Sustainable energy use in houses

Will the energy use increase with time?

Study of literature and computer estimations

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Report TVBH-3041 Lund 2003
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ISRN LUTVDG/TVBH--03/3041--SE(100)
ISSN 0349-4950
ISBN 91-88722-26-0
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Abstract

Numerous of energy saving measures have been carried out in the Swedish housing stock since the energy crisis in the 70's. Additionally, there have been many low-energy housing projects. However, so far few of these have been followed up after some years in operation concerning the energy use. That the energy use stays on a low level is important from a sustainable perspective. Three follow-ups have been found during the search of literature and they show a slight to a substantial increase (5-40 %) of the usage level after five to ten years in operation. Thus, the main hypothesis of the project "Sustainable energy use in houses" is that the energy use increases with time in buildings. The aim is to verify this as well as parameters influencing the change. The report in your hand presents the findings of the first phase of the project, the literature study. In addition, the results from a theoretical sensitivity analysis using the energy computer program Enorm 1000 are given.

In general there seems to be a lack of research, especially field research, on the topic of durability and performance over time for a number of building-related parameters. Some of the findings in the literature studied are: The air tightness of the building and parameters affecting it do not show any major deterioration over time. There seems to be a general tendency of a reduction in the airflow in the ventilation systems. Inspections of loose fill insulation materials show that there is a problem with settlement some years after installation. Gas leakage and other kinds of deterioration might also be a problem. There seems to be a gap to fill concerning the research of ageing of windows, long-term performances of heat pumps and control systems. Regarding the household electricity, no investigations on the long-term performance of electrical appliances and lighting have been studied.

The residents of the house influence a number of parameters significant to energy use. The greatest contribution from the residents is the variations in the energy use between one household and another. The literature points towards that the habits of the residents are of great importance to these variations. The investigations do not agree when it comes to relationships between the size of the household, the age, the social status, the activity, the life style etc. and the amount of the energy used.

Long-term changes in energy use related to the residents are very briefly brought up in two studies, where changes in the size of household and the age of the children are possible explanations. These changes are unfortunately not discussed in more details.

The results from the sensitivity analysis in Enorm showed that the main impacts of the heated floor area, the outdoor air temperature, the ventilation flow and the U-value of walls, roof and floor are the most significant factors to the energy use (of the eight factors tested). One limitation of Enorm was clearly shown in the sensitivity analysis, as the window area was found to not have any impact on the energy use, which seems strange.

Key words: single-family houses, sustainable energy use, durability, long-term performance, changes over time, residents, Enorm, theoretical energy computer estimations, sensitivity analysis, literature study

Contents

Preface

The report describes the first phase in the project ”Sustainable energy use in houses” and includes background information, a literature study of parameters’ performance over time, the influence of the residents and a sensitivity analysis, altogether valuable to the project.

The report has been written at SP Swedish National Testing and Research Institute, with the support from Ingemar Samuelson (supervisor) and Anker Nielsen, as well as Arne Elmroth (supervisor and examiner) and my colleagues at the Department of Building Physics at Lund Institute of Technology.

Finally, the project “Sustainable energy use in houses”, including this study, will result in a licentiate’s degree of the author, which is financed by the Swedish Research Council for Environment, Agricultural Sciences and Spatial Planning (FORMAS), the Swedish National Energy Administration and SP.

Carolina Hiller
Borås 2003

1 Introduction to the literature study

The report in your hand is a study of literature found in the field of energy use in single-family houses. It is to be regarded as a first phase, part of the project "Sustainable energy use in houses". The literature examined refers to, predominantly, Swedish conditions, including Swedish building technique and the Nordic climate. The search of literature has mainly been concentrated to the Swedish libraries, especially the University libraries, reports conducted at SP Swedish National Testing and Research Institute, the data base "Byggdok"[1] and reports of the Department of Building Physics at the Lund Institute of Technology. Additionally, tips on literature have been given by supervisors and colleagues at SP and the Department of Building Physics at Lund Institute of Technology.

Initially, in Chapter 2, the project "Sustainable energy use in houses" is described as well as some previous projects where the energy use in houses have been followed up after some time in operation. Chapter 3 states the objectives of the literature study. In Chapter 4, short background information of the Swedish housing stock and the energy use of houses are given. In Chapter 5 different parameters affecting the energy use are highlighted, especially regarding their durability over time. In Chapter 6 attention is given to the residents' influence on the energy use. In Chapter 7 the results from a sensitivity analysis in Enorm (a computer program used to estimate the energy use in a house) are presented.

It is not always easy to analyse and interpret literature in a correct way. One difficulty when analysing literature is to know the quality of it[2] . Another difficulty is that different terms are used referring to the same thing. As mentioned, the literature presented in this report is mainly considering single-family houses. A clear definition of this type of house is not always given in the reports, books and papers studied. When the term single-family house is used in this report primary detached houses are regarded, although terrace and semi-detached houses might be included within the term, intentionally or unintentionally, when referring to some literature.

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[1] http://www.byggdok.se/

[2] Haugbølle, K. and Clausen, L. (2002). *Kortlægning af bygge/boligforskningen i Danmark.* Hørsholm: Danish Building and Urban Research.

2 Description of the project "Sustainable energy use in houses"

2.1 Sustainable energy use

Since the report Our Common Future (Hägerhäll, 1988), also known as the Brundtland Report, the term *sustainable development* has been widely spread and is given the definition:

Development that meets the needs of the present without compromising the ability of the future generations to meet their own needs.

The report brings up three key areas that are part of a sustainable development: environmental protection, economic growth and social equity.

The production of energy is greatly impaired by a number of environmental problems such as the emission of carbon dioxide, nitrogen oxides, sulphur dioxide, dust, heavy metals, volatile organic compounds, etc. Fuels such as oil, natural gas, coal, etc., consumed for energy production, are examples of finite resources that must be used with consideration, as they are not part of a sustainable society. The environmental problems connected with energy production can be reduced by a more efficient production, a reduction of the amount of emissions and a conversion to more environmental friendly fuels and techniques. However, all techniques of today seem to be associated with environmental problems, more or less. It is therefore of interest to also focus on the *usage of energy*. The energy that is never produced is much better than the used energy in whichever way it was produced. Here the residential sector has an important responsibility as it stands for a substantial part of the energy used in Sweden. The residential, commercial, service sectors stands for almost 37 % of the total energy use in Sweden (Swedish National Energy Administration, 2001).

There has been a number of energy saving measures carried out the last 25 years, primary in the newly built housing stock. In a sustainable perspective it is of great importance that the energy use stays on a low level the entire lifetime of the building and not only when it is newly built or reconstructed. In order to fulfil the requirement of low energy use over time the factors influencing the energy use need to perform well even in a long perspective.

2.2 Previous studies - Follow-ups

There have been many energy saving housing projects, but few of these have been followed up after some years in operation. An interesting question is if the energy use has remained on a low level. To study the long-term energy use of these low-energy projects is of importance, especially in regards to the implementation of energy saving measures to the ordinary housings stock.

Below three projects, where the performance of low-energy single-family houses after some years in operation has been studied, are presented.

2.2.1 "Fifteen years of low-energy houses in Sweden and Germany"

In this Master's Thesis (Weber, 1996) a large number of low-energy housing projects were investigated and evaluated. Four Swedish projects were chosen to determine the long-term energy use of the houses. Here only the findings from Gribbylund (Täby) are presented as the others are described in Chapter 2.2.2.

In Gribbylund 20 low-energy single-family houses were built in 1985. The total energy use measured in 1985 to 1986 is compared to the energy use of the years 1992 to 1995, where figures were obtained from the local electricity supplier.

The results show that there is a slight general increase in the energy use of just above 1500 kWh/year. This corresponds to an increase of approximately 13 %. There are great variations between the different houses where some have even decreased their use. The reasons behind the increase have not been further examined. One speculation is that the there has been increases in the hot water use and domestic electricity use.

2.2.2 "The Low Energy Buildings of the 1980s"

In this report (Berggren et al., 1997) three low-energy housing projects were followed up after ten years in operation. The projects in question, Lättbygg 85, SPARSAM and Rockwoolhusen, constitute in total 25 houses built in the mid 80's. The aim was to document the operational experiences, the energy use and the perceived indoor climate of the houses. One question put forward is whether or not the energy use has remained the same during this period. Any changes made to the buildings were also documented.

The findings were that there occur significant changes, affecting the energy use, in the houses during a period of ten years. The energy use was higher, on an average between 4000 – 5000 kWh/year, in the houses, which means a percentage of up to 40 %. Changes in the residents' demands and wishes had affected the houses and the energy use. This was expressed by reconstructions and altered ventilations flows, which meant an increase in the energy use. Furthermore, there was a considerable number of failures and disruptions in the operation of different appliances. The performance of the heat pumps had in some of the buildings decreased caused by a shortage of working fluid. The failure had not been taken care of due to that there was no equipment indicating the defect. This is the usual case for older heat pumps. Hence, the owner had not notice the decrease in working fluid straight away. A gradual increase of the energy use might be noticed for the observant owner.

2.2.3 The Gothenburg follow-up

The purpose of this project (Nilson and Uppström, 1997) was to make extensive energy efficient retrofits in nine electrical heated single-family houses guaranteeing a comfortable indoor climate. The retrofits gave energy savings of 15 to 50 % of the electricity needed for heating and hot water production. The energy saving project was completed in 1991. Five years after the retrofits had been made the electricity use was investigated again. In most houses the use remained on a low level, although with a slight tendency to increasing electricity consumption. The average energy use during the five year follow-up period had been 18 200 kWh, which is approximately 900 kWh more (5 % increase) than when the retrofits had been made. The reason behind this increase ought to be changed behaviour of the residents, such as changes in the indoor temperature, or changed size of the household. In exceptional cases the increase was due to deterioration in performance of the building services.

It is not unusual, when making energy saving retrofits that the effect of the measures decreases after some time in operation, according to the authors. In some cases there might be technical reasons behind the increase in energy use but mostly the reasons are behaviour-related changes over time.

2.2.4 Comments on the studies

In the Gothenburg study the houses investigated were only nine and the follow-up was only done over a five-year period. The houses in the Gribbylund project were not thoroughly investigated and there was no examination of the underlying causes to the energy increase. The follow-up of the so-called Lättbygg 85, SPARSAM and Rockwoolhusen seem to be the most thorough study with some more parameters measured. All the same, the number of houses investigated in all these follow-up studies was low, which means that the conclusions cannot be said to apply to the housing stock in general. Furthermore, all the houses studied are experimental, low-energy, houses, i.e. the projects have to be seen as pilot projects. The findings give indications of that the energy use might increase or at least vary over time, which is of interest to study further by conducting investigations of a larger number of "normal" houses.

An interesting observation made in the follow-ups of Lättbygg 85, SPARSAM and Rockwoolhusen as well as the Gothenburg study was that the residents chose to have rather high indoor temperatures. One reason might be that in a low energy house it is relatively cheap, compared to a normal house, to increase the temperature. Another reason can be that there might be a difference in the actual temperature and the temperature that the residents think they have. The latter theory was confirmed in the Gothenburg study since the residents thought they had a lower temperature than measured (Berggren et al., 1997; Nilson and Uppström, 1997).

2.3 The hypothesis and the objectives of the project

As described above, there is first of all a lack in the number of follow-ups of the energy use in single-family houses (be it experimental houses or ordinary houses) and secondly there are some tendencies of increasing energy use in the studies made. The project "Sustainable energy use in houses", was initiated after a presentation of the findings of the pilot project "The Low Energy Buildings of the 1980s".

The main hypothesis of this project is that the energy use increases with time in buildings and the aim is to verify the hypothesis. The houses in question are ordinary *modern* single-family houses that have been in operation at least 10 years and the focus will be on some common constructions and service systems. The overall goal of the study is to enlighten the field of sustainable energy use in houses. The study can be of value in the choice of techniques and also in the planning phase of buildings.

Questions hoped to be answered are:

- How the energy use in single-family houses changes with time and how this possibly can be prevented.
- How different energy-related parameters, associated with the building and building services, deteriorate over time and which of these parameters that are most significant to changes in the energy use.

The aim is that the project will differ from the studies presented in Chapter 2.2 by investigating a larger number of houses and making a more thorough investigation. Additionally, the project will focus, as already mentioned, on 'normal' modern houses, built after the Swedish energy conservation codes were introduced, which might lead to different results compared to the experimental houses.

2.4 Changes in energy use over time

As stated above, the main hypothesis of the project is that the energy use increases with time in buildings. This increase can be due to a number of factors, such as:

1. Retrofits and reconstruction made to the building
2. Changed performance of the components and materials of the building as well as the building services
3. Maintenance of the building and its components and building services
4. Changes in residential habits

In the literature study the main focus will be on the second and fourth factors, the other ones are only mentioned briefly in the different chapters below.

2.5 Methods

To verify the hypothesis and to find the parameters influencing the changes in energy use the most, the project is divided into a number of steps seen in Figure 2:1.

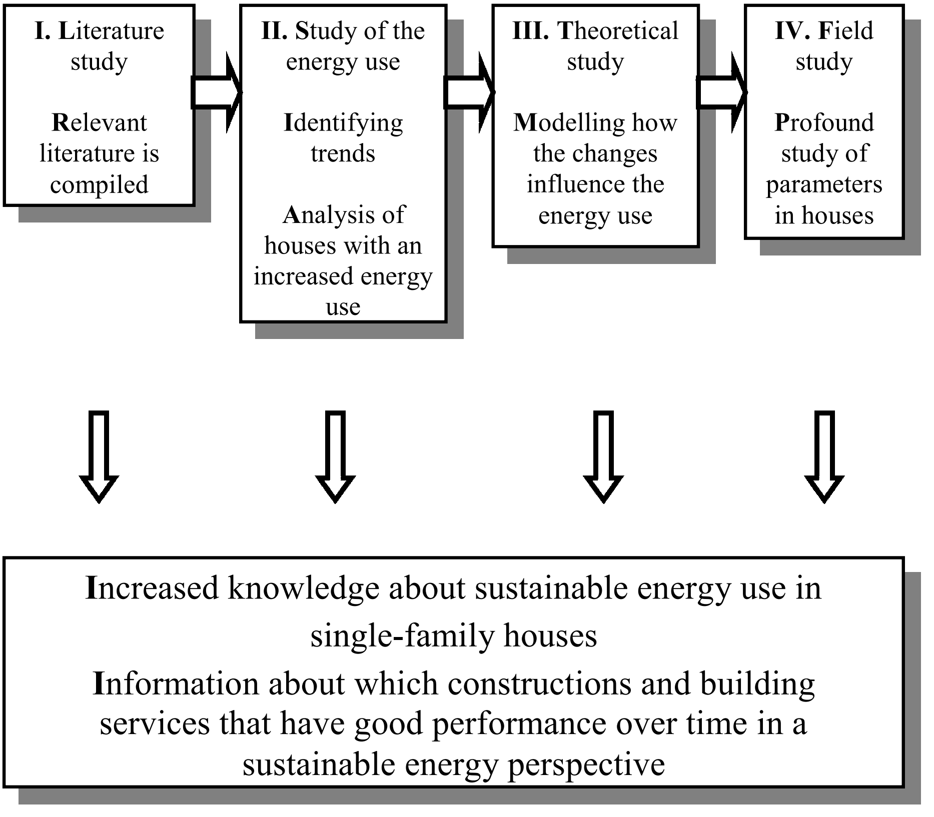

Figure 2:1 The steps in the project ”Sustainable energy use in houses”

The literature in this report will be used and supplemented throughout the project. In the next step of the project energy data will be collected for a large number of houses and trends will be identified. Houses with an increased energy use over a period of time will be analysed further. Using simulation models, in step three, the significant parameters to the change of energy use will be recognised. A field study in a number of houses will thereafter be carried out. The focus will be on the parameters identified in the simulation. The degree of changes of these parameters will be measured and evaluated.

3 The objectives of the literature study

The objectives of this report are to present topics of interest, found in literature, regarding:

- The energy use in houses, especially modern single-family houses
- The performance over time for building components and services affecting the energy use in houses
- The influence of the residents of the house on the energy use

Additionally, a sensitivity analysis will be carried out with the purpose of recognising the parameters most significant to the energy use in houses.

The aim is to compile information that will be relevant to the project "Sustainable energy use in houses".

4 Energy use in single-family houses

The following chapters gives a brief insight into the Swedish housing stock, regarding the number of houses, the most common constructions and building services as well as the energy situation of the housing stock. Some of the major energy saving changes carried out are also brought up as well as some proposed strategies for the future development regarding the energy use in buildings. These chapters give background facts of how the housing and energy situation is at the present as well as some years back. Even if the project "Sustainable energy use in houses" only focus on modern houses, built in the late 70's and forward, Table 4:1 includes building years as early as before 1940. The reason being that the characteristics and trends of the housing stock and energy use, even some years back, gives a wider picture of the situation, which is valuable general knowledge. Unfortunately, recent data for houses built in the 90's have not been found in most cases.

