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2020

Document Version:
Publisher's PDF, also known as Version of record

Link to publication

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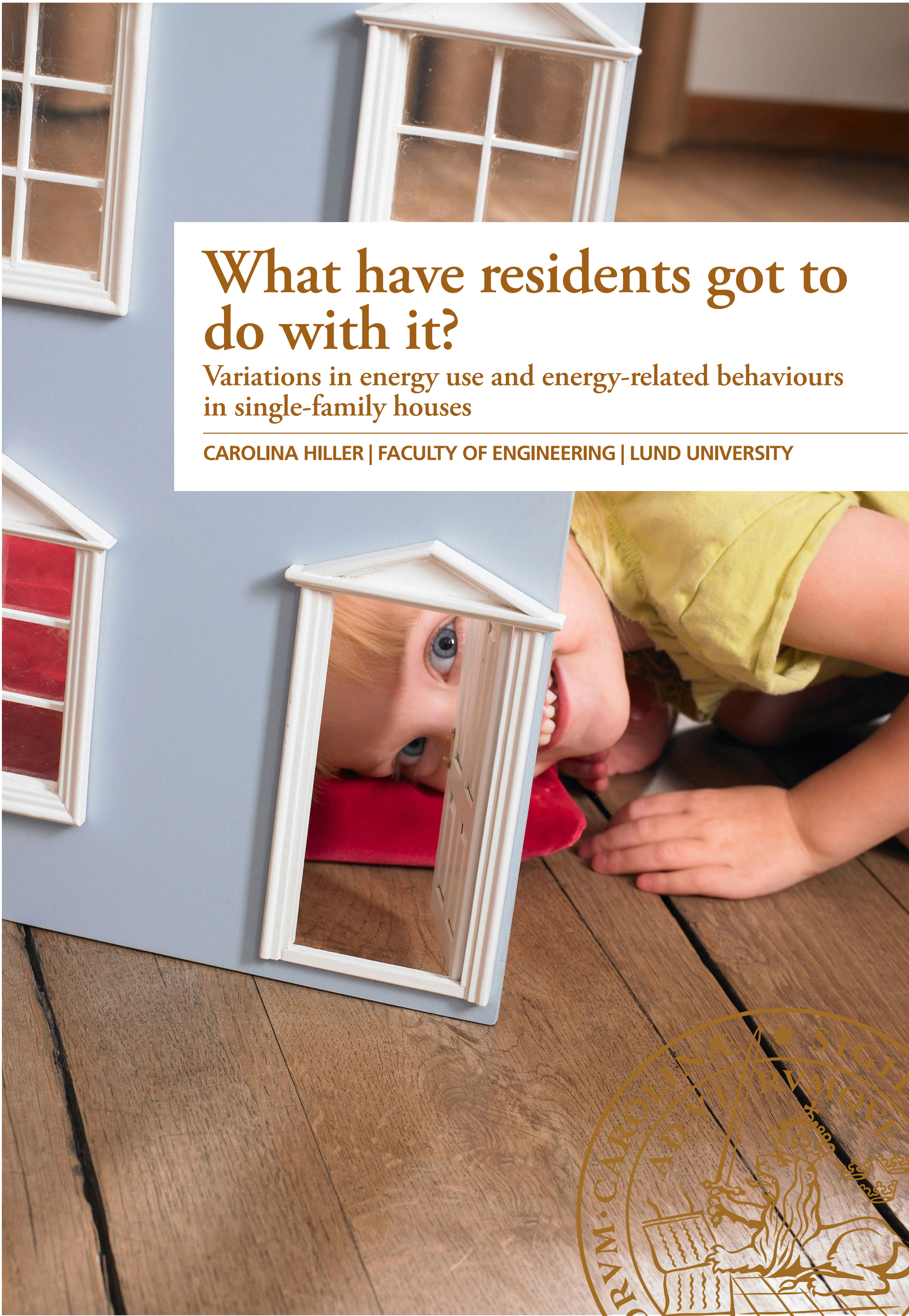

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Carolina Hiller

LUND UNIVERSITY

DOCTORAL THESIS

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Cover picture (back): Gittan Hiller

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Report TVBH-1023

ISRN LUTVDG/TVBH - 20/1023 – SE(235)
ISSN 0349-4950
ISBN 978-91-88722-66-9 (print)
ISBN 978-91-88722-67-6 (pdf)

Printed in Sweden by E-husets tryckeri, Lund University
Lund 2020

Preface

What a journey! The road has been crooked, very long and truly enlightening – not least have I learned how to write scientifically and keep my focus. Now, in the end, it is finally here, my doctoral thesis! Many lonely hours of effort are behind this work. There are, of course, a bunch of people who have supported me during this work and whom I would like to thank.

To start with, I would like to express my appreciation to Professor Arne Elmroth, one of the initiators of the Ph.D. project, for his guidance, inspiration and for being a believer in multidisciplinary studies. Unfortunately, you did not get to see my finished thesis – but thank you for believing in me right to the end.

Next, I want to acknowledge my supervisor, Professor Jesper Arfvidsson at the Division of Building Physics, Lund University, and my co-supervisor, Professor Thorbjörn Laike at Environmental Psychology, Lund University, for giving me the opportunity to carry out my Ph.D. project. It has surely been interesting to gain insights into a social science discipline. My mentor, Dr. Charlotta Isaksson at the Division of Built Environment, RISE, and at the Division of Psychology, Pedagogy and Sociology, University West – I am sincerely grateful you took my case on board! We have certainly 'juggled' texts back and forth – your guiding words 'keep it short and concise' and 'think of the scientific sharpness' still echo like mantras in my head! Thank you for supporting me in reaching the finish line.

I am thankful to my colleague Svein Ruud at RISE, who besides helping me review the more technical content of the thesis, also practically assisted me in mounting measuring equipment in the houses. Maria Håkansson at RISE has read and checked the consistency in the thesis, as well as given wise and encouraging comments. Mattias Hellgren at Linköping University has reviewed the quality analyses of the diary study and given me feedback on the statistics. Thomas Ljung has contributed with his linguistic reading of several chapters. I want to say thank you to all of you! I would also like to take the opportunity to express my appreciation towards my current and former colleagues at RISE – thank you for cheering me on, even though I have been somewhat absent for the past year or so. I am very much looking forward to working more closely with you again.

I wish to draw attention to the participating households, without whose involvement the studies would not have been possible. I am enormously thankful to you for so generously inviting me into your homes, sharing your everyday lives and answering all my questions.

I would like to acknowledge the Swedish Research Council for Environment, Agricultural Sciences and Spatial Planning (FORMAS), the Swedish Energy Agency, Region Västra Götaland and RISE Research Institutes of Sweden for funding my work. Invaluable funding for the completion of the thesis was also received from the foundations Åke och Greta Lissheds stiftelse and Maj och Hilding Brosenius forskningsstiftelse.

Last but not least, I am so grateful for my friends and family who were there for me; I really appreciate you. Martina, thanks for not giving up on me even though socialising has not been my top priority lately! My love goes to my mum and dad – my best friends and my biggest supporters. And Hannah and Nils, I am glad you have 'distracted' me so that I could direct my attention towards you for a while. You both, in your own different ways, keep me level-headed; you are my priority and my heart.

A doctoral thesis may not save the world, but it can create a greater understanding of how we humans affect climate change through the resources we use such as energy. My wish is that this thesis will be a contribution to this understanding.

I hope you enjoy your reading.

Written on a green spring day in 2020, in my home office in Floda, Sweden, during strange pandemic times.

Abstract

To achieve global energy goals, energy use in residential buildings must decrease. The implementation of technical measures is crucial but alone it is not sufficient; residents need to change their behaviour as well. However, households are not a homogeneous group in terms of their energy use and behaviour; rather, the use varies between households and over time. To promote energy savings in buildings, these variations need to be explored. The main objectives of this thesis were therefore to examine how energy use in single-family houses varied and how energy-related behaviours of households influenced the use of energy. The examined energy variations included changes over time, differences between households and variations of energy use throughout the day. The impact on these variations from the residents' activities and everyday behaviours was studied as well. A partially multidisciplinary approach was employed, whereby the following methods were combined: energy data analyses with interviews, energy performance measurements with calculations, and time-use diaries with energy measurements. A literature review was also conducted. The participating households lived in electrically heated, detached, single-family houses, built in Sweden in the 1980s. The residences spanned three different housing areas, each of which encompassed similar houses.

The thesis showed that on an aggregated level, the energy use was stable over years of occupancy. An individual household's energy usage could, however, both increase and decrease over time, depending on several activities occurring over the years. On a group level, the daily electricity load curves differed between weekdays and weekend days, with clear power peaks in the morning and evening on weekdays. That is, during these peak hours the households contributed to potential power deficits in the energy system. Large differences between similar houses' energy use were demonstrated, similar to findings in other research. Differences of a factor of two to three between the highest and lowest energy usages were discovered; for water use, the differences were even greater, namely a factor of six.

The studies found that there were many ways to be a high or a low consumer. That is, most of the households exhibited a range of different energy-related behaviours contributing to their energy use. In addition, there was a spread between households in how long they performed various activities. Moreover, the thesis showed a parallel use of electronic devices of the same type, which meant that each household

member owned their own set of devices, potentially leading to an increased use of electricity at the household level.

The findings in the thesis are of value when measures are designed to encourage residents to save energy and reduce power peaks. By field measurements, the empirical studies provided technical and resident-related information that is useful when estimating and verifying energy use of buildings. Additionally, the thesis contributed to the field of multidisciplinary research on household energy use as both technical and social perspectives were in focus – an approach that not only attempted to measure actual energy data, but also to reveal the behaviours that were concealed behind the data.

Contents

1 Introduction

There is a common understanding of the urgent need for climate action, where IPCC[1] declares that human influence on the climate is clear and the more negative the impact, the higher the risk for irreversible, undesirable changes (IPCC, 2014). However, IPCC also states that we have the means to limit climate changes and create a sustainable future. Some of the central actions concern energy measures in the building sector – such as low carbon energy supply, improved energy efficiency and reduced energy use. Besides technical improvements in this area, IPCC recognises people, their consumption and their behaviour as important in combating climate change (IPCC, 2018).

Energy saving in buildings, contributing to the reduction of climate change, is the concern of this thesis. The focus is on energy use in residential buildings and the impact of people's energy-related behaviour performed in their homes.

1.1 Energy use and behaviour in residential buildings

During recent decades, the EU has set up energy and climate change objectives for its member countries. For example, there shall be a 20% improvement in energy efficiency by 2020 (Communication COM(2010) 639 final), which thereafter will be followed by new energy targets within the 2030 framework for climate and energy (Communication COM/2014/015 final).[2] It is emphasised that energy efficiency is important throughout the whole energy chain, from production to final use, which especially concerns the building sector (Directive (EU) 2018/2002). Approximately 40% of the EU's total final energy use (i.e. delivered energy) stems from residential and commercial buildings, corresponding to 36% of the EU's total CO_2 emissions (European Commission, 2019). In Sweden, during 2018, residential buildings and non-residential premises, land use and other services accounted for above 39% of the total energy use, corresponding to 147 TWh, of which residential buildings represented 59% (corresponding to 87 TWh) (Swedish Energy Agency,

[1] IPCC stands for the Intergovernmental Panel on Climate Change (see www.ipcc.ch).

[2] The new energy targets include a 32.5% reduction in energy use through energy efficiency (European Commission, n.d.).

2020). Also in Sweden, political agreement on the long-term energy direction has been reached (Committee report 2016/17:MJU24), with a goal for 2030 to have 50% more efficient energy use compared to that of 2005 (Prop. 2017/18:228).

To achieve the international, as well as national, goals of reducing energy use in our buildings, several measures are needed, including activities addressing households (e.g. SOU 2018:76). For instance, in 2016, the European Committee launched a legislative initiative called the *Clean energy for all Europeans package* (Communication COM(2016) 860 final). The package has a strong focus on consumers as key players, potentially involving them more in the energy market (European Commission, 2016b), as an opportunity to influence their energy use and costs (European Commission, 2016a). In relation to buildings and to strengthen the empowerment of households, consumer information, smart electricity meters[3] and access to information from the metering and billing of household individual energy use[4] is especially promoted (Directive (EU) 2018/2002; Directive (EU) 2019/944).

In Sweden, where this research has been conducted, several technical energy measures have been implemented in residential buildings. The phasing out of oil boilers and the rapid introduction of heat pumps are important examples, together with improved windows and insulation, as well as energy-efficient electrical appliances. In recent years, investments in photovoltaics have also had an impact on the progress towards EU's energy and climate targets (SOU 2018:15). However, much more can be done, and, in this respect, we can highlight a gap between the potential energy efficiency and what is being achieved in practice (Hirst & Brown, 1990). This gap can be referred to as the energy efficiency gap, which means that people are not often enough choosing or implementing energy-efficient technology, even if it is economically profitable (Blasch, Filippini, & Kumar, 2019; Camarasa, 2019; Cooremans, 2012; Jaffe & Stavins, 1994). Other studies show that although energy-efficient technology is implemented, it is not maintained and used as intended. In addition, people tend to use more devices and for a longer time when the efficiency is improved (Herring, 2006; Isaksson, 2009). Such behaviour explains why the anticipated energy savings are not realised, which often is referred to as the performance gap (e.g. Bagge, 2011; de Wilde, 2014; Hamburg & Kalamees, 2019; van den Brom, Meijer, & Visscher, 2019). For example, studies show that improvements in houses heating systems and insulation levels lead to a higher indoor temperature than before (e.g. Halvorsen et al., 2016; Oreszczyn et al., 2006),

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[3] Smart meters (or rather smart metering systems) refer to electronic systems capable of measuring electricity consumption or electricity fed into the grid. Smart meters communicate electronically and provide more information than conventional meters (Directive (EU) 2019/944).

[4] The Energy Efficiency Directive promotes the implementation of (individual) metering and billing of energy use, which usually means that each household's consumption of electricity, gas, heating/cooling and domestic hot water is metered and paid for directly by the individual household (Directive (EU) 2018/2002).

and that the installation of energy-efficient lighting leads to lights being switched on for longer periods (Dütschke, Peters, & Schleich, 2013).

These gaps demonstrate that technology per se is not enough to reduce energy use so that we can reach energy targets; but in addition, behaviour changes are also needed. As previous research has acknowledged, and which in recent years has gained more political recognition, residents' everyday activities and their maintenance of buildings and equipment play significant roles in energy savings efforts (IEA, 2010). Researchers therefore emphasise the importance of understanding people's everyday lives and behaviour, and how it affects the energy use (Gram-Hanssen & Georg, 2018; Isaksson, 2009; Isaksson & Ellegård, 2015; Shove & Walker, 2014).

To understand different perspectives on household energy use, a multidisciplinary approach is employed in the thesis. Multidisciplinary studies are those in which the research include perspectives from more than one discipline, which is a shift from purely monodisciplinary approaches (Pellegrino & Musy, 2017). In this thesis, it means the inclusion of methods – and previous research – from both the technical and the social science fields. These two branches of energy research have traditionally been separated, both internationally and in Sweden (Abrahamse & Shwom, 2018; Clayton et al., 2016; Ellegård & Widén, 2006; Lutzenhiser, 1993; Widén, 2010). However, researchers highlight the value of approaches involving many disciplines in energy research, where technical and social perspectives are combined, as energy technologies do not operate isolated from their social surroundings (e.g. Abrahamse & Shwom, 2018; Clayton et al., 2016; Dunlop, 2019; Schoot Uiterkamp & Vlek, 2007; Sovacool, 2014; Widén, 2010). In spite of this, few studies have been found that connect behaviour data with energy measurements. There are some exceptions, for instance, Sernhed's study (2004), in which diary data offered explanations to load curves in ten electrically heated houses. Newer studies with a social science approach but also including technical data are (Abrahamse & Steg, 2011; Carlander, Trygg, & Moshfegh, 2019; Eon, Morrison, & Byrne, 2017; Gram-Hanssen, 2010b, 2014; Gram-Hanssen, et al., 2020; Ortiz & Bluyssen, 2019).

When residents are addressed, for example, in policy reports and information campaigns, they are often seen as a homogeneous group related to their energy use and behaviour (e.g. Abrahamse, Darby, & McComas, 2018; Ben, 2019). This means that efforts to influence residents to decrease their energy use and to adopt energy-saving behaviour are designed in too uniform a fashion, without regarding households' different energy-related behaviours and variations in energy use. Then, one primary issue to consider is if differences in energy use are due more to the technology used or to the residents' behaviour. This thesis revolves around such differences, which are specified further below.

1.2 Objectives of the thesis

The main objectives of this thesis are to examine how energy use in single-family houses varies and how the energy-related behaviours of households influence the use of energy. The variations studied are changes in energy use over time, differences in household energy use and diurnal variations of electricity consumption (that is, the power load at a certain time during the day). The residents' energy behaviours related to these variations are herewith examined.

In order to study how energy use varies in single-family houses and how the residents' energy-related behaviours impact energy use, the following research questions are in focus:

1. How does the energy use in houses change over time, after years of occupancy, and what may affect it?
2. How does the energy use of households living in similar houses differ?
3. What are the characteristics of household energy use in terms of electricity consumption patterns during the day (i.e. daily load curves)?
4. How do the residents' behaviours influence the energy use in their homes?

The research questions are illustrated in Figure 1 below.

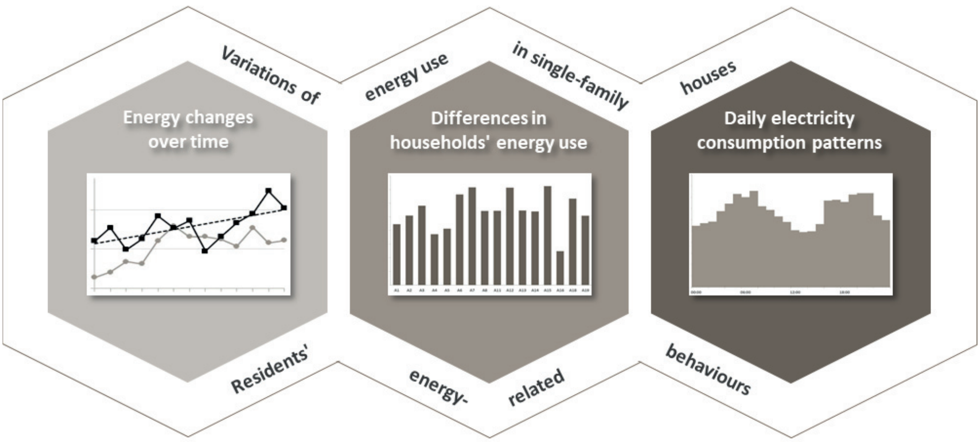

Figure 1 Overview of research questions, where different kinds of variations of energy use in single-family houses and residents' energy-related behaviours are studied.

1.3 Approach of the thesis

To study variations in energy use and household energy-related behaviours, residents living in single-family houses have participated in the empirical studies of this thesis. The houses are electrically heated detached houses built during the 1980s and are situated in three different housing areas of Sweden, with each area being made up of similar houses. They have furthermore normal energy performance, built after the Swedish building regulations on energy conservation came into force,[5] which represent a significant part of the Swedish single-family house stock[6] (Statistics Sweden, 2020a). The houses have been occupied for several years, which is a prerequisite for examining changes over time.

The first research question treats how the energy use changes after years of occupancy, and what may affect it. It is examined by analysing energy use over a ten-year period for 38 of the houses described above. This was motivated and initiated by studies that had followed up low-energy houses and found that the energy use had increased after some years in operation (Berggren et al., 1997; Nilson & Uppström, 1997; Weber, 1996) – see the author's licentiate thesis (Hiller, 2003a) for details. Given that there had been an increase in energy use for these houses, the question was raised whether this had also been the case for houses with normal energy performance. And if so, what are the reasons for an increase? Since buildings have long lifetimes, their function should remain as intended, not least concerning their energy performance. The empirical studies comprise analyses of energy data for the group of houses. These are combined with semi-structured interviews with residents of six of the households about alterations they have performed in their houses over the years, as well as other changes that may have had an impact on energy use, for example, related to household composition (Hiller, 2003a; Paper I in Appendix A).

Research question two treats how the energy use of households living in similar houses differ. Apart from observing differences in households' yearly energy use, the question is investigated by conducting a detailed study measuring two houses' energy performance (comparing the specific heat losses), while also performing energy calculations. It is analysed whether the different levels of energy use are due to the house (the building itself) and its building services or if it is due to the residents (Hiller, 2003a; Paper II in Appendix B). Differences between households'

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[5] SBN 1975 and the subsequent SBN 1980 were the prevailing Swedish building regulations when these houses were built (SBN 1975; PFS 1980:1), where the energy standards of the buildings were more in focus as a result of the so-called oil crisis in 1973–1974 than in preceding regulations.

[6] In 2019, houses built between 1971 and 1990 represented 31% of the single-family housing stock in Sweden, with almost 21% built during the decade of 1971–1980 and more than 10% during the second decade of 1981–1990 (Statistics Sweden, 2020a).

energy use is also investigated, with short-term energy measurements during a four-day period for 57 of the houses (Paper III in Appendix C).

The third research question addresses the empirical data obtained from the short-term energy measurements as well. From measured hourly energy use, daily load curves are formed and analysed in order to find out the characteristics during different days and especially when there are peak loads in the consumption (Paper III).

While examining energy data for the single-family houses, it is seen that similar technical conditions can give rise to large differences in energy use, which points towards the residents' influence on energy use. Hence, the fourth research question is about energy behaviour and is primarily examined by combining a diary study with the short-term energy measurements. The residents write diaries of their day-to-day activities over four days, while, simultaneously, energy and water usage, and indoor and outdoor temperatures, are measured. In this way, how the everyday behaviour relates to household energy use is examined, including which energy-related behaviours are performed for the longest time. It is investigated if households can be grouped based on common characteristics associated with their energy-related behaviours and energy use (Paper IV in Appendix D).

In a literature review, the main objectives of the thesis are examined by compiling research and experience from measurement studies and surveys of households' different energy usages, variations in energy use and how the everyday activities of the residents influence energy use in buildings (Chapter 3). In addition, the review presents theoretical perspectives and explanatory factors for energy-related everyday behaviours, as well as how energy-related activities can be influenced. The results from the empirical studies of the thesis are discussed in relation to the findings of the literature review in Chapter 6.

1.4 The contributions of this thesis

The thesis contributes to the research field of energy use in buildings by examining variations in energy use and behaviour for households living in single-family houses through a multidisciplinary approach combining technical and social science-oriented methodologies. A strength of this multidisciplinary approach is that the technical data show more objectively how it is – for example, related to different levels of energy use – while the social science methods capture behaviours and activities of the residents, which gives explanations and a greater understanding of how the (measured) energy use is affected by the residents.

Research about how energy use and behaviours vary between different households, constitutes valuable input to policy measures promoting energy savings and influencing energy behaviours. For example, the creation of energy-saving information and communication would benefit from addressing target groups with different life situations and everyday lives. Furthermore, to have insights into people's everyday behaviour is beneficial in the design of energy-efficient technology. The insights can be used to better adapt the technologies to people's daily lives, as well as to design technologies to promote energy-efficient use of devices in homes (e.g. Glad, 2015; Gram-Hanssen, 2014).

The thesis provides both technical and resident-related data, such as water use, indoor temperatures and presence at home, which are useful in energy calculations, as there is usually a lack of well-substantiated, credible input data when predicting and verifying energy use in buildings. The energy measurements also give knowledge of daily households' electricity consumption patterns, which is of significance to understand more about how electricity use varies during the day in relation to the electricity grid's capacity to meet the demand, and in relation to the potential for reducing electricity use at power peaks.

1.5 Limitations

One limitation in this thesis is related to the multidisciplinary approach described above. Combining technical and social science-oriented perspectives leads to certain compromises in the design of studies. In the thesis, this means that the empirical data are not analysed from a theoretical perspective which is common in social science studies. However, the results will be discussed in relation to other behavioural and social science research. It also means that lengthy measurements, covering different seasons during a year are not conducted, which are common in technically oriented studies. A longer measurement period is not applicable in the diary study as the participants' required commitment to taking part needs to be kept to a minimum.

Another limitation is in regard to how representative the participating households are in relation to households in general. To only include those living in housing areas with many similar single-family houses implies a limitation regarding diversity related to socioeconomic and demographic aspects, such as income levels, age of the residents and the type of housing ownership. This means that the findings of the thesis may well have been different if the participants had lived in various types of housing areas, from student homes to wealthy areas with large villas.

A third limitation is that some amount of time has passed since the data collection was conducted. This may affect the applicability of the results of the thesis. In the thesis, this passage of time is, on the one hand, handled by relating the empirical results to older as well as contemporary energy research. On the other hand, it is handled through reflecting on the development of applied methodologies and the results of the empirical studies on energy data analyses and energy performance evaluations.

1.6 Outline of the thesis

This section gives an overview of the thesis and guides the reader of this report to the contents of the different chapters and how they are interlinked. The publications that the thesis is based on are also listed, together with the author's contribution to the publications.

After the overall *introduction* to the thesis given above, Chapter 1 continues with a technical introduction to the energy use and energy balance of a house, a presentation of different kinds of energy-related behaviours and a short outline of a few directives and regulations of relevance for energy use in residential buildings.

Chapter 2 on *methodology* provides descriptions of the houses and participating households, as well as the methods and analysing procedures for the empirical studies of the thesis. The participation and response rates of the studies are thereafter presented, together with analyses of missing values and quality measures for the diary study and energy measurements. The methodology of the literature review is lastly described, as well ethical considerations.

In Chapter 3, the *literature review* of energy use in residential buildings and the residents' behaviour is presented. In Chapter 4, the *main results*, from the papers and the licentiate thesis (listed in Table 1 below), are summarised for each research question of the thesis.

Chapter 5 *reflects* on the methodological developments and the results since the energy data analyses, energy performance measurements and estimations were carried out. Chapter 6 first *discusses* and relates the main results of the papers and the licentiate thesis to the research presented in the literature review. The chapter ends with a discussion of the shortcomings of chosen approaches and methods in the thesis. The *conclusions* of the thesis are addressed in Chapter 7, together with *the application of the results* and *future outlook*.

Table 1 List of publications that the thesis is based on and the author's contribution to each.

Type	Reference and the author's contribution
Licentiate thesis	Hiller, C. (2003). *Sustainable energy use in 40 houses. A study of changes over a ten-year period.* (Report TVBH-3044). Division of Building Physics, Lund Institute of Technology, Lund University. *Contribution: The author conducted the empirical studies and wrote the licentiate thesis.*
Paper I (Appendix A)	Hiller, C. and Elmroth, A. (2005). Sustainable energy use in 40 Swedish houses – A study of changes over a ten-year period. In *Proceedings of the World Sustainable Building Conference*, Tokyo, Japan, 27–29 September 2005. *Contribution: The paper was written by the author who also conducted the empirical studies. Elmroth commented on the manuscript.*
Paper II (Appendix B)	Hiller, C. and Elmroth, A. (2005). Sustainable energy use in Swedish houses – A study of energy data and energy performance. In *Proceedings of the 7th Symposium on Building Physics in the Nordic Countries*, Reykjavik, Iceland, 13–15 June 2005. *Contribution: The paper was written by the author who also conducted the empirical studies. Elmroth commented on the manuscript.*
Paper III (Appendix C)	Hiller, C. (2012). Influence of residents on energy use in 57 Swedish houses measured during four winter days. *Energy and Buildings, 54*, 376–385. *Contribution: The paper was written by the author who also conducted the empirical studies.*
Paper IV (Appendix D)	Hiller, C. (2015). Factors influencing residents' energy use – A study of energy-related behaviour in 57 Swedish homes. *Energy and Buildings, 87*, 243–252. *Contribution: The paper was written by the author who also conducted the empirical studies.*
Other related publications	
Report	Hiller, C. (2003). *Sustainable energy use in houses. Will the energy use increase with time? Study of literature and computer estimations* (Report TVBH-3041). Lund Institute of Technology.
Report	Hiller, C. (2011). *Energianvändning i bostadsbebyggelsen – Brukarbeteendets betydelse. En översikt över energimätningar i 57 småhus* (SP Rapport 2011:21). Borås: SP Sveriges Tekniska Forskningsinstitut. *In Swedish*

1.7 The energy balance, behaviours, directives and regulations

The following sections introduce the energy use and energy balance of a house, present different kinds of energy-related behaviours and outline directives and regulations of relevance for energy use in residential buildings.

1.7.1 Energy use and balance of a house

In Sweden, the traditional energy use for existing single-family houses can roughly be divided into 60% for space heating including ventilation, 20% for hot water production and 20% for household electricity.[7] The trend is that total energy use of houses is typically decreasing (Swedish Energy Agency, 2019). The heat demand in new houses is less due to increased insulation and improved air tightness of the building envelope compared to older houses. In addition, the energy use for heating is less due to increased heat recovery and system efficiencies. Moreover, the energy efficiency of appliances and devices has improved, which contribute to savings for the domestic hot water usage and household electricity.

An energy balance between the energy losses from and the energy supply to a building is illustrated in Figure 2. The energy supply for heating, hot water and household electricity is on the energy supply side. Typically, in colder climates, there is no cooling in residential buildings. Solar gains, heat given off by the residents (metabolic heat) and recovered energy are also included on the supply side. On the energy loss side, there are energy flows of unused energy and losses related to ventilation, transmission, hot water and the heating system.

[7] See Fig. 1 in Paper III, Appendix C.

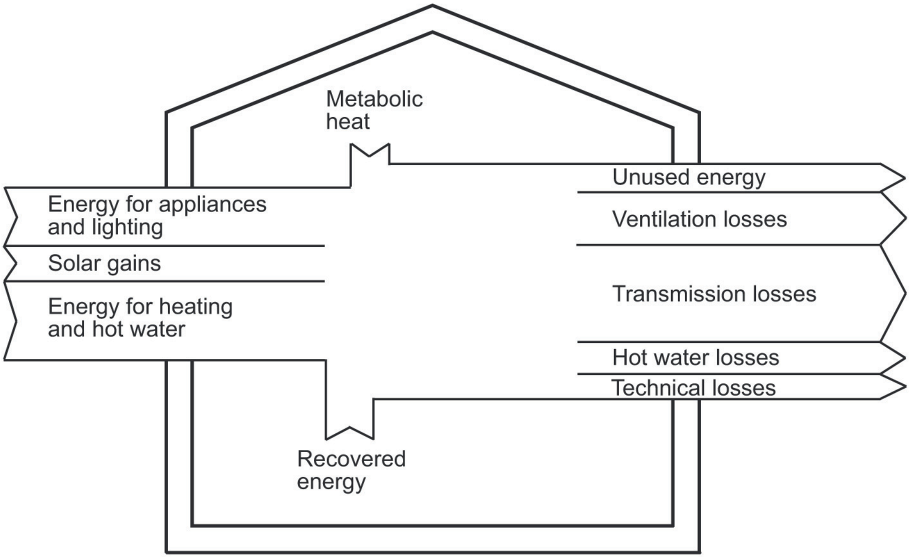

Figure 2 Schematic illustration of the energy balance for a residential building (Hiller, 2003b). (Note that this is one way of illustrating the energy flows. In the figure, the boundary is the building envelope and the energy production is carried out outside the building.[8])

The terms can be explained in the following way (Hiller, 2003b). On the energy supply side:

- *Metabolic heat* is the heat given off by the residents and is dependent on the number of persons, their activity and the 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

[8] 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, heating systems with electric or district heating have their main losses outside the boundary, while heating systems producing energy with oil, wood or pellet furnaces have their main losses inside the boundary. Secondly, the common division into the two sides – energy supply and energy loss – 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 instance, newly built houses usually have a lower heat demand due to decreased transmission losses, decreased air leakage losses, greater heat recovery and improved efficiencies. Additionally, there are diurnal and seasonal variations, as well as the influence of the residents' activities, which affect the energy flows (Hiller, 2003b).

the appliances is dependent on the efficiencies of the appliances, the number of appliances and their frequency of use.

- *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 or other adjustable solar shadings.
- *Energy for heating and hot water* is supplied by the heating system of the building. In the figure, it is illustrated as a flow into the building, which means that in houses where biofuels (pellet and wood) or oil is used, the flow represents primary energy (i.e. the theoretical energy contents). The energy used for hot water production includes heat gains from the hot water pipes.
- *Recovered energy* occurs, for example, by a mechanical supply and exhaust ventilation system with heat recovery.

On the energy loss side:

- *Unused energy* is described as the share of the heat gains (metabolic, appliances and solar) that cannot be utilized for any useful purpose. 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* include the hot water that is leaving the building, such as heat losses to the cold and wastewater pipes.
- *Technical losses* are the total heat losses of the heating system, dependent on the efficiency of the system. These include losses in the heat generation, heat distribution, control system etc.

The technical conditions of the building and the building services, such as insulation levels and efficiency of the heating system, have a large impact on the energy flows of the energy balance. However, the residents and their activities influence several of the energy flows as well, from the metabolic heat to the use of electrical appliances and lighting, as well as the use of hot water. Also, the residents' choice of indoor temperature and their airing behaviours influence the ventilation and transmission losses from the building.

In this thesis, the energy use is measured, which includes the two energy flows on the supply side, *energy for appliances and lighting* and *energy for heating and hot water*.

