl\text{-}g}$ and $C_{ground\,fl}$ and recalculate until $\left|\overline{T}_\varepsilon\right|$ reaches a minimum. Adjust the next until $\left|\overline{T}_\varepsilon\right|$ reaches a lower minimum etc. The changes can be made by hand, or by some automated procedure (macro). Repeat until the changes of $R_{f\text{-}fl}$, $R_{fl\text{-}g}$ and $C_{ground\,fl}$ are within an acceptable accuracy.

Following this procedure, $R_{f\text{-}fl}$ corresponds to a resistance m = 0.34, $R_{fl\text{-}g}$ corresponds to a resistance m = 0.077 and $C_{ground\,fl}$ = 4 400 Wh/K.