4.1 The Swedish housing stock

According to the Statistics Sweden, SCB, the number of single-family houses that were permanently lived in, in 1999, is estimated to above 1.5 millions (1 568 000). This corresponds to a floor space[3] (living area) of 188 400 000 m^2 or a total heated floor space of 228 500 000 m^2. The total heated floor space for the entire number of houses and non-residential premises is 563 400 000 m^2, which means that the single-family houses represents around 40 % of the heated area in Sweden (Statistics Sweden, 2001a; Statistics Sweden, 2001b). The trend is an increase in built area and for the entire housing stock the increase in heated area has been more than 40 % (1970 to 1995) (Andersson and Klevard Setterwall, 1995). There is a problem related to expressing energy data per square metre due to that the area of a building is defined differently depending on the source of information used. It is not always clear if the area corresponds to all floor area, just heated floor area, only living area, etc. In addition the estimations carried out in reports are based on various methods of data collection[4] . Hence, a correct comparison between data from different reports is difficult.

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[3] The areas given are the ones accounted for in questionnaires. Adjustments to these data might be necessary to get more correct figures.

[4] As an example it can be mentioned that the Statistics Sweden base their data on questionnaires.

In Table 4:1 the dominating constructions and building services of single-family houses are presented, divided into groups of building year. The information does not tell if the heated area, the building services, the construction and the thermal insulation are the original ones. It only gives the state of the building at the time of the questionnaire.

It can be seen that a dominating part of the houses were built before 1940 and in the 60's-70's. Regarding building services there have been great changes both concerning heating and ventilation systems over the years. Most single-family houses have their own heating systems, consisting of oil furnaces or bivalent systems of oil, electricity and/or biomass. In houses built before 1941 the combination of electricity and wood for heating is dominating. For houses built in the period 1941 to 1960 oil is mostly used. After 1960, and especially in houses built in 1976 or later, electric heating systems are increasing in numbers (Statistics Sweden, 2001a; Andersson and Norlén, 1993).

Older single-family houses built 60 or earlier, have natural ventilation. The mechanical exhaust air ventilation became more common in the 70's and the mechanical exhaust and supply air system were more frequently installed in the 80's and 90's (Andersson and Norlén, 1993).

Most single-family houses built 1940 or prior were built with a cellar or crawl space. Of the houses built in the 40's to the 60's the majority have cellars but there are fewer houses with crawl spaces. During the years 61-75 there was an increase in the number of crawl spaces and also the number of houses built with slab on ground. The picture was almost the same for these foundations in the period between 76-88, but there was a major decrease in the number of houses with cellars (Andersson and Norlén, 1993).

Further, it is shown that the U-values for walls and attics generally have decreased for newer houses compared to older ones. A comparison between these U-values and a study carried out nearly twenty years ago (called the ERBOL-study[5]) show that supplementary insulation has been placed in walls in houses built before 1940 and on attic floors in houses built prior to 1960. Additionally it can be added that the most common roof construction for all years is gable roofs (Tolstoy et al., 1984 see Tolstoy et al., 1993).

[5] In the ERBOL-study 1500 houses were inspected and their energy statues was decided. Tolstoy, N., Sjöström, C. and Waller, T. (1984). *Bostäder och lokaler från energisynpunkt.* Gävle: The National Swedish Institute for Building Research. (Bulletin/Meddelande M84:8).

Table 4:1 The dominating constructions and building services of Swedish single-family houses, divided into groups of building year[6]

Building year	**No. of houses / Heated area** (Tolstoy et al., 1993)	**Building services** **Heating**[7] (Andersson and Norlén, 1993; Statistics Sweden, 2001)	**Ventilation** (Andersson and Norlén, 1993)
1940 or prior	526 000 / 86 Mm^2	1 Bivalent system of wood and electric heating 2 Electric heating only 3 Oil furnace only	*Majority:* Natural ventilation
1941-60	324 000 / 42 Mm^2	1 Oil furnace only 2 Electric heating only 3 Bivalent system of oil and electric heating	*Majority:* Natural ventilation
1961-75	499 000 / 81 Mm^2	1 Electric heating only 2 Oil furnace only 3 Bivalent system of wood and electric heating	*Majority:* Natural ventilation *Increase:* Mechanical ventilation
1976-88	346 000 / 52 Mm^2	1976-90 1 Electric heating only 2 Bivalent system of wood and electric heating 3 District heating 1991- 1 Electric heating only 2 Bivalent system of wood and electric heating 3 Other heating system[8]	*Majority:* Mechanical ventilation *Decrease:* Natural ventilation

[6] Note that the number of houses in each group are not based on the total number of houses in Sweden, rather on representative populations.
[7] The three most common heating systems are given, with 1 as the most common and with 3 as the third most common system.
[8] Other heating system can include the usage of a central boiler, natural gas, etc.

The development of windows towards more energy efficient since the mid 70's is clear. What also can be seen when comparing with the ERBOL-study is that there has been an improvement from two to three pane windows for about 9 % of the two pane windows (Tolstoy et al., 1984 see Tolstoy et al., 1993).

Table 4:1 above is not complete and it would be of interest to include typical values for air tightness, type of construction and insulation for walls, type of insulation for attics and U-values for foundations.

Table 4:1 continued.

Building year	Constructions and Thermal insulation (U-value)			
	Foundation (Andersson and Norlén, 1993)	**Walls** (U-value) (Tolstoy et al., 1993)	**Attics** (U-value) (Tolstoy et al., 1993)	**Windows**[9] (Tolstoy et al., 1993)
1940 or prior	*Majority:* Cellars or crawl spaces	0.50 W/m^{2o}C	0.33 W/m^{2o}C	23 %
1941-60	*Majority:* Cellars *Decrease:* Crawl spaces	0.52 W/m^{2o}C	0.31 W/m^{2o}C	11 %
1961-75	*Majority:* Cellars *Increase:* Crawl spaces and slab on ground	0.37 W/m^{2o}C	0.24 W/m^{2o}C	9 %
1976-88	*Majority:* Crawl spaces or slab on ground *Decrease:* Cellars	0.25 W/m^{2o}C	0.18 W/m^{2o}C	81 %

[9] The percentage is given as the window area, which corresponds to three or four pane windows, divided with the total window area (one, two, three or four pane windows) for the particular building year (Area (3 and 4 panes)/ Area (1, 2, 3 and 4 panes)).

4.2 Energy balance and influences on the energy use

In Sweden the energy demand for many existing single-family houses can roughly be divided into 60 % used for heating, 20 % used for hot water production and 20 % used for household electricity. In new houses the average percentages are somewhat different, with a decreased portion of energy being used for space heating.

An energy balance of the energy flows for a residential building can be set up as in Figure 4:1. The balance includes energy for heating, hot water production and household electricity. The energy flows through the walls, floor and the roof of the house, i.e. the building envelope[10], as well as the heat generation (activity) inside the house are demonstrated in the figure.

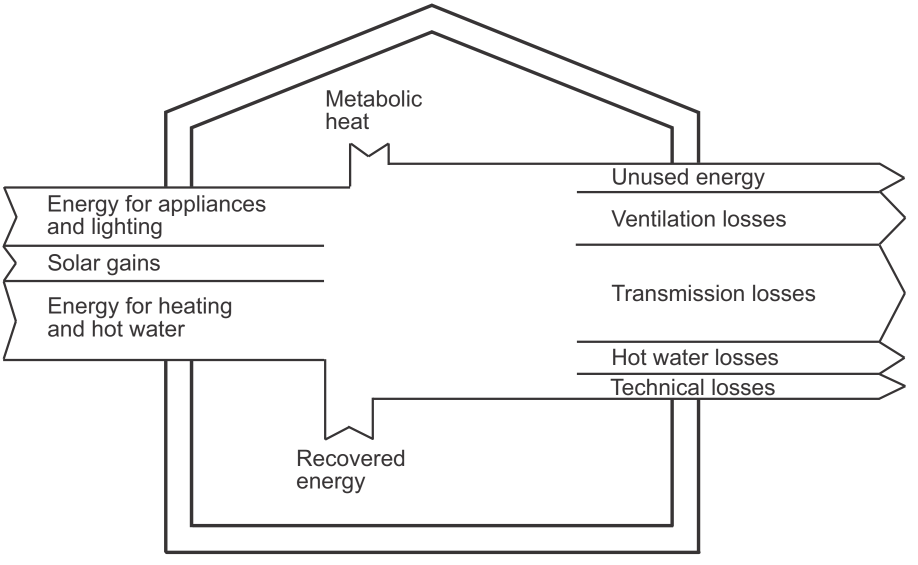

Figure 4:1 Energy balance for a residential building

[10] The building envelope is defined as the boundary or barrier separating the interior heated environment from the exterior environment. The exterior environment could be the surrounding air, the ground, or partly heated or non-heated spaces.

There are some difficulties with designing a figure of the energy flows to, from and inside a building. Firstly, the boundaries of an energy balance are not easily defined. This means that it is not straightforward to design *one* figure that is representative for all kinds of buildings and building services. For example, if the boundary is defined as the building envelope, a heating system with electric or district heating has its main losses outside the boundary, while heating systems producing energy with oil or wood furnaces has its main losses inside the boundary.

Secondly, the common division into the two sides; energy supply and energy loss (see the explanations below), is not always fortunate. For example, it is not obvious which side recovered heat belongs to. It could be seen as a heat supply to the building, but also as a decrease in losses (e.g. ventilation or hot water losses).

Thirdly, the sizes of the energy flows vary greatly from one building to another. For example, newly built houses have usually a lower heat demand due to decreased transmission losses, decreased air leakage losses and greater heat recovery, as well as improved efficiencies. Additionally, there are of course diurnal and seasonal variations. The influences from the residents, the external climate and the building and building services on the energy use are further discussed below and in Appendix A.

Here follows an explanation to the terms used in Figure 4:1.

On the energy supply side:

- *Metabolic heat* is the heat given off from the residents and is dependent on the number of persons, their activity and time spent in the building.
- *Energy for appliances and lighting* is used to operate the devices, but is also partly given off as heat to the surroundings. The amount of heat gain from the appliances is dependent on the efficiencies of the appliances as well as the number of appliances and how frequently they are used.
- *Solar gains* are dependent on the amount of solar insolation on the geographical location, the size and orientation of the glazing, the shading and the usage of curtains.
- *Energy for heating and hot water* supplied by the heating system of the building. Here it is thought of as a flow into the building, which means that in houses where wood or oil is used the flow represent primary energy (i.e. the theoretical energy contents). The energy used for the hot water production includes heat gains from the hot water pipes.
- *Recovered energy* from e.g. the ventilation and hot water system.

On the energy loss side:

- *Unused energy* is described as the share of the heat gains (metabolic, appliances and solar) that cannot be used for space heating. The size of the unused energy is dependent on the time constant of the building.
- *Ventilation losses* are due to both controlled ventilation through the ventilation system as well as the air leakage dependent on the tightness of the building envelope.
- *Transmission losses* are due to heat transmission through the building elements.
- *Hot water losses* are the hot water that is leaving the building, including heat losses to the cold and waste water pipes.
- *Technical losses* are the total heat losses due to the heating system, dependent on the efficiency of the system. These include losses in the heat generation, heat distribution, control system, etc.

In Appendix A Table A:1 the influences on the energy use from three categories; the residents, the external climate and the building and building services are listed. It can be seen that a number of factors (named factor 1º in the table) are influenced by e.g. both the residents and the building and building services, or both the residents and the climate. As an example the hot water usage can be mentioned, where both the armature (the building and building services) and the residents affect the amount of water used. That there are not always a simple relationship between the factors and the influences can further be exemplified with the ventilation flow. The ventilated flow is dependent on the type of ventilation system (the building and building services), the amount of air let in by the residents and the pressure picture over the building due to the climate. Note that the Table A:1 refers to an existing residential building that have a certain design and construction as well as building services. In the design phase of a new building the choice of e.g. the insulation level (U-value) is affected by the climate at the geographical location of the building as well as the type of construction.

4.3 Energy trends and savings

The residential, commercial, service sector etc. used in 2000 144.5 TWh, which stands for almost 37 % of Sweden's total energy use. (After making corrections for the climate conditions of 2000 the amount is 154 TWh.). The total temperature-corrected use of energy in this sector has remained relatively stabled between 1970 and 2000 (Swedish National Energy Administration, 2001). This trend can be explained by that energy savings made have been "eaten up" by the increased heated area. It has been estimated that without the energy saving measures carried out in the period of 1970 to 1995 the energy use would be 50 TWh higher (Andersson and Klevard Setterwall, 1995). Even though the total energy use has been on approximately the same level the last 30 years the energy sources have changed dramatically, especially at the end of the 70's and beginning of the 80's. For single-family houses the change has mainly been from oil dependency to a dependency on electric heating, Figure 4:2 and Figure 4:3.

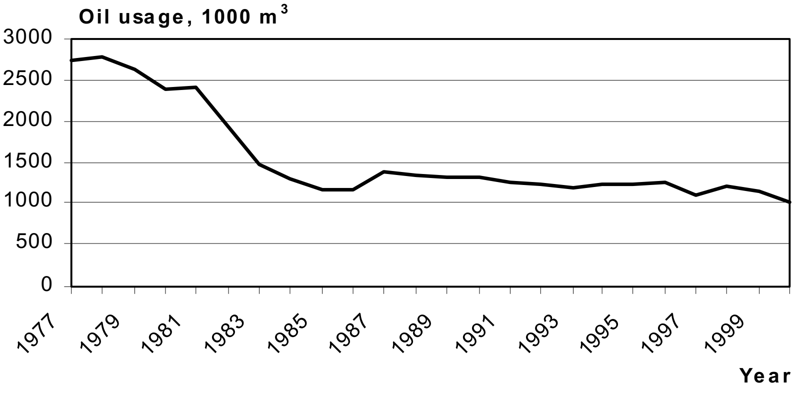

Figure 4:2 Oil usage from 1977 to 2000, single-family houses, Sweden[11]

Comment 1 The consumption has not been corrected with the outdoor temperature.
Comment 2 The oil consumption includes both houses heated with oil only as well as houses with bivalent systems.
Comment 3 Possibly is the oil consumption underestimated for the years 1985 and prior.
Comment 4 In 2000 the definition of one- and two-dwelling buildings is somewhat widen.

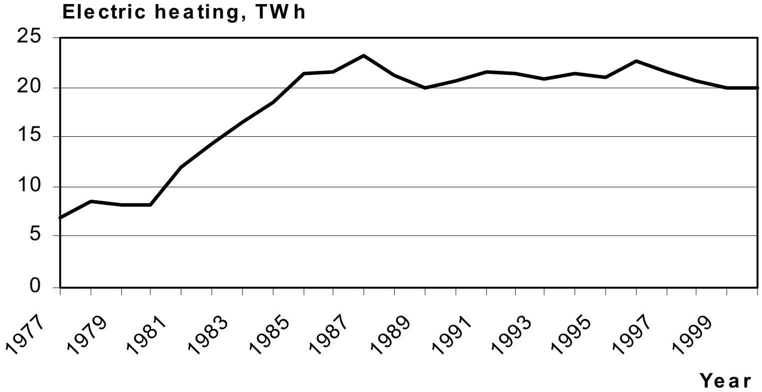

Figure 4:3 Electric heating from 1977 to 2000, single-family houses, Sweden[11]

Comment 1 The usage has not been corrected with the outdoor temperature.
Comment 2 The energy used for electric heating includes both houses, which have electric heating only, as well as houses with bivalent systems (except for the year 1977).
Comment 3 The energy presented includes both electric heating as well as household electricity for the houses in question.
Comment 4 In 2000 the definition of one- and two-dwelling buildings is somewhat widen.

In a report by Carlsson (1992), data concerning the energy use in houses and non-residential premises during the years 1970-1990 have been analysed. A major part of this work consists of analyses of energy statistics from the Statistics Sweden. In the report a more detailed description of underlying factors of the energy use trend during the 70's and 80's are put forward.

[11] Statistics Sweden (1978-2001). *Energy statistics for one- and two-dwelling houses* 1981:13.2, E 1982: 12.1, E 1983.14.1, E 1984:17.2, E 16 SM 8504, E 16 SM 8601, E 16 SM *in 1977-2000* found in Statistic Bulletins Bo 1978:17, Bo 1979:12, Bo 1980:20, E 8702, E 16 SM 8801, E 16 SM 8902, E 16 SM 9003, E 16 SM 9102, E 16 SM 9302, E 16 SM 9305, E 16 SM 9403, E 16 SM 9504, E 16 SM 9603, E 16 SM 9703, E 16 SM 9801, E 16 SM 9901, EN 16 SM 0003 and EN 16 SM 0101.

Table 4:2 Energy use per square metre living area, kWh/m² (Carlsson, 1992)

		1970	1990
Total annual gross (bought) energy[12]	Single-family houses	350	207
	Multi-family houses	340	226
Annual net heating energy[13]	Single-family houses	183	102
	Multi-family houses	191	116
Household electricity	Single-family houses	28	33
	Multi-family houses	32	41

Comment The figures in Table 4:2 have been corrected with the outdoor temperature of the year in question.

[12] The gross (bought) energy is defined as: i) the energy distributed to the house in the case of electric heating, district heating and natural gas and ii) the theoretical energy contents (i.e. the primary energy) in the case of wood and oil furnaces. In other words, no losses in the heating system are taken into consideration.