1.7.2 Different kinds of energy-related behaviours

There are different types of energy-related behaviours, where some are performed frequently, and others are carried out less often. There are s*tocktaking behaviours*, which are small conscious decisions, typically not performed with great frequency. These include exchanging incandescent lamps for energy-efficient lighting or fixing the draught-proofing of the house (maintenance work). These measures are relatively cheap but still have an important energy impact. Infrequent c*onsumer behaviours*, on the other hand, are usually based on major conscious decisions, where pros and cons of different alternatives are evaluated. These measures, associated with higher costs, include the purchase of products of different kinds, such as electrical equipment, white goods or building services. Many of these devices are replaced when worn out, and the replacement with more energy-efficient ones leads to energy savings. Finally, *everyday behaviours* – those mainly focused on in this thesis – are routinized activities performed on a daily basis without much consideration. Small changes in these everyday activities can in the long run make a difference in the energy used. The costs associated with these behaviours are usually low or non-existent, for example, how the laundry is dried or whether the lights are turned off in unoccupied rooms (IEA, 2010; Laitner, Ehrhardt-Martinez, & McKinney, 2009). As illustrated in Figure 3, energy-related behaviours can either be categorised by the costs related to activities (horizontally) or by the frequency of activities (vertically).[9] Cost and frequency are the most common attributes related to categorisation of energy-related behaviours found in the literature (Karlin et al., 2014).

[9] There are several ways to categorise and define different types of behaviours (e.g. Johansson & Neij, 2017), where Figure 3 shows one way. Two of the most common divisions used are curtailment behaviours and efficiency behaviours (which to a great extent, but not exclusively, correspond to everyday behaviours or consumer behaviours in Figure 3), but Karlin et al. also argue that it may be valuable to distinguish maintenance behaviours (here corresponding to stocktaking behaviours), studying these specifically (Karlin et al., 2014).

	Infrequent	Frequent
No/low cost	*Stocktaking behaviours* Energy-efficient lighting Temperature setbacks Draught-proofing	*Everyday behaviours* Turning off computers and other devices Air-drying laundry Taking short showers Energy-efficient washing programs
High cost /investment	*Consumer behaviours* Energy-efficient white goods/appliances Energy-efficient windows Additional insulation Heat pumps	

Figure 3 Categorisation of different types of energy-related behaviours, with examples of energy-saving activities associated primarily with single-family houses (modified from figure presented by Laitner et al. (2009)).

Examples of energy-saving activities are given in Figure 3. Energy savings and energy efficiency are many times used synonymously in literature (Herring, 2006). However, *energy efficiency* means that the same benefits are obtained but with less energy. *Energy savings*, on the other hand, covers all types of savings but do not necessarily lead to the same benefits. To separate these terms in relation to people's behaviour is difficult, hence, all behavioural changes that save energy will primarily be described as *energy-saving behaviours* in this thesis. In addition, energy-related *behaviours* and energy-related *activities* are used interchangeably in the thesis.

1.7.3 Directives and regulations of relevance for energy use in residential buildings

As mentioned in the introduction, there are several legislated items that relate to the energy use of buildings. One is the Energy Efficiency Directive which sets targets for energy efficiency where measures aimed at households include information provision, metering and billing of households' individual energy use and smart metering (Directive (EU) 2018/2002). Two other legislative acts affecting the energy use of households are the Energy Labelling Regulation (Regulation (EU) 2017/1369) and the Ecodesign Directive (Directive 2009/125/EC), which promote consumer guidance and energy efficiency for energy-related products, including many found in the home, such as white goods and lighting. One directive that is particularly relevant to this thesis is the Energy Performance of Buildings Directive (EPBD), which will be briefly described in this section, together with its impact on the Swedish building regulations. The section also explains how resident-related aspects are taken into account in the regulations.

The EPBD says that energy performance requirements shall be established, which means national requirements for new buildings, for major renovation of buildings and for replacement or retrofit of building elements (e.g. heating and cooling systems, roofs, walls) (Directive 2010/31/EU).[10] The directive also requires that a certificate declaring a building's energy performance shall be available in a buy/sell or rental situation, guiding consumers in their choices (regulated in the Swedish regulations for energy performance certificates (BFS 2007:4 – 2018:11)). The next step in the revised version of the directive is a strong focus on transforming the existing building stock into energy-efficient buildings (Directive (EU) 2018/844).

As a consequence of EPBD, changes and stricter requirements have been introduced in the Swedish building regulations. One of the main changes has been the shift from requirements on the energy demand of the building (hence focused on limiting the energy losses) to requirements on the amount of delivered (bought) energy a building is allowed to use per heated floor area (which is included in the supplied energy to the building, see Figure 2 above). This shift has, consequently, steered the development towards lower actual specific energy use in new buildings (first introduced in regulations of 2006 (BFS 1993:57 – 2006:12)). In addition, the building regulations have established that the energy use in completed buildings need to be verified (by measurements or calculations). As a result of EPBD recast introducing nearly zero-energy buildings[11] in 2010, the prevailing Swedish building regulations have changed the system boundary to incorporate the primary energy use. This has meant that the energy performance of a building is now specified as a primary energy number[12] (BFS 2011:6 – 2019:2).

As part of verifying that the energy requirements are met in the Swedish building regulations, additional regulations were released in 2016, which determine buildings' energy use at normal use and during outdoor climatic conditions in a

[10] The first EPBD was launched in 2003 (Directive 2002/91/EC), which in 2010 was replaced by a recast of the directive (Directive 2010/31/EU).

[11] In the recast of the directive, all new buildings must be nearly zero-energy buildings by 31 December 2020 (public buildings by 31 December 2018) (Directive 2010/31/EU). A nearly zero-energy building means a building with very high energy performance, where required energy is covered to a large extent by energy from renewable energy sources.

[12] This primary energy number means that the total building energy use per heated floor area is included (except for household electricity, which is the same as before), weighted with the primary energy factors for each energy carrier. The energy for space heating is adjusted for different outdoor climates with the use of a geographical adjustment factor (BFS 2011:6 – 2019:2). (There is a proposal for a new version of the building regulations and if it is approved, the definition of the primary energy number will change. Turn to www.boverket.se for the latest information.)

standard year[13] (BFS 2016:12).[14] The normalisation is much linked to how resident-related aspects shall be handled, primarily in new buildings, but the data can also be used in existing buildings. For example, these regulations state how to determine standardised usage of household electricity (used for internal heat gains), domestic hot water and indoor temperatures, with the intention to carry out energy calculations or normalise measured energy use in an equivalent way for all buildings. In Appendix F, the input data used in the energy calculations performed in this thesis are compared to the typical values stated in these regulations.

Normalising the energy use to a standardised usage for each building is beneficial for verifying whether the technical performance of a building is sufficient to meet the energy requirements. Nevertheless, in order to reduce the total energy use in the built environment, the actual usage of the building and its building services must be considered as well, including the energy-saving behaviours of the residents and their choices of energy-efficient devices. The regulations include some incentives to carry out energy-efficient measures related to hot water use, for example. An energy reduction of 10% (maximum) for the installation of energy-efficient taps could be made (BFS 2016:12 – 2018:5). Other aspects that the residents influence, such as household electricity, is, however, not included in the energy performance requirements at all.[15] Regarding the indoor temperature, the regulations are focused on buildings having a good indoor climate by providing a temperature of 21°C, whereas limiting high indoor temperatures is not encouraged.

At the time of the empirical studies in this thesis,[16] EPBD had not yet been implemented in the Swedish building regulations. As mentioned, the regulations were then focused on limiting energy losses from buildings, which had been the case ever since the first building regulations on energy use came into force, including the regulations that were relevant when the houses in the thesis were built.[17] Hence, the actual usage of the building and the everyday behaviours of the residents were even less in focus in the previous regulations.

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[13] Referring to a standard year means using normal values of outdoor climatic conditions calculated as long-term averages over a certain period of time.

[14] An updated version was published in 2017 (BFS 2016:12 – 2017:6), with minor changes added in 2018 (BFS 2016:12 – 2018:5).

[15] However, the regulations do state that the requirements shall not be easier to meet simply because a household is a major consumer of household electricity (due to behaviour patterns, inefficient appliances etc.) as this would contribute to the internal heat of a house, decreasing the need for space heating (BFS 2016:12 – 2018:5).

[16] The empirical studies of the thesis were carried out in 2003 and during the heating season of 2005/2006.

[17] SBN 1975 and the subsequent SBN 1980 were the prevailing Swedish building regulations when the houses in the thesis were built during the 1980s (SBN 1975; PFS 1980:1).

2 Methodology

In this chapter the choice of housing areas and the methods used in the thesis are presented, as well as how the empirical data have been analysed.

As described in the introduction, the thesis has a multidisciplinary approach where methods with traditions in both the technical and the social science fields have been partially combined to address the research questions. How the research questions were examined by various methods is summarised as follows:

- The first research question, regarding how energy use in houses changes over time, was the starting point of the thesis and was examined by energy data analyses and interviews with residents.
- The second research question, treating how energy use of households living in similar houses differ, which was initiated after findings in the energy data analyses, was further investigated by energy performance evaluations and by short-term energy measurements for four days.
- The third research question, dealing with diurnal electricity consumption patterns, was addressed by short-term energy measurements for four days.
- The fourth research question considered energy-related behaviours – as this was pointed out to contribute to large differences in energy use between households living in similar houses – and was examined by a diary study combined with energy measurements during four days.

The main objectives of the thesis were also examined by a literature review covering publications on energy use and energy-related behaviour in single-family houses.

The chapter begins with a description of the houses and the participating households. Then, the decision on methods and analysing procedures for each of the empirical studies of the thesis are explained. Thereafter the household participation and response rates of the empirical studies are presented, together with analyses of missing values and quality measures for the diary study and energy measurements. The chapter ends with an outline on how the review of literature was carried out and a description of the ethical considerations which have been taken in the empirical studies.

2.1 Description of the houses and households

The reasons to why the houses and housing areas were chosen will be explained in this section. The section also covers technical descriptions of the houses and brief descriptions of the participating households.

2.1.1 The choice of houses and housing areas

Several criteria were significant when choosing houses and housing areas, namely:

- The houses should represent houses with normal energy performances, built after the Swedish building regulations on energy use came into force (SBN 1975).[18]
- The houses should be electrically heated with their own meters so that energy use could easily be measured for each household. However, electrically heated houses would mean that energy use for different purposes (household electricity, space heating and domestic hot water) were not measured separately.
- The houses needed to be detached houses, as this was a prerequisite for comparing the energy usage of individual houses and households with each other.
- The houses needed to have been in operation for several years and historical energy data should be readily available, in order to be able to study energy use over time (relevant for housing area A[19]).
- Each housing area should comprise at least 30 houses of the same type (i.e. nominally identically built). This allowed a comparison between the households' energy use without taking into account differences in the construction of the houses. A considerable number of similar houses allowed division into subgroups in the analyses.
- The geographical location of housing area A[19] should have climate data available (heating degree-days).
- The housing areas had to be located within close proximity of the author of the thesis due to the number of visits made to the areas (a convenience criterium).

[18] See Section 1.3 for further background to the studies and which houses were in focus.

[19] Explanations of denotations and descriptions of housing areas are given in Section 2.1.2.

Information about possible houses and housing areas, such as maps over areas, technical descriptions and drawings of houses, were primarily gathered from town planning departments. Several potential housing areas were also visited by the author. From the above criteria, a sample was made, leading to three suitable housing areas, which will be described in more detail in the next section.

2.1.2 Technical descriptions of the houses

The three selected housing areas were located in western parts of Sweden and the houses were built in the 1980s. The areas will be denoted as housing areas A, B and C in this thesis.

The technical descriptions of the houses in the three housing areas, explained in the following sections, are based on the original designs when the houses were newly built. In addition to these descriptions, the heated floor area including any extended areas, are listed for each house in Table 8 in Appendix E. In all, the size of the houses varies between 104 to 159 m^2 heated floor area, with an average of 125 m^2. The size of the houses fairly represents typical Swedish single-family houses, which in 2018 had an average floor area of 122 m^2 (Statistics Sweden, 2020b). In housing area A, many houses have extensions, while in the other housing areas, B and C, only minor changes to the size of the floor areas have been made. Moreover, most houses in housing areas A and B have common garage houses where the electricity of any heaters, such as engine preheaters and car heaters, was not measured on the individual house meters.

2.1.2.1 Housing area A

In housing area A there were 41 houses of the same type. A typical house is shown in Figure 4 and a brief technical description of the houses is given in Table 2. In addition, Figure 2 in Paper I (Appendix A) shows the construction of the original houses in housing area A.

Figure 4 House in housing area A. Picture: C. Hiller

Table 2 Short description of the houses in area A

Housing area A	**Description**
Type of house	Detached, one-floor, single-family houses
Construction	Wooden framework. Foundation is concrete slab on ground
Heated floor area	104 m^2
Year of construction	Mid-1980s
Heating system	Waterborne electric heating (electric boiler)[a]
Ventilation system	Mechanical exhaust ventilation system
Windows	Triple glazed
Thermal insulation:	
- Wall	170 mm mineral wool
- Foundation	70 mm cellular plastic
- Attic	120 mm + 230 mm glass wool (loose fill)

[a] Heating system equipped with central control system with the ability to do regular temperature setbacks (e.g. nightly lowering of indoor temperature).

2.1.2.2 Housing area B

In housing area B there were 31 houses of the same type. A typical house is shown in Figure 5 and a brief technical description of the houses is given in Table 3.

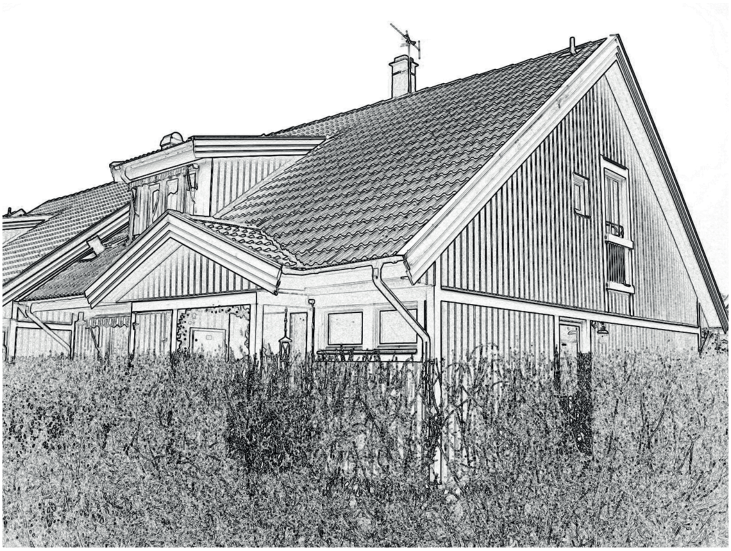

Figure 5 House in housing area B. Picture: C. Hiller

Table 3 Short description of the houses in area B

Housing area B	Description
Type of house	Detached, 1½-floor, single-family houses
Construction	Wooden framework. Foundation is concrete slab on ground
Heated floor area	130 m^2 (13 houses), 132 m^2 (6 houses)
Year of construction	1980/1981
Heating system	Direct electric heating[a]
Ventilation system	Mechanical supply and exhaust ventilation system with heat recovery
Windows	Triple glazed
Thermal insulation:	
- Wall	145 mm mineral wool
- Foundation	50 mm cellular plastic
- Attic	220–250 mm mineral wool

[a] Heating system equipped with central control system with the ability to do regular temperature setbacks (e.g. nightly lowering of indoor temperature).

2.1.2.3 Housing area C

In housing area C there were 33 houses of the same type. A typical house is shown in Figure 6 and a brief technical description of the houses is given in Table 4.

Figure 6 House in housing area C. Picture: C. Hiller

Table 4 Short description of the houses in area C

Housing area C	Description
Type of house	Detached, 1½-floor, single-family houses
Construction	Wooden framework. Foundation is concrete slab on ground
Heated floor area	122 m^2 (9 houses), 121 m^2 (6 houses), 120 m^2 (1 house)
Year of construction	First half of 1980s
Heating system	Waterborne electric heating (electric boiler)[a]
Ventilation system	Mechanical supply and exhaust ventilation system with heat recovery
Windows	Triple glazed
Thermal insulation:	
- Wall	170 mm mineral wool
- Foundation	70 mm cellular plastic
- Attic	250 mm mineral wool

[a] Heating system equipped with central control system with the ability to do regular temperature setbacks (e.g. nightly lowering of indoor temperature).

2.1.3 Participating households

The participating households were selected based on their living in the chosen areas and houses. To ensure that individual households could not be identified, each household was given a code, such as A1, where the letter A refers to housing area A.[20]

In Table 8 (Appendix E), the household composition, that is the number of household members and their ages, are listed for each participating household. Based on household composition, the participants were divided into different types of households (Table 5), inspired by the categorisation in a Swedish measurement campaign (Zimmermann, 2009).

Table 5 Categories of participating households (participating households in the diary study and energy measurements)[21]

Household types[a]	**Housing areas**			
	A	B	C	Total
I Single persons, 26–64 years	1	0	0	1
II Single persons, 65 years and above	0	0	0	0
III Couples without children, 26–64 years	7	3	4	14
IV Couples without children, 65 years and above	0	5[b]	0	5
V One or two persons with children	14	11	12	37
Total number of households	22	19	16	57
Total number of persons	66	52	53	171

[a] Only in a few cases was it not clear which category the households belonged to. An assessment of which category was most relevant was then made.

[b] One couple was categorised as household type IV, although they were not quite 65 years old, because they were close to the retirement age and because one person in the household was retired (disability pension) and the other person was unemployed at the time of measurement.

Table 5 shows that the majority of the participants were households consisting of one or two persons with children. Only one single-person household was included in the study, and the few retired couples participating lived in housing area B. The

[20] The denotation of the households was different in the studies of data analyses and interviews, as well as in the energy performance evaluations, which is seen in Paper I and II (Appendices A and B). Turn to Appendix E and Table 8 for further clarification on denotations, and detailed information about the individual households.

[21] In Paper III and IV, household type V was called families.

distribution of households between the different household types was similar to that referred to in the measurement campaign (Zimmermann, 2009).

2.2 Choice of methods and procedure

The research questions for this thesis led to the design of empirical studies involving combined methods in the following ways:

1. Data analyses and interviews examining energy use over time (38 and 6 households)
2. Energy performance evaluations by measurements and estimations (2 households)
3. Diaries and energy measurements investigating energy use, including diurnal variations, and everyday behaviours (57 households)

The next sections will describe the choice of methods and procedures used for data collection, treatment and analyses for the empirical studies.

The methodology development and the relevance of the results of the data analyses, as well as the energy performance measurements and estimations are further reflected on in Chapter 5.

2.2.1 Energy data analyses and interviews

With the intent to examine energy use over time, after years of occupancy, a longitudinal study[22] was performed, where energy data and water data were gathered and analysed for 38 houses in housing area A, covering a period of more than 10 years. The data analyses were combined with interviews with six households about measures that had been carried out to the houses and changes related to the households, which had impacted their energy use over the years.

Longitudinal studies, examining items over time, can be carried out in different forms, for instance, as prospective studies or as retrospective studies (Caruana et al., 2015). As potential changes in energy use over a longer period were to be studied, a prospective study was not possible for this study that would only last a few years. Although looking back in time has its disadvantages, for example, data inaccuracies are difficult to correct afterwards, a retrospective approach was feasible since data for several years were already available. The choice to analyse and follow up annual energy data over time for the same houses has been done in other studies as well

[22] Longitudinal studies examine items over time (Caruana et al., 2015).

(e.g. Berggren et al., 1997; Nilson & Uppström, 1997; Sikander et al., 2011; Weber, 1996).

Energy data showed how household energy use changed, but further information was needed to examine what has affected it over the years, which was why the energy data analyses were combined with interviews with the households. The interviews were an opportunity to discuss each household's specific energy-related activities and compare it to their energy use.

2.2.1.1 Data Analyses: Annual Energy Use

Annual energy and water data were available from the local energy supplier for 38 of the houses in housing area A and was derived from the period of 1988/1989 to 2000/2001. The readings of the electricity and the water meters were mostly done at the end of May/beginning of June every year.

The energy data referred to the total bought energy use, that is, the energy for the hot water production, the space heating and the household electricity. The water data referred to the total water consumption, including both the cold and hot water use. Corrections were made in order to be able to compare the energy use between different years and to analyse any general trends or changes in energy use. First, the data were corrected for the number of days in a year so that it corresponded to the energy use of 365 days. Second, the data were corrected for varying outdoor temperatures during the time period studied, using the degree-day method. The energy data were analysed on a household level as well as on a group level.

Corrections with heating degree-days

The purpose of using degree-days (*DD*) in an energy follow-up is to enable a comparison between a building's energy use of one year to another by limiting the influence of varying outdoor climates. Degree-days take into account, and correct for, how much the outdoor temperature differs compared to what is normal for the location in question. The heating degree-day method was the prevailing climate-correction method at the time of the energy data analyses and is still today a common method for correcting for varying outdoor temperatures (Heincke, Jagemar, & Nilsson, 2011). The heating degree-days were obtained from the Swedish Meteorological and Hydrological Institute (SMHI).

Heating degree-days are calculated by summing up the differences between the so-called balance temperature of a building and the actual outdoor temperature of each day. The balance temperature is defined as the lowest temperature (outdoor) where the building's heating system does not need to supply heat to reach the desired indoor temperature. Instead, heat losses from the building are covered by internal heat gains, such as heat from solar insolation, persons, lighting and household appliances. The sum of differences between the balance and outdoor temperatures is compared to 'normal' degree-days for the location, which means considering the long-term average temperature over a certain period of time.[23] The corrected energy use is obtained by dividing the actual energy use with SMHI's correction factor, DD_{actual}/DD_{normal}.

The SMHI degree-day method assumes a steady-state situation and a balance temperature of 17°C for all buildings. The choice of balance temperature is very important as this has a direct impact on the number of degree-days and hence how well the correction works for a specific building (Lindelöf, 2017).[24] For the electrically heated houses in housing area A, with not very much insulation, the method was considered to be sufficient to correct for variation in outdoor temperature.

As the energy data obtained from the local energy supplier included all fractions of energy used in the houses, the energy use dependent on the outdoor climate needed to be separated from the total energy, before correcting for varying outdoor temperatures. Typical values for the temperature-independent energy use, such as household electricity and domestic hot water, were estimated as there was little information about the households at this stage of the thesis.[25,26] Various values were chosen in order to test their effects on the corrected energy use.[27]

Comparison to other climate-correction methods

Corrections with heating degree-days is a simple method without the need for a lot of input data, but as it does not take the type of building into consideration, the choice of balance temperature will not be representative for all kinds of buildings. For example, the degree-day correction is less appropriate for buildings with a lower heat-loss coefficient and which are mainly heated by internal heat or solar insolation (Heincke, Jagemar, & Nilsson, 2011).

The degree-day method does not consider climate conditions other than the outdoor temperature; a variant is therefore the energy index method (recommended in the Swedish regulations determining the building's energy use under normal conditions (BFS 2016:12 – 2018:5)). Besides the outdoor temperature, the energy index

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[23] Changes in time periods for calculating normal values are further discussed in Section 5.1.1.

[24] Different international standards and norms use different balance temperatures (e.g. ASHRAE, 1997; CIBSE, 2006; Eurostat, 2007; ISO, 2007).

[25] Tested values on household electricity were 3000, 4000 and 5000 kWh/year for all participating households. These estimates were based on available typical consumer data but also energy measurements (NUTEK, 1994; Swedish Consumer Agency, 2002).

[26] Tested values of the share of hot water of the total water consumption were 20%, 30% and 48%. These values were chosen after a conversation with the water supply and sewerage department at Borås municipality (Borås Municipality, 2001). The figure of 48% derived from recalculating the energy needed to heat all water to an average of 30°C, i.e. corresponding to the temperature of the outgoing wastewater.

[27] Typical values are also discussed in Section 5.1.2.

method also considers solar and wind data together with the location of the building, the technical energy properties of the building and the way the building is used. For this method, a heat balance model has been developed for a number of predefined typical houses (SMHI, 2020).

Another climate-correction method is the energy signature, which is building-specific and calculates the building's average power demand as a function of the average (monthly) outdoor temperature (and is also called the building's total heat loss). Using historical data for the specific building and assuming constant indoor temperature, the energy signature is illustrated by linear regression in a graph, from which the corrected average power demand can be calculated with the help of the normal outside temperature (Dahl, 2012). An advantage is that the part of the energy use that is independent of the outdoor temperature does not need to be considered. However, the need for historical data leads to the method being unusable during the first years for a newly built house (Heincke, Jagemar, & Nilsson, 2011).

The accuracy of the different climate-correction methods has been tested in building simulations, keeping other variables constant (Isakson & Carling, 2012). In these simulations, the SMHI's degree-day method showed a surprisingly good accuracy for most tested building models. For low-energy buildings, however, the corrections work less well. In other tests with real data, the findings were that no method worked better than all the others (Dahl, 2012).

2.2.1.2 Interviews: Energy-related activities over time

Interviews were held with the residents (adults) of six households in housing area A at the end of January 2003. The reason for conducting these interviews was to gain explanations for the appearance of individual houses' energy curves over the years. All households in housing area A were informed about the study, its purpose and were asked to participate through a written letter. The six households were selected from those willing to participate.

The interviews started off as structured interviews, following a questionnaire with questions about the house and energy-relevant items, but ended up covering all the prepared questions but not in strict order, which made them resemble semi-structured interviews.[28] The questions covered measures, activities and events having an influence on the energy use that had occurred over the years. This meant that events that had happened many years back had to be recalled by the residents which was problematic; this is a recognised drawback of retrospective data collection methods, especially those involving data collection from people (Trost, 2001). The questions regarded changes made to the existing building (including building envelope, heating and ventilation systems), and if extensions had been

[28] Semi-structured interviews are when all the participants are asked the same predetermined questions, but that the order of the questions varies; also, follow-up questions can be asked (Bryman, 2011).

made. The questions also covered purchases of new white goods and how the household composition changed over the years. The interviews were supplemented with background questions, as well as questions and discussions regarding the household's energy curve over the years.

The information from the interviews were matched with each household's energy curve using simple illustrations to symbolise the potential effect that different activities have on the energy use. No grading was made at this stage to the size of the energy impact; the symbols were merely used to guide a first visual analysis. An alternative could have been to conduct more detailed analyses of the energy impact of the information collected to examine how well these estimates corresponded to actual energy data. However, this was not considered relevant as the time resolution of energy data was on an annual basis and the time indications for specified activities were very approximate.

2.2.2 Energy performance evaluations

In order to investigate households' different levels of energy use, detailed investigations of two houses' energy performances (households A6 and A13), measured as specific heat losses[29] together with energy calculations, were carried out. These investigations were a consequence of the energy data analyses described in the previous section and was a way of exploring if the different levels of energy use were due to the energy performance of the houses themselves or was due to the impact of the residents.

There are various ways to evaluate the actual energy performance of buildings (Farmer, Johnston, & Miles-Shenton, 2016). To enable comparisons between different buildings' performance, one aspect that needs to be addressed is the impact of the residents on the energy use. This can be done by employing typical values for the use of buildings, which is done, for example, when the energy performance of houses shall be verified in accordance to the Swedish building regulations (BFS 2011:6 – 2019:2). But to avoid assumptions about residents' behaviour, there are measurement methods that instead require unoccupied houses (Mangematin, Pandraud, & Roux, 2012), which is most easily done when the houses are newly built or possibly when a relocation of the residents takes place. In this thesis, however, one of the prerequisites for measuring energy performance was that the residents were able to stay in their houses while the measurements were ongoing. This was an important reason why the chosen heat loss method was particularly suitable, as data could be used at night to minimise the impact of the residents (Sandberg & Jahnsson, 1995). Moreover, the houses' heating and ventilation

[29] The description of the method referred to in this thesis uses the term *specific heat loss* (Sandberg & Jahnsson, 1995), but terms such as *heat loss coefficient* are also used in other publications (e.g. Farmer, Johnston, & Miles-Shenton, 2016; Mangematin, Pandraud, & Roux, 2012).

systems could operate as usual; in addition, the employed method is applicable for the type of houses found in housing area A, that is, detached, light, wooden-framed houses with electric heating and mechanical ventilation.[30]

2.2.2.1 Specific heat loss measurements

Most commonly, the purpose of measuring specific heat loss is to compare it to the estimated heat loss in order to actually follow up that the building performs as was predicted.[31] The method has not been developed for comparisons of different houses' energy performance, but in this case the houses were ‘identically’ built, which made a comparison suitable. The use of the specific heat loss means that the influence of factors that can vary a lot depending on who lives in the house and on the climate conditions are minimized (Farmer et al., 2016; Mangematin et al., 2012; Sjögren, Andersson, & Olofsson, 2009; Vesterberg, 2014).

The method gives a momentary value of the energy performance of the house and its building services at the time of measurement. The specific heat loss, F_T, used in this thesis is defined as the sum of the transmission and ventilation losses per degree of temperature difference between the indoor and outdoor environments (Sandberg & Jahnsson, 1995).

The method meant that indoor and outdoor temperatures were noted for ten measuring periods (nights) together with the electrical meter readings. As no loggers or sensors were installed for this part of the study, it meant that the residents had to participate with manual data registration. During the measuring time, and in particular during the night-time, the residents had to follow a number of restrictions such as no usage of other energy sources (e.g. cast iron stove), no usage of hot water and outdoor lighting, and no window opening (for more details, see the author's licentiate thesis (Hiller, 2003a)). In this way, the energy use reflected the performance of the house as much as possible and uncertainties were kept to a minimum. For these reasons, only nightly time periods were used, which then meant that there was no solar insolation and that the effect of energy-related behaviours (mainly related to household electricity and domestic hot water) were minimised as the residents were sleeping. The field measurements were performed during the winter period to obtain large enough temperature differences between outdoors and indoors as well as to get long nights. This also meant that the effect from solar insolation during the daytime was limited.

Still, to completely remove all heat gains from other sources than the heating system was not possible. Therefore, to get closer to the average power demand of the

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[30] Other variants of heat loss methods include buildings with greater thermal masses (i.e. greater time constants), where heat storage in the building frame needs to be handled in a more thorough manner (Andersson et al., 2011).

[31] Expressed as a temperature-dependent power demand.

building, a number of corrections were made to the electrical meter readings. Heat given off by persons during the measurement periods was estimated and added to the electrical consumption. Corrections were also made for unstable indoor temperatures[32] and the electrical consumption of the exhaust air fan was subtracted (more details in licentiate thesis (Hiller, 2003a)).

The specific heat loss includes one part that is proportional to the temperature difference between indoors and outdoors and one part that is proportional to the temperature difference between indoors and the ground. In this study, the losses to the ground were assumed to be constant and independent of the temperature difference, which meant that the heat loss could be estimated from linear regression. With the intention to refine the estimations of the specific heat losses for the two houses, the heat losses to the ground were calculated using the program HEAT2 (version 5.0). The HEAT2 program can be used to calculate two-dimensional transient and steady-state heat transfer.

The advantage of the chosen heat loss method is that it is a simple field method, but the drawback is that its accuracy is limited. The accuracy of the method is dependent on many aspects. That the indoor temperature is stable and that there is minimal heat storage in the building have already been mentioned as important factors. Another aspect is that the measurements should be performed during relatively stable weather conditions. A general estimate of the measurement error of the method has been found to be up to 10% (Sandberg & Jahnsson, 1995).[33]

The question of participating in the heat loss measurements was asked during the interviews and two households agreed to participate. These households were suitable as their energy usage was on different levels. A few days before the measurements, the two households were visited in order to mount the temperature sensors indoors and outdoors. The residents were instructed on how to do the readings and the restrictions that had to be followed. During the home visits the ventilation flows of the two houses were measured.

The measurements were carried out during the first part of February 2003.

2.2.2.2 Energy use calculations in Enorm

To compare the measured values to estimated ones, both the total energy use and the specific heat losses of the two houses were calculated using the energy computer program Enorm 1000. Enorm was chosen as it was specifically developed for single-family houses (Hagengran & Stenberg, 2005) and was a program commonly used

[32] Corrections due to variations in indoor temperature were made to compensate for presumed heat storage in or heat release from the building frame, as well as the interior of the house.

[33] In the linear regression used to estimate the specific heat loss (see Equ. 2, Equ. 3 and Fig. 3 in Paper II in Appendix B), a lower coefficient of determination, r^2, means a higher uncertainty.

in the building sector at the time of this study (Bergsten, 2001; Nilsson & Johansson, 2000).

Most of the information on the houses and the input data for the calculations were gathered from the households, the urban planning department in Borås and the company that built the houses. For the indoor temperature and ventilation flow, data from the heat loss measurements were used.

Also, annual energy data were gathered and analysed for two additional years – 2001/2002 and 2002/2003 – for the two households.

Energy calculation programs

Since the time of the study, Enorm has continued to be used by building and housing companies to calculate the energy use of buildings (Levin & Snygg, 2011; Sveby, 2012), as well as in research to estimate the effect of different energy efficiency measures on houses' heat demands and to calculate the energy performance of buildings (e.g. Gustavsson & Joelsson, 2007; Haglund & Svedlund, 2012; Joelsson & Gustavsson, 2009). In general, the continuous development of energy calculation programs has resulted in a variety of different programs with varied complexity and focuses on the market, which are used to evaluate the energy performance of residential buildings, such as TRNSYS and IDA ICE (programs frequently used in research projects are listed in the review by De Boeck et al. (2015)).