[13] The net heating energy correspond to the bought energy which is actually used in the building for heating subtracted with the conversion and distribution losses as well as the heat given off to the surroundings from electrical appliances.

Table 4:2 shows that in the period of the 1970 to 1990 the total annual gross (bought) energy per square metre living area has decreased from 350 kWh to 207 kWh for single-family houses. As a comparison it can be mentioned that the decrease is less in multi-family houses, from 340 kWh to 226 kWh (Carlsson, 1992). For the same period the net heating energy use per square metre and year has decreased from 183 kWh to 102 kWh for single-family houses and from 191 kWh to 116 kWh for multi-family houses.

The decrease in bought energy can partly be explained by the reduced net energy used for heating, but also by a reduction in conversion losses during the period of 1970 to 1990. The reason behind this can be found in the shift from oil and wood based heating to electric heating for single-family houses (Carlsson, 1992).

The household electricity used in the residential, commercial, service sector has more than doubled, from 9.2 TWh to 19.7 TWh, between 1970 and 1999.

The increase in the sector as a whole can be explained by an increasing number of households and an increase in the number of electrical appliances (Swedish National Energy Administration, 2001). For single-family houses, the electricity bought for domestic purposes during the period 1970 and 1990 has increased slightly from 28 kWh/m^{2}year to 33 kWh/m^{2}year (Table 4:2). The corresponding figures for multi-family houses are 32 to 41 (Carlsson, 1992).

When it comes to energy saving technology for new buildings it has primary been focused on increasing thermal insulation and air tightness of the building envelope, introducing mechanical ventilation systems with heat recovery and installing efficient heating systems (Adamson et al., 1996). In addition more energy efficient windows have been introduced as an important energy saving measure. This can also be seen in Table 4:1.

The finding of an assessment of the energy use during the life cycle of single-family houses is presented in a report by Adalberth (1995). It was learned that 85 % of the energy use occurs during the residential period. This result gives incentives to additional energy savings during the operation of buildings. In addition it is important to bear in mind that it is not only the energy per square metre that needs to be lowered. In the end it is the total energy used for the residential sector that is significant, which means that the future trend of the amount of heated area is of great importance. These findings also entail that the performance of buildings, influencing the energy use, do not deteriorate over time. The durability of components and systems of the building will be discussed in detail in Chapter 5 in this report.

Finally, it is important to remember that, predominantly, figures for the energy use are given as averages, but there are large variations between different houses and hence the mean values from different studies varies to a great extent. In a number of projects, altogether incorporating 232 single-family houses (including terrace, semi-detached and detached houses), the mean value of the energy use varied between 87 and 244 kWh/m^2 (Dyrstad Pettersen, 1997). The variations and uncertainties of the energy use have been investigated by Pettersen (1997). She concludes that the uncertainties represented by the inhabitants are responsible of about 70 % of the total variation of the energy use, while the building construction (including the building services) causes about 20 – 25 %. The rest is due to uncertainties in the data that describe the outdoor climate. Hence, the uncertainties caused by the outdoor climate might be neglected if uncertainties due to inhabitants are taken into account. These findings are also confirmed in studies by Gaunt and Socolow (1985; 1978).

4.4 The Swedish Building Regulations

The Swedish regulations have in the past focused mainly on the performances of separate buildings components and systems but are today leaning towards requirements on the performance of the entire building. This can be expressed by saying that the focus has changed from *how* the buildings ought to be designed to *what* the buildings should perform (Andersson and Klevard Setterwall, 1995).

The first Swedish energy conservation code came into force in 1978. The characteristic of the Swedish building regulations is that they only regulate the heating demand and not the electricity use. The thermal insulation levels are specified in the regulations as well as the air tightness. In the 1980 edition of the Building Regulations (SBN 80) improvements were made to the rules so that they looked at the building as a whole regarding heat losses of the house (Adamson et al., 1996). It can be added that thermal bridges was not included.

The major change came when the new version of "Plan- och Bygglagen", PBL, (the law on planning and building) was introduced in 1987, which was accompanied by "Nybyggnadsregler", NR, (the rules on new constructions), replacing "Svensk Byggnorm", SBN, (the Swedish building codes). The energy conservation chapter in NR gives two options. One is still to meet requirements on separate parts of the building, involving thermal insulation, air tightness and building services (heat recovery). The second option is to meet the requirements of energy use of the entire building, where there is maximum average heat transmittance coefficient (U-value) stated for the building (Munther, 1996).

In 1994 the NR were replaced with "Boverkets[14] byggregler", BBR, (the rules on building).

[14] Boverket is the National Board of Housing, Building and Planning.

Some of the requirements stated in BBR are:

- Air tightness — a maximum air leakage of 0.8 l/m^2s (m^2 envelope area[15], at a pressure difference of 50 Pascal)

- Indoor temperature — a minimum of 18ºC (directed operative temperature)

- Ventilation — a minimum supply air of 0.35 l/m^2s (m^2 floor area)

- Average heat transmittance coefficient, (U-value of the building) —

$$U_{building} \leq U_{maximum}$$

$$U_{building} = \sum_{i=1}^{n} U_i \times A_i \,/\, \text{Envelope area}$$

U_i and A_i are the U-value and area of each building element included in the building envelope

$$U_{maximum} = 0.18 + 0.95 \times \text{Area of windows, doors, etc.} \,/\text{Envelope area}$$

New constructions as well as rebuildings are greatly influenced by rules and codes. This does not imply that the codes are the most effective mean for a better energy management. In particularly, house-owners have claimed that the present energy codes mean too high production costs and that they, due to the deregulation of the energy market among other things, are not profitable. In a study from the National Board for Industrial and Technical Development (NUTEK[16]) it is pointed out that the Swedish building codes have had a certain effect on the management of energy, but the direct effect of the codes have been limited (Diczfalusy, 1996).

[15] The envelope area is the total area of all surfaces of the building envelope, i.e. the area of all floors, walls and ceilings facing the interior of the building. The building envelope is defined as the boundary or barrier separating the interior heated environment from the exterior environment. The exterior environment could be the surrounding air, the ground, or partly heated or non-heated spaces.

[16] Now included in the Swedish National Energy Administration.

4.5 Proposed strategies affecting the energy use in dwellings (SOU:s[17])

In 2000 the Swedish Climate Committee wrote the report “Proposed Swedish Climate Strategy” (an English summary of SOU 2000:23). The committee suggests that the National Board of Housing, Building and Planning is assigned to draw up guidelines for stricter building regulations of new constructions. The committee proposes a maximum energy use of 110 kWh/m^2year by 2003 and a maximum energy use of 90 kWh/m^2year by 2010. A further step towards an energy use reduction to 60 kWh/m^2year should be considered. The requirements should include energy for heating, hot water and installed household appliances (Klimatkommittén, 2000).

A characteristic of the building sector is the long-term perspective. Half of the housing stock of today is built prior to 1965 and approximately 90 % of the houses that will exist year 2020 are already built. The Climate Committee stresses that rules for reconstructions and extensions of existing buildings should be introduced, leading to gradual energy efficiency (Klimatkommittén, 2000).

Energy efficient household appliances, requirements on windows, higher levels of attic thermal insulation and façade measures are some of the areas pointed out where information, education and other means of actions should be taken towards reaching the energy targets. Investigations of obstacles and driving forces for building contractors, property owners and tenants (residents) to act energy conscious are suggested as well as carrying out measurements in buildings to find out the actual energy use, which will enable a better evaluation of different measures that have been taken (Klimatkommittén, 2000).

In an other report compiled by the Swedish Committee on Environmental Objectives, “The future environment - our common responsibility” (an English summary of SOU 2000:52), strategies on 14 of the 15 national environmental quality objectives introduced in 1999 are presented. In the national goal of “A good urban environment” it is among other things stated that there should be an efficient use of energy. This committee suggests steps similar to that of the Climate Committee. Additionally, a reduction of the

[17] SOU = Statlig Offentlig Utredning

energy use in the entire housing stock to 1995 year's level by the year 2010 and to at least 50 % by 2050 is proposed. Furthermore, it is suggested that that a system for environmental and energy certification of buildings is developed. The certification should involve a guarantee of the performance of the building envelope and producer liability (Miljömålskommittén, 2000).

Work has already started regarding environmental classification of buildings including energy aspects. "A first generation" of systems are being designed and reaching the market. One Swedish system[18] and one system in Norway[19] are known to the author. How the market perceives these systems will be of great interest.

The Committee on Environmental Objectives also enlightens that technical development on its own is insufficient, cause the improvements are mostly "eaten up" by an increase in consumption. In the end it is the total environmental impact that is of significance and the committee believes in technical development supplemented with economical driving forces (Miljömålskommittén, 2000).

It should be added that the targets of energy savings do not only involve the national environmental quality objective "A good urban environment", but also the objectives concerning limited impact on the climate, clean air and natural acidification (Miljömålskommittén, 2000).

[18] Institutet för Byggekologi (2000). *Inventering - Miljöbedömning av fastighet.*
[19] Dyrstad Pettersen, T. (2000). *Økoprofil* [internet publication]. Norwegian Building Research Institute.

5 Performance over time for building components and services

In this chapter a number of parameters affecting the energy use will be analysed regarding their performance over time. These parameters might influence each other. This implies that the effects on the energy use of these parameters cannot be studied on their own. A further discussion on this topic is made in Chapter 7.

A sustainable energy use in buildings is dependent on the durability of the components, materials and building services. This means that building components and materials and building services that are significant to the energy use need to keep their performance over time. The environment surrounding the material during its time in service is also decisive to its expected lifetime, performance and maintenance period (Tolstoy et al., 1993). Workmanship is yet another factor influencing the performance of materials and components (Bankvall et al., 1986).

During the lifetime of a building there will be changes made to a building. To maintain the performance of the building, such as energy efficiency, even after that changes have been made is important. This implies that the building, including its construction and systems, have to be flexible to these changes.

In a report conducted in 1986 concerning the durability of the components and building services (Bankvall et al., 1986), the lack of research in a large number of fields is put forward. Eight years later Samuelson (1994) states that the research areas in need of attention is principally unchanged. This indicates that there is most probably still a shortage of investigations carried out in a number of fields concerning durability in buildings.

The parameters brought up in this chapter have been limited to the ones thought to have the largest impact on the energy use. A selection of studies found on the durability of certain components, materials and building services are presented. Studies carried out in field have been prioritised. Some parameters are only briefly commented, as the author has not come across any research in this field. Hence, there might be an unjustified attention given to certain parameters in regards to their significance to the energy use. The parameters primary discussed below are air tightness, ventilation, windows, thermal insulation, heat pumps, ventilation systems with heat recovery, control systems, electrical appliances and lighting. Changes in the efficiency of the heating and distribution system are not explicitly brought up.

The literature found are summarised in tables in each chapter where the method used, the number of years (time period) and changes are stated. The text in each chapter describes the literature in more detail.

5.1 Air tightness

The building envelope is the shield between two different climates, the indoor and the outdoor climate, having different characteristics, which also varies during the year. In this respect the building envelope has to fulfil certain requirements to keep a comfortable indoor environment, which also has to be maintained throughout the lifetime of the building. One requirement of the building envelope is to be airtight in order to prevent air leakage. The materials included in the building envelope have to be durable and keeping their performance over time (Isberg et al., 1996).

The air tightness is directly linked to the need of heating, which will increase with increasing air leakage. Pettersen states that the air change through holes in the building envelope depends on the outdoor climate, the quality of the craftsmanship and how complicated the building is (Dyrstad Pettersen, 1997).

The deterioration of the building's air tightness might be caused by a number of factors such as the ageing of building gaskets, the mounting of pictures and electrical fittings, which might puncture the airtight layer, or new bushings made through the building envelope (e.g. due to the installation of a cast iron stove) (Nilsson et al., 1993).

Knowledge of materials in the building envelope and the design of joints, connections, weather stripping for windows and doors have since the regulations were introduced in the 70's (see Chapter 4.4) been learned. Investigations carried out have been thought to be sufficient to meet the requirements. However, there is a lack in research about the durability of these materials, although experiences from houses, 5-10 years old, do not show any particular deterioration of the materials. If there is a future development towards even tighter buildings there is a call for more knowledge on this topic (Isberg et al., 1996).

Table 5:1 Presentation of literature found concerning the performance over time for the air tightness of the building

Parameter analysed	Method	No. of years	Changes	References
Air tightness				
Air tightness (air changes per hour)	Measurements in 44 single-family houses.	3-10 years	Before: On average 1.02 h^{-1} After: On average 1.29 h^{-1} Slight deterioration. In most houses no considerable change.	(Nilsson et al., 1993)
Performance of EPDM[20] rubber gaskets in joints	Samples tested in laboratory from an experimental house.	14 years	No significant deterioration, although notable changes after 1-4 years. Fulfilled the requirements of a good airtight wall.	(Holmström, 1996)
Performance of LDPE[21] films as air and vapour barrier	Samples tested in laboratory from an experimental house.	14 years	No indication of deterioration, although there was a reduction of stabilizer. Fulfilled the requirements of a good airtight wall.	(Holmström, 1996; Möller et al., 2001)
Performance of LDPE films as air and vapour barrier	Laboratory tests with LDPE films surrounded by wet concrete.	Not known	Components of the wet concrete accelerate the ageing.	(Jakubowicz and Klaesson, 1997)

[20] EPDM stands for ethylene propylene diene monomer and is a rubber material.
[21] LDPE stands for low-density polyethylene and is a plastic material.

In a Swedish study of 44 single-family houses the durability of air tightness was followed up. The houses were built in 1982-89 by the contractor Hjältevad AB and at the time of construction they were very airtight. 34 houses had an air leakage of less than 1 air change per hour at a pressure difference of ± 50 Pa over the building envelope. At the time of the measurements, which was 3-10 years later, the air tightness has in most houses not changed considerably although the result showed an average of 1.29 air changes per hour, which means a slight deterioration. The reason being changes made, such as the installation of a cast iron stove and insulating the attic, to some of the houses with the unfortunate and needless outcome of a less airtight building envelope (Nilsson et al., 1993).

The evaluation of the results is, according to the authors, that the changes in the air tightness is not of such magnitude that they can be associated with serious defects of the performance of the building's envelope. There is nothing indicating that there is time aspects linked to the slight deterioration of the houses' air tightness (Nilsson et al., 1993).

Rubber and plastic materials exist in many different applications in today's buildings, such as air and vapour barriers in the building envelope. When putting a house together joints appear between building components. If the house is prefabricated the length and the amount of joints can be large. In this perspective it is obvious that the design and the durability of the joints are of significant importance to the building's entire performance (Burström, 1992). Barriers of LDPE[22] films have also an important role to play regarding the performance of the building.

In an experimental wooden house at SP the durability of several materials and compounds have been tested since 1981. The house consists of a number of prefabricated elements. All through the testing period a normal indoor climate has been maintained (Holmström, 1996).

After more than 14 years of exposure the fourth evaluation of the EPDM[23] rubber gaskets was done. The gaskets are placed in vertical and horizontal joints in addition to joints in connections with the frame and wall joists. The conditions for these gaskets are different. The horizontal gaskets, for example, are constantly exposed to compression (Holmström, 1996).

The gaskets fulfilled the requirements of a good airtight wall. The results were rather surprising, as there had been notable changes in performance at the evaluations after 1, 2.5 and 4.5 years of exposure. This implies that the major physical and chemical changes occurred at an initial stage after only some years of installation (Holmström, 1996).

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[22] LDPE stands for low-density polyethylene and is a plastic material.
[23] EPDM stands for ethylene propylene diene monomer and is a rubber material.

In the same experimental house changes in the air and vapour barrier made out of polyethylene have been studied. There were no indications of deterioration of the LDPE film (Holmström, 1996). The results of the investigation of concentration of stabilizer (antioxidant) in the foil are presented in a paper by Möller and colleagues (2001). The findings were that a reduction of approximately 75 % stabilizer of a film inside the wall construction had occurred compared to a film hanging freely exposed to the room environment. The antioxidant had most probably migrated to the materials surrounding the film in the wall. It was also found that the polymer itself, i.e. the LDPE, did not seem to have degraded.

In another investigation, LDPE films were tested, in laboratory conditions, to find out the effect of wet concrete. Wet concrete can be the surrounding environment that the film is exposed to in certain building constructions. The results showed that there are components in the concrete that accelerate the degradation of LDPE films (Jakubowicz and Klaesson, 1997).

5.2 Ventilation

Most of the energy used for ventilation is used to heat the supply air, which thereafter is exhausted out of the building. By using a mechanical system the flow of air can be better controlled even though some energy is needed to operate the fans.

A mechanical system does not necessarily imply that there is a well-performing ventilation system in the building. In Pettersen's thesis work (Dyrstad Pettersen, 1997) she states that mechanical ventilation systems are connected with significant uncertainties. The reasons are:

- It is not always known if the planned and actual ventilation rates are the same.
- The ventilation rate during a longer period is a major problem or uncertainty.
- There is often accidental maintenance.

The Swedish government decided 1991 to implement compulsory ventilations inspections in non-industrial buildings including dwellings. The main reason being a number of reports on increasing health problems, in particular for children in schools and day nursery (Månsson, 1998). The ordinance (SFS 1991:1273) came into effect on January the 1st 1992. The purpose of these compulsory ventilations inspections is to control that the performance of the system is in accordance with the prevailing regulations. At the successive inspections the ventilation system is readjusted to the performance it had at the time of installation.