Regardless of the degree of complexity of different energy calculation programs, the calculations in this thesis, as with other energy calculations, will always be a simplification of reality and therefore coupled with a certain level of uncertainty, which has been discussed in a number of articles by Bergsten (2010a, 2010b, 2010c). Evaluations of the conformity with actual measured values show quite mixed results (e.g. Jansson & Wetterstrand, 2005; Levin, 2016; Levin & Snygg, 2011; Nilsson, 2003; Ruud, 2011a) and for the same buildings the outcome between different programs can also vary (Ardalani & Holm, 2010; Levin & Snygg, 2011). A general assumption is that deviations of 10% between calculated and measured energy data are expected (Harrysson, 2009; Levin, 2008; Levin & Snygg, 2011). How well calculated values correlate with measured values is connected to how well the program is suited to different types of buildings. Enorm was primarily developed to check whether a building met the Swedish building regulations' requirements on energy. The program does not differentiate its calculations depending on the type of building but is best suited to residential buildings and, as mentioned above, was specifically developed for single-family houses (Hagengran & Stenberg, 2005).[34]

[34] It may be worth noting that Enorm does not calculate accurately for buildings with great window areas or great heat storage capacities. Also, as the conditions are assumed to be constant over day and night, the program does not correspond well with actual values for buildings with great

Input data to energy calculations in Enorm

In Table 6, the main input data for the two houses studied are summarised.[35] Household A13 made an extension to their house in summer/autumn of 2001, which increased the heated floor area by 26.7 m^2. The extended part of the house, which was included in the energy calculations, has larger window areas compared to the original house.

The choice of input data is of importance for the outcome of the energy calculations, especially to keep the uncertainties of the estimations at reasonable levels (Bergsten, 2010b). In Appendix F, the data are discussed and compared to regulations and recommendations on input data for energy estimations, primarily stated in earlier and prevailing Swedish building regulations, as well as the regulations determining building's energy use under normal conditions.

changes in operation or for houses designed to make use of passive solar energy (e.g. Nilsson & Johansson, 2000).

[35] More detailed information on the choices of input data can be found in the author's licentiate thesis (Hiller, 2003a).

Table 6 Main input data to the energy calculations (in Enorm) for households A6 and A13.

Input data	Household A6	Household A13 original	Household A13 extension
No. of persons	4 persons	2 persons	
Heated floor area	104.2 m^2	104.2 m^2	26.7 m^2
Air leakage (at 50 Pa pressure difference)	0.64 $l/(m^2 \cdot s)$	0.66 $l/(m^2 \cdot s)$	
Geographical location (outdoor temperature)	Borås, Sweden (6.1°C)	Borås, Sweden (6.1°C)	
Indoor temperature	23.0°C	19.5°C	
Area of:			
- Ceiling	104.2 m^2	104.2 m^2	29.4 m^2
- External walls	98.9 m^2	88.9 m^2	26.7 m^2
- Floor	104.2 m^2	104.2 m^2	26.7 m^2
- Doors	4.6 m^2	5.2 m^2	
- Windows	12.6 m^2	10.6 m^2	15.4 m^2
Glass areas facing different directions[a,b]	N: 4.0 m^2 E: 0.2 m^2 S: 2.3 m^2 W: 1.7 m^2	N: 2.4 m^2 E: 1.0 m^2 S: 2.0 m^2 W: 1.7 m^2	N: 5.7 m^2 E: - S: - W: 5.8 m^2
U-value of:			
- Roof construction	0.22 $W/(m^2 \cdot K)$	0.22 $W/(m^2 \cdot K)$	0.16 $W/(m^2 \cdot K)$
- External walls	0.32 $W/(m^2 \cdot K)$	0.32 $W/(m^2 \cdot K)$	0.32 $W/(m^2 \cdot K)$
- Floor	0.13 $W/(m^2 \cdot K)$ (multiplied by 0.75)	0.13 $W/(m^2 \cdot K)$ (multiplied by 0.75)	0.10 $W/(m^2 \cdot K)$ (multiplied by 0.75)
- Doors	0.8 $W/(m^2 \cdot K)$	0.8 $W/(m^2 \cdot K)$	
- Windows	1.9 $W/(m^2 \cdot K)$	1.9 $W/(m^2 \cdot K)$	1.9 $W/(m^2 \cdot K)$
Type of heating	Electric boiler	Electric boiler	
Type of ventilation	Exhaust	Exhaust	
Basic ventilation flow	120 m^3/h	113 m^3/h	
Household electricity	4472 kWh/year	4472 kWh/year	
Domestic hot water	2599 kWh/year	1368 kWh/year	
Heat gains from persons	1146 kWh/year	573 kWh/year	
Airing	-	-	

[a] The glass areas exclude the window frame, but include the glass area in doors.

[b] The orientation of the 'south' walls of the two houses are roughly facing south-east, the direction entered into the Enorm program.

2.2.3 Diaries and energy measurements

In this empirical study, household members of 57 households (22 in area A, 19 in area B and 16 in area C) – in total 141 individuals – wrote time-use diaries while energy use, indoor temperatures and water consumption were recorded. Combining these field investigations in a multidisciplinary approach gave insights into how everyday behaviours relate to a household's energy use. As the measurements provided data on the actual consumption levels, the diaries revealed data on the daily activities carried out by the residents in their homes. In addition, diurnal electricity consumption patterns were examined from the measured energy data, comparing load curves for different days of the week. The combined study, using a mix of methods, has been designed to suit both the diary study and the energy measurements.

Alternatively, the study could have been conducted with a monodisciplinary approach, for example, involving only technical data collection by detailed electrical measurements on an appliance level. This would have provided a lot of energy data but would have required very extensive measurement equipment to include all the devices used in a home.[36] Hence, diaries were used as they are recognised as an appropriate method to capture everyday behaviour of individual residents (see Section 2.2.3.2 below).

The diary study and energy measurements were conducted during the heating season, over a four-day period in each housing area, namely in November 2005 in housing area A, in December 2005 in housing area B and in February 2006 in housing area C. The heating season was chosen in order to analyse the total energy use (i.e. energy for space heating, domestic hot water and household electricity).

The following sections will describe the methods used in more detail.

2.2.3.1 Energy measurements

Since the houses were electrically heated, the total energy (here, electricity use) use was measured by connecting a pulse meter to the houses' electricity meters, where the pulses were recorded every minute. The field measurements were feasible thanks to the cooperation of the local energy company.

The indoor temperatures were recorded every hour by one sensor on each floor of the houses. Depending on the number of floors, one or two temperature sensors were set up on a central wall in the house at a height of about 1.1 m from the floor. The measuring spot was chosen to avoid proximity to heat sources and exposure to too much sunlight.

[36] At the national level, a measurement campaign with detailed measurements was made later in the years 2006–2008. More can be read on this subject in the literature review in Section 3.1.1.1.

Similarly, the outdoor temperature was recorded every hour in each housing area. A temperature sensor was mounted on a pole 2–3 meters above the ground. The sensor was protected with a cover to limit the effect of solar radiation, wind and precipitation.

The water use was obtained from each house's water meter by one meter reading at the start of the measurement period and one at the end. The water use included both the hot and cold water used by the residents.

Measuring equipment

The measuring equipment used were these:

- Logger / pulse monitors Tinytag TGPR-1201 and EasyLog 40IMP for measuring pulses of electricity.
- Logger / sensors Tinytag TGU-4017 and EasyLog 24RFT for measuring temperatures (indoor).
- Logger / sensors Tinytag TG12-0017 for measuring temperatures (outdoor).

Temperature sensors were calibrated at RISE Research Institutes of Sweden, which at the time was called SP Technical Research Institute of Sweden.

Measurement uncertainties

The measurement uncertainty for the temperature recordings was estimated to be less than ±0.5°C for the sensors used. This measurement uncertainty concerns only the temperature at the position where the sensor has been placed. The uncertainty regarding the mean temperature on an entire floor of a building is larger and can be estimated to be ±1°C (Ruud, 2011b).

The measurement uncertainty for the recording of the electricity consumption was estimated to be approximately ±4% (SP Measurement Technology, 2011).[37] The measurement uncertainty for common water meters in residential buildings is around ±4% at normal usage.[38]

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[37] This figure of ±4% is based on oral communication with the department of Measurement Technology at SP Swedish Technical Research Institute (today part of RISE Research Institutes of Sweden) about the general requirements for electricity meters in Sweden at the time of the study. The maximum allowable error was ±8%, but based on experience of calibration of electric meters and considering that a large proportion of the measurement error is temperature dependent and greatest at extreme temperatures (which was not the case at the time of these field measurements), ±4% was a more reasonable assessment of the measurement uncertainty for a large variety of meters (SP Measurement Technology, 2011). The measurement uncertainty for some individual meters and brands may be even less; possibly as low as ±2% (Directive 2004/22/EC).

[38] An uncertainty of ±4% is in accordance with the Swedish regulations and guidelines concerning periodic inspections of water and heat meters in field (Swedac, 2007), which is based on the EU

2.2.3.2 Diary study

The following sections explain the background and grounds for choosing a diary study to examine a households' everyday behaviours. This is followed by sections describing the design of the diary, procedure of the diary study, handling of diary data and analysis methods.

Examining everyday behaviour: time geography and time-use

The purpose of the diary study was to gather information about residents' everyday energy-related behaviours. Studying activities performed in people's day-to-day lives is not as simple as it may seem at first glance. People usually do not reflect on how they carry out everyday activities, as these activities tend to be habitual and not easily described. Ellegård and Wihlborg (2001) illustrate this by the example of describing to a visitor how to get to your home. The way to your home is so familiar to you that details are usually not observed – details that might be very important for a first-time visitor to find the way.

One way of ‘capturing’ everyday behaviour is by self-reporting time-use diaries. The time-use diaries applied in this thesis were based on a time-geographical approach. This approach, which originated from the research of Hägerstrand (1970), is in line with people's way of thinking about the activities they carry out in day-to-day life (Ellegård, 1999). In short, this can be explained by that activities are prioritised over time in people's minds. The sequence of activities performed during the course of the day is easier to report than is frequency reporting (i.e. how often an activity is carried out during a certain time period (Corral-Verdugo & Figueredo, 1999)) or for how long activities are performed (added time-use).

Diaries with a time-geographical approach have been developed by Ellegård (e.g. Magnus, 2019). Time-geography is an approach to understand temporal and spatial processes, including people's activities (Ellegård, 2019). Time-geography has been applied in research related to the energy sector, for example, by Glad (2006) regarding the implementation of passive houses in Sweden, by Karresand (2014) in relation to households' use of electrical appliances, and by Palm, Ellegård and Hellgren (2018) in utilising time-use data to visualise and analyse daily activity sequences and aggregated estimated electricity load curves.

Time-use research is typically dedicated to learning how people allocate their time during an average day. Many countries conduct national time-use surveys aiming for a representative picture of how citizens in a country on average spend their time (IATUR, 2019).[39] Information on how people use their time has traditionally been

Directive on measuring instruments (Directive 2004/22/EC). These figures have been discussed with Åke Eriksson, former head of the accredited inspection body 4409 VODAK Mätarkontroll AB (Eriksson, 2011).

[39] The performance of time-use studies really got started in the mid-1960s and lead to the formation of IATUR, the International Association for Time-Use Research (this name was taken in 1988).

connected to several social issues, such as gender equality and division of labour (e.g. Statistics Sweden, 2012). However, researchers have also used the national data for other purposes, for instance, examining energy-related activities (e.g. Hellgren, 2015; Palm, Ellegård, & Hellgren, 2018). The diary format can be used in these large national time-use surveys, but diaries are also a common method to collect empirical data about people in smaller research projects.

In sections below, the diary study design of this thesis is compared with the guidelines for the larger time-use surveys (CES Task Force, 2013; Eurostat, 2019; U.S. Census Bureau, 2019).

Diaries – pros and cons

The diary format chosen in this thesis is a self-reporting method, which is the most frequent method for assessment of environmental behaviours (Gatersleben, Steg, & Vlek, 2002). The diary format is particularly applicable in understanding private behaviours as examined in the thesis (Sommer & Sommer, 2002). It is advantageous that all different kinds of behaviours were recorded in the diaries (information is not missed due to e.g. 'poorly' formulated questions in a questionnaire) and hence the participants in this diary study did not have to determine whether activities were energy-related or not. That the participants were instructed to report *all* everyday behaviours – not just energy-related behaviour – reduced the effect that the research might have had upon the participants and the data collected (Sommer & Sommer, 2002). Continuous writing, which was recommended in the diary study, meant that the participants did not have to reflect, retrospectively, on their actions (Bavaresco et al., 2020). In addition, as explained above, simplicity was in focus when the design of the diary sheets was chosen, hence the diaries were easy to fill in. All together, these features increased the validity and reliability of the diaries (Bryman, 2011; Ellegård & Nordell, 1997; Ellegård & Wihlborg, 2001; Fisher & Layte, 2004; Sernhed, 2004).

As learnt in the diary study, one drawback was that the required commitment was quite large for the participants, which increased the risk of dropouts. The required commitment is a consequence of the participants being asked to continuously fill in the diaries, of how many diary days the study is going on (discussed in a section below) and of the expected level of detail to fulfil the objectives of the study (CES Task Force, 2013). For example, in the diary study of the thesis, reporting turning on and off lighting was not emphasised to a great extent in the instructions, as it was considered to be on too-detailed a level for many of the participants. Furthermore,

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IATUR has pushed the development of the diary format for time-use surveys and has together with other international organisations, such as EUROSTAT and several UN agencies, produced guidelines to harmonise time-use surveys carried out in many different countries (e.g. CES Task Force, 2013; Eurostat, 2019). Another major contributor to this field is the American Time-Use Study, ATUS (Harvey, 2004; U.S. Census Bureau, 2019).

as diaries are more disruptive and intrusive than responding to a questionnaire, the risk of changed behaviour might be large (Bryman, 2011). As with all methods asking people for information, there is subjectivity in the data collection as people will document what they think to be relevant, which will vary from person to person (Bryman, 2011; Ellegård & Nordell, 1997). This meant that the level of detail given in the participants' diaries varied, that is, there was a reporting variability in regard to detail (UN Statistics Division, 2005). Another aspect to consider is that the procedures of diary studies are quite time-consuming for the researcher (Bavaresco et al., 2020). For example, the experience in this thesis was that the preparatory work to engage and instruct the participants, as well as to code the data after the diary writing required a lot of time.

Design of diary sheets

Simplicity was prioritised in the design of the diary, making it easy to understand for all ages of diary writers. The diary used in the thesis was designed as a structured diary with open time intervals (shown in Figure 7). The headings were decided on after investigating previous time-use studies based on a time-geographical approach (e.g. Ellegård & Wihlborg, 2001; Sernhed, 2004). Different diary designs are suitable for different purposes (CES Task Force, 2013; Ellegård, 1999; UN Statistics Division, 2005), and in this section the chosen design of the diary sheets will be explained.

For registering time on the diary sheets (first and second column in Figure 7), open time intervals were chosen as it suited the purpose of registering all kinds of energy-related activities and matched the energy use which was continuously measured (every minute). It was decided to include a separate column with the heading ‘end time’, as it was considered uncertain whether participants would register, for example, switching off appliances as new activities (on a new line).

There are, however, pros and cons with open time intervals versus fixed intervals. In Eurostat guidelines, a fixed ten-minute time slot is described (Eurostat, 2019), whereas in the American Time Use Survey open interval diaries are used (U.S. Census Bureau, 2019). According to previous experience, there is a tendency for greater variation in data quality for open time intervals than for diaries with fixed intervals. On the other hand, when using fixed intervals, activities that do not last long but are still important can be left out. Also, the exact time duration of activities will not be reported.

Time start	Time end	What am I doing?	Use of equipment, lighting or hot water - Household appliances - Lamps (including number of lamps) - Other electronic equipment - Regulating temperatures (radiators) - Hot water usage - Etc.	Where? - which room in the house - garage - storage - garden	Comments

Figure 7 Diary sheet used in the study (translated from Swedish and modified from diaries presented by Ellegård and Wihlborg (2001) and Sernhed (2004)).

The activities performed were written down in the third column in this diary format.[40] The inclusion of column four, 'Use of equipment, lighting or hot water', reflected the focus on energy use in this study. The reason for adding this column was to draw the participants' attention to reporting on the specific devices being used, so that the diary writers noted both the time different activities occurred and the length of time devices were operated.[41] In the fifth column, contextual information related to the activity was reported. In this thesis, this information has proven useful. When all household members' diaries were cross-examined, one could identify which specific electronic equipment, or such like, was being used, as many homes might have multiple TVs, computers etc. turned on simultaneously. Lastly, the participants had the possibility to give comments in the sixth column.[42] The participants filled in the diary sheets by hand.

Procedure of diary study

It has been proven that various actions will improve the response rate and the quality of diary studies, such as clearly communicating expectations, giving logical instructions and showing examples of diary entries (Bryman, 2011; Corti, 1993; Ellegård & Nordell, 1997; Eurostat, 2019). Hence, data collection for this thesis

[40] In some time-use surveys, e.g. the Swedish national survey (Statistics Sweden, 2012), an additional activity column is included where activities performed simultaneously can be stated. In other studies, this column is not included (U.S. Census Bureau, 2019), as it may lead to that simultaneous activities are somewhat underreported compared to if they are stated explicitly (on a new line).

[41] In the latest Eurostat guidelines, a new column has been added were diary writers record whether they have used any ICT devices when performing their activities (Eurostat, 2019).

[42] In other diary designs there may be a column for with whom an activity is performed. However, in this thesis, it was considered redundant, as social relations within a household was not studied.

included sending introductory letters, making phone calls and paying home visits to the residents to ask for their participation and to give instructions.

All household members aged 12 and above were asked to participate. This meant that *the household* served as the sampling unit, the reason being that the diary data were aggregated on the household level as it was examined together with the energy use as measured per house. One disadvantage of focusing on the whole household is that the response rate might be lower than if individuals were the sampling unit, which is common in national time-use surveys (e.g. Eurostat, 2019).

Because the required commitment of participation was quite large, an age of twelve years[43] was chosen as appropriate; for younger children, the parents were encouraged to include the children's activities as much as possible in their own diaries.

During the researcher's first home visit, instructions were given both orally and in writing to as many household members as possible. An example of an already-filled-in diary was handed to the households. The instructions were to write down everyday activities carried out at home and to do this during the course of the days. This meant that each individual recorded the activities they performed and how and when they did them. The participating persons were encouraged to fill in the diary continuously, as recording during or immediately after the behaviour occurs has proved to be the most effective method (Sommer & Sommer, 2002). The participants were informed that the empirical data would be handled with confidentiality and during the home visit each person was given an individual code. As recommended by other researchers, it was pointed out to the participants that the purpose of the diary was not to control anyone's life (Ellegård & Nordell, 1997).

Two visits to each house were made prior to the field measurements to install temperature sensors and to read the water meters, which gave an opportunity for the residents to raise any questions they had concerning the diary writing.

After the diary study, the participants were asked during a final home visit to give additional information about their house and household as well as to discuss any uncertainties they might have about the diaries. A majority of those who declined participation in the diary study also responded to some general background questions.[44]

[43] In the Eurostat guidelines it is recommended that persons of 10 years and above is included in the surveys (Eurostat, 2019). However, in some countries the age threshold is higher (Zuzanek, 2009), e.g. in the latest Swedish survey an age limit of 15 years was used (Statistics Sweden, 2012).

[44] The questions mainly concerned information about household composition and changes made to the house and its building services.

In addition, a pilot study was conducted before the actual diary study was started, where the instructions and the diary sheets were tested on a number of persons of different ages to evaluate ease of understanding of the diary sheets and the instructions.[45]

Selection of diary days

This section describes various aspects considered when selecting diary days. First, since this thesis primary dealt with the ordinary everyday activities, and not those done more seldom, there was a need to capture what 'all people do most days and in which nearly all people engage on any given day' (CES Task Force, 2013). To represent ordinary days, a large number of households participated in the study, which meant that any 'exceptional circumstances' or 'unusual' activities for one or two households had lesser effect on the overall results than if only a few households had participated. Another way of ensuring that ordinary days were studied was to avoid public holidays and periods of common vacations.

Second, a key issue is the number of diary days. It is considered that a great number of days will decrease the quality of the diary data (fewer details and less accuracy) as the required commitment for the participants increases, leading to a dropoff in motivation. With greater commitment, the risk for non-responses also increases (Eurostat, 2019; Sommer & Sommer, 2002). In this thesis, the four-day approach was chosen to gather enough information without jeopardizing the response rate.

Third, to be able to capture short-term temporal variations of everyday activities, two weekdays (Thursday and Friday) and the two weekend days were included in the diary study, where Fridays differ somewhat compared to the other weekdays. With this setup, a wider range of activities that households undertake are covered (CES Task Force, 2013). For practical reasons, the investigator had access to the water meters on Wednesday evening and Sunday evening; hence these times had to be the start and end points, respectively, for the diary writing. Also for practical reasons, such as the installation of measuring equipment for the technical measurements, consecutive days were chosen.

Fourth, with the purpose of limiting the effect of common external factors, such as varying outdoor temperatures affecting energy use, *all* participants who lived in the same housing area, wrote diaries on the *same* days. This meant a better comparison between households' energy use could be made.

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[45] Sommer and Sommer state that a pilot study will contribute 'in improving the precision, reliability and validity of the data collected in the actual study' (Sommer & Sommer, 2002). Pilot studies can be formulated in many different ways and testing different features; pilot studies are of special importance when new situations occur – be it a new researcher or any other new aspect that influences the design of the study (Bryman, 2011; CES Task Force, 2013; Japec et al., 1997; U.S. Census Bureau, 2013).

Data handling of diaries

It is significant for the data quality and for the subsequent analyses that the data are handled in a systematic and structured way.

In the thesis, the focus was on activities having an impact on energy use; therefore, common energy-related activities (variables) were identified from the diary data. The energy-related activities were categorised under themes, inspired by the previous literature (e.g. Carlsson-Kanyama, Lindén, & Eriksson, 2003). The themes were Cooking/Kitchen, Personal Hygiene, Clothes Care, Comfort and Electronics. Two additional themes were Others and Presence at Home. All the activities and themes are listed in Paper IV, Table 5 (Appendix D). For each energy-related activity, the total time spent performing the activity during a certain hour was summed up for all household members. For some activities, the number of times that the activity was carried out was given instead, that is, the frequency of the activity. Different levels of detail have been handled by aggregation of diary data with a high level of detail.[46,47] The procedure of data handling was carried out for each household.

Moreover, uncertainties and missing values of the diaries – regarding descriptions of activities, duration and times of activities – were well documented and handled in a systematic way. Although there were diaries with a lot of uncertainties and missing values, these diaries were not disregarded, as the focus was to investigate as many activities as possible that influenced energy use, and as the energy use was measured per household, a removal of one household member's diary would affect the analysis of the whole household. Hence, as extensively as possible the uncertainties were corrected and missing values were filled in (via imputation), wherever possible, with the information available from other activities in the diaries, from checking other household members' diaries, or by estimating values. See Appendix G for more detailed information about the procedure of handling uncertainties and missing values.

2.2.3.3 Analyses and presentations of diary data and energy measurements

To find out which energy-related activities were performed in the homes and for what duration, the average time the households spent on activities was presented for the different diary days (Paper IV). The average time spent per day on different activities is typically also calculated in national surveys, although commonly

[46] Another way of structuring and handling different levels of detail given by diary writers is by using a categorisation scheme when coding the diaries, e.g. a hierarchical activity code system with a number of levels of detail (Eurostat, 2019; Ellegård & Cooper, 2004).

[47] An example of data that has been aggregated in this diary study is that related to the activity of airing. Airing is generally quite vaguely reported in the diaries. Therefore, when some diary writers gave more detail on this activity – for example, how many windows that were operated and to what degree they were opened – this was still noted as the activity ‘airing’.

representing individuals' time-use instead of households' time-use (e.g. Eurostat, 2019; U.S. Census Bureau, 2019).[48]

The households were arranged according to their diary information using cluster analyses, which are iterative and explorative methods to group data into subgroups (clusters) based on similarities within a group as well as dissimilarities between groups. Cluster analyses are useful when the groupings are not known in advance (Byrne & Uprichard, 2012). In the thesis, the intention with the cluster analyses was to group the households in regard to common characteristics associated with their energy-related behaviours and energy use, and specifically to explore what distinguished high and low electricity consumers.

When clusters had been formed, their relevance was tested by one-way analysis of variance (ANOVA),[49] that is, seeing if and how the formed subgroups actually differ. The effects of background factors (housing areas and household types) on the cluster solutions were tested by performing chi-squared tests,[50] asking whether the households in the different clusters were randomly distributed among the housing areas and the household types. In addition, the cluster analyses were applied to estimated energy use, using typical power values and formulas together with the diary data (see Table 9 in Appendix H). Finally, a grouping was constructed based on a frequency analysis related to the measured energy use of the households. For more detailed descriptions on the analyses, turn to Paper IV (Appendix D).

Furthermore, the measurements of energy use, indoor temperature and water use were analysed and compared among the different households and household types. Load curves of electricity use at different times of the day and for different days of the week were presented both on the household and the group level. Characteristics of temperature curves based on hourly data were moreover presented for the households. More details on the analyses and presentations are given in Paper III (Appendix C).

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[48] In the thesis ‘time-use’ is used as a general term for the data derived from the diaries. In some cases, a more accurate term would be ‘operating time’ of appliances.

[49] One-way ANOVA is a statistical method typically used to test differences among groups by comparing mean values of tested variables of the groups (Everitt & Skrondal, 2010). ANOVA is particularly useful when there are more than two groups to be tested, as in the study in this thesis. However, the data should be normally distributed which was not quite the case for the diary data.

[50] Chi-squared tests show if the differences between an actual distribution and an expected distribution are caused by chance (Everitt & Skrondal, 2010). The chi-squared tests can also be carried out for categorical variables, e.g. the background factors of housing areas and household types in this study.

2.3 Household participation, missing values and quality measures

This section starts with a presentation of the household participation and response rates of the empirical studies in the thesis. Thereafter, the results of missing value analyses of the diary study and energy measurements are described. The section ends with an account of quality measures of diaries and the relevance of short-term measurements.

2.3.1 Participation and response rates

An overview of the participation for each data collection method is given in Table 7.

Table 7 Overview of participation and response rates

Methods	Housing area	No. of households		Response rate	Comments
		Total sample	Partici-pation		
Data analyses	A	41	38[a]	n/a	Data from the local energy supplier were available for 38 houses.
Interviews	A	41	6	n/a	23 out of 41 answered the question about participation. Out of the 16 yeses, six households were selected (A6, A7, A11, A13, A23, A27).
Energy performance evaluations	A	6	2	n/a	The question of participation was asked during interviews. Two households said definitely yes to participation and they were also suitable as their energy use differed (households A6 and A13).
Diaries and energy measure-ments	A	41	22	54%	
	B	31	19	61%	
	C	33	16	48%	
All housing areas		105	57	54%	

[a] The number refers to the same household (owner) over the studied time period in most cases, except where there has been a shift in ownership during the last five years of the studied time period.

The intention of the data analyses was to study the energy use for all households in housing area A, with the households also being asked to participate in interviews. Energy data were available for 38 of the houses for time periods of 6 to 12 years.

Six households were selected for the interviews and two of these households participated in the energy performance evaluations.

All household members aged 12 and above in the three housing areas were asked to participate in the diary writing and energy measurements. Only one household out of the total sample of 105 households could not be reached. Consequently, time was not a limiting factor to the response rate. The response rate of the study was on average 54%. This figure is in line with some other diary studies (Molén, 2011; Rydenstam & Wadeskog, 1998; Statistics Sweden, 2003) and higher than the latest national time-use survey in Sweden, which had a response rate of 41% (Statistics Sweden, 2012). In this thesis, the response rate refers to the household level, with everyone in the household over 12 having to participate; otherwise, the household was a dropout. In addition, the diary study was carried out for four days, which meant a longer commitment compared to the other studies which commonly covered just one or two days (e.g. Statistics Sweden, 2012).

2.3.2 Missing value analyses of the diary study and energy measurements

Missing value analyses were performed for the diary study and energy measurements to find out if there were any systematics in the way values were missing or if they occurred at random. The analyses were performed on different levels: household level, individual level (individual diary writers) and activity level. The first part focused on the dropouts, where an overall non-response analysis on the household level was performed, looking for what characterised the dropouts compared to the participating households. The second part focused on uncertainties and missing values of the individual diaries, including which activities were mostly connected to reporting errors.

2.3.2.1 Overall non-response analysis

There were various reasons why households chose not to participate in the diary study and energy measurements. For instance, some residents were about to move, some were away when the studies were conducted, while others just stated they did not want to participate. Detailed information about those who did not participate were not known. However, household composition was known for most non-participating households and can thus be compared with the participating group. In Figure 8, the distributions are shown for the five different household types – explained in Table 5 in Section 2.1.3 above – for both participants and non-participants. Figure 8 shows that the distributions were similar in both cases. Household type V (one or two persons with children) was in the majority followed by household type III (couples without children, 26–64 years). The findings implied that there was no significant bias between those participating and those not participating in the study, when considering household composition.

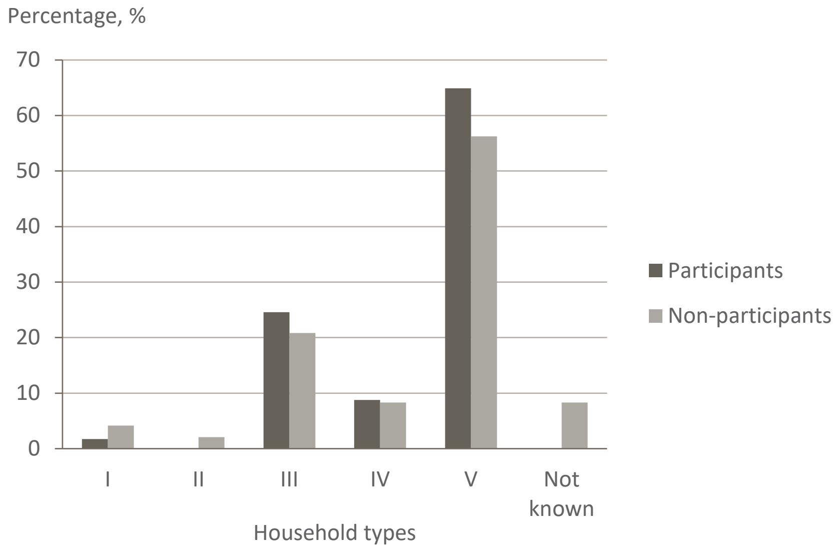

Figure 8 *Distribution of household types, showing participants and non-participants (in percentages) in housing areas A, B and C.*

2.3.2.2 Uncertainties and missing values in diaries

The documentation of uncertainties and missing values in the diaries (described in brief above in the section *Data handling of diaries*) resulted in a list of 1556 remarks related to uncertainties and missing values regarding descriptions of activities, duration and times of activities. This meant there were uncertainties and missing values for approximately 0.2% of the total number of possible observation hours[51] during the diary days or 9.0% of the total number of observation hours when there was actually registered time-use (or equipment turned on).

The number of uncertainties and missing values varied from one household to the next and among the individual diary writers, and it was found that they were not quite randomly spread amongst the participants considering different aspects such

[51] *The total number of possible observation hours = no. of variables × no. of hours during diary days × no. of diary writers*. No consideration for individual diary writers' sleeping hours or absence from home was taken for this estimate.

as housing areas,[52] cluster solutions,[53] adults versus children and gender.[54] Imputations served as a way to handle uncertainties and missing values, that is, missing values were replaced with likely values (see Appendix G).

Considering types of activities, uncertainties connected to being present at home or the sleeping hours were overrepresented (with over 250 remarks).[55] This confirms previous experience, as the UN's report (2005) states that one of the most common errors is not reporting a night's sleep. Other activities with a high number of occurrences were the use of a coffee machine (171 remarks), taking a shower (132), the use of a microwave (114), watching TV (107) and the use of a stove (99).

2.3.3 Quality measures and relevance

With the intent to evaluate the diary study and the relevance of short-term energy measurements, several validity and reliability tests were performed, which are traditional measures of quality. In addition, a non-traditional, diary-specific measure of quality, the number of episodes, was analysed.

2.3.3.1 Episodes in diaries

The number of *episodes* recorded per day in a diary is seen by the time-use community as an indirect measure of the quality of the diary. Based on the definition in the guidelines (e.g. Eurostat, 2019), the interpretation of episodes in this diary study was that a new episode was counted for each stated activity or equipment. A higher number of episodes indicates a more thoroughly completed diary (CES Task Force, 2013). However, fewer episodes does not automatically mark a diary as poorly written (Molén, 2011; Rydenstam & Wadeskog, 1998). Having few episodes can be totally relevant due to fewer activities being carried out, such as for someone with long working hours. Hence, no absolute criterion exists to evaluate the number of episodes against.

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[52] Significant differences were found between the housing areas according to a chi-squared test ($p < .05$), where households with many uncertainties and missing values were overrepresented in housing area A and underrepresented in area B.

[53] According to chi-squared tests ($p < .05$), households with many uncertainties were not randomly divided amongst the cluster solutions.

[54] Adults' diaries had many more uncertainties and missing values on average than children's diaries, and women's diaries (including girls') had more uncertainties and missing values on average than men's diaries (including boys').

[55] Consistency checks of sleeping periods were performed, checking whether a night's sleep had been reported four times for all members of the participating households during the diary days. Uncertainties regarding sleeping hours were found in roughly 20% of the expected cases of sleeping periods in the diaries. It was also noticed that sleeping periods for young children and teenagers were reported less often than for adults.

The present study showed the diaries having an average of 24 episodes per day,[56,57] which can be seen as a satisfactory number of episodes (Rydenstam & Blanke, 1998; Rydenstam & Wadeskog, 1998), especially since only activities when diary writers were present at home were considered. However, there were large variations between those diaries including 10 or fewer episodes and others with more than 40. Women had a larger number of episodes than men, and adults had more episodes than children, which confirmed previous experience (Rydenstam & Wadeskog, 1998). Another observation was that for these groups of writers with diaries comprising the most episodes (i.e. women and adults), there were generally more uncertainties. Hence, one can ask, does a more extensively written diary mean a higher risk for errors or does a greater number of episodes not automatically mean a better diary?

2.3.3.2 Validity and reliability

The validity of the diary study and energy measurements was evaluated by two different tests to show the extent to which the study measured what was intended. The first test evaluated whether the diaries actually reflected everyday energy-related activities. The (measurement) validity was investigated by comparing the estimated energy use from diary data with the measured energy use for a short time slot and for ten chosen households (see Appendix I for a description of this validity test). The validity of the diary study was found to be fairly good.

The second validity test was carried out with the intention of getting an indication of the relevance of the short-term energy measurements of the study, which was estimated by calculating a linear correlation between the annual energy data and the energy use during the measurement period. The question was whether a household with high consumption on a yearly basis would also consume large amounts of energy during the diary study. The calculation was done for housing area A, as yearly energy use was available for these households. The correlation[58] was found to be 0.60 ($p < .05$) for the annual energy data of 2004/2005 compared to energy data during the four days of measurements from a Wednesday evening to a Sunday evening in November 2005. This indicated that the validity of the short-term measurements was fairly good considering energy use.

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[56] Days where no diary had been written at all were not included.

[57] Even though the number of episodes was not normally distributed in the diary study, the mean is used as the average value in order to compare it to other time-use surveys and guidelines. As an alternative average value, the median was 21 episodes.

[58] The correlation was calculated using Spearman's rank correlation coefficient, which is a measure of the correlation between two variables considering the ranking of the variables, whose values need not be normally distributed (Everitt & Skrondal, 2010). The coefficient ranges from –1 to +1.

The reliability of the diary study was evaluated by two different tests to reveal the consistency of the study and how independent it was, no matter who was interpreting the data. First, the reliability was evaluated as expected consistency or non-consistency over the diary days. Comparisons were made between activities carried out on similar days (two weekdays and a Saturday and a Sunday), as well as on dissimilar days (a weekday and a weekend day). Overall, the reliability test showed in most cases that the diaries were in line with expected day-to-day patterns.

Second, the reliability was examined by an interrater reliability test. For a number of examples from the diaries, two different coders (so-called raters) interpreted the diary data and then compared how well the different assessments corresponded. The interrater reliability was found to be on an acceptable level, although there was a certain range in the assessments for the examples tested, ranging from moderate to substantial agreement between the two raters.

Appendix I contains descriptions of the two reliability tests.

2.4 Literature review

The compilation of literature was based on a review of technical, social science-oriented and behavioural science research on energy use in residential buildings, comprising both national and international research. The intention was to describe findings of other studies addressing the objectives of this thesis, that is, how energy use in single-family houses varies and how the energy-related behaviours of households influence the use of energy. Hence, the review covered households' different energy usages and residents' everyday activities, as well as presenting theoretical perspectives and explanatory factors for energy-related everyday behaviours, and how these can be influenced.

The digital library LUBsearch at Lund University was the main source of literature. LUBsearch contains approximately 320,000 e-books, around 200 databases and more than 78,000 e-journals.[59] Other sources involved search functions for projects and publications on websites of universities[60], authorities (e.g. the National Board of Housing, Building and Planning and the Swedish Energy Agency) and organisations (e.g. the European Commission and the International Energy Agency). Proceedings from conferences, such as eceee Summer Studies, ACEEE and BEHAVE, have been another source of information. Reference lists in review

[59] For more information, turn to http://libguides.lub.lu.se/lubsearchandelectronicresources

[60] Including the DiVA portal, which is a joint search service for research publications and student essays produced at 47 Swedish universities and research institutions.

articles and in other relevant articles have been looked over, as well as the publication lists of several researchers.

The focus of the literature search has been on residents and households, primarily in single-family houses. Keywords have been combined related to energy, for instance *energy use*, *energy conservation*, *energy saving*, *energy efficiency*, with keywords such as *behaviour*, *habits*, *attitudes* and *demographic factors*. Similarly, keywords related to *household electricity* and *load curves*, *domestic hot water* and *space heating* have been applied in different forms and combinations. Searches have been done on specific appliances and activities, including *tumble dryer*, *dishwasher*, *cooking* and *airing*. Keywords associated with policy instruments and interventions aimed at changing energy behaviour have also been used. To include field studies in the literature review have been of particular relevance, for instance the experiences of energy measurement campaigns, as adequate comparisons with the data obtained in this thesis thus could be made. Hence, most studies on modelling and simulations have been excluded.

More than 300 scientific journal articles, conference papers and reports were included in the compilation. In addition, there were references to relevant EU directives, regulations, guidelines and statistics. A majority of the literature items were from the 2000s and onwards, but plenty of examples of earlier studies were selected as well. Approximately 30% of the references were Swedish studies and 45% were from other countries in northern and western Europe (where the UK stood out). Outside Europe, particularly the United States, Canada and Australia were represented. This direction towards countries with colder climates and western societies was taken as their outdoor climates and cultures do not differentiate all that much from the situation in the empirical studies of this thesis, thus facilitating a comparison.[61] This comparison was made in Chapter 6 (Discussion).

2.5 Ethical considerations

Ethical considerations have been taken into account in the energy data analyses and in the contacts with the residents related to the interviews, energy performance measurements and diary study.

Before conducting the energy data analyses, a request was sent to the Swedish Data Protection Authority as to whether the collection of households' energy and water

[61] One exception was the Australian references, with considerably different outdoor climate conditions. One reason why publications from Australia were included in the literature review was that there were many Australian studies on household water use, conservation and behaviour (which is a result of certain regions in Australia suffering from water shortages at times).

data was in accordance with the applicable Personal Data Act[62] at the time (SFS 1998:204).[63] The authority replied that research is considered to be a task of general interest and the registered persons should not be required to give their consent to the personal data processing that takes place within the research project. Related to the obligation to inform about the registered data, the main rule is to inform the persons, unless the research conducted is in the public interest. Moreover, in discussions with the Swedish Data Protection Authority, the information gathered in this study was not considered to be of a particularly sensitive nature, and hence the information was considered to be acceptable for research use.

The contacts with the residents was conducted in accordance with the principles of basic research ethics outlined in the Swedish Research Council's book *Good Research Practice* (2017). The residents were *informed* about the studies and their purposes through written letters, phone calls and home visits. The participation was voluntary, where the residents' *consent* was given in writing or orally, and the participants could at any time withdraw their participation. The diary study included the entire household's daily activities, and children from the age of 12 were asked to write a diary themselves, with the consent of their parents.[64] *Confidentiality* of the residents was considered by not publishing results from the studies so that it would be possible to identify individual houses and households. Hence, publications from the research describe the housing areas, households and diary writers with codes, where the explanation of the codes has been stored separately.

[62] Personal Data Act is a free translation of the Swedish Personuppgiftslagen.

[63] Since the time of this study, this Swedish Personal Data Act has been replaced by the EU's General Data Protection Regulation (Regulation (EU) 2016/679).

[64] There are special rules for research involving children. The Act on Ethical Review (SFS 2003:460) says that, as far as possible, children shall have an insight into what they are participating in, and if they can, also give their consent. Otherwise, it is the guardians who must give their consent. Children aged 15 years and above must be informed and give their consent to participate in research (Codex, 2020).

3 Literature review on energy use and behaviour in residential buildings

Since the main objectives of the thesis are to examine how energy use in single-family houses varies and how the energy-related behaviours of households influence the use of energy, the intention behind the literature review is to give an in-depth insight into how this is addressed in other research. The review covers measurement studies and surveys of households' different energy usage, and how the energy use is affected by the everyday activities of residents. In addition, it presents social science perspectives, explanatory factors for energy-related behaviours and how energy-related activities can be influenced.

3.1 Elements of energy use

The following sections is a compilation of studies on household electricity, hot water usage and space heating. Other aspects of energy use, such as daily electricity consumption patterns, residents' presence at home and variations in energy use between similar houses are also highlighted.

3.1.1 Household electricity use

Residents typically carry out several everyday activities that impact the household electricity use. Below are sources discussing the use of electrical appliances for carrying out activities that are associated with clothes care, cooking, dishwashing, entertainment and getting information, as well as lighting. First, however, trends in household electricity use over time will be described.

3.1.1.1 Trends in household electricity use

By comparing results from different measurement campaigns, trends of household electricity consumption can be seen over time. Although larger measurement campaigns are not that common, as they are typically quite time- and cost-consuming,[65] two Swedish measuring studies in single-family houses are well-known. The first study was performed in 1991–1992 and comprised 40 houses[66] (NUTEK, 1994). The second study was carried out in 2006–2008 and included 199 houses[67] (Zimmermann, 2009). When comparing the results of the two studies, shown in Figures 9a and b, it is clear that household electricity use is less in the later study and that energy use for many categories has decreased over the years, especially for refrigeration, but also for the categories of cooking, dishwashing and laundry.[68] The improved energy efficiency of white goods during this period is a major reason behind this development. The phase out of incandescent lighting had not started at the time of the second measurement, which explains that the consumption for lighting has not changed considerably. Furthermore, trends towards larger and more TVs in homes together with the market penetration of PCs are not found to increase ‘the wall outlet categories’[69] to a great extent during the time period between the two campaigns (Bennich et al., 2009).

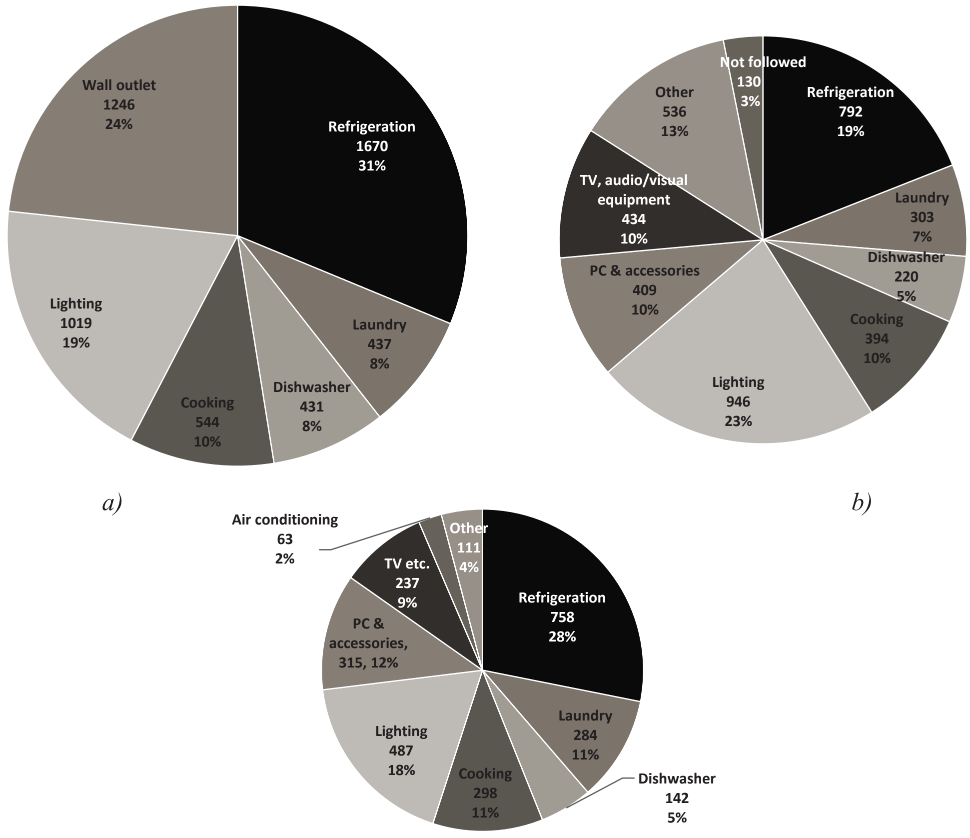
[65] In addition, the question of representativeness of measuring projects is relevant, as these kinds of studies are usually case studies. Nevertheless, to actually measure gives clues for interpreting more general data, such as national statistics.

[66] The houses, heated by direct electricity and naturally ventilated, were built between 1970 and 1975 and situated in different parts of Sweden. (In total, the study comprised 66 houses, but the household electricity use could only be reported for 40 of the houses.)

[67] A varied selection of different households and types of houses was the aim of this measuring project, but the location was limited to the region around lake Mälaren (Bennich et al., 2009). Forty households were measured for one year; the rest were measured for a month. Yearly consumption was estimated for all households.

[68] That the household electricity consumption seems to have decreased is in contrast to the national data, which show an increase in household electricity use over the years – i.e. from 1970 to 2018, the national data showed that household electricity consumption increased from 9 to 22 TWh/year (Swedish Energy Agency, 2020). This discrepancy is explained by pointing out that a substantial amount of electricity is consumed by heat pumps and comfort heating (i.e. floor heating and towel dryers), and as the national statistics are based on electricity bills for a sample of households, this consumption will be included in the national statistics (but not in the measurement campaigns). It has been estimated that as much as 37% of the reported household electricity in the national statistics is actually used for heating purposes (Bennich et al., 2009).

[69] ‘The wall outlet categories’ refers to the category ‘Wall outlet’ in Figure 9a and the categories ‘Other’, ‘TV, audio/visual equipment’ and ‘PC & accessories’ in Figure 9b.



c)

Figure 9 Comparison of three measurement campaigns of household electricity shown in kWh and percentages for different end uses. The areas of the circles are proportional to the average size of household electricity. (With the exception of the category 'Other', the categories in the three different measuring projects have been checked so that they, more or less, included the same kinds of appliances.)
a) Measurements in 1991-1992 in 40 Swedish single-family houses, with an average consumption of 5346 kWh/year (NUTEK, 1994)
(Wall outlet included all other electrical appliances.)
b) Measurements in 2006-2008 in 199 Swedish single-family houses, with an average consumption of 4164 kWh/year (Bennich et al., 2009)
c) Measurements in 2007/2008 in 1300 households in 12 European countries, with an average consumption of 2695 kWh/year (Grinden & Feilberg, 2010)

In Figure 9c, average data from a European measurement campaign performed in 2007–2008 are presented, where household electricity was measured in 1300 households in 12 European countries[70] (Grinden & Feilberg, 2010). Compared to the latest Swedish study, the average household consumption was 35% less in the European study. Refrigeration was on the same level for these two studies but stood for the largest share in European households, indeed, for more than a quarter of the consumption. It can further be seen that electricity use for lighting in particular was much less in Europe than in the Swedish study.

These measurement campaigns are now a few years old and since they were performed further improvements have been attained in energy efficiency of electrical appliances and devices. This development, driven by the EU's Ecodesign Directive and Energy Labelling Regulation (Directive 2009/125/EC; Regulation (EU) 2017/1369), covers a wide range of products commonly used in homes, including refrigerators and freezers, dishwashers, washing machines and several other electrical devices, as well as lighting. These legislative acts can also encompass the specific functions of products. For instance, Ecodesign now limit consumption in standby and off modes (Commission Regulation (EC) No 1275/2008; Commission Regulation (EU) No 801/2013).

Besides the rapid increase in the energy efficiency of appliances, changes in the residents' behaviour also influence the trends in how appliances are used and affect the associated electricity consumption. As an example, in a comparison of measurement studies of French households, it was seen that the electricity use for washing machines had decreased drastically as the electricity use per washing cycle had declined, but also due to behavioural aspects such as the number of (hot) cycles decreasing over the years (Dupret & Zimmermann, 2017). The following sections will further highlight literature having examined how the residents' behaviours influence the household electricity consumption for different purposes.

3.1.1.2 Residents' activities related to household electricity use

Clothes care

Several activities associated with taking care of clothes consume electricity and water, such as the use of washing machines and tumble dryers (Carlsson-Kanyama, Lindén, & Eriksson, 2003). Studies have shown that almost 25% of households use the washing machine every second day (Lindén, 2008) and that more than half of Swedish households are equipped with a tumble dryer, which is used in both summer and winter (Alborzi, Schmitz, & Stamminger, 2017; Schmitz & Stamminger, 2014; Zimmermann, 2009). The way that people do their laundry

[70] The participating countries were Belgium, Bulgaria, Czech Republic, Denmark, France, Germany, Greece, Hungary, Italy, Norway, Portugal and Romania. The measurement campaign took place for two weeks, the data from which were used to estimate annual consumption. Both single-family houses and multifamily buildings were included. It was, however, stated that family households with children were probably somewhat overrepresented in the samples.

affects the electricity use to different degrees. For example, use is affected by the choice of washing programmes and temperature levels – with 40˚C and 60˚C common in Sweden (Schmitz & Stamminger, 2014). Another aspect of importance is how well-loaded the washing machine is, with households declaring that they often use the washing machine fully loaded (Carlsson-Kanyama, Lindén, & Eriksson, 2003; Martinez-Espineira & Garcia-Valinas, 2013; REMODECE, 2008; Schmitz & Stamminger, 2014). Laundry behaviour and the connected energy use have been shown to vary between households (e.g. Zimmermann, 2009). One explanatory factor is the number of persons living in the household, which affects the frequency of washing and thereby the electricity use (Alborzi, Schmitz, & Stamminger, 2017; Zimmermann, 2009), but variations between households of the same size are still clearly seen. Variations have also been found between households in different European countries (Alborzi et al., 2017; Schmitz & Stamminger, 2014). In comparison, Swedish households have quite a high consumption, with the higher prevalence and usage of tumble dryers and higher washing temperatures being contributing factors.

Cooking and related kitchen activities

The preparation of food represents a large share of a household's electricity use, with refrigeration being the largest part, followed by cooking and (machine) dishwashing. Several types of everyday behaviour related to cooking and other kitchen activities affect the amount of electricity consumed, as well as water use. Examples of dishwashing behaviour that benefit lower use are that Swedish households do not wash dishes by hand as much, but use the dishwasher to a great extent (Stamminger, Schmitz, & Hook, 2018; Stamminger, Suljug, & Hillenstedt, 2007) and that most households claim to wash with fully loaded dishwashers (Carlsson-Kanyama, Lindén, & Eriksson, 2003; Martinez-Espineira & Garcia-Valinas, 2013; Stamminger, Suljug, & Hillenstedt, 2007). Other washing behaviours lead to (unnecessary) water use and higher electricity use, for instance households' pretreatment routines[71] (Lindén, 2008; Richter, 2011; Stamminger, Schmitz, & Hook, 2018; Stamminger et al., 2007), as well as Swedish households' choice of high dishwasher temperatures, with an average of 61˚C (Stamminger et al., 2007). Regarding cooking, it has been demonstrated that the electricity use is dependent on the number of persons in the household. At the same time, cooking in larger households is more energy efficient, considering the consumption per person (Zimmermann, 2009). Another tendency seen, is that less time is being spent on cooking, particularly amongst younger households (Carlsson-Kanyama & Lindén, 2001; Warde et al, 2007). The literature identifies some likely reasons behind this trend, such as an increased supply of convenience foods, new kitchen technologies and an increased time spent on eating away from home. In a compilation comparing refrigeration between different countries, it was not found unusual for households

[71] That is, residents manually prerinse dishes before using the dishwasher.

(all types of housing) in countries such as the USA, Japan and Australia to own more than one refrigerator (Cabeza et al., 2018), while Swedish households usually only own one (Zimmermann, 2009). In Sweden, on the other hand, it seems more common to own a freezer (especially in single-family houses but also in apartments) than in the above-mentioned countries.

Electronics used for entertainment and information

Electronics used for entertainment and information concerns TVs, computers, audio/visual and communication equipment, of which many today are mobile devices with an internet connection that are also used outside the home. A number of trends on how these technologies are used, leading to higher electricity consumption, have been identified in the literature (e.g. Green & Ellegård, 2007; Karlsson & Widén, 2008; LeBlanc, Cooper, & Reeves, 2012; Pothitou, Hanna, & Chalvatzis, 2017). First, there is a fast development and market penetration of ICT devices (information and communication technology), which are often being used for long operating times (Bedir & Kara, 2017; Cabeza et al., 2018; Terry & Palmer, 2016). In recent years, this includes the installation of permanent broadband connections with routers constantly running. Second, instead of sharing the devices, the trend is that every household member has and uses their own set of devices (Karlsson & Törnqvist, 2009), and, third, there seems to be a trend to choose more advanced and larger products when old equipment is replaced. For example, many households choose a larger TV when buying a new one (Lindén, 2008; Pothitou et al., 2017). Furthermore, the standby mode of devices is a convenience for the user but due to long operating hours it leads to unnecessary electricity use (Lindén, 2008; Zimmermann, 2009). In fact, approximately 10% of household electricity is allocated to standby consumption (Fonseca et al., 2009; Pothitou et al., 2017). In relation to the average European household, Swedish households have been found to use more electricity on equipment associated with 'entertainment and information', but between Swedish households the consumption varies for both the category of TV and audio/visual equipment, as well as for computers (Zimmermann, 2009).

Lighting

A major use of electricity in homes concerns lighting. Sweden is characterised by large seasonal variations, with a dark winter period leading to high usage of lights (Zimmermann, 2009). The lighting culture can be described with many small sources of light being used with low lumen lamps in order to create a warm and cosy light environment, which typically means that unoccupied rooms are lit up (Bladh, 2008, 2011; Bladh & Krantz, 2008; Lindén, Carlsson-Kanyama, & Eriksson, 2006). Although there are common similarities in how Swedish homes are illuminated, variations can be found related to differences in lighting behaviour including operating times, the number of lamps and the kinds of lamps, which leads to variations in the electricity use (Bladh, 2008, 2011; Bladh & Krantz, 2008;

Zimmermann, 2009). Lighting behaviour also varies between countries, where for example European households have been found to be more concerned about turning lights off in unoccupied rooms (REMODECE, 2008) and have an average of 24 lamps per household (Tichelen, 2009), while Swedish households in different studies have been found to have on average 35 (Schäppi et al., 2014), 39 (Gerhardsson, Laike, & Johansson, 2019) or 42 light sources (Zimmermann, 2009).[72] A consumer survey also demonstrated the variation of the number of lamps between different European countries – ranging from 19 lamps to over 35 lamps per household on average (Schäppi et al., 2014).

During the past decade, the development and introduction of energy-efficient lighting has been great as a consequence of EU regulations (European Commission, 2018). In general, people have a positive attitude towards the phasing out of incandescent bulbs, even though there were some initial concerns (Bladh, 2008; Bladh, 2011). Surveys have shown that almost 90% of the households use energy-efficient lamps (Das, Richman, & Brown, 2018; Swedish Energy Agency, 2011) and that the acceptance of LED lamps has increased in recent years (Gerhardsson et al., 2019).

Other activities

There are various electrical devices in a home and not all of them are mentioned in detail here. For example, activities connected to the households' vehicles, such as the use of engine preheaters and car heaters, as well as the anticipated market penetration of electrified cars. Other recent trends in Sweden are the installation of electrically heated outdoor hot tubs and robotic lawn mowers.

3.1.2 Household water use

Household water consumption, and the associated energy used to produce hot water, both depend on the amount of water used and the temperature of the heated water. These aspects, in turn, are consequences of residents' behaviour and of the water/energy efficiency of household devices (washing machines, dishwashers, water taps, etc.). In the following sections, findings related to household water use are presented, covering studies of water measurements and residents' water-related behaviours, as well as experience from the installation of water-saving equipment in homes.[73]

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[72] Size and dwelling type varies between the studies. For example, Zimmermann's study (2009) includes about 50% single-family houses, while the corresponding figure in the study by Gerhardsson et al. (2019) is 43%.

[73] Losses in the production and distribution of domestic hot water (DHW) also affect the energy use. However, this is not the focus of this chapter.

3.1.2.1 Trends, typical values and variations in water data

In general, a downward trend in water consumption per capita can be seen in Swedish national data, even though the total water consumption is on a similar level today as some decades ago (total water use includes both hot and cold water use).[74] Generally, not that many Swedish measurement studies of the water usage in single-family houses (Swedish Energy Agency, 2012) are available.[75] In one of the few studies available, the average water usage of 35 single-family houses was measured to be 130 litres per person and day (Swedish Energy Agency, 2009). Similar figures were found in a study from 2004, using data from a Swedish municipality (Swedish Energy Agency, 2009). The downward trend in water consumption was also noticed in the data from the municipality, where a consumption of 151 litres per person and day was registered in 1994 (Swedish Energy Agency, 2009). Higher historical usage is confirmed by a number of older Swedish studies from the 1980s, where the measured daily consumption levels, expressed as litres per person, were 154 (Lundström, 1982), between 127–164 (Ds Bo 1983:4), 148 (Gaunt, 1985) and 185 (Karlsson, 1988).

Concerning domestic hot water usage in single-family houses, the measurement study of 2009 estimated a daily average of 41 litres per person (Swedish Energy Agency, 2009). This is at the lower end of the range of usual values used in Sweden. However, it corresponded to 33% of the total water usage (hot and cold water use), which is around the typical percentages used (Swedish Energy Agency, 2009, 2012).[76] Another typical value is the amount of energy used for domestic hot water production – assumed to be around 20% in Sweden – compared to the total energy usage of a house (National Board of Housing, Building and Planning, 2008). However, the above measurement study observed that for electrically heated single-family houses water heating stood at 8% to 15% of the total energy usage, depending on the household composition (Zimmermann, 2009), which is possibly an indication

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[74] The total Swedish water consumption in 2015 was estimated at almost 565 Mm^3 and national data show that this is approximately on the same level as in 1990. Considering the population growth, this means a 13% decreased consumption per capita during this period, resulting in a daily consumption of 157 litres per person (Statistics Sweden, 2011b, 2017, 2018). Paper III (Appendix C) states that the Swedish figure presented in the Eurostat statistics was 142 litres per person and day (52 m^3 per person and year) for 2007, thus a much lower figure. However, it was reported that the measurement uncertainty is too large for this reported water usage and it was for that reason eliminated in the national public statistics (Statistics Sweden, 2011a).

[75] In Sweden, more water measurement studies have been performed for residents of apartments in multifamily houses than in single-family houses. Generally, water use tends to be higher for apartment households (e.g. Levin, 2012; Swedish Energy Agency, 2009).

[76] In the Swedish regulations determining the building's energy use under normal conditions, a value of 35% is recommended for all residential buildings, if no other data are available (BFS 2016:12 – 2018:5).

that the prevalent values need to be revised (National Board of Housing, Building and Planning, 2011).

Generally, large variations are reported of Swedish household water consumption (e.g. discussed in a report from the Swedish Energy Agency (2012)). In the already mentioned measurement study (Swedish Energy Agency, 2009), the highest and lowest use was 235 and 53 litres per person, respectively, which means a difference by a factor of 4.4, and the same spread was seen in the water data from the municipality mentioned above. Furthermore, large variations exist between the average consumption of households in different countries. For instance, German figures were reported to be on levels similar to the Swedish measurement study, namely 127 litres per person and day, while Norwegian data were much higher, with an average consumption of 221 litres per person and day (Eurostat, n.d.). A similar high consumption was found in US households living in single-family houses, namely 222 litres per person (Water Research Foundation, 2016).[77] The water situation (related to availability, quality and pricing), as well as cultural aspects, is very different across the world, contributing to the variation between countries and most likely influencing the water behaviours of residents (e.g. Rathnayaka et al., 2014; Willis et al., 2013).

3.1.2.2 Water-saving appliances and residents' activities related to water use

Water-saving functions of household appliances and devices, and how these are used by the residents, are discussed below.[78]

Improved efficiency of dishwashers, washing machines and other water-saving devices, such as low-flow shower heads, toilets with low flush volumes and energy-efficient taps, have contributed to water saving in homes (e.g. Water Research Foundation, 2016). Promoting this development are the EU Directive on Ecodesign and the Regulation on Energy Labelling, which besides being driving forces when it comes to energy efficiency, also support the reduction of water consumption for dishwashers and clothes washing machines (Directive 2009/125/EC; Regulation (EU) 2017/1369). In Sweden, there have been measurement projects to investigate how much hot water is actually saved by replacing standard taps with energy-efficient taps. In a study by Folkeson, Fernqvist, and Normann (2017), the replacement of the (rental) apartments' taps, resulted in a significant decrease of 28%, which confirmed the results of an older Swedish study (Wahlström, 2000). Furthermore, there were no signs that the savings decreased over time (Folkeson et

[77] Note that the American figures exclude outdoor water consumption. Further, it was found that the water leakages were quite substantial for some of the American houses (Mayer et al., 1999; Water Research Foundation, 2016).

[78] Many energy-related activities, such as washing dishes and clothes washing, also influence water usage. Hence several of the studies already addressed in Section 3.1.1 are also relevant to water use.

al., 2017), which was also the case in an American water-saving project (Lee, Tansel, & Balbin, 2011). Water-saving appliances and devices can obviously be beneficial, but what factors increase households' motivation to install them? Factors found in the literature are if people own their own home and if they have their own water meter (Babooram & Hurst, 2011; Sharpe, Osborne, & Skerratt, 2015).

Residents use water and water-consuming appliances for various everyday activities. Activities related to personal hygiene – showering in particular – have been found to be the most water-consuming activities (e.g. DEFRA, 2008; Mead & Aravinthan, 2009; SWWA, 2017; Water Research Foundation, 2016). Water usage for showering is influenced by household size and composition as well as the efficiency of the shower heads (Makki et al., 2013). The way we wash ourselves has in many countries undergone a shift in behaviour, with taking baths being replaced by showering for the majority of people (Carlsson-Kanyama, Lindén, & Eriksson, 2003; Nauges, 2014), even though there are exceptions, such as Japan, where the tradition of bathing is still strong.

Several studies have shown that household size plays an important role in the level of water usage (Levin, 2012; Makki et al., 2013; Swedish Energy Agency, 2009), but not all studies have found a strong relationship between the number of persons and usage (Karlsson, 1988; Lundström, 1982). In addition, large-scale advantages – consumption per person decreases in larger households – have been seen in some studies (e.g. Mayer et al., 1999). The identified advantages concern water-related behaviours such as operating washing machines and dishwashers fully loaded (Martinez-Espineira & Garcia-Valinas, 2013).

3.1.3 Energy use for space heating

Two of the main influences of the residents on energy use for space heating are choice of indoor air temperature[79] and window opening behaviour,[80] and these are discussed in this section.[81]

[79] The relationship between the indoor temperature and its effect on energy usage depends on the properties of the building, such as the thermal insulation, airtightness of the building envelope and the type of heating and ventilation system and its control system.

[80] Residents' airing behaviours affect the air change rate of buildings and hence also the energy usage. The air change rate is dependent on the temperature difference between outdoors and indoors and on the wind, as well as on how many (and which) windows the residents have open and also on the opening angle. Furthermore, how often and for how long airing is carried out are important aspects for its effect on energy usage.

[81] Residents can influence several other factors affecting the energy used for space heating, especially in owner-occupied houses. For instance, the residents can adjust the settings of the heating and control system, and more or less often, carry out maintenance work of the building envelope and of the building services. The residents can also affect how comfort floor heating, extra radiators, etc. are used. The residents' usage of adjustable solar shadings can influence

3.1.3.1 Choice of indoor temperature

Studies of indoor temperature in residential buildings have focused on actual measured indoor temperatures, people's preferred indoor temperatures and how residents interact with their heating system through the use of thermostats. In general, there have been fewer studies on indoor temperature and thermal comfort[82] in residential buildings, compared to investigations in commercial buildings and offices (Vadodaria, Loveday, & Haines, 2014).

Field measurements have found indoor temperatures of 20.9–21.2°C to be common in Swedish single-family houses during the heating season (National Board of Housing, Building and Planning, 2009b; Sjögren, Kronheffer, & Blomkvist, 2010). A temperature of 21°C also shall be used for single-family houses when verifying that Swedish building regulations are met under normal conditions (BFS 2016:12 – 2018:5). However, there are examples of studies with higher average temperatures of 21.9°C (Swedish Energy Agency, n.d.).[83]

A number of aspects can be highlighted from measurement studies of the indoor temperature. Firstly, no clear trend has been identified indicating a general, significant increase in indoor temperature in Swedish homes when the above studies are compared to older studies (Andersson & Norlén, 1993; Gaunt, 1985; Holgersson & Norlén, 1982; Widegren-Dafgård, 1983).[84] Similarly, little or no increase in the indoor temperature has been found in other countries (e.g. Vadodaria et al., 2014). Yet temperature measurements performed in modern, very energy-efficient houses have given results well above standard values (Enerbuild, 2012; Schroeder et al., 2018). Secondly, although a range in indoor temperature in Swedish households may exist, the temperatures tend to be reasonably within the span recommended by the World Health Organization (Ranson, 1988; WHO, 1987),[85] one reason being

transmission losses and the solar heat gains. In addition, the residents contribute to the internal heat generation inside their home, by their activities, their use of electrical appliances and the amount of time they spend at home. Lastly, how people choose to furnish their rooms, as well as having internal doors closed or not, does affect how heat is distributed through and between rooms.