Table 5:2 Presentation of literature found concerning the performance over time for the ventilation of the building

Parameter analysed	Method	No. of years	Changes	References
Ventilation				
Performance of ventilation systems	Evaluation of 5625 compulsory ventilation inspections of ventilation systems in schools, offices and multi-family houses.	Not known	66 % did not pass the inspections.	(Engdahl, 1998)
Performance of ventilation systems	Evaluation of 10 289 compulsory ventilation inspections ventilation systems in multi-family houses, schools, offices and other premises.	Not known	66 % of the systems did not work sufficient.	(Månsson, 1998)
Performance of ventilation systems	Technical inspections and measurements of ventilation systems in single-family houses (estimated to represent the total housing stock).	No follow up	Approx. 86 % of the single-family houses had ventilation rates below the prescribed rate[24]. On average 0.24 l/m^2s.	(Andersson and Norlén, 1993)
Ventilation rates	Measurements in 44 single-family houses.	3-10 years	A reduction on average of 25 %.	(Nilsson et al., 1993)
Exhaust air flows	Measurements in 18 single-family houses.	3-4 years	A decrease in nine houses with more than 10 %.	(Nilsson and Thornevall, 1995)

[24]The prescribed rate is 0.35 l/m^2s.

In a paper written by Engdahl an evaluation of Swedish ventilation systems is presented. Of the 5625 evaluated systems 34 % passed the compulsory ventilations inspections. The inspections were carried out in schools, offices and in multi-family houses, which were naturally ventilated or had mechanical ventilation systems with exhaust air, exhaust and supply air with or without heat recovery. The time of installation was not known which means that a fair comparison between the different systems cannot be done. Some of the main reasons for failing the test were that the airflow was too low and the systems were unbalanced (Engdahl, 1998).

Other findings were that sufficient maintenance instructions plays a significant role and it was also pointed out that the systems needs to be flexible in case of changes, such as changes in the number of residents and their activities (Engdahl, 1998).

In a report, of the same year, yet again the experiences of the compulsory ventilations inspections are accounted for. It was found that 2/3 of the systems do not work sufficiently at the turn of the year 1997/98. The most common failure was due to that the flow of air was not satisfactory. There was also a difference in the number of shortcomings between different ventilation systems. The buildings with natural ventilation had most deviations, while the exhaust and supply air ventilation (balanced system) with heat recovery had the fewest failures. The later system is equipped with an alarm system indicating when there is something wrong, which is given as a probable explanation to that this system had the fewest failures. Another finding was that recurrent inspections resulted in a reduction in the number of failures (Månsson, 1998).

In the above described follow-up reports on the performance of ventilation systems only multi-family houses are accounted for. A similar study of the compulsory ventilations inspections in single-family houses is not known to the author.

In 1991-92 a nation-wide study, called the ELIB-study, regarding the indoor climate in Swedish houses was conducted. More than 3300 households, in both single- and multi-family houses, were taken part in a survey. In 1100 of these houses technical inspections and measurements have been carried out. It was found that the ventilation rate was low. A majority, approximately 86 %, of the single-family houses had ventilation rates below the prescribed rate (0.35 litres per second and m^2, corresponding to 0.5 air changes per hour). The average ventilation rate was found to be 0.24 l/m^2s. The corresponding figure for multi-family houses was 0.35 l/m^{2}s (Andersson and Norlén, 1993).

Taking into consideration the year of construction, the average ventilation rate for single-family houses built in the years of 61-75 was 0.20 l/m^{2}s, while the ventilation rate for the remaining housing stock (single-family) seems to be just above the total average of 0.24 l/m^{2}s. The reasons behind these results are not directly discussed in the ELIB-report (Andersson and Norlén, 1993).

Further analyses of the findings in the ELIB-study show that the average ventilation rate is 10 % higher in older houses built 1960 or prior. In houses built after 1960 a comparison between different ventilation systems in single-family houses show that houses with natural ventilation on average have lower levels of ventilation, followed by exhaust air systems, which means that exhaust and supply air systems have the highest ventilation rate. Reconstructions done to the buildings do not show any significant effect on the ventilation rate in this investigation (Andersson and Norlén, 1993).

In the Hjältevad study, discussed in the previous chapter, the performance of the ventilation systems in the 44 single-family houses was measured. At the time of installation of the mechanical exhaust air ventilation systems, the requirement of 0.5 air changes per hour were met. At the follow-up, 3-10 years later, the ventilation rate in almost all houses had been reduced, on an average with 25 %. No thorough investigation to find the causes behind the reduction has been done. The frequency of cleaning the exhaust air filter seems to have little influence on the size of the reduced ventilation rate, although the number of houses is too few for any general conclusion to be drawn (Nilsson et al., 1993).

In another follow-up study of single-family houses, built 1990 and 1991, the exhaust airflow was measured after 3-4 years of operation. It was found that the exhaust airflow on average had decreased in the houses and in nine of them (totally 18 houses) the reduction had been greater than 10 %. Some of these houses even had a reduction as large as approximately 30 %. It was concluded that the ventilation systems are in need of frequent maintenance work, e.g. the cleaning of the exhaust air filter. The cleaning of the exhaust air filter or/and the cleaning of the air terminal devices was carried out in five of the houses and improved airflow rates were achieved in these houses (an average increase of approximately 14 %). In three additional houses the air terminal devices were cleaned with the same result, i.e. an increase in the exhaust airflow (an average increase of approximately 13 %) (Nilsson and Thornevall, 1995).

5.3 Windows

Up to as much as 25 % of the heat losses can be transmitted through the windows of a house. This is of course dependent on the orientation of the windows, types of windows (the number of panes, insulating gas, low-emission layers, etc.) and the size of the windows.

Changes over time in air tightness and insulating performance, and the effect of moisture are aspects to consider, especially for gas filled windows and windows with a selective emission layer (Bankvall et al., 1986).

Unfortunately, no Swedish reports of field studies on the long-term performance of the characteristics of the windows with importance to the energy use have been studied. Regarding the ageing of the weather strips used to air tighten the window the reader is referred to the chapter dealing with air tightness. Two Danish reports on long-term testing in laboratory are here presented.

Table 5:3 Presentation of literature found concerning the performance over time for the windows of the building

Parameter analysed	**Method**	**No. of years**	**Changes**	**References**
Windows				
Gas leakages	Two accelerating ageing tests of gas filled double-glazing.	Corresponds to 10-20 years	Test one: no significant leakage Test two: 4 % mean reduction	(Christensen, 1983)
Gas leakages	Accelerating ageing tests of gas filled double and single sealed units using different sealings.	Not known	Double sealed units with polysulphide had a gas leakage below the requirements. Double sealed units with other sealings and single sealed units had gas leakage above requirements[25].	(Knudsen et al., 2000)

[25] The gas leakage should be less than 1 vol. % per year.

The results from two accelerating ageing tests on gas filled double-glazing units showed no significant gas leakage in one test and 4 % mean reduction of the gas in the other test. It is stated that the test approximately equals to 10-20 years of outdoor (Danish) climate (Christensen, 1983).

In the second Danish study (Knudsen et al., 2000) laboratory tests were made to see if the requirement of a gas leakage of less than 1 volume % per year can be met for doubled sealed pane units with an outer sealing of polysulphide. Some other sealings were also tested as well as single sealed units. The double sealed units with polysulphide had a gas leakage below the requirements. The double sealed units with other sealings and the single sealed units had gas leakage above requirements.

A project on the durability and expected lifetime of energy efficient windows has recently started at SP. A study will be made on how the windows age and if the U-value of the glazing units changes over time.

5.4 Thermal insulation

A variety of insulation materials are used in buildings for different applications. One trend that can be recognised is that the level of thermal insulation in the building envelope has increased over the years. As an example attic insulation of single-family houses can be mentioned. In 1975 a common thickness was 150 millimetres (slabs of mineral wool), which is corresponding to a figure of approximately 500 millimetres today (loose fill insulation) (Isberg et al., 1996).

Table 5:4 Presentation of literature found concerning the performance over time for the thermal insulation of the building

Parameter analysed	Method	No. of years	Changes	References
Thermal insulation				
Ageing of closed cellular plastic	E.g. the diffusion of the insulating gas was tested in laboratory.	Corres-ponds to 10 years	Increased thermal conductivity for one insulation material.	(Kokko and Fan, 1995)
Deformation of insulation materials (slab on ground)	Test of load on insulation material in laboratory.	8 000-20 000 h in laboratory	Deformation increases, although not always a clear relationship.	(Bergström, 1990)
Settlement of loose fill insulation (attic floors)	Inspections in totally 33 buildings (15 were follow-ups).	5-10 years	Thickness below projected: 11 cases Thickness below settlement allowance: 4 follow-up cases	(Serkitjis, 1997)
Settlement of loose fill insulation (attic floors)	Inspections in a number of houses.	1, 3 and 10 years	After 1 year: 12.7 % After 3 years: 15.4 % After 10 years: 18.5 %	(Svennerstedt, 1998; 1986)

The thermal conductivity of cellular plastic materials, such as polystyrene and polyurethane with gas filling other than air, has a tendency to change over time. This is can be due to that the insulating gas diffuses out of the pores of the material and is replaced by air. In the 1980's this matter became particularly stressed due to the discussion of the environmentally harmful CFC:s gases (Bankvall et al., 1986; Isberg et al., 1996). It should be added that most polystyrene insulations are not gas filled.

The ageing of closed cellular plastic insulation has been investigated in a Finish study. Among other things different insulation materials were analysed considering the diffusion of the insulating gas. It is pointed out that there is a need of investigations of new products as the traditional gases are phased out. In the study it was found in the laboratory that the average thermal conductivity increases after 10 years with 0.0045 W/mK for one of the insulations commercially available. The facing foil, preventing the diffusion of the gas, is naturally of great importance for the durability of the material. The foil needs to be without defects and tightly attached to the insulation (Kokko and Fan, 1995).

The service life of thermal insulation below a concrete slab on the ground, e.g. mineral wool or cellular plastics, is affected by factors like the climate and the load conditions of the ground (Bankvall et al., 1986). The difficulty is that the materials used need to fulfil the requirements of good bearing capacity, good stiffness and little creeping as well as high thermal resistance. A good insulating material is often a low-density material and used below a slab on ground there is high risk of compression of the material, which can cause settings in the building. Settings might lead to deviations in the performance of building components and building services. Furthermore, the thermal resistance of the insulation is reduced when exposed to compression. In a study carried out at SP the influence over time of the load on insulation materials below a slab on ground were investigated. The report shows how the deformation increases over time for the insulation materials. The relationships are not always obvious as the effect of moisture complicates the picture for e.g. mineral wool (Bergström, 1990).

Insulation of attic floors with loose fill materials became more widely spread as a general insulation method in 1983. To start with the method was only used when there was a need of supplementary insulation but are now frequently used as insulation of new buildings (Löfström and Johansson, 1992).

The thermal resistance of loose fill insulation materials has a tendency to decrease over time due to settlement, i.e. a reduction in the insulation level. Cellulose fibres are affected the most, but inorganic substances also have a tendency to settle to some extent. The main factors influencing the settlement are gravity, vibration and varying moisture and temperature conditions. This ageing is important to investigate further in order to be able to compensate with the correct amount of material (Isberg et al., 1996).

Convection is one thing that affects the performance of the loose fill insulation. If the pore system is open as in mineral wool, air movements can arise due to natural convection, which causes an increase in the heat transfer through the material. Forced convection caused by the wind and mechanical ventilation can also increase the heat transfer in the construction (Serkitjis, 1997).

According to the author of the paper "*The influence of air movements and workmanship on ventilated attic floors insulated with loose fill material*" there is a lack of knowledge of loose fill insulation materials. Further more he refers to the results of a study of random inspections of insulations carried out by SP in the period of 1988 to 1996. The insulation materials on attic floors inspected include glass wool, mineral wool and cellulose material. A general improvement can actually be seen during this period, but the author points out that the deviations concerning density and thickness are nonetheless too many. Deviation in thickness, regarded as a settlement of the insulation material, must be taken into account when placing the insulation. The settlement allowance for cellulose material is today 20-25 % and for mineral wool 5 %, which must be met during the whole lifetime of the building (Serkitjis, 1997).

To determine the long-term performance of loose fill insulation materials on attic floors an investigation has been conducted in 1997. Visits were paid to a total of 33 buildings, where the installation of the insulation had taken place during the period of 1987-1992. Some of the visits were revisits, because inspections had been done fairly soon after the installation, and others were first time visits. Glass wool, mineral wool and cellulose insulations were investigated. The findings did not point out any single material to be worse than the others. Things found to affect the insulation materials can be summarised in the following factors:

- Settlement
- People
- Mice
- Conflict between different contractors
- Wind (air movements)

The workmanship when installing the material most probably affects some of these factors.

In 11 of the buildings the thickness was below the projected level. In 4 of the revisit buildings the thickness was even less than the level allowed to settle. Furthermore the investigation showed that a reduction in thickness in 70 % of the buildings was due to compact damages caused by humans and mice. When building new houses the time of placing the insulation can be a conflict between the insulation contractor on the one hand and the building contractor on the other. The consequences of placing the insulation at a too early stage can be compact damage. The wind can cause rearrangement of the insulation, especially insulation of low density. This had happened in 13 % of the cases (Serkitjis, 1998).

According to both measurements and calculations, forced convection of ventilated attic floors can cause 10 % larger heat losses through the construction. Moreover can compression of loose fill insulation materials, caused by mice or humans, lead to a 40 % reduction of the thermal resistance. The influence of natural convection can be regarded as negligible (Serkitjis, 1997).

The number of houses investigated has to be seen as too small, which means that no general conclusions can be drawn (Serkitjis, 1998).

In another field test four attics were additionally insulated in 1984 with loose-fill insulations. The original insulations were considered to not settle further. The insulation material used for two of the attics was cellulose fibre made out of cut recycled newspaper, treated to resist fire, moisture and fungus damage. The other two attics were insulated with mineral wool made out of rock wool insulation respectively fibreglass insulation. The average settlements for the cellulose fibres were 12.7 % and for the mineral wools 3.9 % after one year. Three years after the installation the settlements were 15.4 % respectively 4.0 %. The final measurements were carried out 1994 (i.e. ten years after the installation) and the results were that the cellulose fibres had settled on average 18.5 %. The corresponding average for the cellulose fibres was 4.7 % (Svennerstedt, 1998; 1986).

5.5 Heat pumps

The heat pump technique had a great expansion during the second half of the 70's and the first half of the 80's, including exhaust air heat pumps with an effect of just above 1 kW used in single-family houses. In the 90's the installations of these small heat pumps have been dominating the market (Granryd, 1996).

According to some authors heat pumps are of great environmental interest and the technique is described as the recovery of heat energy that are "leaking" from our buildings. The energy savings that can be made, compared to electric heating, can amount to 60 to 70 percent. A problem with heat pumps is to manage to supply heat even on the coldest days. A heat supplement is thus needed, which means that a bivalent heating system should be installed (Granryd, 1996).

Bankvall (1986) points out the areas in need of research such as the leakage of working fluid, which contributes to a gradual deterioration of the coefficient of performance. The lifetime of the compressor and an increase in dirt contents and the clogging of the evaporator are other problems that needs to be investigated.

The relative short existence of heat pumps and the phasing out of CFC-based working fluids might contribute to the lack of reports on the long-term performances of heat pumps. Exhaust air heat pumps is integrated with both the heating and ventilation systems, which increases the complexity of the system and maybe also the sensitivity. Compressors have been investigated in other applications and have been found to have expected life times of 15 to 20 years according to some studies. The working fluid will gradually leak out to the surrounding. The older types of heat pumps have a greater leakage than newer pumps, which are tighter. The leakage of the older installations did not automatically mean a declination of the performance while these heat pumps had an excessive amount of fluid to start with[26].

Table 5:5 Presentation of literature found concerning the performance over time for heat pumps in the building

Parameter analysed	Method	No. of years	Changes	References
Heat pumps				
Performance of heat pumps	Interviews with 100 heat pump owners.	1-9 years	The no. of failures decreased with the no. of years in operation.	(Granryd, 1996)

In a study of the performance of heat pumps after some years in use it could generally be concluded that the number of failures of the heat pumps had decreased with the number of years in operation. This indicates that there had been start-up defects that had been discovered and repaired. The heat pumps had been in operation for one to nine years during the period of investigation (1985-91). It should be stressed that the study is based on the experience of the residents, which might differ from the actual performance of the heat pumps (Granryd, 1996).

[26] Per Fahlén, Swedish National Testing and Research Institute, phone call spring 2001.

5.6 Ventilation systems with heat recovery

In single-family houses built 1975 or prior it is estimated that 1.5 % have exhaust and supply air ventilation with or without heat exchanger (the total number of single-family houses built 1975 or prior was estimated to 1 350 000)[27, 28]. For houses built 1988 and prior the fraction of exhaust and supply air ventilation with or without heat exchanger had increased to 7.7 % (the total number of single-family houses built 1988 or prior was estimated to 1 695 000)[29]. As can be seen the number of houses with exhaust and supply air ventilation has increased in the 80's (Tolstoy et al., 1993).