[82] Thermal comfort describes how a room is perceived by people in terms of temperature (for a more thorough description, turn for example to the standard SS-EN ISO 7730:2006 from the Swedish Institute for Standards (SIS, 2006)).

[83] The temperature data are unpublished results in the Swedish Energy Agency's measuring study on improving energy statistics for dwellings and commercial buildings (referred to in Section 3.1.1.1).

[84] Older Swedish studies have shown results between 20.4 and 21.2°C (Andersson & Norlén, 1993; Gaunt, 1985; Holgersson & Norlén, 1982; Widegren-Dafgård, 1983). However, note that some of the older studies include measurements performed during months outside the heating season.

[85] According to the Public Health Agency of Sweden, the indoor temperature needs to be at least 20°C so as not to be of inconvenience to human health (FoHMFS 2014:17). For sensitive groups,

that houses in Sweden are relatively well insulated. In other countries, where the situation is somewhat different, studies have demonstrated temperatures below the WHO recommendations (e.g. BRE, 2013; Huebner et al., 2013; Magalhães, Leal, & Horta, 2016).

How people perceive thermal comfort does not seem to be completely straightforward and can vary from one person to the next.[86] An interview study of 70 British households found that what was perceived as a comfortable temperature did differ considerably among the participants (Fell & King, 2012). This is in line with differences found in people's preferred temperatures (e.g. Lindén, Carlsson-Kanyama, & Eriksson, 2006) and household discussions on thermostat settings (Sintov, White, & Walpole, 2019). Furthermore, several studies show that thermostats are not always used as intended, which might be a missed opportunity for both energy savings and a comfortable indoor climate (e.g. Fell & King, 2012; Glad, 2012; LeBlanc, Cooper, & Reeves, 2012; Meier et al., 2010). However, newer studies indicate that 'smart thermostats'[87] can reduce peak loads, while generally satisfying the residents as well (Robinson et al., 2016).

3.1.3.2 Airing behaviour

Generally, more studies on airing behaviour have been carried out in offices than in residential buildings (Calì et al., 2016; Polinder et al., 2013; Roetzel et al., 2010) and many have focused on developing models for the human behaviour of window opening, which can be used in building simulations (Fabi et al., 2012; Polinder et al., 2013). In addition, airing habits have not been investigated as much in single-family houses as in multifamily buildings, at least not in Sweden (Levin, 2012).

In one large Swedish field study, it was shown that 50% of people living in single-family houses opened their windows daily during the heating season. 12% had at least one window open all day/night and 34% had their windows opened for a few hours (National Board of Housing, Building and Planning, 2009a). Generally, newer studies seem to report on less frequent airing than older studies, at least this is true for residents living in apartments (Boork, 2015; Hansson & Nordquist, 2010; Levin, 2012).

As with many other types of behaviour, airing habits have been found to vary between different households (Andersen et al., 2013). On top of that, there are

like the elderly, it needs to be at least two degrees higher, which is in line with WHO guidelines (Ranson, 1988; WHO, 1987).

[86] The experience of thermal comfort is dependent on individual factors such as a person's clothing and activity level as well as age and health status, together with surrounding conditions, including air movement, relative humidity, evenness and changes of temperature (Ranson, 1988; WHO, 1990).

[87] Smart thermostats refer to programmable thermostats that customers can control remotely (Robinson et al., 2016).

diurnal and seasonal variations that are to a large extent connected to outdoor temperature variations (Andersen et al., 2009; Calì et al., 2016; Erhorn, 1988; Fabi et al., 2012). The main purpose of airing during summertime has been identified as achieving better thermal comfort (e.g. Boork, 2015; Hansson & Nordquist, 2010), while airing in winter seems more dependent on the air quality (e.g. Andersen et al., 2009; Boork, 2015; Knudsen, 2019; Knudsen et al., 2016; Van Dongen, 1986). Another reason for window opening stated in surveys, is that it is just 'an old habit' (Hansson & Nordquist, 2010; Sandberg & Engvall, 2002).

3.1.4 Households' electricity consumption patterns

This section highlights electricity consumption patterns in households, that is, how the electricity use varies during a certain period, for instance during a day. At what time and for how long the electricity is used forms the household's diurnal load curve. The aggregated load curves of a community of households determine the electricity demand for a specific part of the energy system. The peak demands, which occur when a lot of households use electricity at the same time, are becoming an increasingly important aspect, especially with a shift towards a greater share of renewable energy sources in the system, leading to uneven electricity generation (Aghaei & Alizadeh, 2013). Hence, from an energy system perspective, knowledge about electricity consumption patterns gives an insight into how the electricity use potentially can be matched with the electricity production, to better balance the supply and demand of electricity.[88] Residents are anticipated to play an active role in this balance by shifting their electricity usage to off-peak hours with cheaper electricity prices – so-called demand response (e.g. Parrish, Gross, & Heptonstall, 2019; SOU 2018:15), or by producing, using and selling their own electricity.[89]

Literature on households' electricity consumption patterns often illustrates daily load curves for different weekdays, either from measured data (e.g. Aydinalp Koksal, Rowlands, & Parker, 2015; Cetin, Tabares-Velasco, & Novoselac, 2014) or from time-use surveys (e.g. Lampaditou & Leach, 2005; Widén et al., 2009). For instance, in the measurement campaign reported by Zimmermann (2009), average daily load curves for the total electricity use of electrically heated single-family houses showed clear differences between the patterns of weekdays and weekend days. Weekdays displayed notably more distinct power peaks in the morning and in the evening. This was true for households with children and for couples of ages 26–64 years without children. For retired people, on the other hand, the appearance of

[88] An electricity grid that facilitates an optimisation of the energy system in this way, is often referred to as a smart grid.

[89] However, in order to increase the opportunity for residents to become active consumers, both smart meters and dynamic pricing of electricity is required (Directive (EU) 2019/944; Forum för smarta elnät, 2017; Swedish Energy Markets Inspectorate, 2016).

the load curves was similar for all days of the week. In addition, this group of households exhibited a less distinct peak in the evening than the other household categories. Similar diurnal patterns for electrically heated single-family houses have been presented in older studies (e.g. Norén, 1998; Pratt et al., 1993; Stovall, 1989). Electrical load curves have, however, been studied even more related to household electricity use (compared to total electricity use, where space heating and domestic hot water are included as well). In these studies, the patterns described above are clear but with a more defined evening peak and a lower morning peak (e.g. Aydinalp Koksal et al., 2015; REMODECE, 2008; Zimmermann, 2009). Studies concentrated on diurnal patterns of household electricity use also distinguish between different groups. For instance, in the study by Kmetty some households carried out many electricity-related activities in the afternoon/evening, which resulted in a high electricity peak at that time of day (Kmetty, 2016). Another group had a lower peak in the morning and a medium-sized peak in the afternoon/evening. Other households had two distinctive peaks of similar size during the day. Similar distinctions between different groups were presented in the study by Yilmaz, Weber, and Patel (2019).[90]

Since high peaks in electricity use put pressure on electricity production and transmission in the electricity grid (Torriti, 2017a), various studies have investigated which activities and electrical appliances cause the peak demands of households' electricity curves (e.g. Kilpatrick, Banfill, & Jenkins, 2011). For instance, in a study where the use of individual electrical appliances was carefully metered, it was learnt that most household appliances contributed to the maximum electricity demand of which tumble dryers, dishwashers and electric cookers were the three largest contributors for these households (McLoughlin, Duffy, & Conlon, 2012). In Section 3.2.3.3, further studies on how residents can contribute to reducing the peaks in electricity use, for instance, by load shifting, are brought up.

3.1.5 Presence at home

How much time people spend at home can give an indication of the level of plausible energy use, especially for household electricity and hot water use. A study by Guerra Santin, Itard, and Visscher (2009) showed that a high grade of presence at home increases the energy use in contrast to cases where the residents are almost never at home or where their presence varies a lot. The residents' presence at home also affects the amount of heat given off from the residents themselves, depending on the activities they perform. A Swedish study from the mid-1990s, showed that the participants on average spent 14.8 hours per day at home during the weekdays and 17.5 hours per day during the weekend (Ellegård, 2002). This means an estimated

[90] Although not identical, but similar patterns have been identified for three groups of households' diurnal domestic hot water usages (Gram-Hanssen et al., 2020).

average of 15.6 hours per day, taking all days of a week into consideration.[91] Several studies from other countries show similar findings, for example, 15.7 h/day in Germany (Brasche & Bischof, 2005), 15.8 h/day in Canada and 15.6 h/day in the USA (Leech et al., 2002), however more recent publications have reported higher US figures of approximately 18 h/day (Mitra et al., 2019). Also, a Danish study estimated weekly averages of 18.1 h/day during summertime and 18.2 h/day during wintertime (Barthelmes et al., 2018). Similar differences between weekdays and weekends are however reported in the study by Barthelmes et al., as in the Swedish study above (Ellegård, 2002). In addition, research examines and develops representative curves of time spent at home throughout the day (Aragon et al., 2019; Mitra et al., 2020), which are often used in modelling to simulate the energy demand of buildings (e.g. Martinaitis et al., 2015; Motuziene & Vilutiene, 2013) or in energy impact analyses (e.g. Aerts et al., 2013, 2014; de Meester et al., 2013; Richardson, Thomson, & Infield, 2008).

3.1.6 Differences in energy use between households

As demonstrated in the previous sections, energy used for various purposes can differ between households. Many studies intend to study the reasons behind these differences in order to understand more about what makes some households use a lot of energy, while others use very little. To study differences, the energy use of households living in similar single-family houses have been investigated, as the technical situations are then comparable. Below, literature focusing on the size of the differences, and on factors contributing to them, will be highlighted.

In older studies of similar houses, a factor of two between the highest and lowest use of total energy was found (Gaunt, 1985; Lundström, 1982), and comparable figures were demonstrated for gas consumption in Socolow's study (1978). More recent studies show differences in line with this, with factors of 2.5 and 3 between the highest and lowest use for space heating and household electricity (Gill et al., 2011; Nylander, Johansson, & Johnsson, 2006). Additionally, studies of households living in energy-efficient houses, with a lower level of energy use than traditional houses, have shown differences, for example with a factor of two (Ruud & Lundin, 2004). It is not uncommon with even greater differences between households' water use, including hot water consumption. Several studies have reported on differences of factors between four and seven and above, between the households with the highest and lowest consumption (e.g. Björk & Wiklund, 1982; Lundström, 1982;

[91] As a comparison, in the Swedish regulations determining the building's energy use under normal conditions, the value of 14 hours per day is stated as an average for the whole year (BFS 2016:12 – 2018:5); this value is to be used for estimations on heat given off by the residents (metabolic heat).

Swedish Energy Agency, 2009). Individual differences of water use per person are similarly large (Gill et al., 2011; Mayer et al., 1999; Willis et al., 2013).

The differences in energy and water use may be explained by a number of factors (Gram-Hanssen, Kofod, & Petersen, 2004; Hirst, Goeltz, & Hubbard, 1987; NUTEK, 1994; Rathnayaka et al., 2014), for example, heated floor area and the number of persons in the households. However, these factors are not enough to explain the differences; instead, studies indicate that the residents' energy behaviour is also an important factor, in similar houses (e.g. Gaunt, 1985; Gill et al., 2011; Gram-Hanssen, Kofod, & Petersen, 2004; Kristensen & Petersen, 2017; Lundström, 1982; Palmborg, 1986), as well as in studies of different types of housing (Bartusch et al., 2012; Krnjajic et al., 2018). As demonstrated in older, and newer, studies, the significant role of the residents' choices and behaviour is even more evident in studies where the energy use of houses that have changed owners is compared before and after the shift in ownership (Gaunt, 1985; Lundström, 1982; Sonderegger, 1978; van den Brom et al., 2019). A heterogeneity in households' electricity consumptions has also been found (e.g. Frondel, Sommer, & Vance, 2019). Studies have moreover shown that there are a variety of everyday behaviours that contribute to these differences (De Lauretis, Ghersi, & Cayla, 2017; Yilmaz, Firth, & Allinson, 2017). For example, the sections above have demonstrated variations between households' estimated annual energy use for dishwashers (Zimmermann, 2009), laundry routines (Schmitz & Stamminger, 2014; Zimmermann, 2009), airing behaviour (e.g. Andersen et al., 2013; Hansson & Nordquist, 2010) and lighting behaviour (Bladh, 2008; Bladh & Krantz, 2008).

In the following sections, explanatory factors and the residents' role for the energy use will be in focus and further highlighted.

3.2 Perspectives and explanatory factors for energy-related behaviours

This section first gives an overview of common theoretical perspectives for understanding households' energy-related behaviours, followed by demographic factors explaining energy use and households' energy-related activities. Thereafter, research on how energy behaviours can be influenced, as well as studies with estimations of potential energy savings are highlighted. Environmental research will also be mentioned, as several studies have investigated energy behaviours together with other environmental-related behaviours.

3.2.1 Understanding energy-related (everyday) behaviours

The following overview presents perspectives from behavioural and social science research to understand energy-related behaviours. Concepts of values, attitudes and knowledge are brought up, as well as the role of habitual behaviours. In relation to routinized everyday behaviours, a brief description of the theory of social practice is given. Lastly, time-use studies used in energy research are highlighted.

3.2.1.1 Values, attitudes and knowledge

To understand what shapes and motivates people's energy-related behaviours, environmental psychology research has focused on the concepts of values (i.e. guiding principles of what is important for people), attitudes (i.e. people's mental dispositions towards something) and knowledge of individuals. Research has found that these factors may have an impact on energy use (Abrahamse & Shwom, 2018; Abrahamse & Steg, 2011; Gifford & Nilsson, 2014; Johansson & Neij, 2017; Steg, Perlaviciute, & van der Werff, 2015). For example, a European project demonstrated that people who explicitly stated they cared about the environment (i.e. high pro-environmental values and attitudes) and also felt morally bound to save energy, were more likely to carry out energy-saving activities, such as running fully loaded machines and turning off lights and electronic equipment (van der Werff, Ruepert, & Steg, 2018). Similarly, in the empirical study of Pothitou, Hanna, and Chalvatzis (2016), the importance of environmental knowledge, together with pro-environmental values, was highlighted. The study showed that these factors increased the likelihood for positive attitudes and behaviours towards energy savings related to everyday activities and consumer behaviours. Bruderer Enzler, Diekmann, and Liebe (2019) found that higher environmental concern related to actual lower electricity use.

However, values, attitudes and knowledge are not always clearly connected to the way people actually behave. An ‘attitude-behaviour gap’ has been found, which means that people think and say that environmental issues are important, but still do not act in a pro-environmental way (Bell et al., 2001; Flynn, Bellaby, & Ricci, 2009; Kollmuss & Agyeman, 2002; Poortinga, Steg, & Vlek, 2004). This is also true for energy issues (e.g. Frederiks, Stenner, & Hobman, 2015; Huang & Warnier, 2019). Research suggests that certain knowledge constitutes a prerequisite for energy-efficient behaviours, but that it is not enough for behavioural changes. For behaviour change to happen, it is also required that people are motivated and that they feel that they are able to take on these behaviours (Johansson & Neij, 2017).

3.2.1.2 The role of habits

A considerable amount of literature shows that our everyday behaviours are usually governed by habits (Bourdieu, 1990; Jacobsen, 2017; Maréchal, 2010), hence also including people's energy-related behaviour (Butler, Parkhill, & Pidgeon, 2016; IEA, 2010; Maréchal, 2010; Wagenaar, 1992.) Many of the daily routines affecting energy use are characterized by a high degree of automated actions, which do not require much cognitive effort, such as switching on and off lights (Jackson, 2005; Maréchal, 2010). Thus, explanations claiming that our behaviours are rational and based on well-informed decisions are not true for many of our everyday energy activities (e.g. Abrahamse & Shwom, 2018; Gram-Hanssen, 2010b; Kurz et al., 2015).

That habitual behaviours take place without much thought and intent, and often in stable familiar environments such as the home (Kurz et al., 2015; Ouellette & Wood, 1998), can explain why many energy-related everyday behaviours continue despite people's increased knowledge about energy and environmental issues (Maréchal, 2010; Martiskainen, 2008).

3.2.1.3 Social practice

People's habits are also a cornerstone in the theory of social practice (e.g. Reckwitz, 2002; Shove, Pantzar, & Watson, 2012; Warde, 2017), which nowadays is a well-established theory within energy research to understand energy-related activities (e.g. Anderson, 2016; Butler et al., 2016; Gram-Hanssen, 2010b, 2014; Jalas & Rinkinen, 2016; Maréchal & Holzemer, 2018; Shove & Walker, 2014; Torriti, 2017b). Briefly, a practice can be described as a routinized way of doing something, such as how people cook, shower or listen to music. How people participate in practices depends on the materials used (e.g. technologies and appliances), the competence of the person carrying out the activities, and lastly the meanings of the practices (why they are carried out) (Shove et al., 2012). How a practice is carried out influences the energy use. For example, the energy use related to showering is impacted by the thermostat used (technology), how people learned to shower (competence) and why people shower the way they do (norms and meaning). However, the main purpose for people is to carry out a practice, not to save energy (Gram-Hanssen, 2010a).

The social practice theory's strong focus on common activities, routinely performed in daily life, thus highlights activities that are ordinary and inconspicuous. For example, practices related to the everyday routines of using standby functions were examined by Gram-Hanssen (2010b). Activity patterns and daily timing of energy-related practices have also been investigated (Gram-Hanssen et al., 2020; Torriti, 2017b), for example, at what times during the day laundry practices are carried out (Anderson, 2016). Others have used a practice approach to study heating practices – how these influenced the energy use (e.g. Eon, Morrison, & Byrne, 2017) and the housework around the heating systems (e.g. Jalas & Rinkinen, 2016).

3.2.1.4 Time-use studies to understand how everyday life influences residential energy use

As a way to collect information and to understand people's everyday life, including how it affects the energy use in more detail, time-use studies have been conducted.[92] In Sweden, three national time-use surveys have been performed,[93] in which data from the latest survey has been utilised within energy research, for example, studying the energy impact of households' everyday activities (Hellgren, 2015; Palm, Ellegård, & Hellgren, 2018). Other time-use data that have been examined extensively were collected in a Swedish pilot project, in which diaries from different members of the same household were included (Rydenstam & Wadeskog, 1998).[94] Projects using this time-use data have focused on several energy aspects, such as women's and men's energy use (Nordell, 2003), load curves for household electricity and hot water (Widén et al., 2009), visualisation of domestic energy use (Palm & Ellegård, 2011) and how energy-related activities are socially organised in households (Isaksson & Ellegård, 2015). Recurrent national time studies are of particular value to show trends and changing patterns in citizens' energy-related activities (Jalas & Juntunen, 2015; Sekar, Williams, & Chen, 2018), such as changes in laundry habits and their consequences for the electricity load (Anderson, 2016).

Diaries are not only used in these large national time-use surveys; they are also a common method to collect empirical data about people in smaller research projects. For instance, time-use diaries with a time-geographical[95] approach were used to examine electricity use and load management in electrically heated houses (Sernhed, 2004), to examine residents' water use (Krantz, 2005) and electricity use (Green & Ellegård, 2007), to investigate energy-related behaviours in retirement homes (Carlander, Trygg, & Moshfegh, 2019), and to visualise energy use in households (Löfström, 2008). Other types of diaries have been used to study the use of office lighting (Maleetipwan-Mattsson, Laike, & Johansson, 2013) and to analyse the use of dishwashers (Richter, 2011).[96]

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[92] Time-use research is typically dedicated to learning how people allocate their time during an average day (IATUR, 2019).

[93] The national time-use surveys were conducted in 1990/1991, 2000/2001 and 2010/2011 (Statistics Sweden, 2003, 2012).

[94] To include different family members of the same household is not normal procedure in national time-use studies.

[95] Time-geography is an approach to understand temporal and spatial processes, including people's activities (Ellegård, 2019) – for more information, see Section 2.2.3.2.

[96] Diaries could be used for completely other purposes than to gather data in research projects, e.g. in the therapeutic and health care field (Löfström, 2008).

3.2.2 Demographic factors explaining energy use and energy-related behaviours

This section describes how traditional demographic factors, such as gender, age and income, explain energy use as well as differences in energy-related behaviours. Cultural differences between countries in relation to energy use are briefly brought up. In addition, it is highlighted how housing-related demographic factors, including housing ownership, household size and household type, affect energy use.

3.2.2.1 Gender

Research demonstrates that there is still a traditional division of household tasks, with women performing everyday tasks in the home to a greater extent – many of which affect the energy use (Carlsson-Kanyama, Lindén, & Wulff, 2005; Nordell, 2003). For instance, women spend more time cooking, hence more energy is used by women for preparing food (Ellegård, 2004). Also, research demonstrates that there is a division regarding energy-saving activities, where men are found to take responsibility for the technical aspects of energy efficiency and women are saving energy by behavioural changes (Clancy & Roehr, 2003). However, an ongoing shift related to the traditional division of household tasks between men and women is shown in a study where changes in laundry practices over a period of two decades in UK households were investigated (Anderson, 2016).

In general, however, the results are not clear in terms of how gender relate to energy use (Frederiks, Stenner, & Hobman, 2015). For example, studies show that women exhibit more environmentally positive behaviours, while this cannot be demonstrated in other studies. One possible cause of unclear and conflicting results may be that few studies have gender as a starting point when analysing energy use and energy-related behaviours, and more research in this field has been requested (Carlsson-Kanyama, Lindén, & Wulff, 2005).

3.2.2.2 Age

When comparing different generations or age-groups,[97] results seem to be pointing in different directions regarding how this factor influences residential energy use (Carlsson-Kanyama, Lindén, & Wulff, 2005; Huebner et al., 2016; Johansson & Neij, 2017), as well as water use (Martinez-Espineira & Garcia-Valinas, 2013; Tiefenbeck et al., 2013). This will be exemplified below with results typical for older age groups. To start with, there are, on one hand, age-related behaviours and characteristics that are likely to increase the energy use in the home. Elderly have

[97] Note that when studies refer to a certain age-group, this means that when people reach a certain age, they are associated with specific attributes and behaviour. When referring to a generation, this means a specific period of time which influenced the behaviour of the people living during this period (Bladh & Krantz, 2008). However, this distinction is not always made in literature (Carlsson-Kanyama, Lindén, & Eriksson, 2005).

been found to have a tendency to hold on to what they already have got (e.g. Carlsson-Kanyama, Lindén, & Eriksson, 2003; Deutsch & Timpe, 2013; Engel, Hansen, & Kronenberg, 2011; Lindén, 2008; Mills & Schleich, 2012; NUTEK, 1994; Swedish Energy Agency, 2011). This is reflected in the fact that older households generally tend to stay in their houses even when their children have moved out, hence increasing the per capita living space. Another example is that the elderly often possess old and energy-*in*efficient appliances and lighting. Previous literature also highlights that older households tend to spend more hours at home (Deutsch & Timpe, 2013), do dishes by hand (Lindén, 2008) and have baths instead of showers (Carlsson-Kanyama et al., 2003). On the other hand, there are behaviours and characteristics common to the elderly that contribute to a decreased energy use. Several studies have found that the elderly have an economical behaviour, due to having been brought up under conditions with generally much lower consumption levels (Carlsson-Kanyama et al., 2003; Gifford & Nilsson, 2014). Even though the primary reason behind these behaviours might not be to save energy (Bladh & Krantz, 2008; Carlsson-Kanyama et al., 2003; Gifford & Nilsson, 2014), it still results in a reduced use, for example, by a less frequent use of the washing machine (Alborzi, Schmitz, & Stamminger, 2017; Carlsson-Kanyama et al., 2003; Nordell, 2003; NUTEK, 1994).

3.2.2.3 Household income

Studies show that household income, as a determinant of residential energy use, does give an indication of what effect a small, sufficient or large amount of money has on energy use (Carlsson-Kanyama, Lindén, & Wulff, 2005). A review found that household income is one of the strongest sociodemographic determinants of residential energy use (Frederiks et al., 2015). Most literature points to income as positively correlated to energy use, meaning that a high-income household consumes more energy than a low-income household (Brounen, Kok, & Quigley, 2012; Hansen, 2016). On the other hand, high-income households do have greater possibilities to invest in energy-efficient buildings, technology and newer electrical appliances (Das, Richman, & Brown, 2018). Furthermore, when households with the same expenditure or income are compared, great variations in energy use have been found (Alfredsson, 2002; Vringer, 2005). Different housing districts have also been studied, where single-family houses in wealthier districts had a larger heated floor area, a higher heat use and a 20-40% higher average electricity consumption per person than in most other areas (Jensen & Gram-Hanssen, 2000). The water usage, on the other hand, showed no clear relationship with the level of wealth of residential districts.

3.2.2.4 Cultural differences between countries

Other determinants, such as tradition and culture in relation to energy use, seem to have been sparsely examined, with the exception of the oft-quoted study by Wilhite et al. (1996). In this study, energy use behaviours in Japanese and Norwegian households were compared, and the differences found could be explained, at the time of this study, by dissimilarities in norms and traditions related to space heating, lighting and hot water usage. For instance, lighting was important for Norwegian households to create a 'cosy' atmosphere at home and, therefore, many small lamps were used. On the other hand, Japanese residents saw functionality as central, which meant that ceiling fixtures with fluorescent light were often used in the living room. Later cross-country comparisons can be found (e.g. Alborzi et al., 2017; Long, Mills, & Schleich, 2018; Schmitz & Stamminger, 2014; Stamminger, Suljug, & Hillenstedt, 2007), in which no cultural analyses have been made, but with the general results that findings related to energy behaviours in one country are not necessarily valid for another country (Annika Carlsson-Kanyama, Lindén, & Wulff, 2005).

3.2.2.5 Housing ownership

Regarding types of housing ownership and occupancy, great differences exist between the situations in rental apartments and in owner-occupied houses. Owning one's own home usually means a long-term tenure in the home, as well as being in a more financially secure situation than renters (Frederiks et al., 2015; Sardianou, 2007). Besides, homeowners may have a sense of control and a feeling of belonging to their housing that encourages them to consider how to save energy (Barr, Gilg, & Ford, 2005). The monetary incentives to save energy through energy-saving measures and behavioural changes depend on who pays for the investment and energy usage. Metering and billing the electricity consumption is standard in most countries, but metering heating, including domestic hot water, varies from country to country (Terés-Zubiaga et al., 2018). Many Swedish studies show that the water consumption per person is higher for apartments than for single-family houses where the energy bill is paid for directly by the household, and not indirectly through the rent (Levin, 2012). But there could also be situations with a split incentive, where the housing owner (e.g. the landlord) is responsible for investments in energy-efficient appliances, while any reduction in the electricity bill will favour the renter (Serret & Brown, 2014).

3.2.2.6 Household size and type[98]

Household size is a factor often considered in studies, and several reviews show that it is a very important factor indeed for energy use (e.g. Carlsson-Kanyama & Lindén, 2002; Frederiks et al., 2015; Hayn, Bertsch, & Fichtner, 2014; Wahlström & Hårsman, 2015). Typically, larger households have greater energy demands for a number of energy-related activities, and usually possess and use more electrical equipment (e.g. Huebner et al., 2016). For example, energy used for clothes

[98] Household type refers to the household composition, comprising both number and age of household members, such as single-person households, retired couples, households with children etc.

washing, cooking and activities related to ‘information and entertainment’ has been shown to depend on the size of the household (Zimmermann, 2009). Furthermore, the person-dependency of water usage has been reported in numerous studies (e.g. Levin, 2012; Makki et al., 2013; Martinez-Espineira & Garcia-Valinas, 2013; Mayer et al., 1999). But from an energy perspective, there are advantages to having a larger household (regarding energy usage per person) (Carlsson-Kanyama, Lindén, & Wulff, 2005; Frederiks et al., 2015; Hayn et al., 2014). This can be seen, for example, in electricity consumption for cooking (Zimmermann, 2009), refrigeration and dishwashing (NUTEK, 1994), water usage (e.g. Martinez-Espineira & Garcia-Valinas, 2013; Mayer et al., 1999) and space heating. Hence, the overall societal trend towards smaller households in many countries is a concern, as it counteracts the benefits of larger households and risks an overall increase in energy usage (e.g. Das et al., 2018).

Regarding household size, one review suggested that the stage of a family's life cycle – that is, the change in household composition over time – appears to be a strong predictor of household energy use, typically peaking for households with children (Frederiks et al., 2015). Households with teenagers are also more likely to be higher consumers of electricity (Brounen et al., 2012; Jones & Lomas, 2015). In addition, research has pointed out how energy-saving attitudes change with family life cycles. For example, middle-aged couples (37–50 years) with or without children seemed to have more positive attitudes towards saving energy compared to households in other phases of the family life cycle (Belaïd & Joumni, 2020).

3.2.3 How energy-related behaviours can be influenced

There are various types of policy instruments focusing on increasing the potential for energy-saving behaviours and choices in our homes (Lindén, 2008; Lindén, Carlsson-Kanyama, & Eriksson, 2006). Firstly, informative instruments, which are typically voluntary, can include information campaigns, energy advisers and energy labelling on products. Then, economic instruments can function as catalysts when people already have started considering a particular measure. These can include tax reductions for installation of energy-efficient measures in existing houses and heating systems. Furthermore, administrative instruments are immediate and force people to make certain choices, such as building regulations with energy performance requirements and regulations on energy performance certificates for houses. Lastly, physical instruments can make it easier for consumers to change or maintain their behaviours by changing the designs of products or services, such as the design of water-saving armatures with automatic shutoff of water flow.

This section focuses on informative instruments, in terms of informative interventions to influence energy savings, since they have been commonly examined within behavioural and social science research. Physical instruments and conditions will also briefly be mentioned, as well as paying for your own consumption as an example of an economic instrument. This is followed by critical aspects regarding how informative interventions are commonly designed.

3.2.3.1 Does information work?

Several interventions have adopted an informational strategy, focusing on providing information on energy savings with the intention of increasing awareness and understanding to motivate people to change their behaviours. The information can either be of a general nature or more specifically to target certain behaviours or solutions that are relevant for the target group. Specific information is considered to work somewhat better and this seems to be the case for several interventions (Fischer, 2008; Koletsou, 2015; Lewis et al., 2012; Lopes, Antunes, & Martins, 2012; Uitdenbogerd et al., 2007). Results from various studies demonstrate that information alone does not work if people are not motivated and if people feel that they lack the ability to engage in energy-saving behaviours (Abrahamse & Shwom, 2018; Johansson & Neij, 2017; Pothitou et al., 2016). In addition, whether a source of information is perceived as trustworthy has an impact on how people are influenced by the information (Steg et al., 2015).

3.2.3.2 Feedback and visualisation of energy use

As energy is perceived as a hidden commodity and daily behaviours are associated with a high degree of unawareness, regular feedback and visualisation of energy and water usage has been a method used in numerous intervention studies (Bertoldi, Serrenho, & Zangheri, 2016; Khosrowpour et al., 2018; Paone & Bacher, 2018; Sønderlund et al., 2016; Tiefenbeck et al., 2013, 2018; Zangheri, Serrenho, & Bertoldi, 2019). Feedback can be delivered in many shapes and forms, both as indirect feedback on more or less informative bills, and as direct feedback and visualisation on displays, in some cases including smart interaction. Previous studies have illustrated that real-time metering and visualisation support tenants' awareness of their own energy use, and many feedback studies have shown encouraging results in regard to saving energy, especially when the feedback is given frequently (Abrahamse et al., 2005; Bertoldi et al., 2016).

Different types of feedback can be visualised. For example, feedback can be appliance-specific, historical, social/normative (i.e. a comparison with other households). Experience has shown that it can be beneficial when the feedback is specified for different appliances (Asensio & Delmas, 2016; Fischer, 2008) and when it is personalised (Lewis et al., 2012). However, there are examples of feedback having no effect, when results showed both increased and decreased electricity usage during the examined time period (Pyrko, 2011). Furthermore, a lack of clarity can exist regarding the effectiveness of comparing energy data, in the form of both historical and normative (social) feedback (Abrahamse & Steg, 2013; Delmas, Fischlein, & Asensio, 2013; Fischer, 2007; Harries et al., 2013). For instance, some indications are that households with low energy usage can increase their use after being compared to other households, hence social comparisons of energy use need to be implemented with care (Abrahamse & Shwom, 2018; Vassileva & Campillo, 2014).

A recurrent issue is the question about the long-term effects of visualisation and feedback projects (also regarding intervention projects in general). There is a need for more studies with a longer duration to enable the examination of whether results last and how to engage people over time (Delmas et al., 2013; Ehrhardt-Martinez, 2011). There are examples of longitudinal studies where feedback – either on its own or combined with other activities – has shown lasting effects (Agnew et al., 2013; Foster & Mazur-Stommen, 2012), in particular when it has focused on high-level energy consumers (Russell et al., 2014; Stieß, Fischer, & Kresse, 2017). Studies also demonstrate that there may be initial savings but thereafter prospects of further reductions may be slim (Hargreaves, Nye, & Burgess, 2013; Köhler, 2017). Other studies have shown that people easily fall back into their old habits of energy and water usage sometime after the feedback intervention (Peschiera, Taylor, & Siegel, 2010; Stewart et al., 2013; van Dam, 2013). In general, concluding from a comprehensive review of over 70 studies, the longer the duration of the feedback intervention, the smaller the energy savings that were achieved (Zangheri et al., 2019).

3.2.3.3 Focusing on electricity peak demands

The problem of a potential power shortage when many users consume electricity at the same time was briefly brought up in Section 3.1.4. Households can contribute to level out the electricity demand by either decreasing their electricity use at peak times or shifting their usage to off-peak periods (load shifting), for example, by using washing machines and dishwashers at night (e.g. Kantor, Rowlands, & Parker, 2017). The greatest potential for load shifting during the heating season is with customers living in electrically heated houses (e.g. with a heat pump (Andersen et al., 2017)). Another way is to use self-produced electricity (Šćepanović, Warnier, & Nurminen, 2017). However, there seems to be low – or at least large variations in – interest and 'willingness' for residents to be active and flexible in regard to their energy use (e.g. Katzeff et al., 2017; Renström, 2019).

One driving force for users to be more flexible when they perform activities is differentiated electricity tariffs, but so far, studies show both positive, little or no effect on varying electricity prices (Abrahamse & Shwom, 2018; Rivers, 2018; Šćepanović et al., 2017; SEAI, 2018; Throndsen, 2017). Nevertheless, Öhrlund et al. suggest that the mere existence of differentiated pricing draws attention to activities using electricity, which may lead to households changing the times when they perform activities, unless it affects their everyday lives to a great extent (Öhrlund, Linné, & Bartusch, 2019). It is evident that future interventions, aiming for moving residents' activities from peak periods of electricity use, need to consider how time-dependent practices are (Torriti, 2017b).

3.2.3.4 Supportive material conditions and change of context

It is believed that interventions should consider how material and technical conditions can be changed to support more energy-saving practises (Jacobsen, 2017). For instance, energy-efficient washing programs can become easier to choose or spaces can be made available for air drying (Glad, 2015). Or technology rearrangements can support the possibilities for changing habits to decrease standby energy consumption (Gram-Hanssen, 2010b).

Regarding the use of water, some previous studies found a positive correlation between the installation of water-saving technology and a change towards more water-saving behaviours (Martinez-Espineira & Garcia-Valinas, 2013).[99] However, a study by Pérez-Urdiales and García-Valiñas (2016) found the opposite was true, showing a negative relationship between having water-saving devices, such as low-flow taps and shower heads, and shower behaviours, such as taking shorter showers. Thus, more research on how water can be saved through behaviour-changing technologies is called for (Levin & Muehleisen, 2016).

Previous studies consider that a change in context or situation can open up for an increased possibility that existing habits can be more easily influenced, as the stability of the familiar settings are weakened. A change of context, such as a shift in housing, can hence be seen as a ‘window of opportunity’ for interventions (e.g. informational campaigns). However, few studies exist on how a change of housing can be related to households' energy use. An exception, although it did not focus on daily energy habits, examined energy subsidies and found that a change of housing made the residents more receptive to the proposed energy measures (Maréchal, 2010).

3.2.3.5 Paying for your own consumption

It has been shown that a shift from collective (building level) to individual (household level) payment, by the installation of individual metering and billing for the energy use of domestic hot water,[100] does not automatically translate into changed behaviours and water savings, but the experiences reported by building owners differ. Previous Swedish compilations have found savings of 15–30% on domestic hot water, although there were great variations between households (Berndtsson, 2003), while a later compilation found that that in several cases the expected savings were not gained (Levin, 2012). In the thesis by Krantz (2005), no change in residents' water-related behaviour was found, whereas new routines were revealed in Köhler's study (2017). Generally, however, a lack of research studies

[99] The direction of causality was however not examined.

[100] In Sweden, more focus has been on the installation of individual metering and billing of energy use for domestic hot water, while individual metering for space heating is not as common (National Board of Housing, Building and Planning, 2014).

and follow-ups on the effect of the implementation of individual metering and billing[101] remains the case (National Board of Housing, Building and Planning, 2014).

3.2.3.6 Two-way communication

There are some criticisms directed at one-way information campaigns, as it is not known how the information is received or even if the recipients have read the information (Simcock et al., 2014). By not actually talking to the residents about how they view their energy use, we miss the opportunity to get a greater understanding of the residents' perceived difficulties, experiences and needs in regard to their homes (Heiskanen & Lovio, 2010).

Research, also in the field of energy use, is therefore increasingly showing the importance of involving strategies where two-way communication is prioritised (Isaksson, Hiller, & Lane, 2019). By creating a dialogue, with energy experts and residents exchanging experiences and learning from each other, the conditions for achieving savings increase. So far this resident-expert dialogue technique has primarily been used with regard to houses' energy systems (e.g. Glad, 2012), where experts have knowledge of the technical solutions, while the users have knowledge of what is important for them (motivations and needs), in which context the technology is used and their own possibilities and limitations in regards to operating the energy systems of the buildings (Heiskanen & Lovio, 2010).

3.2.3.7 Too much focus on energy?

There are further critical voices reacting to today's interventions and current feedback approaches in particular, as these typically address the energy use of individuals and thereby miss what is important for people (Jacobsen, 2017; Pothitou et al., 2016; Shove, 2003). By focusing on energy use only, the interventions tend to background people's reasons (motivations) for doing certain practices (Gram-Hanssen, 2010a). Rather, there should be more focus on the needs and norms of people and how to influence their choices (Strengers, 2011, 2012). What is commonly considered as ‘normal’ in our society plays an important role, including expectations of our home life, such as indoor temperature, comfort, cleanliness and convenience (Ehrhardt-Martinez, 2008; Shove, 2003). These norms need to be challenged as they can constitute a constraint, preventing energy-saving habits (Pothitou et al., 2016; Shove, 2003). One example where norms were challenged was in a study on cleanliness related to how often people wash their jeans (Jack, 2013a, 2013b). The study showed that it was possible to negotiate, alter, and even accept, new standards involving less frequent washing and reduced expectations of cleanliness.

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[101] The implementation of individual metering and billing on energy use for domestic hot water is included in EU's Energy Efficiency Directive (Directive (EU) 2018/2002).

In addition, within a single household, family members' social interactions and norms matter, and an individual member's changes towards energy-saving behaviours may affect other persons in the household (Hellgren, 2015). However, such changes are not always leading in an energy-saving direction (Isaksson & Ellegård, 2015). Family members have different motivations and needs, and these can be demonstrated through quite different practices, as shown by Eon, Morrison, and Byrne (2017), where diverse heating practices were found due to differences in how individuals perceived the details of thermal comfort.

3.2.3.8 Combining strategies

The combination of different kinds of strategies is generally found to enhance the effect of energy-saving interventions (Iweka et al., 2019; Koop, Van Dorssen, & Brouwer, 2019), including combining goal-setting and feedback (Wokje Abrahamse et al., 2005; Šćepanović et al., 2017). Information strategies may also benefit from being combined with other interventions, such as energy-efficient product designs so that a product is used as intended (Lindén, 2008; Lindén et al., 2006) or tailored energy audits including customized advice (Šćepanović et al., 2017).

The effect of combining intervention methods is not totally clear, especially regarding which combinations are the most effective in achieving long-lasting energy savings (Barbu, Griffiths, & Morton, 2013; Pothitou et al., 2016). In the literature, however, a number of plausible reasons for why combined intervention strategies could work better have been identified. Firstly, in similar contexts – such as the home environment – a variety of different kinds of behaviours are performed, a variety that are captured better by employing multiple strategies (Ehrhardt-Martinez, 2011; Maréchal, 2010). Secondly, since it has been found that the effects of interventions benefit from targeting the intended recipients (Fischer, 2008; Koletsou, 2015; Lewis et al., 2012; Uitdenbogerd et al., 2007) and that different types of interventions appeal to recipients in various ways (e.g. Foster & Mazur-Stommen, 2012); hence, applying multiple strategies increases the chances for energy savings. Thirdly, to initiate changes by addressing the different elements of practices,[102] several intervention methods may well be needed to improve the likelihood for successful changes (Gram-Hanssen, 2010b; Katzeff & Wangel, 2015).

[102] The elements of social practices are knowledge, materials and motivation (read more in Section 3.2.1.3). So far, not that many empirical studies on how to achieve changes in social practices exist, hence strategies based on this practice concept still need to be tested and evaluated (Kurz et al., 2015).

3.2.4 Potential savings and rebound effect

Energy and water savings due to behavioural changes have been *quantified* and *estimated* in various studies (e.g. Lopes et al., 2012). Below, reported savings from intervention studies that addresses different types of households' energy-related behaviours are accounted for. The last paragraph highlights the rebound effect, which can counteract so that the anticipated energy savings are not realised.

A review of 100 behavioural intervention projects in 11 European countries, covering different energy behaviours and target groups in society including households found that the saving potential for energy behaviour may reach as high as 20% (Gynther, Mikkonen, & Smits, 2012). Similar figures were reported by Zhang et al. (2018), who estimated the potential savings related to changes in households' behaviour at 10% to 25%. As described above, to give feedback on the residents' energy use is a common intervention method that often affects everyday behaviour, such as watching TV, cooking and clothes washing. A compilation of feedback interventions reported that electricity savings ranged from 1% to over 20%, but usually the resulting savings were between 5% and 12% (Fischer, 2008). Reviewed articles by Bertoldi et al. (2016) and Zangheri et al. (2019) confirmed these figures,[103] while others report more modest likely savings of 3% (SEAI, 2018). That feedback studies can show a range of savings was also evident in a review on feedback on water savings, which showed decreases in the range from approximately 3% to 30%[104] (Sønderlund et al., 2016). Other types of interventions that often focus on daily behaviour have likewise identified energy-saving potentials. For example, studies on goal setting and commitments point at savings of around 10%, even though further studies are needed to confirm this (Andor & Fels, 2018). Another finding is that combinations of intervention methods have been reported to enhance savings (e.g. Fischer, 2008).

Energy-saving behaviour that is performed relatively infrequently[105] – such as installation of energy-efficient lighting and draughtproofing around windows and doors – has been estimated to potentially save approximately 12% in energy use (Gardner & Stern, 2008). Savings related to consumer behaviour, such as the replacement of inefficient appliances by energy-efficient technology have been considered to be as high as 48% of the household electricity consumption (de Almeida et al., 2011).[106]

[103] The reviewed articles on feedback interventions conclude that savings are likely of 5–10% for electricity use and heating purposes (Bertoldi, Serrenho, & Zangheri, 2016; Zangheri, Serrenho, & Bertoldi, 2019).

[104] One out of the 21 reviewed studies showed an increase in water use, and in one study no significant decrease could be established.

[105] Referred to as stocktaking behaviour in Figure 3, Section 1.7.2.

[106] This estimate also comprises improved everyday behaviour and reduced standby consumption.

The above-mentioned studies show that behaviour changes can save energy use to different degrees. However, the contexts of the studies differ greatly, and this variety of settings affects the reported savings and the generalisations of the results (Lopes et al., 2012).

Rebound effect

Energy efficiency measures can often be associated with a reduction in energy use, but studies also show that the expected savings cannot always be taken for granted (Galvin, 2014). In relation to this, the expression *rebound effect* is relevant (e.g. Greening, Greene, & Difiglio, 2000; Sorrell, 2007). The rebound effect means an 'increased usage of an appliance or increased demand of a service following an increase in its energy efficiency' (Dütschke, Peters, & Schleich, 2013). That anticipated energy savings are not always realised or lasting can occur for a range of different measures (Aydin, Kok, & Brounen, 2017; Suffolk, 2016). For example, it has been reported that after installation of energy-efficient lighting residents have chosen brighter lighting and that the lights are switched on for longer periods (Dütschke et al., 2013). The installation of improved heating and insulation measures in a building often leads to higher indoor temperatures than before (e.g. Halvorsen et al., 2016; Oreszczyn et al., 2006).

3.3 Summarising the literature review

In this literature review, research in the field of energy use and energy-related behaviour in single-family houses has been in focus. The review shows, on the one hand, household electricity and water use trending lower due to improved efficiency (expressed per household and per person). On the other hand, these gains are often offset by other trends affecting energy use, such as the growing market penetration and usage of new electronic products, not the least those related to 'entertainment and information' in homes.

Furthermore, the review demonstrates how energy and water usages vary in different ways. Both older and newer studies show how usages can differ between households, although the technical circumstances are similar. Research highlights how electricity use can vary on a daily or weekly basis; the residents' willingness and incentives to be flexible about when energy-related activities are performed, are also examined in this context.

The literature review covers a period of around 40 years, where it seems more social science research in the energy field has been performed during the later decades. Many studies have examined the effect of household size and income to explain different levels of energy use, but in recent years other explanations and theories have been developed to obtain a more in-depth understanding of residents' impact on energy use. The theory of social practice is one example, with performances of everyday practices being in focus. Then the point of departure is not the energy usage, since the everyday activities are not driven by energy motives, but rather the key factors are the households' competence, motivation and technology used when performing ordinary practices. To successfully promote energy-saving behaviour by, for example, information and feedback interventions, people's needs and everyday situation must be considered.

Finally, the review shows that there is a need for multidisciplinary research which combines energy measurements with social science studies to gain further insights into the activities behind the energy data, as similarities in energy use can relate to very different behaviours. In this regard, the thesis is a contribution, using a multidisciplinary approach, to explain variations in energy use and energy-related behaviours. The main results from the empirical studies of the thesis, presented in the next chapter, will be discussed in Chapter 6 in relation to the findings of this literature review.

4 Results: Variations of energy use and energy-related behaviours

This chapter summarises the main empirical findings for each research question of the thesis. The first section covers changes in energy use over a longer period of time, followed by sections on differences in household energy use and daily electricity consumption patterns. The last section is focused on the influence of the residents' energy-related behaviours.

4.1 Energy changes over time

As buildings have long lifetimes, it is central that their function remains as intended, not least concerning their energy performance. At the start of this research, follow-up studies of low-energy single-family houses had found an increased energy use after years of occupancy (Berggren et al., 1997; Nilson & Uppström, 1997; Weber, 1996). The issue was therefore raised whether similar tendencies can be found in houses with normal energy performance, and the research question was formulated as: *How does the energy use in houses change over time, after years of occupancy, and what may affect it?*

To address this research question, a longitudinal study was performed, using historical yearly energy and water data over more than a ten-year period for 38 single-family houses. To be able to compare energy data of different years with varying outdoor temperatures, the data were corrected with reference to normal climate, in this case by using the heating degree-day method. As the energy data obtained from the local energy supplier included all energy used in the houses, typical values for household electricity and domestic hot water were used to separate these fractions from the energy used for space heating. In addition, six households were interviewed about events and measures that had taken place in their houses and households over more than the last decade and that may have had an impact on the energy use. The purpose of these interviews was to try to find the explanations for the appearance of the energy curves of individual households. Identifying trends in energy use over time has been done at both the individual (for individual houses) and the group level (for the entire housing area).

The results from the analyses of energy data over the years demonstrated that the energy use at the group level was relatively stable after years of occupancy. At the individual house level, however, the energy use had increased, decreased or stayed at the same level.

As for the trend on the group level, this is demonstrated for the 38 houses in Figure 10, where each point represents the total energy use (corrected with degree-days) for a house in a specific year. The total energy use includes the electricity use for space heating, household electricity and electricity use for hot water production. The average energy use (for the housing area) for each year is represented by the line and its trend line (the dashed line). No general indication of an increase or decrease can be found from the graph. However, it can be clearly seen that the level of energy use varies greatly from one house to another.

Figure 11 shows examples for individual houses, with each graph being the energy use of a house, including the actual annual energy use (the circles), the degree-day corrected energy use (the squares) and the trend line for the corrected energy use (the dashed line). Every point is the energy usage for a specific year. It can be noted that in some cases it is difficult to insert a trend line, because the energy use can suddenly change direction (as in the case of household A7). The curves illustrate that the energy use can be very different for different houses.[107]

[107] Another way of showing the differences in energy use between the six households is shown in Figure 4 in Paper I (Appendix A), with the average total energy usage over the time period being presented.

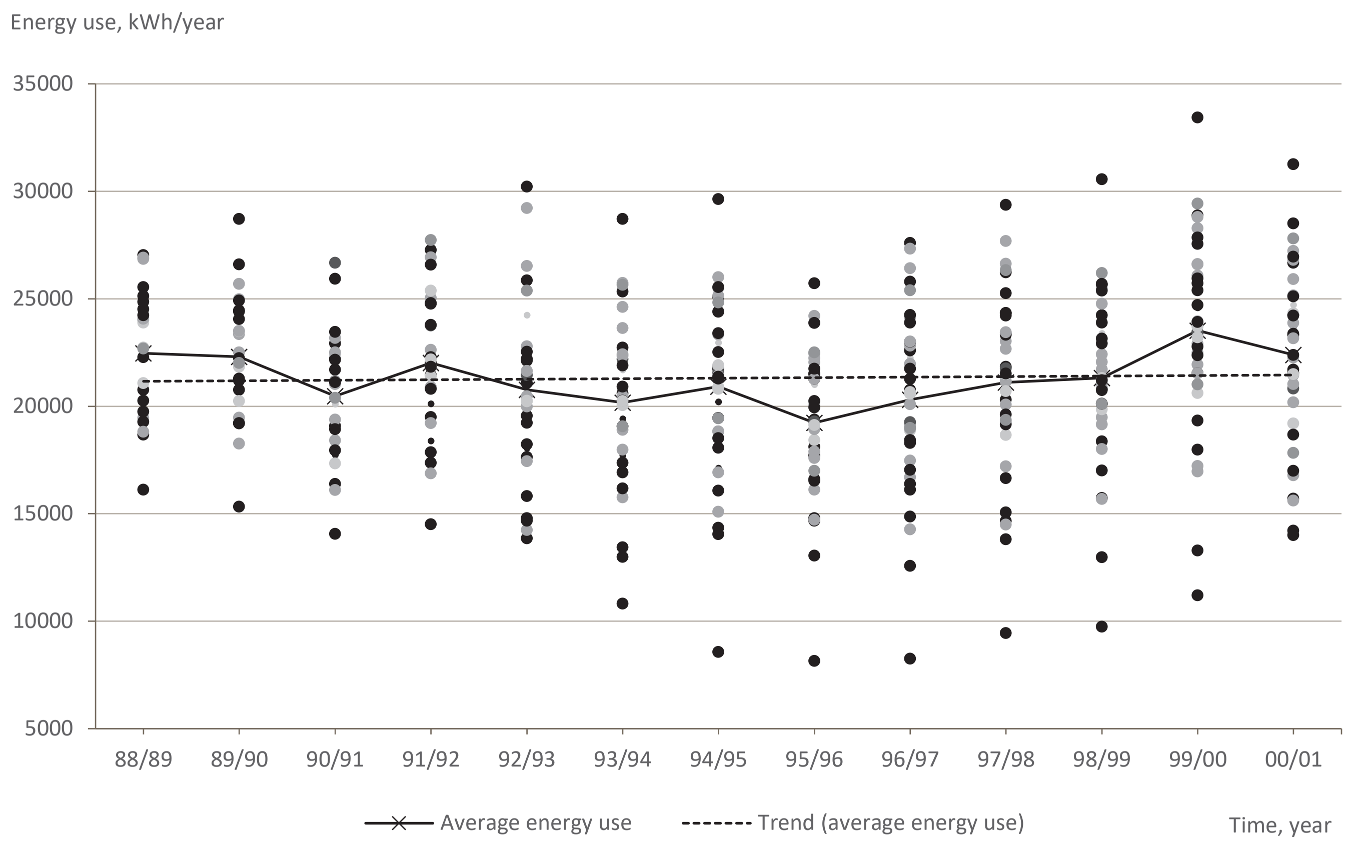

Figure 10 Total annual energy use (corrected with degree-days) for 38 houses situated in housing area A (kWh/year). Each dot corresponds to one house's energy use during a particular year. The curve represents the average total energy use for all houses for each year. The dotted line represents the trend for the average energy use.

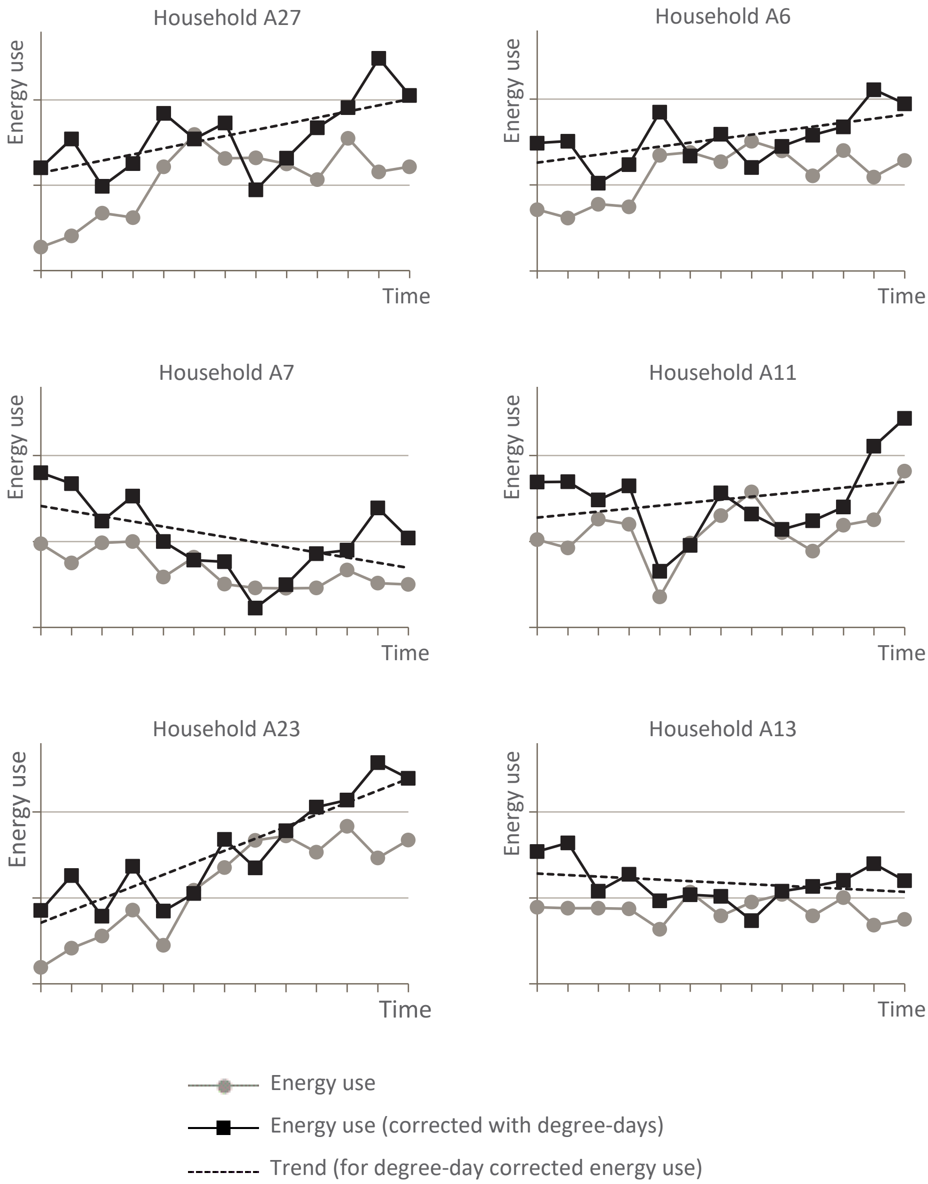

Figure 11 Total annual energy use (y-axis) in kWh/year over a 12-year period (years on x-axis) for six households. The actual energy use, the degree-day corrected energy use and the trend for the energy use are presented. (Note: The scale is the same in all graphs, even though the energy use is on different levels for the households.)

The results from the interviews demonstrated that changes in energy use over the years might be due to several reasons. The potential impact on the energy use from different types of activities is illustrated with various symbols; see the example for one house in Figure 12. For instance, an extension of the house would affect the energy use upwards, while replacement of old white goods with more energy-efficient ones would affect it downwards. The effect of other installations depends on the frequency of use, such as the installation and usage of a tiled stove. Naturally, changes in the household composition also occurred over the years studied, such as an increased number of household members, which usually correlates with increased energy use, for example, for domestic hot water purposes. The visual presentation shows that sometimes several events have occurred simultaneously or fairly close together in time (Figure 12), which makes the connection to the household's energy curve less straightforward.

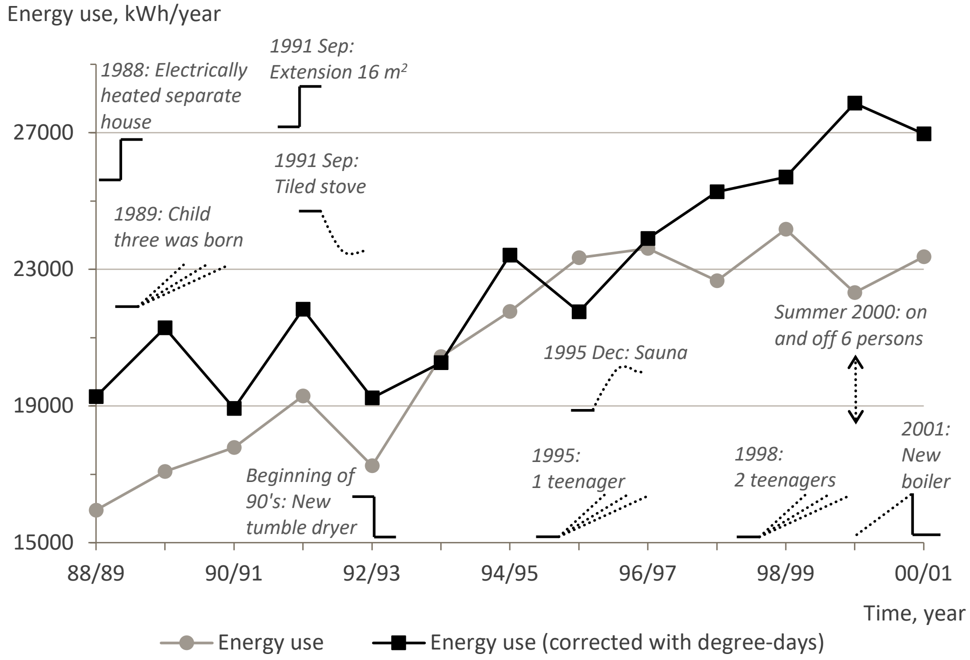

Figure 12 Interview answers (including symbols) and yearly energy use (kWh/year) from 1988/1989 to 2000/2001 for household A23. The actual energy use and the degree-day corrected energy use are shown.

4.2 Differences in household energy use

The analyses of the energy data, explained in the previous section, not only contributed to the investigation on how energy use can change over the years but also showed that energy use can differ significantly between similar detached single-family houses. This led to the next research question: *How does the energy use of households living in similar houses differ?*

This research question was first examined by further analysing the yearly energy data described above. As mentioned, there were large spreads between the houses' energy use every year, and the data also showed, to some extent, an increased variation during the later part of the studied period, calculated as an increased standard deviation which in 1988/1989 was 2868 kWh/year and in 2000/2001 was 4101 kWh/year.[108] The changes that have occurred in the houses and households over the years can be expected to have influenced this increase.

To gain an in-depth understanding of why the energy use of different households living in similar houses differ, detailed investigations of two houses were carried out. As a measure of their energy performance, heat loss measurements of the two houses were performed, which were compared to their estimated energy use.[109] The specific heat loss is the sum of the house's transmission and ventilation losses divided by the temperature difference between inside and outside. A higher specific heat loss means greater losses than a lower value (further explanation can be found in Paper II in Appendix B). The purpose was to determine whether the house with the higher energy use also had the larger heat loss. As part of this detailed investigation of the two houses' performance, the estimated yearly energy use was calculated in Enorm, an energy calculation program that was common at the time of this study.

The results from the in-depth examination of the two houses demonstrated that the residents apparently accounted for the differences between the houses' energy use. An indication of the residents' influence was that the house with the higher energy use (household A6) was found to have a lower or equivalent specific heat loss compared to the other house (household A13), and vice versa.[110] The differences could partly be explained by different indoor temperatures and water use, while other behaviour-related differences are not known at this stage.

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[108] The yearly energy use was normally distributed.

[109] Estimations of the specific heat losses were also calculated in Enorm and are discussed in Section 5.2.3.

[110] For details on the results of the heat loss measurements turn to Section 5.2.1 and Paper II (Appendix B).

The resulting energy use calculated for the two houses was approximately 21,400 kWh/year for household A6 and approximately 20,400 kWh/year for household A13. This meant that the estimated energy use was on similar levels, despite a number of factors being different for the two houses and households, such as the heated floor area, indoor temperature and number of household members. The measured energy use, on the other hand, showed a difference between the houses of about 3000 kWh/year.[111]

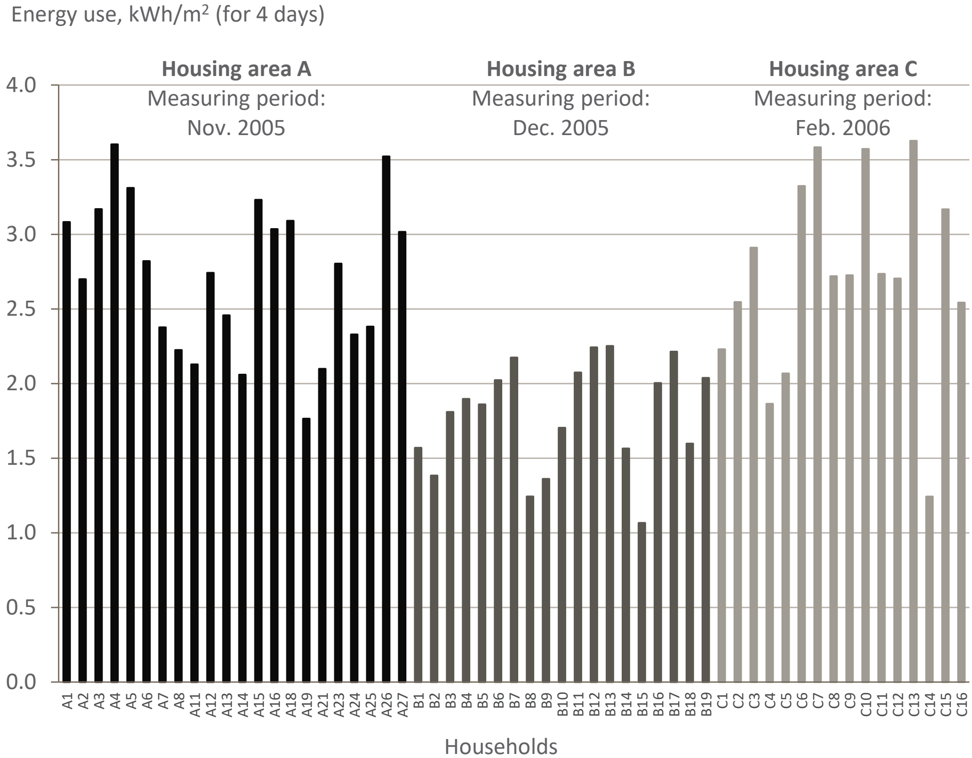

Figure 13 The total energy use (kWh/m² for 4 days) of the households during the short-term measurement. The total energy use includes the electricity use for space heating, household electricity and electricity use for hot water production. (Note: The energy use has not been corrected for different outdoor temperatures.)

A further investigation of differences between houses with similar technical specifications was possible from short-term measurements in 57 households living in three housing areas. The energy and water use, as well as indoor and outdoor

[111] For a graphical presentation, see the curves for the years 2001/2002 and 2002/2003 in Fig. 2 in Paper II, Appendix B. These are the years that are relevant to compare with, as the energy calculations included the extension that household A13 made in 2001.

temperatures, were measured during four days for these households. It was found that the energy use differed by a factor of two to three between the highest and lowest usage, depending on which housing area was considered (see Figure 13). It was further seen that the differences between the households' energy use could not be explained only by differences in indoor temperatures, regular temperature setbacks (such as nightly lowering of indoor temperature), number of persons, household types (based on household composition), or by differences in the building services.

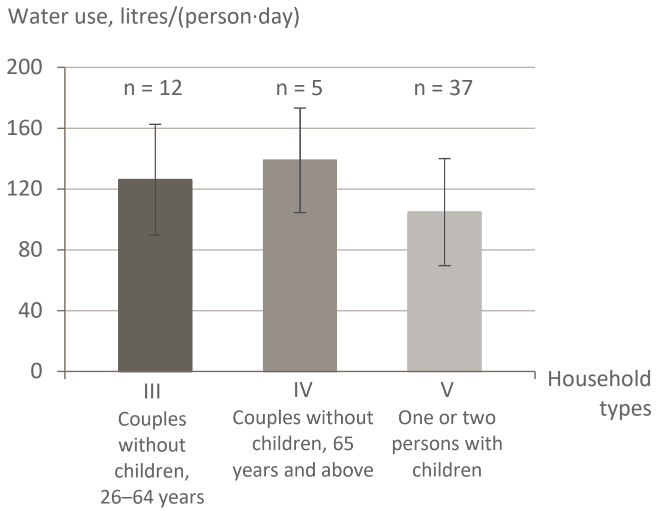

Figure 14 The households' water use during the short-term measurements, shown as average usage for different household types expressed in litres per person and day (including both hot and cold water use). The number of households for each type is stated in the figure, as well as the standard deviation.[112] *The average (mean value) use was 116 litres/(person·day) for 55 households.*[113]

The average water use showed even greater differences with a factor of six between the households with the highest and lowest consumption. (Note that no allowance was made for the 'presence at home' factor during the four days of measurements.) Considering household types, households consisting of one or two persons with children had the lowest average water use per person (including both hot and cold water use), while the few senior households represented the highest use (Figure 14).