In the thesis work by Pettersen (1997) it is stated that the average recovery efficiency during the lifetime of the ventilation system is mostly lower than the efficiency measured in the laboratory. She also points out that the efficiency of heat recovers is fairly uncertain, especially for long periods. This is due to irregular maintenance.

This was confirmed in an evaluation of low-energy houses. Heat exchangers and heat pumps were found to reduce the bought energy needed for space heating significantly, although they did not always reach the expected performance. Furthermore it was found that the heat pumps, used for space heating and hot water, compared to the heat exchangers, gave a greater reduction in energy use[30] (Weber, 1996).

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[27] The group of houses that have exhaust and supply air ventilation *without* heat exchanger is small and are therefore included in the group of houses that have exhaust and supply air ventilation *with* heat exchanger.

[28] 95.0 % of the houses were estimated to have natural ventilation and 3.6 % to have exhaust air ventilation.

[29] 79.8 % of the houses were estimated to have natural ventilation and 12.4 % to have exhaust air ventilation.

[30] The comparison between heat pumps and heat exchangers was made between measured values in houses with heat pumps and calculated values for the same houses as if they were installed with heat recovery instead of heat pumps. The main energy reduction is due to a reduction in the energy used for the hot water production.

Table 5:6 Presentation of literature found concerning the performance over time for heat recovery systems in the building

Parameter analysed	Method	No. of years	Changes	References
Heat recovery systems				
Performance of exhaust and supply air systems with heat recovery	Follow-up of ten exhaust and supply air systems with heat recovery.	5 years	Exhaust airflow changed on average with –38 %, although great variations. Supply airflow had not changed on average.	(Fahlén et al., 1993)

A five-year follow-up of ten exhaust and supply air ventilation systems with heat exchanger was conducted during the period of 1983 to 1990. One of the findings was that the airflows had changed significantly. The exhaust airflow had changed on an average with –38 %, even though the variations were large between the individual systems. The supply airflow had not changed on average. With one exception, the inspections and interviews with the residents indicated that the systems were performing well. The exception was the deposition in the exhaust air ducts, which was found to be a problem. After cleaning had been done in one of the systems the exhaust airflow was increased with 32 % and the temperature efficiency[31] increased with 7 %. In another system the heat exchanger was cleaned, which resulted in an increase of the exhaust airflow with 21 % and supply airflow with 3 % (Fahlén et al., 1993).

5.7 Control systems

A well-functioning control system is a prerequisite for a well performing heating and ventilation system in a building. The amount of control system in a building varies greatly between different types of buildings and is strongly dependent on the type of activity in the building. In single-family houses the amount of control system is limited.

The amount of energy that can be saved differs from application to application. As an example insufficient thermostats can be mentioned. In spite

[31] The temperature efficiency is defined as the actual change in temperature divided by the greatest available temperature difference.

of that the temperature is set to 20°C, the temperature of the room may vary between 18°C and 22°C. The change from insufficient thermostats for electrical radiators to temperature control system can lead to energy savings of 10 % (Swedish National Energy Administration and The Swedish Consumer Agency, 1999/2000). Additionally, this might lead to that the thermal comfort increases. Another example is the switch from controlling the heat manually to a central automatic control system, which can give savings of 20 – 30 % for waterborne heating. Still it is important to adjust the system when significant changes occur over time in a building, such as supplement insulation, changed habits of the residents, etc. (Lagergren, 2001).

In a summary of two IEA[32] annexes the author put forward that a better operation of a building's HVAC-system (Heating, Ventilation and Air Conditioning) leads to a more efficient use of the supplied energy. With the development of computerised control systems, a more efficient optimisation of the service system in a building, suiting the demand of the residents, can be possible. For this to be realized there is a need of development of a system taking into account the relationships between the building, the heating and cooling system and the ventilation system. Other factors like the residential behaviours and outdoor climate need to be considered as well (Månsson, 1995).

Expected service life of the electronics and the supply of spare parts, as well as skill of the maintenance staff are some problem areas that need to be addressed according to Bankvall et al (1986). Another example is that changes over time in the thermostatic radiator valve need to be highlighted.

An integration of the building, the heating and cooling system and the ventilation system creates both prospects and problems Fahlén (1993) states in his report about long-term performance of the control systems. He further declares that the systems often operate insufficiently and that the problems mostly occur when integrating the different systems of a building.

Fahlén (1993) finds that it is common with a disagreement of the stated data and the actual performance of certain equipments, such as circulation pumps and fans. This leads to incorrect flows in the system, which can result in adjustment and controlling problems. Another problem is deposition in the impeller. Regarding regulators there seems to be a lack of knowledge of how they are correctly set. Common problems with valves are deposition and

[32] IEA stands for International Energy Agency.

corrosion as well as degradation of sealing material, resulting in leakage. Another area presented by Fahlén are sensors. Temperature sensors seem to maintain their performance pretty well, even if problems of different kinds might occur. There is a lack of repetitive inspections of the sensors, which results in that their performance is actually not known until there is a break down or there might be an obvious miss-showing of e.g. the temperature. These were some examples highlighted in the report and the general conclusion is that there seems to be a lack in systematic work in the field of durability and maintenance work regarding control equipments in buildings.

5.8 Electrical appliances and lighting

Figure 5:1 gives some rough percentages of energy use for different electrical household appliances. It can be seen that the refrigerators and freezers constitute a large fraction of the total household electricity. The development for cooling devices towards more efficient use of energy can be illustrated by the energy use given in kWh per litre and year. In 1980 it was around 1.80 compared to below 1.50 in 1993 for new refrigerators/freezers. For the ten most efficient ones the corresponding figures were 1.50 and below 0.90 kWh per litre and year (Sandberg, 1996).

As seen in Figure 5:1, roughly 20 % of the household electricity is consumed by lighting. Most of this is given off to the room as internal heat gain. Today energy efficient lights are on the market and in spite of the higher prices the total costs (investment and operation) are less than for ordinary lights.

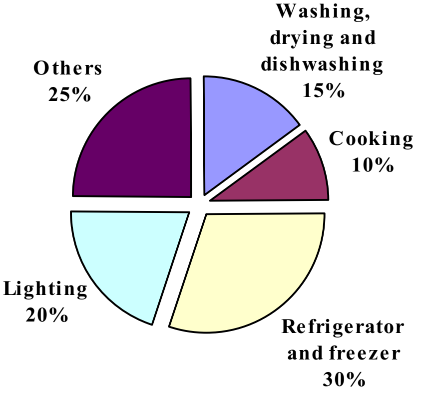

Figure 5:1 The percentages of the energy use for different electrical household appliances (Sydkraft, 1998)

Table 5:8 presents examples from literature on average usages as well as the best available technology (BAT). A completely fair comparison between the different data is difficult as the definition of each category of appliances might be different in the four cases. This applies in particular to the categories cooking and others. The sizes of the different appliances might also differ somewhat.

The reference from NUTEK (1994) in Table 5:8 describes the measured average electricity used in 40 single-family houses (before replacements of appliances hade been taken place). Of course these figures vary a great deal from one household to another. The variation is dominated by the uncertainty of having the appliances. Other factors influencing the energy used for electrical appliances and lighting are the energy efficiencies of the equipments (which are affecting the amount of heat given off to the surroundings), the use of the appliances and the number of persons in the household. The use of the appliances is discussed further in Chapter 6.1.3 (Dyrstad Pettersen, 1997; Sydkraft, 1998).

The building year of the houses in question are also important. New houses have most probably more energy efficient white goods than older houses. On the other hand, if the houses are old enough they might have replaced some of their old white goods with more energy saving ones.

The ongoing development of technology towards more energy efficient appliances is clear between 1987 and 1995/2002. It can further be seen that a large amount of energy can be saved by replacing refrigerators and freezers with energy efficient ones. Lighting is another example where savings can be made.

Table 5:8 Average energy use for different electrical household appliances found in studies, kWh/year

	Average household 1987	**BAT 1987**	**Measurement 1991-1993**	**BAT 1995/2002**
	(Elmroth et al., 1987)	(Elmroth et al., 1987)	(NUTEK , 1994)	(The Swedish Consumer Agency, 2002; Lövehed, 1995)
Washing and drying	750 (450 + 350)	475 (250+225)	437 (299 + 138)	357 (170 + 187) [1)]
Dishwashing	370	230	153	198 [1)] (including hot water production)
Cooking	1030	770	544	568 [2)]
Refrigerator and freezer	1450 (450 + 1000)	563 (336 + 227)	1670	394 (157 + 237) [1)]
Lighting	830	320	1019	300 [2)]
Others	650	590	1246	574 [2)]
Sum	5080	2948	5347	2391

1) (The Swedish Consumer Agency, 2002)
2) (Lövehed, 1995)

Any investigations on the long-term performance of white goods or lighting have not been studied in this report. Most literatures found are focused on the replacement of older appliances by newer, more energy efficient, ones. For refrigerators and freezers the performance of the compressor and the leakage of working agent might be of interest to study further. Moreover is the general wear and tear of these cooling devices, like the opening/closing of the doors, of interest for their long-term performance.

5.9 The effect of moisture, workmanship and maintenance

Moisture can be part of the environment surrounding the material, thus affecting the durability of the material. It also affects the performance that the material should fulfil in its installation. An example is the effect of moisture on the thermal resistance of the material. A change in the thermal resistance means that the temperature distribution and heat flow through the material will be changed. The effect of moisture on the energy use is however thought to be of minor importance. The exception is the drying of building moisture in cellular lightweight concrete, which has some effect on the energy use.

That the different components of a building are correctly installed and/or adjusted to meet the requirements of the house in question is obviously the basis for a well-performing house. The effect of workmanship on the durability might not always be easy to determine and no study has been found where the effects has been followed up over a period of time.

As already mentioned in this report, the literature study has not been focusing on the maintenance of the building and its different components. It has only been briefly brought up here and there in previous chapters. To do regular maintenance work is of great importance especially regarding the performance over time for the buildings components and its service systems.

6 The residents' influence on the energy use in houses

The residents of a house influence the energy use of the building. Some researchers claim that the lifestyles of the residents are of equal significance to the total energy use as energy codes, well insulated houses, the efficiency of different devices, etc. (Diczfalusy, 1996). The large variations in energy use in different houses were briefly mentioned in Chapter 4.3. As Pettersen, Gaunt and Soclow (1997; 1985; 1978) outline, the residents stand for a substantial part of the total variation of the energy use and hence it is of great importance to study the residents' behaviour before a prediction of the energy use is carried out. Only if the residents' behaviour is known the uncertainty may be reduced.

Some parameters influenced by the residents are illustrated in Figure 6:1. The energy use for heating depends on the indoor temperature and the ventilation, and these are parameters that are controlled more or less by the residents. Household parameters like the use of lights, electrical appliances and hot water are controlled by the residents of the house (Dyrstad Pettersen, 1997).

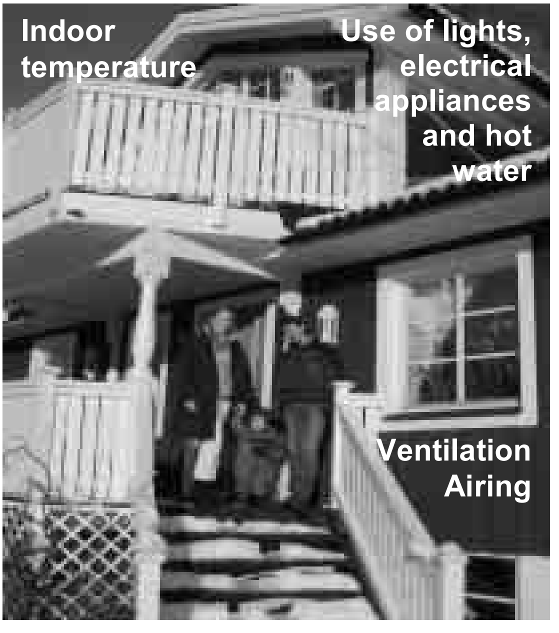

Figure 6:1 The residents of a house influence a number of energy-related parameters.

Additionally there are a number of factors that are not as obviously linked to the residents. Here are some examples that might be important to some degree to the energy use of the building.

- Changes/retrofits could affect the level of energy used.
- The air leakage is dependent on the indoor temperature.
- The usage of curtains influence both the transmission losses as well as the solar heat gain.
- The amount of heat given off from electrical appliances depend on the residents possession and usage of the appliances.
- The time constant (heat capacity) of the building can be influenced by how the rooms are furnished.

The metabolic heat, given off by residents, is yet another factor that have impact on the energy use and there exist a number of values indicating the amount of heat generated by persons to the surroundings. According to Pettersen (1997) these values are uncertain. There are a number of important factors affecting the total heat generation such as the number of persons, the activity and the time spent in the house.

There are many questions yet to be answered on the topic of residents and energy use. To what *extent* do the residents influence the energy use? (*How* do they influence?) What are *the reasons behind the great variations* between different households? Are there *any relationships* between the size of the household, the age, the social status, the activity, the life style etc. and the amount of the energy used? Do the amount of energy used in a household *change over time*? How *energy conscious* are ordinary people? How can the energy used by households *decrease*?

This chapter will be dedicated to some studied reports on the topic of residential impact on energy use with focus on the questions above.

First the term "energy-related habits" needs to be discussed. In this report there is a focus on those everyday household habits that influence the energy use of the house. Such things are housework, hygiene, airing, the usage of different rooms, etc. The indoor temperature is also included within this concept. To only consider every day habits ought to be a good enough limitation as the occasional event has little influence on the energy use in comparison to the every day routines (Gaunt, 1985). Moreover, values and life styles of the residents can be connected to the energy-related habits.

6.1 To what *extent* do the residents influence the energy use? (*How* do they influence?)

How and to what extent the parameters, illustrated in Figure 6:1, are influenced by the residents will be discussed below.

6.1.1 Indoor temperature

It is clear that the energy use for heating is dependent on the indoor temperature and as a general guideline, a decrease of the indoor temperature with 1ºC results in a 5 % decrease of the energy demand for heating[33] .

In the ELIB-study, referred to previously in this report (see Chapter 5.2), the results concerning the indoor temperature show that the temperature has increased between 1982 and 1992 with about 0.5ºC and is 1992 on average 21.0ºC in single-family houses. No significant distinction could be made between the houses regarding the age of the houses, differences in ventilation systems or locations of the houses (Andersson and Norlén, 1993). Pettersen (1997) states that there seems to be a general tendency that the temperature in new buildings is higher than in older buildings.

When it comes to the variations of the temperature in different households, Pettersen declares that the average temperature has a wide variation and it stands for about 23 to 35 % of the total variation of energy, depending on the number of parameters considered as well as the calculation method used (Dyrstad Pettersen, 1997). The study by Gaunt (1985) confirms this, saying that 28 % of the variation in energy use can be explained by the indoor temperature.

It is of interest that evaluations of the energy savings made during the 70’s and 80’s indicate that only a minor part of the savings are achieved by lowered indoor temperatures (Andersson and Norlén, 1993). Possible reasons might be that it is relatively cheap to have a high indoor temperature in an energy efficient house, which means that an increase in the comfort is preferred to a slight decrease of the energy bill. Another reason might be that there is a difference in the temperature that the residents think they have and the measured (actual) temperature in their house.

[33] This is a very rough estimation and originates from that the temperature difference (between outdoor and indoor) in the middle of Sweden is around 20 ºC during the heating season.

6.1.2 Airing / ventilation

Pettersen (1997) states that the uncertainty of the energy loss due to airing is high. Moreover, the numbers of open windows differ significantly from one house to another. The estimated average air change due to airing through windows for Nordic conditions is 0.1 –0.2 air changes per hour. This is quite a substantial quantity considering that the requirement for ventilation is 0.5 air changes per hour.

In a study of airing in Swedish schools the main reasons for airing are the sense of "bad" indoor air and too high indoor temperature. Two reasons for not opening the windows were that the outdoor temperature was too low and that it was too noisy outside (Nordquist, 1998). The reasons given can probably relate to residential buildings as well, although the activities in a school and in a residential house are somewhat different and subsequently the airing habits might differ to some extent.

Gaunt estimates that the variation due to airing gives a variation in the energy use of about 1000 kWh/year for two thirds of the households in her study (Gaunt, 1985).

When it comes to the installed ventilation system of the building, the reader is referred to Chapter 5.2, where maintenance work and adjustment of the system are brought up, which are factors that to some extent are dependent on the residents of the building.

6.1.3 The usage of electrical appliances and lighting

In a study done in Gothenburg it was found that there has been an increase of 60 % in the household electricity consumption per person compared to in the 1970's. This is in spite of that electrical appliances, like freezers, fridges, fans, etc., use less energy today. The reason behind the increase is not known, more than that the standard of living is higher today with more equipments. In multi-family houses the number of person per apartment is less than in the 70's, which might contribute to the increase per person. The results from the study imply that a more effective electricity use do not necessary mean that the total electrical energy use decreases (Wene et al., 1996).

Concerning the usage of refrigerators and freezers it is not only the number of or the size of the refrigerator and freezer that are residential-dependent factors.

The frequency of door opening and amount of food that need cooling are other examples of user dependency having impact on the energy use (Dyrstad Pettersen, 1997).