[112] Since there was only one single-person household, this household's consumption is not shown in the figure. In addition, reliable water data was missing for two other households – hence, data for 54 of the households are shown in the figure.

[113] The median was 111.0 litres/(person·day). (Note: The water data were not quite normally distributed.)

4.3 Daily electricity consumption patterns

Residents' activities are performed at different times during the course of the day, leading to variations in the daily electricity consumption. From the perspective of the national electricity system, the occurrence of power peaks is of importance for the grid's capacity to meet electricity demand. Hence, the next research question asks: *What are the characteristics of household energy use in terms of electricity consumption patterns during the day (i.e. daily load curves)?*

In the short-term measurements described above in Section 4.2, energy use was recorded every minute and could hence be used to investigate this question. In addition, the indoor temperature was measured every hour. The measured energy data were aggregated to hourly data and presented as average power used during one hour, which formed daily load curves for the houses, seen in Figure 15 and Figure 16. Additionally, the figures include the indoor temperature profiles of the houses. The temperature was fairly constant for several houses, while for others it fluctuated quite a lot. This shows that one fixed typical value of the indoor temperature says very little about the actual daily profile of the indoor temperature in a house.

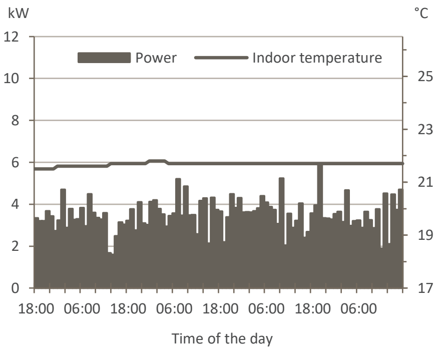

Figure 15 Mean power per hour (kW) and indoor temperature (°C) during four days for household A15.

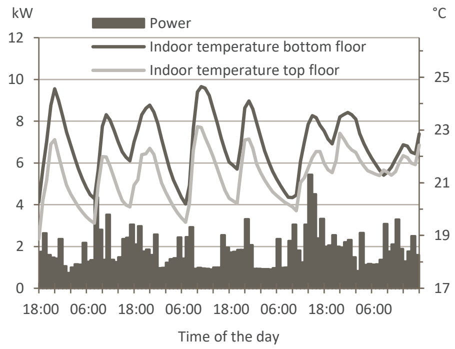

Figure 16 Mean power per hour (kW) and indoor temperature (°C) during four days for household B9.

The results of the energy measurements demonstrated that for individual households the characteristics of load curves looked very different, and there were peaks at different times of the day for different households (for examples, see Figure 17–Figure 20). However, on the aggregated group level, the characteristics of diurnal electricity consumption patterns were apparent, especially in housing area A, forming power peaks in the morning and in the evening during weekdays, see Figure 21. It was further seen that the characteristics of the load curves clearly differed between weekdays and weekend days, with more pronounced peaks during weekdays.

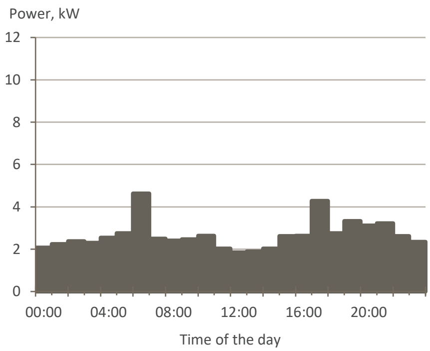

Figure 17 Example of the characteristics of a load curve for one household (A2) in area A on a weekday (Thursday), expressed as mean power per hour (kW).

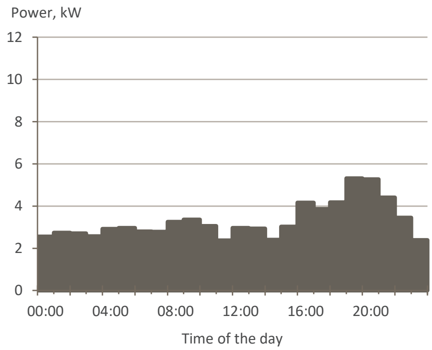

Figure 18 Example of the characteristics of a load curve for one household (A2) in area A on a weekend day (Saturday), expressed as mean power per hour (kW).

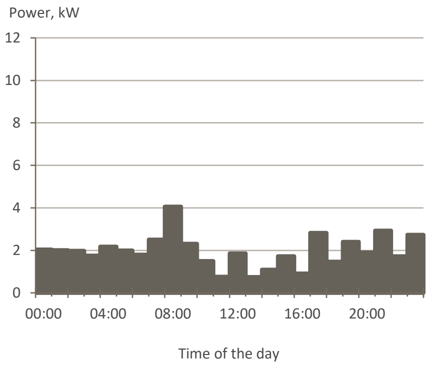

Figure 19 Example of the characteristics of a load curve for one household (C4) in area C on a weekday (Thursday), expressed as mean power per hour (kW).

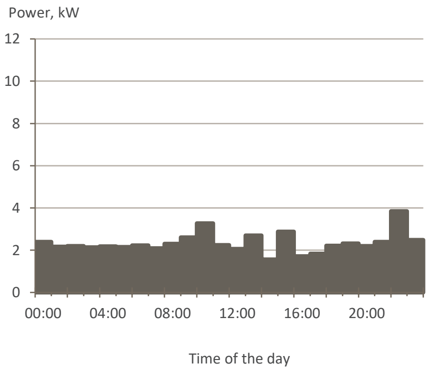

Figure 20 Example of the characteristics of a load curve for one household (C4) in area C on a weekend day (Saturday), expressed as mean power per hour (kW).

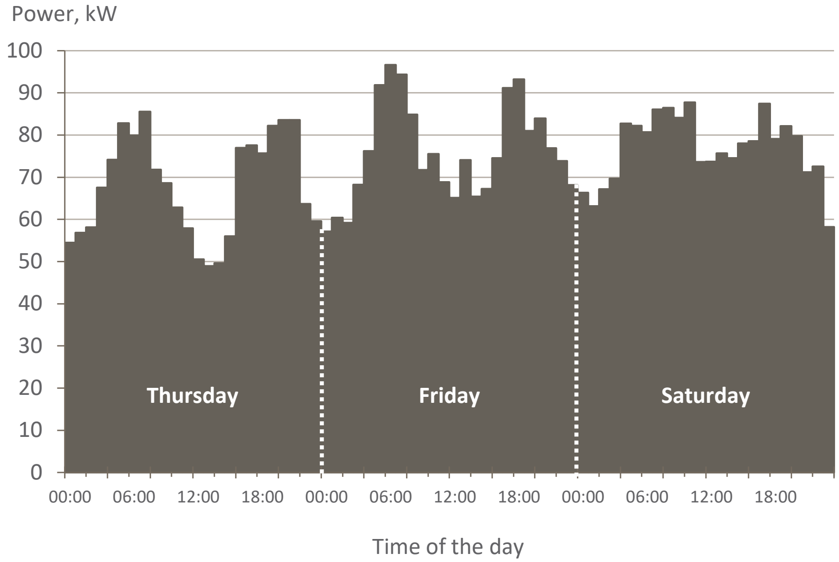

Figure 21 Mean power per hour (kW) of 22 households in housing area A, Thursday to Saturday.

4.4 Residents' energy-related behaviours

The findings from the previous research questions, especially the investigation into how the energy use of households living in similar houses differ, pointed towards the impact that the residents have on the energy use of their houses. For this reason, the next research question asked was: *How do the residents' behaviours influence the energy use in their homes?*

This question was examined mainly by studying everyday activities through diaries. The study collected time-use data from each household member aged 12 years and above in the 57 participating households, a total of 141 individuals. The diary study was conducted over four days in all: two weekdays and one weekend. The everyday activities affecting energy usage were extracted from the diaries and analysed. Primarily, a cluster methodology was used to find characteristics of groups of residents with regard to their energy-related activities. In addition, this was carried out together with typical power values to estimate the energy use of the activities.

During the same days as the diary study was performed, the short-term technical measurements described in the previous sections were carried out. That is, minute values were collected for the total electricity consumption of the houses. The total cold water consumption was read off the water meter during the same period, and the indoor temperature was measured every hour. Outdoor conditions were also noted, including the outdoor temperature that was recorded hourly.

The results from the diary data demonstrated that residents reported long time-use and operating time for activities related to electronic equipment, namely 45% of total reported time (Paper IV in Appendix D). TV had clearly the longest time-use for the average household, with a peak on Saturday, while computers had the second longest time-use. There were also variations between households regarding specific behaviours. For instance, for one group (cluster), computers were used on average four times as much as for another group (see Table 5 in Paper IV). Between individual households, the differences were even larger (a difference of more than a factor of nine between the longest and shortest computer usage). Furthermore, in many households, multiple appliances of the same type were switched on simultaneously on several occasions during the diary period.[114] For example, in more than half of the households, at least two TV sets were used for one or more hours during the diary period (the span was from 1 hour to 17 hours). Corresponding figures for multiple use of computers were that of the 50 households using computers during the diary period, 22% were using at least two computers at the same time for one or more hours (ranging from 1 hour to 19 hours).

The results from the cluster analyses showed that residents who used energy to a greater extent than others were characterized by activities with long operating times in combination with high, and fairly high, typical power ratings. In this study, this meant activities such as the use of engine preheaters, car heaters, fans and additional radiators, as well as airing habits. These characteristics were valid for a rather small group of households (seven or eight households, depending on analysis method). For the rest of the households, it was difficult to identify common characteristics linked to energy-related behaviour. Thus, the majority of households exhibited many different behaviours deciding their energy use. Moreover, the diary data revealed that the same household sometimes practiced both ‘energy-saving’ and ‘energy-wasting’ behaviour. This was seen when groups of households were compared (Table 5 in Paper IV), and even clearer for individual households. As an example, one household reported washing dishes by hand for a much longer time than the average household in the study, while the same household reported a much shorter time for showering. Another household, on the other hand, reported long showering times but watched TV for a much shorter time compared to the average.

Another finding from the cluster analyses was that those households that on average spent less time at home and that had fewer household members, also showed a lower average water usage, measured per household (Paper IV). The daily time spent at

[114] A clarification of the data presented in Paper IV is as follows. The number of hours households spent performing different activities or were having appliances turned on are stated as averages in Paper IV. As is stated in connection to Fig. 3 and Table 5, these average values include *all* devices of the same type in a household, switched on at the same time.

home was estimated at 15.7 hours per person (as an average regardless of the day of the week[115]). However, these characteristics were not clearly shown as reasons for low energy use. Nevertheless, for all households, a positive – although not strong – linear correlation was found between water use and the number of persons in a household (Paper III in Appendix C). Hence, the water usage for a household increases slightly with the number of people in it. In addition, advantages were seen of living in larger households with children, as larger households had the lowest average water use expressed per person (Figure 14).

The results of the temperature measurements showed that the average indoor temperature for all the houses during the heating season was 20.8°C.[116] However, for individual houses, the average temperatures were as low as 18°C or as high as 23°C. Even though the choice of indoor temperature is an important factor for energy used for space heating in a building, the effect of the indoor temperature was not directly seen in the present study on the houses' total energy use on the group level (see Fig. 3 in Paper III). This meant that the indoor temperature alone could not predict the energy use in these technically similar houses.

[115] 15.7 hours was estimated from diary data for two weekdays and one weekend day.

[116] Both the mean and median values were 20.8°C.

5 Reflections on energy data analyses and energy performance evaluations

This chapter reflects on the energy data analyses and energy performance evaluations carried out in housing area A. The main methodological developments since these empirical studies were performed are discussed related to methods to correct for varying outdoor climate used in the energy data analyses. This is followed by sections on measurements and estimations of the energy performance of two houses and how the results of these are compared to other references.

In the chapter, references are made to the requirements stated in the prevailing Swedish building regulations (BFS 2011:6 – 2019:2) and to typical values stated in the regulations and general recommendations regarding determination of the building's energy use at normal use and in a standard year[117] (BFS 2016:12 – 2018:5). The later regulations are applied when verifying that the energy requirements in the building regulations are met, primarily in new buildings but also when existing buildings are altered.[118] In addition, these regulations are utilised for the determination of a building's energy performance and energy class when issuing the building's energy performance certificate (BFS 2007:4 – 2018:11). The regulations determining building's energy use under normal conditions were released for the first time in 2016 and are based on previous Swedish experiences on, for instance, resident-related data. The comparison to these values is a useful reference to what is considered as ‘normal use’ today, even though there is room for further development of the normalisation (Berggren, 2018; Berggren et al., 2019).

[117] Referring to a standard year means using normal values of outdoor climatic conditions calculated as long-term averages over a certain period of time.

[118] The intention is to carry out energy calculations or normalise measured energy use in an equivalent way for all buildings.

5.1 Reflections on corrections due to varying outdoor climate

In this thesis, long-term trends in energy use have been investigated, which meant that energy use during different years was compared. When comparing energy data for different years, corrections due to varying outdoor climate need to be made,[119] which in this thesis were carried out with the heating degree-day method.[120] This section discusses changes related to the heating degree-day method since these energy data analyses were performed. Moreover, typical values of temperature-*in*dependent energy use will be discussed.

5.1.1 The heating degree-day method and changes since analyses

The heating degree-day method was the prevailing climate-correction method at the time of the performance of these energy data analyses. Historical degree-days were available for purchase from the Swedish Meteorological and Hydrological Institute (SMHI). Figure 22 shows how the yearly outdoor temperature varied during the time period studied, as well as the corrected and uncorrected energy use for one household. It can be seen, for example, that the years 1989/1990 and 1999/2000 were warmer than normal.

[119] The Swedish building regulations (BFS 2011:6 – 2019:2) and the regulations for energy performance certificates (BFS 2007:4 – 2018:11) state that energy use needs to be verified under normal conditions, which means that energy use dependent on the outdoor climate needs to be normalised to the conditions for a standard year, i.e. corrected for variations such as the outdoor climate (BFS 2016:12 – 2018:5).

[120] Section 2.2.1.1 includes a brief description of other climate-correction methods, such as the energy index method which is recommended in the Swedish regulations determining the building's energy use (BFS 2016:12 – 2018:5).

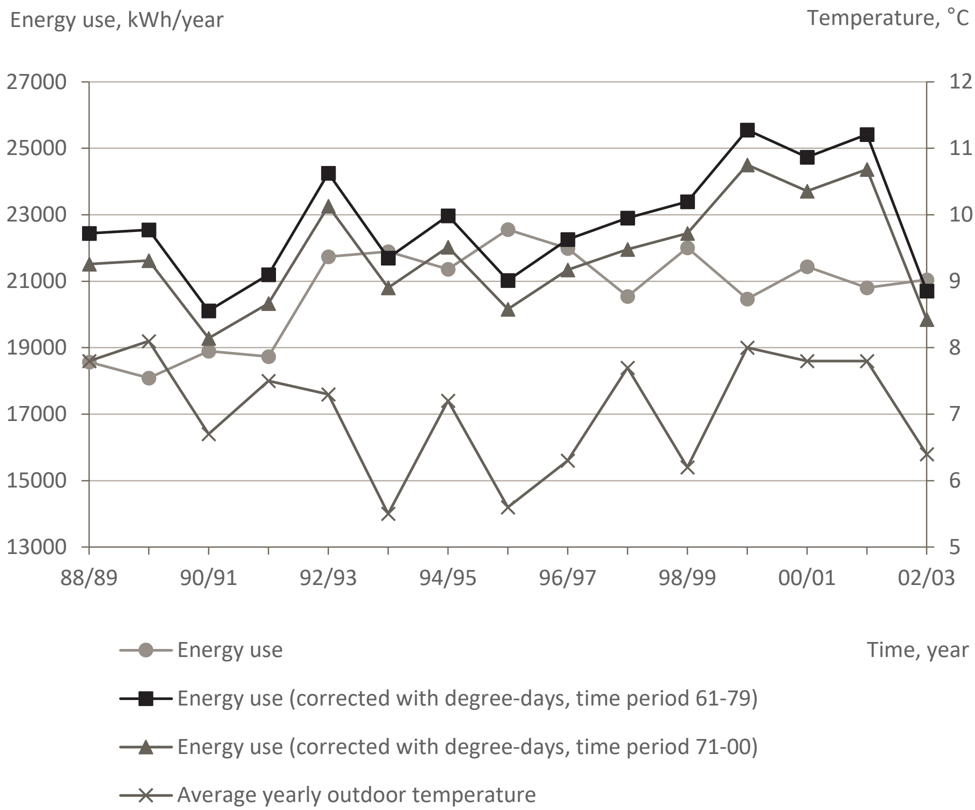

Figure 22 Total yearly energy use and average yearly outdoor temperature from 1988/1989 to 2002/2003 for household A6. The actual energy use and the degree-day corrected energy use, using degree-days from two time periods, are shown.

One of the foundations of the heating degree-day method is to compare the outdoor temperature for each year during the analysis period with normal temperatures calculated as long-term averages over a certain period, which in the analyses of the thesis was the period of 1961–1979. Since the empirical studies of the thesis were conducted, the time period of SMHI's normal degree-days has changed, primarily to reflect the warmer climate, that is, the warmer temperatures during the 1990s and the first decade of the 2000s (SMHI, 2020). In 2003, the period was changed to 1971–2000, and in 2015 it was changed again, to the period of 1981–2010.

In Figure 22, the energy use for household A6 has been corrected with normal degree-days using two different time periods.[121] The corrected energy use, when

[121] The latest time period used to calculate normal values (i.e. 1981–2010) is not included in the figure since it was introduced several years after the energy analyses were performed for this thesis.

using the period 1971–2000, is fairly evenly lower for each year than when performing the correction with data from the period 1961–1979 (the differences vary between 830 and 1050 kWh per year). The uncorrected yearly energy use still lies largely below the corrected energy use (time period 1971–2000) as the period studied (1988–2003) was generally warmer than the period 1971–2000.

Another change made by SMHI in 2015 was to remove the limits in daily average outdoor temperature during April to October, above which no heating is needed, that is, when there is no contribution to the degree-days.[122] These limits were introduced as a way of considering the larger amount of solar insolation during spring, summer and autumn months, but nowadays degree-days are calculated daily and these limits do not represent the solar contribution on a daily basis. This led to a simplification where a so-called balance temperature[123] of 17°C is used as a reference for all days, all year round (SMHI, 2020).

The effect of the change to a warmer time period is that there will be a lower number of normal heating degree-days (DD_{normal}), leading to a larger SMHI correction factor,[124] hence giving a lower corrected energy value than before. The effect of the removal of the limits in daily average outdoor temperature during April to October is that the number of normal heating degree-days (DD_{normal}) increases. But this change also affects the actual number of degree-days (DD_{actual}), which implies that the correction factor can either increase or decrease. It has been found that the effects of these two changes – change of time period for normal values and removal of temperature limits – can, on a yearly basis, even each other out (SMHI, 2020).

5.1.2 Typical values of temperature-independent energy use compared to the Swedish building regulations

To be able to correct for varying outdoor temperatures, the energy use dependent on the outdoor climate needs to be separated from the total energy use. As the houses in this study were electrically heated with only one meter for all electricity use, typical values for both household electricity and domestic hot water were used. For household electricity, the different values tested were 3000, 4000 and

[122] The limits for daily average outdoor temperatures prior to 2015 were 12°C in April, 10°C in May, June and July, 11°C in August, 12°C in September, and 13°C in October.

[123] The balance temperature is the lowest outdoor temperature when the building's heating system does not need to supply heat to reach the desired indoor temperature. Instead, heat losses from the building are covered by internal heat gains, such as heat from solar insolation, persons, lighting and household appliances.

[124] SMHI's correction factor is defined as DD_{actual}/DD_{normal}. The corrected energy use is obtained by dividing the actual energy use by the correction factor.

5000 kWh/year.[125] In the prevailing regulations and general recommendations for determining the building's energy use under normal conditions (BFS 2016:12 – 2018:5) that accompany the Swedish building regulations, household electricity for residential buildings shall be estimated at 30 kWh/(year·m^2 heated floor).[126,127] For the houses in housing area A in this thesis, this would have meant a household electricity usage of 3126 kWh/year (extensions not considered).

Different typical values for the share of hot water of the total water consumption were used in this thesis. Values of 20%, 30% and 48% were tested.[128] When verifying that the energy requirements in the Swedish building regulations are met,[129] a building's energy use for domestic hot water shall be determined according to (excluding losses for hot water circulation): *Energy for DHW* $= A_{temp} \times 20/\eta_{tvv}$ [kWh/year], *w*here η_{tvv} is the yearly efficiency for the production of domestic hot water in the building and A_{temp} is the heated floor area[127] (BFS 2016:12 – 2018:5). For the houses in this thesis, the annual efficiency η_{tvv} can be put at 1.0, as they are heated by electric boilers.[130] Hence, this would mean a typical value for the energy used to produce hot water, for the houses in housing area A, of 2084 kWh/year.

If the cold water use is known, the regulations recommend that the share of hot water use is put at 35% and that $\rho c_p \Delta T$[131] equals to 55 kWh/m^3 (note that this is for Swedish conditions) (BFS 2016:12 – 2018:5). For the houses in this thesis, a value

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[125] These estimates were based on available typical consumer data but also on energy measurements at the time of the study (NUTEK, 1994; Swedish Consumer Agency, 2002).

[126] Note that household electricity is not part of the energy performance of the building according to the definition in the Swedish building regulations (BFS 2011:6 – 2019:2) but is used for calculations and normalisation of internal heat from household electricity (BFS 2016:12 – 2018:5).

[127] The heated floor area is defined A_{temp}, which includes the floor area measured from the inside of the building envelope, heated to a higher temperature than 10°C (BFS 2011:6 – 2019:2). Heated floor area is further discussed in Appendix F.

[128] These values were chosen after conversation with the water supply and sewerage department at Borås municipality (Borås Municipality, 2001). The figure of 48% derived from recalculating the energy needed to heat all water to an average of 30°C, i.e. corresponding to a temperature of the outgoing wastewater.

[129] Energy use for domestic hot water is included in the Swedish definition of energy performance but needs to be normalised before verification of the requirements are done, i.e. the energy requirements shall be met during normal use of hot water.

[130] For electrically heated houses, the energy losses are outside the house, i.e. at the production site and in the electricity distribution network. With the house as the system boundary, the yearly efficiency to produce domestic hot water in the building can be put at 1.0.

[131] $\rho c_p \Delta T$ refers to the equation $E = W_{tot} \times f \times \rho c_p \times \Delta T$ [kWh], where E is energy for the hot water production, W_{tot} is the total water consumption, f is the fraction of hot water (W_{hot}/W_{tot}), ρc_p is the amount of energy needed to heat 1 m^3 of water 1K, and ΔT is the temperature rise.

of near 58 kWh/m^3 was used.[132] With the fraction of hot water mentioned, the product of $f \times \rho c_p \Delta T$ will be less than the national recommendations for the 20% and 30% cases, but greater for the 48% case. Taking the two households, A6 and A13, as examples, this meant average hot water energy usage over the time period studied of: 2045 kWh/year and 830 kWh/year (for $f = 20\%$), 3067 kWh/year and 1245 kWh/year (for $f = 30\%$), and 4907 kWh/year and 1992 kWh/year (for $f = 48\%$). Applying the approximation in the recommendations instead, the figures would have been 3417 kWh/year and 1387 kWh/year for the data from households A6 and A13, respectively. The calculations show that the choice of typical values for the share of hot water use is significant for the estimate.

For the houses in this thesis, the choice of typical values of temperature-independent energy use did not affect the outcome (energy curve) of the heating degree-days correction to any great extent. Another observation was that the corrections did not lead to (the expected) 'normalisation' in the sense that the energy curves evened out after giving consideration to the varying outdoor temperatures (see Figure 22 in Section 5.1.1, for example). Hence, there might have been other changes or activities affecting the curves, some of which relating to the house and household were revealed during interviews with six of the households (see Section 4.1). Clearly, having actual data on the temperature-independent energy use would have been better than using typical values as this would have enabled a more accurate correction due to varying outdoor temperatures.

5.2 Reflections on evaluating the energy performance of buildings

In this thesis, the energy performance of two houses in housing area A – households A6 and A13 – have been evaluated by measuring their specific heat losses and by estimating their energy uses and specific heat losses using the program Enorm. The following sections reflect and elaborate on these measurements and estimates, and compare them to other studies and data.

Information about the examined houses can be found in Section 2.1.2.1. The main input data to the energy calculations are summarised in Table 6 (Section 2.2.2.2) and are further discussed and compared to regulations and recommendations for energy estimations in Appendix F.

[132] $\Delta T = T_{tap\ hot\ water} - T_{into\ the\ house}$ [K], with $T_{tap\ hot\ water} = 55°C$ and $T_{into\ the\ house} = 7°C$

5.2.1 Specific heat loss as a measure of energy performance

Specific heat loss for the two houses was measured at approximately 130 W/K for household A6 and 170 W/K for household A13. A general estimate of the measurement error of the method used is up to 10% (Sandberg & Jahnsson, 1995),[133] which means that the values could vary between 117 W/K and 143 W/K for household A6 and between 153 W/K and 187 W/K for household A13.

The heat loss method is not primarily used for comparing different houses' energy performance, but as the houses in this thesis were 'identical' when newly built, the comparison was applicable. Nevertheless, there were differences between the houses in terms of the number of household members and indoor temperature, but these aspects should not matter when measuring the houses' heat losses (Sandberg & Jahnsson, 1995). The additional floor area and volume of household A13, on the other hand, do matter, because a bigger house is expected to have a larger specific heat loss. To minimize the effect of different areas, the heat loss per heated floor area or per building envelope area, can be calculated. For the two houses in question, the area-specific heat losses are calculated to be 1.25 W/(K·m^2 heated floor) or 0.40 W/(K·m^2 building envelope) for household A6 and 1.30 W/(K·m^2 heated floor) or 0.41 W/(K·m^2 building envelope) for household A13. These calculations show that similar losses can be seen when consideration is taken for differences in the size of the houses.

The results of the measurements of specific heat loss of the two houses were in line with earlier measurements of 15 detached single-family houses in Sweden, using the same method as in this thesis (Swedish Consumer Agency, 1995).[134] The earlier measurements demonstrated specific heat loss with an average of 158 W/K – ranging from 111 to 217 W/K, corresponding to 1.2 W/(K·m^2·heated floor) – ranging from 0.9 to 1.6 W/(m^2·K).

Research have been performed on how to estimate the heat loss coefficient[135] of buildings (Farmer, Johnston, & Miles-Shenton, 2016; Mangematin, Pandraud, & Roux, 2012) and how to use this coefficient as a measure of the energy performance (Sjögren, Andersson, & Olofsson, 2009; Vesterberg, 2014). However, as described in Section 1.7.3 in the introduction of this thesis, the current national approach stated in the Swedish building regulations (BFS 2011:6 – 2019:2) is to verify the energy

[133] In the linear regression used to estimate specific heat losses, the coefficient of determinations, r^2, was quite low for both houses in the thesis, which most likely meant higher uncertainties (see Paper II in Appendix B).

[134] There are various methods for measuring heat loss from houses, which makes it difficult to compare the results of different studies.

[135] In these publications, the term *heat loss coefficient* is used, while in the method referred to in this thesis the term *specific heat loss* is used (Sandberg & Jahnsson, 1995).

performance of buildings by measuring or calculating their primary energy use[136] per heated floor area under normal conditions (BFS 2016:12 – 2018:5).

5.2.2 Energy estimations from Enorm calculations

The results from the Enorm-calculated total yearly energy use for the two houses were not that different, namely approximately 21,400 kWh/year for household A6 and 20,400 kWh/year for household A13, even though the heated floor area was larger for household A13 due to an extension carried out in 2001. The energy use per square meter of heated floor area was 205 kWh/year for household A6 and 156 kWh/year for household A13. In the calculations, consideration was given for the higher indoor temperature, more heat generation from persons and more domestic hot water of household A6. Consideration was, however, not given for the probable differences in household electricity between the two households. Furthermore, the effect of larger window area for the extension of household A13 was not fully known.

The conformity between the estimations and measured energy data was reasonable for certain years, while the deviations were larger for others – compared to the expected 10% deviation mentioned above. To exemplify, compared to the measured temperature-corrected energy use, there were underestimations of approximately –16% for household A6 (compared to 25,415 kWh/year) and –9% for household A13 (compared to 22,345 kWh/year) in 2001/2002 and overestimations of approximately +3% (compared to 20,704 kWh/year) and +17% (compared to 17,474 kWh/year) in 2002/2003.[137]

Compared to national statistics for electricity heated one- and two-dwelling buildings, the electricity use (including electricity for space heating, domestic hot water and household electricity) per house was reported to be 16,000 kWh/year on average in 2018, corresponding to approximately 117 kWh/(year·m^2 heated floor) – these energy usages were not temperature-corrected[138] (Swedish Energy Agency, 2019). For houses built during the same time period as the two houses in this thesis (1981–1990), the figures were 14,900 kWh/year, also corresponding to 117 kWh/(year·m^2 heated floor). For newer houses completed during 2011–2017, the figures were 11,500 kWh/year and 78 kWh/(year·m^2 heated floor).[139] Both

[136] Excluding household electricity use.

[137] For a graphical presentation, see the curves for the years 2001/2002 and 2002/2003 in Fig. 2 in Paper II, Appendix B. The comparison was made with those years as the extension of house A13 was included in the energy calculations (the extension was carried out in 2001).

[138] The outdoor temperature in 2018 was milder than normal (SMHI, 2018/2019).

[139] As a comparison, according to Swedish building regulations, an energy requirement of 90 kWh/(year·m^2 heated floor) – excluding household electricity – applies from 2019 for new houses. For electrically heated houses, the energy use for space heating and domestic hot water

measured and estimated energy use for the houses exceed the reported national average of electrically heated houses in 2018. Probable reasons for this are that 2018 had milder weather than normal and that houses in general have better energy performance than the two houses in the thesis, as a result of energy-saving measures being implemented over the years, such as the installation of heat pumps in many houses (Swedish Energy Agency, 2020).

5.2.3 Specific heat loss in Enorm

Estimations of specific heat loss were also calculated in Enorm. Going through the documentation and calculations in hindsight, it was noticed that the value of the specific heat loss was not given correctly by the program, seemingly due to a programming bug. Enorm calculated the three contributions to specific heat loss, namely transmission losses, ventilation losses and air leakage losses. It then made a correction due to the efficiency of the heating system's heat distribution, which was set at 95%. However, it can be seen that the program in the end missed including the ventilation losses in the output data and hence undervalued the specific heat loss. If this is added,[140] the values change accordingly:

- For household A6, 108 W/K is changed to 151 W/K.
- For household A13, 152 W/K is changed to 193 W/K.

With these corrected values for specific heat loss, the estimated values turned out to be higher than the measured ones (see Section 5.2.1) by approximately 10–15% (corresponding to 20 W/K higher). Thus, the corrected values indicate that the houses had better energy performance than expected. Earlier measurements, on the other hand, have shown that specific heat loss usually exceeds calculated values – in some cases by as much as 50% (Sandberg & Jahnsson, 1995; Swedish Consumer Agency, 1995).

5.3 Availability of data

One issue that the empirical studies of the thesis faced was the selective availability of data. For example, related to the energy analyses, the available data from the local energy supplier did not quite correspond to a yearly energy and water use, as the

must be multiplied by the primary energy factor 1.6 (BFS 2011:6 – 2019:2). (There is a proposal for a new version of the building regulations and if it is approved, the definition of the primary energy number will change. Turn to www.boverket.se for the latest information).

[140] The ventilation losses are calculated from the ventilation flows specified in Table 6 (Section 2.2.2.2).

meter readings were not carried out at exact one-year intervals. These deviations meant that corrections had to be made to the energy and water data so that they represented 365 days – even though the corrections were considered to have marginal effect on the yearly data for most houses and years (Hiller, 2003a). The development since these studies were carried out, with more frequent meter readings and the installation of smart meters, have considerably increased the availability of data and made these types of corrections less needed. This development is likely to continue in the future, also benefiting energy analyses in research (SFS 1997:857 – 2020:73; Swedish Energy Markets Inspectorate, 2017).

6 Discussion

In this chapter, the results of the thesis (presented in Chapter 4) will be further elaborated and discussed in relation to other research regarding energy use in buildings and energy-related behaviours (literature mostly presented in Chapter 3). The chapter ends with reflections on the shortcomings of the chosen approaches and methods in the thesis.

6.1 Variations, diversities and changes

The main topics discussed below are changes in energy use over time of occupancy, differences between households' energy use, and daily patterns in energy use. Moreover, it is elaborated on how residents' activities influence energy use.

6.1.1 Stable energy use over time – on an aggregated level

The thesis has treated how energy use changes over a ten-year period in 38 single-family homes. The result showed, at a group level, that the energy use was relatively stable over the years. From an energy perspective, this demonstrates that the energy performance of the buildings stays on the same level after years of occupancy.

This could be interpreted as favourable, especially if compared to the studies on low-energy houses of the 1980s and early 1990s, which display an increase in the energy use after some years in operation (Berggren et al., 1997; Nilson & Uppström, 1997; Weber, 1996). A more recent follow-up study of later low-energy buildings built in the early 2000s, however, does not demonstrate an increase in energy use, but rather shows that the overall energy performance is stable (Sikander et al., 2011).