As declared in Chapter 5.8 the variation in energy use for electrical appliances is dominated by the uncertainty of having the appliances. The usage of the appliances as well as the number of persons in the households are other factors that influence the variation. In Gaunt's study the variation for two thirds of the houses mounted to 600 kWh/year in the summer period (Gaunt, 1985).

When it comes to lighting Pettersen writes in her report that the use of lights depends on the following factors:

- Time of the year and day
- Window areas
- Planned solution
- Curtains
- Attitude towards the use of lights

The type of light and illumination level also influence the energy use. Pettersen concludes that lighting contribute with a high uncertainty and a variation of 1300-2500 kWh (Dyrstad Pettersen, 1997).

Further more, she states that the total influence of household energy, including energy for lighting, electrical appliances and domestic hot water, is estimated to 17 % - 22% (Dyrstad Pettersen, 1997).

6.1.4 Water consumption

Approximately, 140 litres of water per person and day is used in an average household and of this figure about 30 % is used for personal care (hygiene). 70 litres of the water constitutes hot water (Sydkraft, 1998). The domestic hot water consumption depends on:

- The inhabitant's attitude and habits
- Type of equipment
- Need
- Numbers and age of the inhabitants

The energy use for the hot water usage is for an average household about 5000 kWh/year. It was found in the study by Gaunt that, the water usage explains 60 % of the variation in energy use (Gaunt, 1985). This result seems to contradict the finding of Pettersen (1997), where the influence of hot water together with lighting and electrical appliances amounts to 17 to 22 %, depending on the number of parameters considered as well as the calculation method used. The reasons behind the different findings have not been identified.

As the water consumption showed the greatest impact on the variation in energy use in the study presented by Gaunt (1985) it is of interest to find out which water consuming activity that dominates. Laundry, washing-up, bath and shower were thoroughly investigated. The findings were that showers, calculating with average showers of 8 minutes, both use the most energy and give the greatest variations. The average normalised[34] energy use for showers is 2000 kWh/year. The variation between the household that is using the most and the one using the least is 2000 kWh/year for two thirds of the households and 4630 kWh for all households in the study.

Pettersen (1997) discusses the heat gain from hot water and draws the conclusion that it is difficult to know the gain exactly. The amount of water used as well as how the water is used are factors that influence the heat contribution.

6.1.5 Comments

If all the variations for the different parameters outlined above, according to Gaunt's estimations, are added up it comes to almost 22 000 kWh/year, but the total span of bought energy is 16 000 kWh/year. The reason being that there are no significant relationships between one habit and another, e.g. a household with high indoor temperature might have low water consumption (Gaunt, 1985).

However there might be some relationships between the parameters that actually influence the energy use. The sum of the energy contributions of these parameters measured alone is not necessary equal to the contribution of the parameters when regarding them at the same time. This will be clarified with an example taken from the report "The Low Energy Buildings of the 1980s". It was shown that if the indoor temperature is raised at the same time as the ventilated airflow is increased, the change in energy use is larger than when the parameters are considered separately (Berggren et al., 1997).

[34] The figures are normalised to the same number of persons per household (the average of 3.7 persons per household is used). The influence of the size of the household is further discussed below.

6.2 What are *the reasons behind the great variations* between different households?

Below, studies on the variations of the energy use between different households are presented. It is interesting that already in 1941 “the heat cost investigation” (SOU[35] 1942:20) showed that there were great variations in energy use between different houses that could not be explained by building-related factors (Andersson and Olausson, 1987).

In a report by Gaunt with the title “Household and energy - the influence of everyday habits on energy use in Swedish single family houses” she summarises the knowledge, up to 1985, concerning the question: *Why do nominal identical houses have completely different energy uses?* Indications of that the answer is connected with the habits of the household have been put forward based on two findings. Firstly, it had been shown that the use of energy changed considerably when there was a change in owner of a house. Secondly, it had been found that households with high water consumption generally also have high energy use (Gaunt, 1985).

Prior studies referred to by Gaunt is one by Lundström (1982) and one by Palmborg[36] , which both show that a large portion of the variation in energy use could be associated with residential habits. Lundström has also mentioned the change of owner as a reason to the great variations. According to Lundström’s investigation the variations cannot be explained by the size of the household or the financial statues of the household. In the investigation by Palmborg questionnaires were given to 76 electrical heated single-family houses with similar technical standards. Of the total variations in energy use 50 % were explained by habits of the residents (water consumption 50 %, airing 35 %, indoor temperature 15 %) (Gaunt, 1985).

Here it is in order to present an even earlier report, as yet another example of an investigation of nominal identical houses, carried out as a five-year field study of residential energy use in the 70’s in New Jersey, the USA. One of the conclusions made from the project is that variation in energy use for space heating is associated with the residents rather than those technical aspects that persist independent of the resident. Yet again it is the shift in ownership that

[35] SOU = Statlig Offentlig Utredning (Proposed strategy)

[36] Palmborg, Christer Social habits and energy consumption in single-family houses. Department of Sociology, University of Stockholm. ”Energy” Vol 1. No 7 pp 643-650, 1985

gives the strongest evidence regarding the matter. Another proof is given by studies where houses received identical energy saving retrofits and the result showed that the residents using the most energy are the same and those using the least remains the same before and after the retrofits, i.e. the rank order of the use almost stays the same (Socolow, 1978).

To complicate the picture when studying similar houses it was also known by experiences from technical investigations that one house is never identical to another (Gaunt, 1985). The problem of comparing houses, assuming that they are identical, is also highlighted in the thesis work by Andersson and Olausson (Andersson and Olausson, 1987). Even on an estate where nominal identical houses have been built there are differences in their locations, exposures to the sun and wind, maintenance work and possible defects arisen at the construction of the houses. A comparison between nominal identical houses is still thought to give a pretty fair idea of the influence of other factors than building-related ones.

6.3 Are there *any relationships* between the size of the household, the age, the social status, the activity, the life style etc. and the amount of the energy used?

The answer is not straight forward and different findings are presented in the literature studied. The *size of the household*, i.e. the number of persons in the household, and the *age* of the children influence the energy use to some extent but compared to the relationships of energy use and water consumption respectively indoor temperature, they are small. This indicates that the habits of the household are of much greater significant (Gaunt, 1985). Pettersen (1997) states that the domestic hot water consumption is affected by the numbers of persons living in a house as well as the age of the residents. She declares that youths use more hot water than younger children and adults. The age also influences the indoor temperature according to Pettersen. In a Danish project conducted by the Danish Building and Urban Research[37] significant correlations were found between both high heat and electricity consumption (per person), and few persons per household (Jensen and Gram-Hanssen, 2000). Lundström says on the contrary that the variations in energy and water

[37]In Danish it is called Statens Byggeforskningsinstitut.

use cannot be explained by the size of the household (very weak correlation) or the age of the residents (Lundström, 1982).

The *social status* of the residents did not prove to influence the variations in use according to Gaunt (1985), while the Danish study claims that the social status of urban districts are related to the energy use of that area. For single-family houses it was found that the higher the status of the district, the larger the buildings and the higher the heat use. Regarding the average electricity consumption per person it was 20-40 % higher in the wealthy district than in most other areas. On the contrary to heat and electricity consumption, the water usage shows no clear relationship with the type of residential district (Jensen and Gram-Hanssen, 2000).

Some indices seem to be found to that there is a relationship between the number of *activities* and the energy use of a household. Households with high usage of energy tend to live more extrovert lives and most of these seem to be doing water-consuming activities. The households with low energy use tend to live more "quite" lives (Gaunt, 1985).

The Danish study did try as well to find out to what extent *life style* and energy use are interdependent. The findings, connected to the life style theory used in the project, showed that the form of life, i.e. the cultural inheritance, is mostly related to the heat use, which is explained by the socio-economic factors (social status) of the different residential districts. The electricity consumption seems to have more to do with the life style, which is explained by the social influence and the purchase of a range of electricity consuming appliances. Lastly, the style of the individual is connected with the hygiene and appearance of a person and might therefore be related to the water consuming habits (Jensen and Gram-Hanssen, 2000). In the report by Socolow results from questionnaires handed out to the residents did not indicate that there exist any strong correlations between households with high or low energy use and certain profiles (attitudes, preferences, etc.). Neither could any specific behaviour, except high indoor temperature, be connected to high or low energy use for space heating (Socolow, 1978).

Other factors like the financial status, long-term illness, handicap and staying at home or not did not seem to be related to the energy use of a house. The result concerning the latter factor contradicts to some extent previous assumptions about the connection between higher energy use and staying at home (Gaunt, 1985; Lundström, 1982).

6.4 Do the amount of energy used in a household *change over time*?

This is the most interesting question concerning the project “Sustainable energy use in houses”. Gaunt (1985) explains long-term changes in the household’s energy use with changes in the size of the household and the age of the children. Unfortunately she does not explain or discuss it further. Lundström (1982) brings it up as well without giving any answer to the question.

6.5 How *energy conscious* are ordinary people? How can the energy used by households *decrease*?

The energy awareness of ordinary people is of course very difficult to measure and even if the residents might have the knowledge of energy-related issues the translation from words into action can many times be very difficult. Palmborg[38] has tried to quantify the relationship between the household consumption and the attitude of the households towards energy use and he reports on a correlation factor of 0.48 between the factors (Gaunt, 1985). Pettersen (1997) states that the attitude towards energy use probably has the highest impact on the choice of indoor temperature. The use of hot water and the use of lights are also related to the attitude of the residents.

Gaunt (1985) found that the group in her study that uses the least energy also are the ones that are more energy conscious. If this indication is correct it means that a low-energy behaviour is a conscious choice of the residents.

In the analysis of Sonderegger he puts forward his own belief, that there is no interaction between the residents and their houses. The interpretation of this statement, which is questioned by many scientists, could be that residents of an energy efficient house are not acting energy conscious, no more than people living in an ordinary house (Socolow, 1978).

[38] Palmborg, Christer Social habits and energy consumption in single-family houses. Department of Sociology, University of Stockholm. ”Energy” Vol 1. No 7 pp 643-650, 1985

To put a lot of effort on feedback to the residents of how energy saving measures turned out might work as a very effective driving force to decrease the energy use of households. The outcome of a study, which is presented by the authors Seligman, Darley and Becker (Socolow, 1978), is that feedback on a daily basis on the level of usage to the residents has proven to be successful.

Lindén (1996) has made extensive research on the human's behaviour related to the field of environment and energy. She puts forward that changes in the human's behaviour are affected by the individual's motivation and there is a necessity of thorough and understandable knowledge that awakes feelings. The obstacles and the possibilities to changes that exist in the individual's social surroundings affect the translation of words into actions. A fundamental condition to achieve changes towards environmental behaviour seems to be that residents identify their living area as their home. The worse conditions are found in areas of huge building complexes with a very heterogeneous population and a lot of moving of the population. In areas of privately owned single-family houses there seems to exist a great tendency of environmental behaviour on household basis, in opposite to common environmental solutions for the whole area.

In another report by Lindén, written together with Carlsson-Kanyama, (Lindén and Carlsson-Kanyama, 1998) environmentally adapted patterns of behaviour and lifestyles are further discussed. It is stated that the most demanding kind of actions are those who affect a pattern of behaviour and are part of our life style changes. According to the authors this applies to several savings measures, such as a reduction of the indoor temperature.

The potential of saving energy with changed habits might be different in different houses with different constructions, different heating and ventilation systems, etc., due to different responses to the actions, i.e. different driving forces might exist according to Gaunt. She furthermore states that a change in habits is cheaper than the technical energy saving retrofits that can be done to a house and for the individual household a change in habits can improve the household economy (Gaunt, 1985). A change in habits might be cheaper but the question is if it is the easiest measure to be taken. In the Danish report it is put forward that the difficult target is to save on the energy use connected with the life styles of the consumers. Moreover the changes done in consumer patterns towards a more energy-saving life style must be deeply rooted otherwise they tend to be "eaten up" by a development connected with more consumption, leading to higher energy use (Jensen and Gram-Hanssen, 2000).

7 Sensitivity analysis in Enorm 1000 – Computer estimations

The project “Sustainable energy use in houses” consists of four steps, shown in Figure 2:1. The third step is a theoretical study of the parameters influencing the energy the most, with particular focus on those who have a tendency to change over time. In this chapter a sensitivity analysis is presented using the energy calculation program Enorm 1000 (version 1.10).

7.1 The objectives of the sensitivity analysis

The objectives is to give a first coarse predication of the parameters most significant to the energy use, which will be of use to the third step of the project. Furthermore, the purpose is to learn about the advantages and disadvantages with using a theoretical calculation method, such as Enorm 1000. Note that the analysis does not investigate how parameters affecting the energy use change over time.

7.2 About Enorm

Enorm seems to be the energy computer program most widely spread and used in Sweden. It can be used to check the energy performance of a building in relation to the rules on building (BBR), comparing different buildings, etc. The program calculates the energy use for each day of the year. The characteristics of the building must be known in order to give correct input data to the program. The agreement between the calculated and actual energy use is strongly dependent on the type of building and the activities inside the building. For example, Enorm does not calculate accurately for buildings with great window areas or great heat storage capacities. Furthermore, the conditions are assumed to be constant over the day and night and the solar energy and waste heat is assumed to be used fully, subsequently the program does not correspond well with actual values for buildings with great changes in operation. The knowledge about the studied object must be detailed in order to give correct input data to the program. The interested reader is referred to Enorm’s manual[39] for more information on how the program is built up and operated.

[39] Svensk Byggtjänst (1996). *Enorm 1000 Manual.* Stockholm: AB Svensk Byggtjänst.

7.3 The input data and the values chosen for the input data

Three conditions must be fulfilled in order to get valuable results, namely, a correct method of calculation, the input data should be relevant and comparable for all interesting parameters and the input data should be given correct numeric values. When using a calculation program to predict the energy use in a building the input data is as important as the choice of computer program (Fahlén, 1991).

A ”typical” house was “constructed” in Enorm. To keep it simple the house only had one floor. Eight factors (T_i, A_f, F_v, L_a, A_w, U_w, U_b and T_e), thought to be of great importance to the energy use, were thereafter studied. These were varied between a low and a high value, or kept at an average value representing a typical modern single-family house, see Table 7:1. The numeric values were chosen after considering values found in literature, see Table B:1 in Appendix B.1

Table 7:1 Factors studied in Enorm

Factors		Low value (-1)	Average value / Typical house	High value (+1)
T_i	Indoor temperature (interior)	19 ºC	21 ºC	23 ºC
A_f	Heated floor area	90 m^2	125 m^2	160 m^2
F_v	Ventilation flow (m^2 floor area)	0.2 h^{-1} (0.13 l/m^2s)	0.4 h^{-1} (0.27 l/m^2s)	0.6 h^{-1} (0.40 l/m^2s)
L_a	Air leakage (infiltration, m^2 envelope area[40])	0.5 l/m^2s	1.0 l/m^2s	1.5 l/m^2s
A_w	Area of windows incl. frames	10 % of heated floor area	15 % of heated floor area	20 % of heated floor area
U_w	U-value of windows incl. frames	1.00 W/m^2K	1.50 W/m^2K	2.00 W/m^2K
U_b	U-value of walls, roof and floor	0.15 W/m^2K	0.23 W/m^2K	0.30 W/m^2K
T_e	Outdoor temperature (exterior)	1.5 ºC	4.4 ºC	7.7 ºC

[40] The envelope area is the total area of all surfaces of the building envelope, i.e. the area of all floors, walls and ceilings facing the interior of the building. The building envelope is defined as the boundary or barrier separating the interior heated environment from the exterior environment. The exterior environment could be the surrounding air, the ground, or partly heated or non-heated spaces.

7.4 Experimental design[41]

To vary one factor at the time, keeping the others at average values might result in that a number of correlations between factors will be neglected, the consequences being incorrect outputs. To consider all the combinations between the eight factors would result in 2^8 runs and would be time consuming and probably unnecessary due to that many combinations of factors might have none or very weak correlations. A reduction in the numbers of runs can be made by designing a fractional factor test. The price one has to pay when a reduced number of runs are made is that some effects (impacts) on the output parameter will be confounded (i.e. confused). This means that the effect of some factors or factor combinations cannot be estimated separately from one another.

Each factor have been studied given a low (-1) and a high value (1), consequently a linear relationship between the factors and the energy use is assumed. To reduce the number of runs and to get a first indication of the importance of the factors and the combinations of factors, two factor combinations (2^2- tests) and three factor combinations (2^3-tests), which have been called "*pre-runs*", were made. The factors that were not tested were given average numeric values. The test plans are presented in Tables B:2-5 in Appendix B.2.

The results from the 2^2- and 2^3-tests were analysed and *a fractional factorial design (2^{7-3} test)* was conducted. Each factor and each combination of factors were analysed and the impact on the net heating energy (including energy for space heating and hot water production) are presented. The impact (or commonly called the effect) on the output parameter (here the net heating energy) is a measure of to which degree the output parameter changes when a certain input parameter (factor) changes between a set interval. How the calculations of the effects on the energy use were carried out is explained in Appendix B.3.

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[41] The principals and the theory behind experimental design have been gathered from Pauli, M. (2001). *Statistisk försöksplanering - Faktorförsök.* Göteborg: IVF Industrial Research and Development Corporation and Box, G. E. P., Hunter, W. G. and Stuart, H. J. (1978). *Statistics for Experimenters - An Introduction to Design, Data Analysis, and Model Building.* New York: John Wiley & Sons.

7.5 The results and conclusions from factor tests

7.5.1 ”The pre-run” factor test

Table 7:2 The main effect (impact) of single factors in ***the pre-runs***

Factors	T_i	A_f	F_v	L_a	A_w	U_w	U_b	
Average impact on energy use (kWh)	3287	6846	4848	2101	20	2289	4285	-

The area of windows (A_w) seems to have no effect on the heating energy according to the Enorm calculations. The heated floor area and the outdoor temperature, on the other hand, appears to have a large impact.

Table 7:3 The effect (impact) of two factor combinations in ***the pre-runs***

Combinations of factors	**Impact on energy use (kWh)**	**Combinations of factors**	**Impact on energy use (kWh)**
T_i A_f	949	F_v L_a	60
T_i F_v	655	F_v A_w	
T_i L_a	285	F_v U_w	65
T_i A_w	6	F_v U_b	122
T_i U_w	311	F_v T_e	-1079
T_i U_b	581		
T_i T_e	-261	L_a A_w	
		L_a U_w	27
A_f F_v	1428	L_a U_b	52
A_f L_a	558	L_a T_e	-464
A_f A_w			
A_f U_w	677	A_w U_w	704
A_f U_b	1016	A_w U_b	
A_f T_e	-1699	A_w T_e	
U_w U_b	57	U_b T_e	-946
U_w T_e	-506		

The effect on the energy use is an average effect of the interaction between the two factors. The combinations A_fF_v and A_fT_e seem to have some effects. Note that the area of windows (A_w) is not tested in all possible combinations due to that the factor shows little effect on the heating energy use. After studying the two factor combinations, the three factor combinations of interest are presented in Table 7:4.

Table 7:4 The effect (impact) of three factor combinations

Factor combinations	$T_iA_fF_v$	$T_iA_wU_w$	$A_fF_vU_b$	$A_fF_vT_e$	$A_fU_bT_e$	$F_vU_bT_e$
Average impact on energy use (kWh)	190	92	16	-293	-204	-713

None of the three factor combinations show significant effect on the heating energy.

The fictive typical house has a slab on ground as foundation and electric heating with electric radiators as heating system. A change to a crawl space as foundation and a change to a bivalent system were studied in three simple runs, see Table 7:5. All the other factors were held at average values. According to the Enorm program, the energy use is identical regardless of type of foundation. The impact of different foundations can instead be taken into consideration by adjusting the U-value of the foundation. A bivalent heating system of oil and electric heating with water radiators uses less net heating energy than a electric heating system with electric radiators. Enorm calculates with less waste energy given off to the surroundings in the case of electric heating. The bought energy (excluding household electricity) is on the other hand greater for the bivalent system, due to losses in the distribution. Additionally, the electricity used for fans/pumps in the heat distribution of the bivalent system is included.

Table 7:5 The impact of foundation and heating system

Run	Foundation	Heating system	Net heating energy (kWh)	Bought energy (excl. household electricity) (kWh)
1 *(Typical house)*	Slab on ground	Electric heating (electric radiators)	14560	14823
2	Crawl space	Electric heating (electric radiators)	14560	14823
3	Slab on ground	Bivalent system of oil and electric heating (water radiators)	13582	15958

7.5.2 2^{7-3} fractional factor test

A 2^{7-3} test plan was conducted, where the impacts on the energy use from seven factors (T_i, A_f, F_v, L_a, U_w, U_b and T_e) were analysed. The area of windows (A_w) seems to have little effect on the energy use and was for this reason excluded in the 2^{7-3} factor test.

As previously mentioned, there are a number of effects (impacts) that are confounded when a fractional factorial design is used. In the design used in this sensitivity analysis the main impacts of single factors are confounded with three-factor interactions. But as seen in the pre-runs there does not seem to be any strong impact by the interactions from three factors. This indicates that there does not exist any strong interactions between three factors. Further, the two-factors interactions are confounded with one another as listed below.

Two-factor interactions confounded
$T_iA_f + F_vU_w + U_bT_e$
$T_iF_v + A_fU_w + L_aT_e$
$T_iL_a + F_vT_e + U_wU_b$
$T_iU_w + A_fF_v + L_aU_b$
$T_iU_b + A_fT_e + L_aU_w$
$T_iT_e + A_fU_b + F_vL_a$
$A_fL_a + F_vU_b + U_wT_e$

Interactions of higher order are not thought to be of interest. The confounding pattern is due to the generators chosen, which in this case were $\pm U_w = T_i A_f F_v$, $\pm U_b = A_f F_v L_a$ and $\pm T_e = T_i F_v L_a$. Other confounding patterns will be found if other generators are chosen.

The complete test plan for the 2^{7-3} factor test is shown in Table B:6 in Appendix B.4. In Table 7:6 below the results are shown.

Table 7:6 The effect (impact) of single factors and factor combinations in the ***2^{7-3} factor test*** and ***pre-runs***

Factor / Factor combinations	**Impact on the energy use (kWh)**	
	2^{7-3} factor test	***Pre-runs***
T_i	3077	3287
A_f	6954	6846
F_v	4950	4848
L_a	1978	2101
U_w	2372	2289
U_b	4273	4285
T_e	-6063	-6186
$T_i A_f$	-46	949
$T_i F_v$	834	655
$T_i L_a$	-726	285
$T_i U_w$	1729	311
$T_i U_b$	-967	581
$T_i T_e$	756	-261
$A_f L_a$	144	558
$T_i A_f L_a$	-219	Not tested

The effects (impacts) of the different factors and factor combinations were analysed by plotting the effects on a normal probability paper[42] . This method is used to determine which effects are most significant. The plot shows that the main effects of the heated floor area (A_f) and the outdoor air temperature (T_e) are the most significant factors. Additionally, the ventilation flow (F_v) and the U-value of walls, roof and floor (U_b) are significant. The air tightness (L_a) of the building seems to have less impact on the energy use. The results agree remarkable well with the results from the pre-runs. This indicates that to analyse the main effect from a single factor by a 2^2-test will give a pretty correct picture of the importance of the factor. Note that in a 2^2-test two factors are varied at the same time. To analyse one factor at a time, keeping all the other factors at average values, have not been studied, but might also give results of the right magnitude.

When it comes to the two-factor interactions, none of the effects seem to be very significant by studying the normal plot. If any two-factor interaction had shown significant effects it would have been necessary to supplement the analysis with further runs in order to show the actual impact of the interaction. This is due to that all the two-factor interactions are confounded with other two-factor interactions as has been discussed above. It can be seen that these effects do not agree very well with the results from the pre-runs. This indicates that if a two-factor combination would have been of interest it would not have been sufficient with just varying the factors of interest, keeping the other factors at average values, like in a 2^2-test.

The three-factor interaction, which is confounded with other three-factor interactions, is not thought to be of great importance or interest.

7.6 Discussion of sensitivity analysis

To sum up, there are certain factors that are of great importance to the energy use. The Enorm calculations showed that the most significant factors were the heated floor area (A_f), the outdoor air temperature (T_e), the ventilation flow

[42] The reader is referred to the following literature for a detailed explanation on the analyse method of normal probability paper, Pauli, M. (2001). *Statistisk försöksplanering - Faktorförsök.* Göteborg: IVF Industrial Research and Development Corporation and Box, G. E. P., Hunter, W. G. and Stuart, H. J. (1978). *Statistics for Experimenters - An Introduction to Design, Data Analysis, and Model Building.* New York: John Wiley & Sons.

(F_v) and the U-value of walls, roof and floor (U_b). To study the effect of single factors a small number of runs, where other factors are held at average values, seems to give sufficient estimations of the effect on the energy use. There do not appear to be any strong correlations between the factors studied. However, if any two-factor interaction is thought to be of interest it is advisable to consider the variation of a number of factors in a factorial design, rather than just studying the factors of interest.

The results from the sensitivity analysis showed that one of the factors of significance to the net heating energy is the heated floor area (A_f). That the size of the building is of importance to the energy use is obvious, but one contribution to the result in Enorm is that the hot water usage, heat given off from electrical appliances as well as heat given off from persons are calculated by using the heated floor area. This means that a number of factors not included in the sensitivity analysis are influenced by the heated floor area.

To get a fair picture of the reality using a theoretical model is not an easy task or perhaps even an impossible one. There are many parameters affecting the outcome, such as the model itself but also the choice of input data and the values of the input data. When making a sensitivity analysis the importance of a factor or a certain combination of factors can be difficult to decide without further studies or by experience.

Enorm is widely used but is far from a complete program and is not applicable for all kinds of buildings. One limitation of Enorm was clearly shown in this sensitivity analysis when the window area (A_w) did not have any impact on the energy use, which seems strange. The window area lets heat out of the building, but also permits solar insolation into the building and should therefore influence the energy use to some extent.

Furthermore, different habits of the residents can have a great impact on the energy use but are difficult to include in an estimation. The residents primary contribute to large variations between different houses.

A number of other parameters could have been included in a sensitivity analysis, such as the number of floors, thermal bridges, heat recovery and the choice of white goods[43] .

[43] Note that Enorm does not take into consideration that a more energy efficient fridge or freezer gives off less heat to the surroundings than a “normal” apparatus.

8 Discussion

The change over time for parameters affecting the energy use is of interest from a sustainable perspective. In this literature study a number of parameters have been studied and the literature found are here discussed.

The air tightness of the building and parameters affecting it do not show any major deterioration over time. If the development of even more airtight buildings is persistent there might be a need for more knowledge in this field (Isberg et al., 1996).

Although the reports on the evaluations of the compulsory ventilations inspections do not involve single-family houses, there are indications of that the ventilation systems in our houses do not work to our satisfaction. There seems to be a general tendency of a reduction in the airflow during the ventilation system's service period. An inadequate ventilation system leads to a number of consequences related to the indoor environment, such as bad air quality and bad thermal comfort. The impact of an inadequate ventilation system on the energy use is not as obvious. If the underlying factors are not more thoroughly investigated and the failures taken care of, there might be a risk of over-dimensioning the airflow to compensate for the deterioration in performance. The residents might also compensate by opening windows more frequently, which in the winter will affect the energy use.

There seems to be a gap to fill concerning the ageing of windows. A project on the durability and expected lifetime of energy efficient windows has recently started at SP. A study will be made on how the windows age and if the U-value of the glazing units changes over time. In laboratory tests the gas leakage of insulated windows seem to be related to the type of window and it appears that there are windows on the market that meet the requirements.

Inspections of loose fill insulation materials show that there is a problem with settlement some years after installation. This increases the thermal resistance of the material, subsequently affecting the transmission losses. There are a variety of conditions influencing the settlement and the ageing is important to investigate further in order to be able to compensate with the correct amount of materials needed (Isberg et al., 1996). The gas leakage also affects the performance of insulation materials. The application of the insulation material affects the problem that occurs, where the deformation due to the load underneath a slab on ground can be mentioned. It can be concluded that with the exception of settlement of loose-fill insulation, the knowledge about how the heat transfer is influence by changes over time is not well investigated.

The relative short existence of heat pumps and the phasing out of CFC-based working fluids might contribute to the lack of reports on the long-term performances of heat pumps.

The long-term performance of exhaust and supply air systems with heat recovery seem to have the same problem as ventilation systems without heat recovery, namely too low air flows.

Additionally, the long-term performance of control systems can be brought up and it can generally be concluded that there seems to be a lack in systematic work in the field of durability and maintenance work regarding control equipments in buildings (Fahlén, 1993).

Regarding the household electricity, no investigations on the long-term performance of white goods or lighting have been studied. Most literatures found focus on the replacement of older appliances by newer, more energy efficient, ones.

The residents seem to have an important role to play regarding the energy use in houses. However, the greatest contribution from the residents is the variations in the energy use between one household and another. This has been studied in nominal identical houses. The literature points towards that the habits of the residents are of great importance to these variations. The investigations do not agree when it comes to *relationships* between the size of the household, the age, the social status, the activity, the life style etc. and the amount of the energy used.

Long-term changes in energy use related to the residents are very briefly brought up in two studies (Gaunt, 1985; Lundström, 1982), where changes in the size of household and the age of the children are possible explanations. These changes are unfortunately not discussed in more details.

Some authors put forward that a change in habits is cheaper than the technical energy saving retrofits that can be done to a house and for the individual household a change in habits can improve the household economy. Against this one can argue that a change in habits might not be the easiest measure to take due to that every day patterns of habits are very difficult to change.

The residents will always make changes to their houses. The composition of the household will also change with time. There might also be a shift of owners. These are ordinary changes occurring during a building's lifetime. A building and its building services must be flexible to these changes and still be able to fulfil requirements of good energy efficiency.

It should be pointed out that the building itself to some degree also sets the conditions for the residents. This can be exemplified with that a drought, due to bad air tightness of the house, might be compensated by the residents by increasing the indoor temperature.

The sensitivity analysis made in Enorm points out the parameters affecting the energy the most as well as to what extent they have an impact (of the eight factors tested). The results were that the heated floor area (A_f) and the outdoor air temperature (T_e) are the most significant factors. For an existing building the choice of location (and thus the outdoor temperature) cannot be influenced. The size of the heated area can be changed over the years due to an extension of the house.

Additionally, the ventilation flow (F_v) and U-value of walls, roof and floor (U_b) have a somewhat smaller influence but still stands for a large portion of the energy use.

The indoor temperature (T_i) also has an affect on the energy use and is of course depending on the choice of the residents. The U-value of the windows (U_b) and the air tightness (L_a) have the least impact of the studied factors in the fractional factorial design (2^{7-3}). The window area (A_w) is not even included in the fractional factorial design due to that Enorm does not seem to take it into consideration. The window area of a house is only likely to change over time if the number of windows is increased due to an extension of the house.

It must be stressed that the result is only as accurate as the input data chosen and the calculation method used. The result is somewhat difficult to discuss as it primary shows how Enorm calculates the energy use of a building. In order to investigate how well the impacts of the eight factors agree with the actual impacts on the energy use, measurements in a real building are needed.

An additional parameter of interest to study is the efficiency of the heating and distribution system. Furnaces are generally known to operate less efficient as time passes. To examine literature that deals with how this affects the energy use over time would be valuable.

To do regular maintenance work on the building and its components and building services is significant for a good performance. Further compilation of reports on the importance of maintenance work to changes in energy use over time would be of value to the project “Sustainable energy use in houses”.

The effect of bad workmanship to changes in the performance over time for the building’s components and service systems has not been studied in this report. A guess is that it is difficult to analyse the long-term degradation of the performance and trace it back to bad workmanship.

The difficulties with compiling different literatures have not directly been discussed in this report. Some problems that can be highlighted are that the sources of information differ a great deal concerning the scope of the researches, the methods used, the interpretations and representations of findings, etc. Hence, a fair comparison between data/information from different sources can be difficult to carry out. Furthermore, the quality of the information is not always easy to recognise.

In general there seems to be a lack of research in the field of durability and performance over time for a number of parameters related to the building and building services as stated by Bankvall et al. (1986) and Samuelson (1994). This especially applies to long-term follow-ups in field. That the residents stand for the great variations in the energy use between one household and another is quite clear. The habits of the residents seem to be the main reason behind the variations. The importance of other relationships between, e.g. the size of the household and the energy use, are not as obvious. The sensitivity analysis carried out in Enorm gives a coarse estimation of the importance of different parameters to the energy use. Enorm seems though to have a number of drawbacks, e.g. it neglects the window area, and the results should hence not be taken as the actual values, at least not for all kinds of buildings / constructions and building services. Altogether the findings presented in this report will serve as background information to the project “Sustainable energy use in houses”.

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Appendix A Influences on the energy use

Table A:1 below includes the different energy flows for an existing residential building. The factors that are important for the size of the flow are stated under the heading factor 1° (primary factor). The factors that influence factor 1° are presented under the heading factor 2° (secondary factor). In the fourth column it is stated whether the factor 1° is related to the residents, the external climate and/or the building and building services (three categories). The last column gives some explanatory comments. The table does not focus on the importance of the factors to the energy use.

The category "☺ the residents" includes all aspects that are human-related. Besides the residents themselves, i.e. the people living in the building, it includes the house owner and/or the landlord in the case this is separate from the people living in the house (e.g. in multi-family dwellings).

The category "☼ the external climate" includes the influence by the sun, wind, precipitation and outdoor temperature at the geographical location of the building.

The category "🏠 the building and building services" includes the design and construction of the building as well as the building services (e.g. the heating system, distribution system, ventilation system, control system). Armature for water is another example belonging to this category. Furthermore the workmanship is thought to belong to this group.

The indoor environment is not explicitly brought up in Table A:1, but it is of course affected by a number of factors that are influenced by the three categories.

Table A:1 The influence of residents, external climate and building and building services on the energy use

☺ the residents ☼ the external climate ⌂ the building and building services

Energy flows	Factor 1°	Factor 2°	Influenced by	Comments
Electricity for fans, pumps, etc.	Types of building services and types of devices (efficiency)	Maintenance	⌂	
Household electricity	Types of appliances and lighting (efficiency)		☺	
	Possession of appliances and lighting		☺⌂	The number of persons Habits The area influences the amount of lighting
	Usage of appliances and lighting		☺	The number of persons Habits
Heat from appliances lighting, fans, pumps, etc.	Types of appliances, lighting, building services and devices (efficiency)		☺⌂	The residents influence the household appliances and the lighting The building and building services influence the types of fans, pumps, etc.
	Possession of appliances, lighting, building services and devices		☺ ⌂	Number of persons Habits The area influences the amount of lighting
	Usage of appliances and lighting, building services and devices		☺⌂	Number of persons Habits (The location of the fans, pumps, etc. determine the amount of heat that is useful)
Metabolic heat	The number of persons		☺	
	Their activity		☺	
	Time spent in the building.		☺	
Solar gains			☼	
	Type of window		⌂	
	Window orientation		⌂	
	Window shading		⌂	
	Curtain		☺	Possesion and usage
	Window area		⌂	

Energy flows	**Factor 1°**	**Factor 2°**	**Influenced by**	**Comments**
Energy input for heating	Type of heating system	Maintenance	⌂	
	Distribution system	Maintenance	⌂	
	Control system	Maintenance	⌂	
Recovered energy	Type of heating/ventilation system	Maintenance	⌂	
Unused gains	Time constant of the building		☺⌂	How the residents furniture the rooms (carpets, etc.).
	Airing		☺☼	The temperature difference effect the air exchange. The outdoor temperature affects the tendency to open the windows.
Ventilation losses - Controlled ventilation	Type of ventilation and pipe system	Maintenance	⌂	
	Ventilation flow	Maintenance	☺⌂☼	
	Operation of fans and pumps		⌂	
	Control system		⌂	
	Temperature difference		☺☼	Climate – outdoor temperature Residents – indoor temperature
- Air leakage	Airtight layer / vapour barrier	Materials and conditions of materials surrounding the layer, e.g. wet concrete.	☺⌂	The residents might make changes or retrofits to the building that might puncture the layer.
	Gaskets and weather strips	Compression	⌂	
	Temperature difference		☺☼	Climate – outdoor temperature Residents – indoor temperature

Energy flows	Factor 1°	Factor 2°	Influenced by	Comments
Transmission losses	Type of construction and material (U-value)		🏠	
- Walls	Façade		🏠	Generally the façade does not influence the energy to any great extent.
	Thermal insulation Type of insulation (U-value)	Moisture Workmanship Gas leakage	🏠	Generally moisture only affects the U-value marginally.
	Area		🏠	
	Temperature difference		☺ ☼	
- Windows	Type of window (U-value)		🏠	
	Type of frame (U-value)		🏠	
	Orientation		🏠	
	Shading		🏠	
	Curtains		☺	Possesion and usage
	Area		🏠	
	Temperature difference		☺ ☼	Climate – outdoor temperature Residents – indoor temperature
- Doors	Type of door (U-value)		🏠	
	Area		🏠	
	Temperature difference		☺ ☼	Climate – outdoor temperature Residents – indoor temperature
- Roof	Type of construction and material (U-value)		🏠	
	Roofing		🏠	Generally the roofing does not influence the energy to any great extent.
	Thermal insulation Type of insulation (U-value)	Moisture Convection Settlement Workmanship Compact damages (mice and people) Gas leakage	☺🏠	Generally moisture only affects the U-value marginally.

Energy flows	Factor 1°	Factor 2°	Influenced by	Comments
	Roofing felt/sheet		🏠	Generally the felt/sheet does not influence the energy to any great extent.
	Area		🏠	
	Temperature difference		☺☼	Climate – outdoor temperature Residents – indoor temperature
- Founda-tion	Type of foundation and material (U-value)		🏠	
	Thermal insulation Type of insulation (U-value)	Moisture Compression Gas leakage	🏠	Generally moisture only affects the U-value marginally.
	Area		🏠	
	Temperature difference		☺☼	Climate – outdoor temperature Residents – indoor temperature
- Thermal bridges	U-value		☺🏠	
	Area		🏠	
	Temperature difference		☺☼	Climate – outdoor temperature Residents – indoor temperature
Energy for hot water production/ usage	Armature /Fittings		🏠	Habits (how often, how hot, how much), age, no. of persons
Heat gains from hot water pipes.	Insulation of hot water pipes		🏠	
Heat losses to the cold and waste water pipes.			🏠	
Technical losses	Efficiencies (e.g. for the heating system)		🏠	

Appendix B Tables (Enorm)

B.1 Input data

Table B:1 Typical house - all input data

Page in Enorm	Input data	"Value"	References / Comments
1	Type of building	Single-family house	
	Heated floor area	125 m^2	(Andersson and Norlén, 1993; Fahlén, 1991; Dyrstad Pettersen, 1997; Munther, 1996)
	Air leakage (infiltration)	1.0 l/m^2s	(Adalberth, 2000; Nilsson et al., 1993)
	Heat capacity	25 Wh/m^2K	(Munther, 1996)
2	Geographical location (outdoor temperature)	Gävle (4.4 ºC)	The mean annual outdoor temperature is taken from SMHI, (Swedish Meteorological and Hydrological Institute). Enorm uses statistics from this institute.
	Indoor temperature	21 ºC (every day of the week)	(Gaunt, 1985; Dyrstad Pettersen, 1997; Andersson and Norlén, 1993; Adalberth, 2000; Nilsson et al., 1993)
3	Area of attic ceiling beams	125 m^2	Same as heated floor area.
	Area of external walls	89.9 m^2	See comment 1 below. (Munther, 1996)
	Area of floor (slab on ground)	125 m^2	Same as heated floor area. Slab on ground typical (Andersson and Norlén, 1993).
	Area of windows incl. frames	18.8 m^2	15 % of heated floor area (Adalberth, 2000; Munther, 1996).
	Area of doors incl. frames	3.8 m^2	(Munther, 1996)

Page in Enorm	Input data	"Value"	References / Comments
4	U-value of attic ceiling beams	0.2 W/m^2K	(Dyrstad Pettersen, 1997; Andersson and Norlén, 1993; Adalberth, 2000)
	U-value of external walls	0.3 W/m^2K	(Dyrstad Pettersen, 1997; Andersson and Norlén, 1993; Adalberth, 2000)
	U-value of floor (slab on ground)	0.2 W/m^2K	(Dyrstad Pettersen, 1997; Adalberth, 2000)
	U-value of windows incl. frames	1.5 W/m^2K	(Dyrstad Pettersen, 1997; Adalberth, 2000)
	U-value of door	0.8 W/m^2K	
5	Solar data	Stockholm	Enorm only has solar data for the locations Stockholm, Malmö and Umeå.
	Orientation of the "south" wall	Straight south direction	
	Glass area / Share of solar transmittance / Screening factor		For the glass area see comment 2 below.
	- North	4.5 m^2 / 1.0 / 0.75	(Adalberth, 2000; Munther, 1996)
	- East	2.3 m^2 / 1.0 / 0.75	(Adalberth, 2000; Munther, 1996)
	- South	6.0 m^2 / 1.0 / 0.75	(Adalberth, 2000; Munther, 1996)
	- West	2.3 m^2 / 1.0 / 0.75	(Adalberth, 2000; Munther, 1996)

Page in Enorm	**Input data**	**"Value"**	**References / Comments**
6	Type of heating	Direct electric heating	(Statistics Sweden, 2001a; Andersson and Norlén, 1993)
	Production efficiency	100 %	(Munther, 1996)
	Heat distribution	Electric radiators	
9	Type of ventilation	Exhaust ventilation	(Andersson and Norlén, 1993)
	Ventilation flow	0.27 l/m^2s	(Andersson and Norlén, 1993; Dyrstad Pettersen, 1997; Adalberth, 2000; Nilsson et al., 1993)
	Operational time	24.0 hours per day	(Munther, 1996)
10	Ventilation flow	0.27 l/m^2s (corresponds to 0.4 h^{-1})	(Andersson and Norlén, 1993; Dyrstad Pettersen, 1997; Adalberth, 2000; Nilsson et al., 1993)
	Operational time	24.0 hours per day	(Munther, 1996)
13	Type of refrigerator	Siemens 37 K 20 (E) 359 litres, 197 kWh/year	(Dyrstad Pettersen, 1997; Sydkraft, 1998)
	Type of freezer	Siemens GS 35 S (E) 284 litres, 383 kWh/year	(Dyrstad Pettersen, 1997; Sydkraft, 1998)
14	Type of dish washer	Siemens Lady SN 333 430 kWh/year	
	Type of washing machine	Siemens Siwamat 3403 700 kilograms/year, 0.75 kW/kilogram, 525 kWh/year	
	Type of tumble dryer	Siemens Siwaterm WT 5803(E) 350 kilograms/year, 0.8 kW/kilogram, 280 kWh/year	

Comment 1
Area of walls = Total wall area – Area of windows – Area of doors (constant). Total wall area = 2 × 2.4 × (8.2 + long side), where 2.4 is the height of the house and 8.2 is the length of the short side, which is kept constant. The long side = heated floor area / 8.2.

Comment 2
The glass area is approximately 80 % of the window area including frames. The percentage of the window areas in the different directions is kept constant, namely, 30 % to the north, 15 % to the east, 40 % to the south and 15 % to the west (the long sides are thought to be facing south and north).

Comment 3
In Table 7.1 factor U_b is an average U-value for the attic ceiling beams, external walls and floor and is calculated using the formula $U_{average} = \Sigma (Y_i A_i) / A_{tot}$
Here;
$\Sigma (Y_i A_i)$ = U-value of attic ceiling beams × Area of attic ceiling beams + U-value of external walls × Area of external walls + U-value of floor × Area of floor
A_{tot} = Area of attic ceiling beams + Area of external walls + Area of floor
When the area is changed (factor A_f) the $U_{average}$ changes, but only marginal, hence this change is neglected.

Comment 4
Any extra thermal bridges have not been included in the calculations. Due to that the house has only one floor and no balcony the thermal bridges are reduced, although there will most probably be extra heat losses in the intersection between the walls and the floor and the walls and the roof.

B.2 Test plans for factor tests

Table B:2 The principal test plan for two-factor test (2^2-test)

Run	Factor 1	Factor 2	Combination of factor 1 and factor 2
1	-1	-1	1
2	1	1	-1
3	-1	-1	-1
4	1	1	1

Table B:3 An example of test plan for two-factor test (2^2-test)

Run	Factor T_i	Factor A_f	Combination of factor T_i and factor A_f (T_iA_f)
1	19°C	90 m²	1
2	23°C	90 m²	-1
3	19°C	160 m²	-1
4	23°C	160 m²	1

Table B:4 The principal test plan for three-factor test (2^3-test)

Run	Factor 1	Factor 2	Factor 3	Combinations of - factor 1 and factor 2	- factor 1 and factor 3	- factor 2 and factor 3	- factor 1, factor 2 and factor 3
1	-1	-1	-1	1	1	1	-1
2	1	-1	-1	-1	-1	1	1
3	-1	1	-1	-1	1	-1	1
4	1	1	-1	1	-1	-1	-1
5	-1	-1	1	1	-1	-1	1
6	1	-1	1	-1	1	-1	-1
7	-1	1	1	-1	-1	1	-1
8	1	1	1	1	1	1	1

Table B:5 An example of test plan for three-factor test (2^3-test)

Run	Factor T_i	Factor A_f	Factor F_v	Combinations of - factor T_i and factor A_f (T_iA_f)	- factor T_i and factor F_v (T_iF_v)	- factor A_f and factor F_v (A_fF_v)	- factor T_i, factor A_f and factor F_v ($T_iA_fF_v$)
1	19°C	90m²	0.2 h^{-1}	1	1	1	-1
2	23°C	90m²	0.2 h^{-1}	-1	-1	1	1
3	19°C	160m²	0.2 h^{-1}	-1	1	-1	1
4	23°C	160m²	0.2 h^{-1}	1	-1	-1	-1
5	19°C	90m²	0.6 h^{-1}	1	-1	-1	1
6	23°C	90m²	0.6 h^{-1}	-1	1	-1	-1
7	19°C	160m²	0.6 h^{-1}	-1	-1	1	-1
8	23°C	160m²	0.6 h^{-1}	1	1	1	1

B.3 Calculations

The computer program Enorm calculates the estimated annual energy use (kWh) for the house in question. Here only the energy use for space heating as well as the hot water production is shown.

Calculations of the impacts on the energy use were carried out in accordance with common experimental design methods[44].

The ***main effect (impact) of single factors*** on the energy use is calculated by:

The mean value of the estimated energy use when the factor has a *high* value	—	The mean value of the estimated energy use when the factor has a *low* value

For example, the main effect of factor T_i (indoor temperature) on the energy use is calculated for the 2^{7-3} test (the numeric values can be found in Table B:6 in Appendix B:4) by:

The mean value of the estimated energy use when the factor T_i has a *high* value (23ºC)	=	(7233 + 13420 + 17529 + 25306 + 17172 + 16598 + 10242 + 24482)/8	=	16498
The mean value of the estimated energy use when the factor T_i has a *low* value (19ºC)	=	(7160 + 19680 + 10340 + 11093 + 7922 + 10687 + 14260 + 26221)/8	=	13420
The main effect of factor T_i	=	16498 - 13420	=	3078*

* The result gives 3077. The difference is due to a round off error.

[44] Pauli, M. (2001). *Statistisk försöksplanering - Faktorförsök.* Göteborg: IVF Industrial Research and Development Corporation and Box, G. E. P., Hunter, W. G. and Stuart, H. J. (1978). *Statistics for Experimenters - An Introduction to Design, Data Analysis, and Model Building.* New York: John Wiley & Sons.

The ***interaction effect (impact) of two factor combinations*** on the energy use is calculated by:

(The mean effect of an increased value of factor 1 when factor 2 has a *high* value)/2	—	(The mean effect of an increased value of factor 1 when factor 2 has a *low* value)/2

For example, the effect of two factor combination of factor T_i (indoor temperature) and factor A_f (heated floor area) on the energy use is calculated for the 2^{7-3} test by:

The mean effect of an increased value of factor T_i when factor A_f has a *high* value	=	The mean value of the estimated energy use when the factor T_i has a *high* value (23ºC) (and A_f is high)	—	The mean value of the estimated energy use when the factor T_i has a *low* value (19ºC) (and A_f is high)		
	=	(13420 +25306 + 16598 + 24482)/4	—	(19680 + 11093 + 10687 + 26221)/4	=	3031
The mean effect of an increased value of factor T_i when factor A_f has a *low* value	=	The mean value of the estimated energy use when the factor T_i has a *high* value (23ºC) (and A_f is low)	—	The mean value of the estimated energy use when the factor T_i has a *low* value (19ºC) (and A_f is low)		
	=	(7233 + 17529 + 17172 + 10242)/4	—	(7160 + 10340 + 7922 + 14260)/4	=	3124
The effect of two factor combination T_iA_f	=	(3031)/2	—	(3124)/2	=	-47

* The result gives -46. The difference is due to a round off error.

The ***interaction effect (impact) of three factor combinations*** on the energy use is calculated in a similar way.

Table B:6 Test plan and results of fractional factorial design with 7 factors (2^{7-3})

Run	T_i	A_f	F_v	L_a	U_w	U_b	T_e	T_iA_f	T_iF_v	T_iL_a	T_iU_w	T_iU_b	T_iT_e	A_fL_a	$T_iA_fL_a$	Calculated energy use (kWh)
1	-1	-1	-1	-1	-1	-1	-1	1	1	1	1	1	1	1	-1	7160
2	1	-1	-1	-1	1	-1	1	-1	-1	-1	1	-1	1	1	1	7233
3	-1	1	-1	-1	1	1	-1	-1	1	1	-1	-1	1	-1	1	19680
4	1	1	-1	-1	-1	1	1	1	-1	-1	-1	1	1	-1	-1	13420
5	-1	-1	1	-1	1	1	1	1	-1	1	-1	-1	-1	1	-1	10340
6	1	-1	1	-1	-1	1	-1	-1	1	-1	-1	1	-1	1	1	17529
7	-1	1	1	-1	-1	-1	1	-1	-1	1	1	1	-1	-1	1	11093
8	1	1	1	-1	1	-1	-1	1	1	-1	1	-1	-1	-1	-1	25306
9	-1	-1	-1	1	-1	1	1	1	1	-1	1	-1	-1	-1	1	7922
10	1	-1	-1	1	1	1	-1	-1	-1	1	1	1	-1	-1	-1	17172
11	-1	1	-1	1	1	-1	1	-1	1	-1	-1	1	-1	1	-1	10687
12	1	1	-1	1	-1	-1	-1	1	-1	1	-1	-1	-1	1	1	16598
13	-1	-1	1	1	1	-1	-1	1	-1	-1	-1	1	1	-1	1	14260
14	1	-1	1	1	-1	-1	1	-1	1	1	-1	-1	1	-1	-1	10242
15	-1	1	1	1	-1	1	-1	-1	-1	-1	1	-1	1	1	-1	26221
16	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	24482
Impact on energy use (kWh)																
	3077	6954	4950	1978	2372	4273	-6063	-46	834	-726	1729	-967	756	144	-219	