At the household level, however, the energy use of a participating household could either increase, decrease or stay at the same level. Presumably, this was reflected by the variations in energy use between the houses, which increased somewhat over the years, as shown by an increased standard deviation. Several activities, such as purchase of white goods, change of boilers etc., have occurred in the households and houses over the years, affecting the energy use in different ways (see Section 4.1). These activities were likely the reasons for changes in energy use over time of occupancy. As found in other research, some of the changes in energy use are related to the life cycle of families, including different life phases, such as when households are expanded with children or later when the children move away from home (Frederiks, Stenner, & Hobman, 2015). In addition, an increased household size may cause a need to make extensions to the houses. Such extensions were seen in one of the housing areas participating in this thesis, whose heated floor area was initially smaller than for an average Swedish single-family house.[141] Research also demonstrates that after the children have moved out, the parents still tend to stay in their houses, hence resulting in increased living space per capita (Engel, Hansen, & Kronenberg, 2011).

Other studies describe how the way that the residents maintain their technical systems affects the building's function and energy performance over time (e.g. Dietz et al., 2009; Hiller, 2003b; Laitner, Ehrhardt-Martinez, & McKinney, 2009). Activities related to maintenance are often small but conscious decisions, typically not performed with great frequency (see Figure 3 in Section 1.7.2). However, there is a lack of research examining this type of energy-related behaviour (Karlin et al., 2014). The interviews with the households in the thesis revealed some behaviour of this kind, for instance sealing measures to improve the air tightness of the building (Hiller, 2003a).

6.1.2 Large differences in usage

In this thesis, large differences were shown between different households' energy use, despite living in similar houses. This was the case both when comparing the yearly energy use and when studying the daily energy use. The latter study of the daily energy use demonstrated that the energy use differed by a factor of two to three between the highest and the lowest usages. Great differences have been found in earlier studies (Gaunt, 1985; Lundström, 1982; Socolow, 1978) and this thesis, like other studies, therefore confirmed that the results of these older studies are also valid for more recently built houses (Gill et al., 2011; Nylander, Johansson, & Johnsson, 2006).

Regarding the examination of water use conducted in this thesis, the average water use showed even greater variations than the energy use, with a factor of six between the highest and lowest consuming households.[142] Large variations in household water use, including hot water consumption, are also demonstrated in other studies

[141] The heated floor area of the houses in housing area A was 104 m^2, which can be compared to an average floor area of 122 m^2 in Swedish single-family houses (Statistics Sweden, 2020b).

[142] An average water use of 116 litres/(person·day) was found in this thesis (total water use including both hot and cold water). This is a bit lower than findings in other Swedish studies, e.g. 130 litres/(person·day) was measured in the Swedish Energy Agency's study (2009).

and seem to continue over the years (e.g. Björk & Wiklund, 1982; Gill et al., 2011; Lundström, 1982; Swedish Energy Agency, 2009; Willis et al., 2013).

Factors such as the heated floor area and the number of people in the household do not explain the whole difference in energy use between different houses, which is especially clear when comparing similar houses. Residents' energy-related behaviours are believed to contribute to these large variations (e.g. Gaunt, 1985; Gill et al., 2011; Gram-Hanssen, Kofod, & Petersen, 2004; Kristensen & Petersen, 2017; Lundström, 1982; Palmborg, 1986), as was indicated in this thesis – for example, in the detailed comparison of the energy performance of two houses.

6.1.3 Variable diurnal patterns

The result from examining the daily electricity consumption patterns in 57 households in three housing areas demonstrated that, on an aggregated group level, the electricity consumption patterns (i.e. electricity load curves) clearly varied between weekdays and weekend days. In addition, power peaks in the morning and in the evening during weekdays were shown.[143] As described in the literature review, these variations in electricity consumption during the day and for different days of the week are confirmed by other studies, in which load curves of electrically heated houses have been investigated. However, the patterns can differentiate between individual households and between different groups of households, which was seen in this thesis as well as in other research. For example, in the report by Zimmermann (2009), the electricity consumption patterns of households of retired people show no differences in load curves between weekdays and weekend days and there are not as clear power peaks in the evening as for other household types.[144]

Thus, the results of the thesis revealed when households use more or less energy. Such knowledge is important in intervention studies attempting to influence households' energy use patterns by shifting their use from times of high loads in the grid to times when fewer people are using energy, so-called user flexibility. However, projects report low, or large variations in, interest and 'willingness' for residents to be active and flexible related to their energy use (e.g. Katzeff et al., 2017; Renström, 2019). It is not uncommon that incentives, such as financial incentives with differentiated pricing, fail to motivate households to change their behaviour regarding when to perform activities affecting energy use (Throndsen, 2017). But even though financial savings are not enough motivation, Öhrlund et al. (2019) suggest that the mere existence of differentiated pricing draws attention to

[143] These patterns for the household electricity use were shown for all three housing areas, but the patterns were clearest for the houses in housing area A.

[144] The household types were based on family composition.

electricity-related activities, which may lead to households shifting the times when activities are carried out – unless it causes inconvenience in their everyday lives.

6.1.4 Many ways to be a high or low consumer

The time-geographical time-use diaries demonstrated that a majority of the households performed many different energy-related activities adding up to their total energy use. This was evident in the cluster analyses through the difficulty of forming distinct groups of households in relation to their energy-related behaviour (Paper IV in Appendix D). Similar results have been found in other studies, in which almost all households have shown a unique or nearly unique set of activities contributing to being a high or low energy consumer (e.g. Fell & King, 2012; Gram-Hanssen, 2014). In addition, there is a diversity within households consisting of many individuals, as each individual may have different interests and preferences, hence performing different activities. Even single individuals do not act consistently across all kinds of energy-related behaviours (Corral-Verdugo & Figueredo, 1999; Fell & King, 2012; Green & Ellegård, 2007).

Specific resident behaviours showed variations in how they were performed. In turn, this variance contributes to the large differences in energy and water use between the households as reported in Section 6.1.2. For example, the thesis revealed great variations concerning how long computers were turned on; for one group (cluster) of households, the average duration was four times longer than for another group. The indoor temperature also varied greatly between the examined households, from as low as 18°C to as high as 23°C.[145] Other studies have identified large differences in laundry routines (Schmitz & Stamminger, 2014; Zimmermann, 2009) and airing behaviour (e.g. Andersen et al., 2013; Hansson & Nordquist, 2010).

Hence, from these findings, there are evidently many ways to be a high or low consumer of energy. From a social practice perspective, the diverse ways people perform practices in everyday life are influenced by the technology used, the competence of the person and the meanings of the practices (Shove, Pantzar, & Watson, 2012). For example, some people put a lot of effort into cooking, while others like to watch TV. People also have different preferences regarding indoor temperature and thermostat settings (Lindén, Carlsson-Kanyama, & Eriksson, 2006; Sintov, White, & Walpole, 2019). Everyday activities carried out in various practices are often performed as a routine, without much thought and intent (e.g. Reckwitz, 2002). Therefore, to raise awareness of the impact of 'hidden' habitual

[145] The average indoor temperature for all the houses during the heating season was 20.8°C (see Section 4.4 for more details). This figure is in line with other Swedish measurement studies (National Board of Housing, Building and Planning, 2009b; Sjögren, Kronheffer, & Blomkvist, 2010).

energy activities, visualising and giving feedback to households have been common intervention methods (e.g. Khosrowpour et al., 2018).

However, the way in which practices are carried out is seldom driven by energy-saving motives (Gram-Hanssen, 2010a). Not least, this thesis showed that a single household can practice both ‘energy-saving’ and ‘energy-wasting’ activities, that is, people do not always act consistently in terms of energy impact. Instead, a high energy consumer might simply be following a totally different set of standards when it comes to convenience, comfort or cleanliness (Shove, 2003). Thus, rather than bluntly insisting that households reduce energy use, an alternative way would be to scrutinise what is necessary and reasonable in terms of our standard of living and to actually challenge some of these norms of society.

As demonstrated by the thesis, the differences between households' energy use, as well as the many different ways in which everyday activities can be performed, means there is a potential for savings. Nevertheless, the diversity of energy-related activities carried out by the households might lead to difficulties in communicating the benefit of energy savings to them, as the unique conditions, activities or needs of the people that are to be influenced are not known in advance. This might be an explanation as to why one-way information is rarely the most effective means of convincing people to reduce energy usage (Simcock et al., 2014). Instead, two-way communication is preferable (Isaksson, Hiller, & Lane, 2019), as it provides better opportunities for understanding people's needs and motives for why and how energy-related activities are carried out. To address different types of activities and elements of practices, and to reach more target groups, multiple intervention methods are preferable (e.g. Fischer, 2008; Gram-Hanssen, 2010b; Maréchal, 2010).

6.1.5 Focusing on high consumers: Long operating times and parallel use

The results from the thesis revealed a few shared factors for a rather small group of high consumers. Long operating times in combination with high and fairly high typical power ratings led to higher energy use. The activities included the use of engine preheaters, car heaters, fans and additional radiators, as well as airing habits (reported in Section 4.4). Similarly, the residents reported long time-use and operating time for activities related to electronic equipment, predominately the use of TVs and computers. It was seen that multiple items of similar electronic equipment were switched on at the same time in households, which means that each household member tended to have and use his or her own set of devices, instead of sharing them. This parallel use leads to increased electricity consumption for the household as a whole (Green & Ellegård, 2007; Karlsson & Törnqvist, 2009).

Additionally, the time-use diaries revealed that computers were turned on for long periods without really being actively used all the time, most probably in standby mode.[146] As demonstrated by research, the standby mode of devices is a convenience for the residents, but due to long operating hours it leads to unnecessary electricity use (Lindén, 2008; Zimmermann, 2009). Studies have shown that around 10% of household electricity is allocated to standby consumption (Fonseca et al., 2009; Pothitou, Hanna, & Chalvatzis, 2017).

Nothing suggests these patterns of long operating times and parallel use are about to decline today. Rather, the trend is towards an increased number of electronic devices in our homes, not least seen by the fast pace of innovation and market penetration for new products related to information, communication and entertainment (e.g. Cabeza et al., 2018). The transition to permanent broadband connections with routers constantly running is a recent example. With the penetration of new ICT products with more advanced functions, new ways of using the technology arises, which needs to be considered in terms of energy impact (e.g. Terry & Palmer, 2016; Viegand, Huang, & Maya-Drysdale, 2017). Pulling the balance in the opposite direction is the trend in the continuous development of more energy-efficient products. This process is driven by the EU's Ecodesign Directive (2009/125/EC), which now also applies to standby functions (Commission Regulation (EC) No 1275/2008; Commission Regulation (EU) No 801/2013).

6.1.6 Changes in *where* energy-related activities are performed

The home environment was the context in this thesis. The activities people perform at home affect household energy use, while those performed outside the home have an impact on the energy use somewhere else in society. This section discusses changes in *where* energy-related activities are performed.

The number of hours people spend at home can give an initial plausible indication of the level of energy used for households. In this thesis, the connection primarily spotted was that households which on average spent less time at home also had a lower average water usage (measured per household). From the time-use diaries, the estimated average time spent at home was 15.7 hours per day, which is in line with findings in several other studies (e.g. Brasche & Bischof, 2005; Ellegård, 2002).

Various historical, present and future changes in society affect how much time we spend at home and which activities we carry out within our homes and which occur outside the home. One change which may have led to a decreased energy use in residential buildings is women's increased employment in outside jobs, which affects the time spent at home (Anderson, 2016; Nermo, 2000; Stanfors, 2014). Another example is that many people nowadays choose to go out and eat at

[146] The amount of time equipment was in standby mode could not be extracted as a separate activity from the diary data, which is expected considering it is primarily the activities the residents actively carry out that are reported.

restaurants now and then, instead of spending time preparing food, cooking and washing up at home (Carlsson-Kanyama & Linden, 2001; Warde et al., 2007). One tendency, which could lead to an increased energy use in residential buildings, is when employees can work from home for part of their working hours (Hampton, 2017). The ‘home office’ has been made possible by the increased digitalisation, with many homes today having efficient internet connections and with employees having access to mobile devices (laptops and mobile phones). Another example is activities associated with people's vehicles. In this thesis, activities connected to the use of engine preheaters and car heaters stood out for some households resulting in high energy use. Further impact on household energy usage will be caused by the anticipated market penetration of electrified cars (Bunsen et al., 2018), which means a shift from filling up the car at the gas station to charging the car at home. Thus, the traditional boundaries between energy use connected to various sectors of society, such as the transport and building sectors, are beginning to blur.

6.2 Shortcomings of this thesis

Three particular shortcomings have been identified with the chosen approaches and the methods used in the thesis.

First, the energy data (annual energy use) and energy measurements (daily energy use) refers to total energy usage, that is, the energy used for space heating, domestic hot water and household electricity. This was a limitation when correcting for varying outdoor temperatures over the years, and therefore different typical values had to be used for the weather-independent energy use. This was probably one of the contributing reasons why the correction with heating degree-days did not lead to the (expected) ‘normalisation’ of the energy curves. In addition, only measuring total energy usage constitutes a limitation regarding any detailed analyses of how various everyday behaviours affect the different parts of energy use, leading to a decreased precision in the results.

Second, the multidisciplinary approach, with diaries being combined with energy measurements has its limitations. Measuring household energy usage at the same time the diary study was carried out meant that no random selections of either days or individual diary writers were made (the participating household was the sampling unit). Making random selections is recommended for quantitative studies in general and for national time-use studies in particular (Bryman, 2011; Eurostat, 2019). In addition, the chosen approach entailed that lengthy energy measurements, covering different periods of the year, could not be made, although this is common in technical studies. Thus, the results were not representative of the complete range of activities carried out on any given day during an entire year. However, to improve generalizability – that is, the selected days were representing ordinary days with ordinary everyday activities – a significant number of 57 households from the three housing areas participated in the study, resulting in unusual activities not being prominent. Moreover, a comparison between annual energy usage and the energy use during the short-term measurements showed a fairly good correlation (housing area A), implying that energy usage during the selected days were fairly relevant for the whole year's energy use.

If, instead, a monodisciplinary study based on qualitative research had been conducted, the diary study could have been supplemented with in-depth interviews to gain a better understanding of how residents feel about their energy use, similar to the approach in Löfström's thesis (2008), for example.

Third, there was a reporting variability in regard to the level of detail in the diaries, as well as variations related to uncertainties and missing values, which were not quite randomly spread amongst the diary writers. With the intention to decrease the consequences of uncertainties and missing values, such cases were handled with imputation, that is, replacing them with reasonable substitution values. The overall quality of the diary study was, however, found to be satisfactory. The satisfactory quality measures related to being representative for the participating households (shown in the dropout analysis), the validity of capturing energy-related activities, the consistency during the days of measurements, the consistency between different raters (reliability) and the non-traditional measure of the number of episodes.

7 Conclusions

The main objectives of the thesis are to examine how energy use in single-family houses varies and how the energy-related behaviours of households influence the use of energy.

One main conclusion is that energy use in single-family houses varies in several ways. First, the thesis demonstrates that the use of energy varies during the day, as seen by curves in the diurnal household electricity consumption patterns. On a group level, the hours of peak load show the greatest demands of electricity – most clearly in the morning and in the evening on weekdays – which potentially means a higher risk of power deficit in the energy system. Second, the energy use for the individual households in the thesis changed over time – both upwards and downwards – and various activities happened over the years in the houses and to the households which impacted the energy usage. However, for a group of houses the average level of energy use is stable after years of occupancy. Third, the variations in household energy use while residing in similar houses (i.e. the technical differences are limited) are large – in this thesis, the energy usage differed by a factor of two to three between the highest and the lowest figures. The differences are even greater related to household water usage which reach a factor of six in this thesis. Residents' energy behaviours are believed to contribute to these variations – as indicated in this thesis as well as in other studies.

However, the differences in energy use are not due to just a few main activities. Thus, another conclusion is that there are many ways to be a high or low consumer, which is demonstrated in the thesis as a majority of the households perform a diversity of energy-related activities adding up to their total energy usage. Additionally, the activities are performed in various ways. For example, how the participating households use computers, which also contribute to differences in energy use. Some common features are shown for a smaller group of high consumers. Long operating times, together with high and fairly high typical power ratings, for activities such as the use of engine preheaters and car heaters, led to higher energy use. That there is a tendency for several electronic devices found in homes being switched on for long periods of time – sometimes without even being used – is also demonstrated in the thesis, which together with each household member owning their own set of devices (going from sharing devices to individual parallel usage) means increased electricity consumption.

7.1 Application of the results and future outlook

Even though a considerable length of time has passed since the empirical data of the thesis were collected, the results presented in this thesis are still of high relevance to the field of energy use in single-family houses and household energy behaviours. First, the empirical context is still valid as the study was carried out in ordinary existing houses which will constitute a large part of the housing stock for a substantial period of time. Second, the observation that energy use in single-family houses varies in assorted ways is also confirmed by research and experience found in the literature review, especially related to the large differences in energy use between households.

A valuable contribution of the thesis is the provision of *real* data on energy use and how usage is related to the residents, which is usually lacking in energy calculations. With improved input data from *field measurements*, better predictions and calculations of household energy use can be performed. Further *field studies and measurement projects* are still required. These could include studies on how and why specific activities are carried out, for instance, residents' airing behaviour. It can moreover include studies of technology shifts, examining, for example, the large-scale energy effects of the phasing out of incandescent lamps and how it influences the way we illuminate our homes. Additionally, there is a further need to improve typical values for resident-related data used to verify energy requirements in the Swedish building regulations (particularly for single-family houses). Future (field) studies will benefit from increased availability of energy data, which previously have been a limitation in energy analyses. With the reform made in Sweden regarding more frequent electricity measurements and smart meters, data availability should no longer be a huge problem[147] (although data protection regulation must be considered[148]).

Furthermore, the thesis contributes to the *multidisciplinary research* in the field of household energy use, as it highlights both technical and social perspectives. By combining investigations of measured energy usage together with the behaviours of households, insights are gained. For example, we can learn that many different energy-related activities add up to the households' combined energy usage. Without this multidisciplinary approach, one would either just learn about the amount of energy used in households with no understanding of what is influencing it or learn about the behaviours people perform in their homes without any connection to the

[147] In 2009, the Swedish electricity measurement reform came into force, and in 2012 changes in the Swedish Electricity Act (SFS 1997:857 – 2020:73) meant that electricity consumers are entitled to have their electricity consumption measured per hour. The next generation (smart) electricity meters will potentially open up for even more (frequent) data communication (Swedish Energy Markets Inspectorate, 2017).

[148] In accordance with the General Data Protection Regulation (Regulation (EU) 2016/679).

level of energy usage. To combine research from more than one discipline is increasingly important since it is evident that technological developments are not enough to achieve society's energy targets to combat climate change. People should not, in this sense, be seen as a hindrance in reaching the technical potential for energy efficiency, but rather, the technological developments should be based on people's perceptions, needs and everyday lives. Hence, future studies focusing on motivating households to save energy and to change the times when they perform activities or focusing on technology development promoting energy-saving behaviour would benefit from considering that the residents are a heterogeneous group with varying behaviours and energy uses, as shown in this thesis. This would increase the chances of closing the energy performance gap, so that the anticipated energy savings would be reached.

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Appendix A

Paper I

Sustainable energy use in 40 Swedish houses

– A study of changes over a ten-year period

Carolina Hiller and Arne Elmroth (2005)

Published in *Proceedings of the World Sustainable Building Conference*, Tokyo, Japan, 27–29 September 2005.

Note that the house codes in this paper are in accordance with their earlier denotation in the licentiate thesis. Turn to Appendix E and Table 8 for further clarification of denotations and detailed information about the individual households.

SUSTAINABLE ENERGY USE IN 40 SWEDISH HOUSES - A STUDY OF CHANGES OVER A TEN-YEAR PERIOD

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Keywords: sustainable energy use, single-family houses, changes over time, trends, energy data, degree-day method, residents

Summary

A study has been conducted where sustainable energy use in buildings was highlighted. Sustainable energy use could be interpreted as when the energy use of a household, preferable a low energy use, remains on the same level even after some years in operation of the house.

The main objective of the study was to verify or reject the *hypothesis* that "the energy use increases over time in modern single-family houses in Sweden".

The energy use over approximately a ten-year period has been analysed for 38 houses. Energy and water data have been gathered, treated and analysed in a first step. In a second step structured interviews were made with six house owners in order to relate activities that have occurred over the years to the energy use in their houses.

The result showed no general trend or changes over time of the energy use on a group level. However, for individual houses the energy use could both increase and decrease over the years. In addition, the energy use appeared to differ greatly between the nominal identical houses. The interviews, which entailed a retrospect of energy related activities over the time period, proved to be a less valid technique and no definite conclusions could be made.

1. Introduction

1.1 Background

In Sweden the residential, commercial service sector etc. stands for almost 39 % of the total energy use. The total temperature-corrected use of energy in this sector has remained relatively stabled between 1970 and 2003. This is so in spite of an increase in the heated floor area for the Swedish housing stock during the period. The reason behind this is a dramatic change in energy sources, 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. Other contributing factors are an increase in the number of heat pumps installed, the introduction of energy saving measures and an increased usage of energy efficient household appliances (Swedish National Energy Administration, 2004).

1.2 Definition of problem

There has been a number of energy saving measures carried out the last 25 years, primary in the newly built Swedish housing stock. From 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.

In addition, 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 regard to the implementation of energy saving measures to the ordinary housings stock.

However, three follow-ups have been found. The performance of these low-energy single-family houses was studied after some years in operation (Table 1).

Table 1Follow-ups of low-energy housing projects

Project	Years in operation	Increase in energy use %	kWh	Reference
1	7-10	13	1500	(Weber, 1996)
2	10	up to 40	4000-5000	(Berggren et al., 1997)
3	5	5	900	(Nilson and Uppström, 1997)

In the first study the energy use had increased with 13 % (corresponding to 1500 kWh) after 7-10 years. In another project the increase was after 10 years up to 40 % (corresponding to 4000-5000 kWh). In the final study the increase after 5 years was 5 % (corresponding to 900 kWh). 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.

1.3 Objectives and scope

The main objectives of the present project are to enlighten the field of sustainable energy use in general and in particular to verify or reject the *hypothesis* that the energy use increases over time in modern single-family houses in Sweden.

Issues that will be raised are:

- How the energy use in single-family houses changes over a time period of more than 10 years, both on a group as well as on an individual level.
- The appearance of energy curves, e.g. how it can change from one year to another.
- The variations in energy level between different households.

The study can be valuable in the discussion concerning the analysis of energy data. In the long run the study can be useful in the planning phase of buildings when choosing sustainable techniques with the purpose of keeping the energy level down also after some years in operation.

The project as a whole has been carried out in three major steps and is described in detail in a report from 2003, *Sustainable energy use in 40 houses – A study of changes over a ten-year period* (Hiller, 2003). This paper highlights the findings of step one and two (grey boxes in Figure 1). Step three is described in the paper *Sustainable energy use in Swedish houses - A study of energy data and energy performance*, which is being presented at the 7th Nordic Building Physics Symposium in Reykjavik, June 2005. In the third step measurements of the specific heat loss were carried out in two of the houses in order to relate it to their actual energy use. The aim is to see if the different levels of energy use are due to the houses and their building services or if it can be related to differences in the residents’ behaviours.

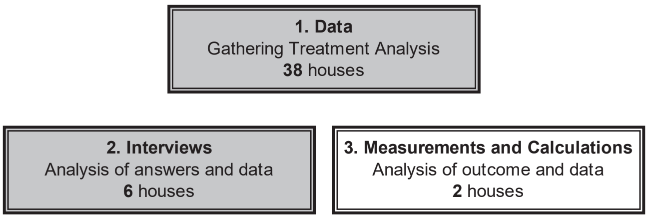

Figure 1 The three major steps in the project

1.4 Description of the houses

In order to find a homogenous group of houses to study the following requirements were set up:

- The construction of the houses and the building services should be known and generally used.
- The houses should be part of a group of houses that are nominally identically built.
- The houses should be modern houses built after 1977, the year that the new Swedish energy conservation codes were introduced.

- Energy data should be available for at least ten years back in time for the houses.
- Climate data should be available for the location where the houses are situated.

The houses studied were a group of 38 modern nominal identical houses erected 15-20 years ago. The detached single-floor houses can be seen as *normal* Swedish houses built with conventional technique. The construction of the houses can be seen in Figure 2. The houses have a wooden framework, a slab on ground as foundation, an unheated attic, an electric boiler with waterborne heat and an exhaust ventilation system. The size of the houses is 104 square meters, which is a bit smaller than the average Swedish house. After some years in operation alterations have been made to some of the houses, for example extensions have been made, heat pumps and tiled stoves have been installed.

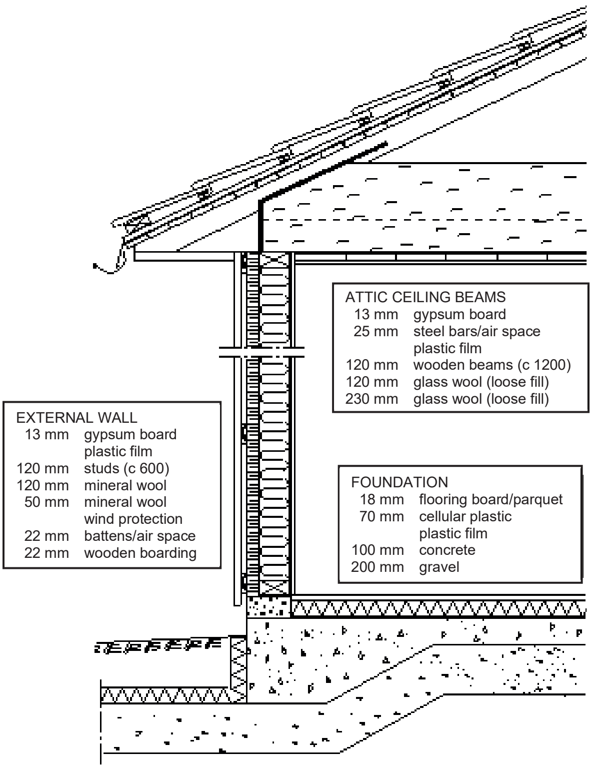

Figure 2 The construction of the houses

2. Methodology

In the first step of the project energy and water data of the single-family houses were gathered for a period of more than ten years. The data were provided by the local energy supplier. Energy data were available for 38 of the houses on the housing estate. The energy data refer to the total bought energy use, i.e. the energy for the hot water production, the space heating and the household electricity. The water data refer to the total water consumption, i.e. both the cold and hot water production. The data were corrected for the number of days in a year so that it corresponds to the energy use of 365 days. The data were also corrected for variable outdoor temperature using the degree-day method. The corrections were made in order to be able to compare the energy use between different years and analyse any general trends or changes in energy use. The energy data were analysed on both an individual level as well as on a group level.

The degree-days were obtained from the Swedish Meteorological and Hydrological Institute (SMHI). The degree-days are calculated by summing up differences between the balance temperature and the outdoor temperature of each day. The balance temperature is defined as the lowest outdoor temperature where the internal heat gain (i.e. heat from solar insolation, persons, lighting and household appliances) precisely covers the heat losses from the building. The problem of choosing a representative balance temperature for all kinds of buildings and internal heat gains is highlighted in (Hiller, 2003). In this project only the total bought energy use is known, which is another problem to overcome as the degree-day correction only is applicable on the weather-dependent part of the energy use.

The next step involved structured interviews with six house owners on the housing estate. The participants were among those house owners that have returned positive replies regarding participation in the study. The interview questions concerned activities and events, having an influence on the energy use, that have occurred over the years. The interview was supplemented with questions and discussion regarding the house owner's energy use. The answers were thereafter analysed together with the energy use. The aim was to obtain explanations to the appearance of the energy use of individual houses. In addition, the difficulties using a retrospective technique was highlighted.

The project shall be seen as a pilot study where the energy use of a group of Swedish houses were analysed as well as a retrospective method was tested. The houses are not low-energy houses and are presumed to be representative for normal modern Swedish houses. In addition, it can be pointed out that the families living in these houses are normal households and are not believed to have any particular energy awareness, more than the public in general.

3. Analysis and results

3.1 Step 1

The identification of any trends in the energy use has been carried out both for individual houses and for the housing estate as a whole. In Figure 3 some examples are shown for individual houses, there each diagram is the energy use for one house. The annual energy use, corrected so it is equivalent to the use of 365 days, is represented by the circles, the annual energy use corrected with degree-days is represented by the squares and the trend line for the degree-day corrected energy use is represented by the dotted line. Each point corresponds to one house's energy use a particular year.

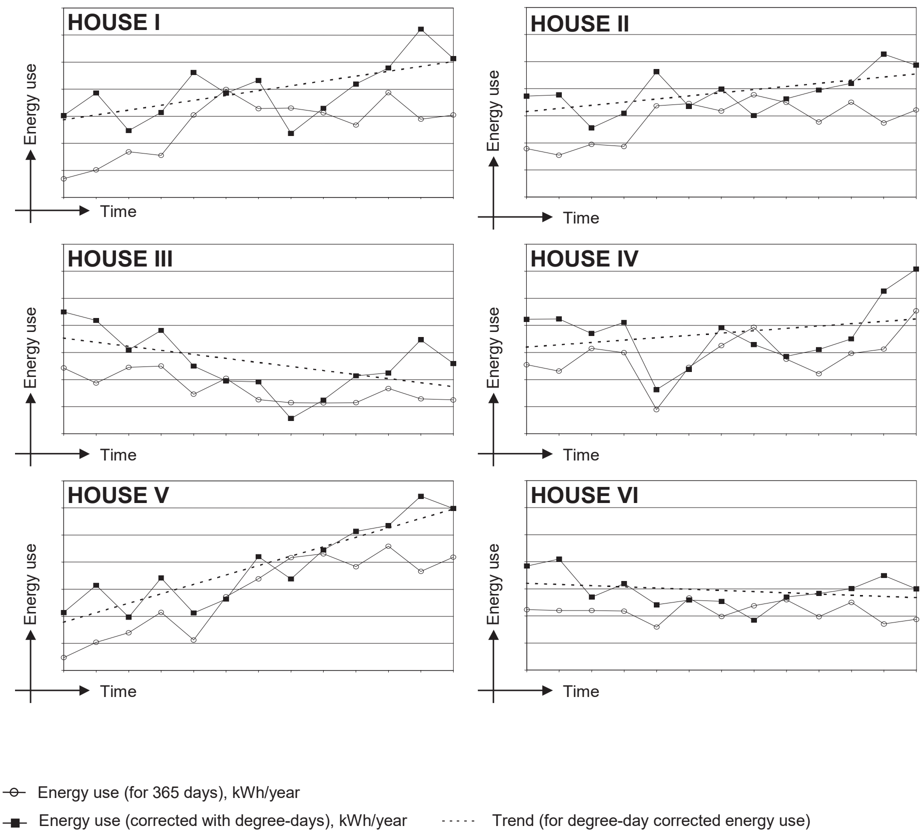

Figure 3 Total annual energy use (y-axis) in kWh/year over a 12-year-period (time on x-axis) for six houses.

The graphs give a picture of that the energy use seems to vary a great deal from one house to another. Furthermore, it can be observed that in some cases it can be difficult to plot a trend line including all the years since the energy use suddenly can change direction, as in the case of house III. Moreover, it can be noticed that the energy use can vary substantially from one year to another, as in the case of house IV.

In Figure 4 the average energy use (kWh/year) for the entire time period is shown for each house. The white columns refer to the average annual energy use, corrected so it is equivalent to the use of 365 days, and the grey columns refer to the average annual energy use corrected with degree-days. The figure illustrates that the levels in energy use can vary a great deal from one house to another. For example, it differs more than 10 000 kWh in energy use between house I and VI.

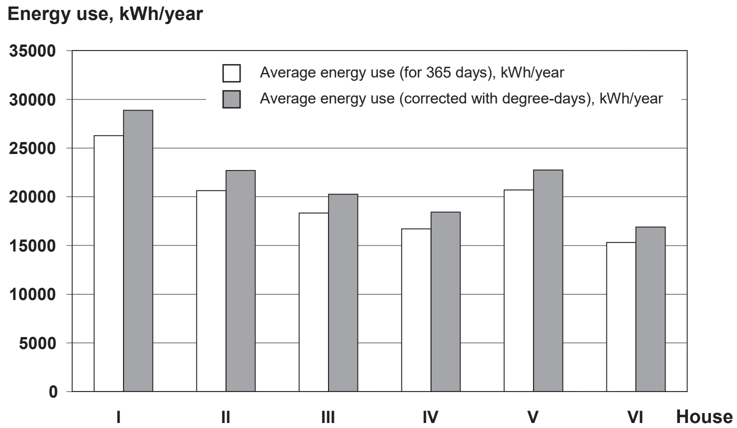

Figure 4 *Average total energy use (kWh/year) of the six houses for the 12-year-period*

Regarding the trend on a group level, it is demonstrated for the 38 houses in Figure 5. Each dot represents the annual energy use (corrected with degree-days) for a house a specific year. Note that energy data have not been available for all years for all houses, hence the number of dots in the graph varies from one year to another. The average energy use (for the housing estate) for each year is represented by the black curve and its trend line is represented by the dotted line. No general indication of an increase or a decrease can been seen in the graph.

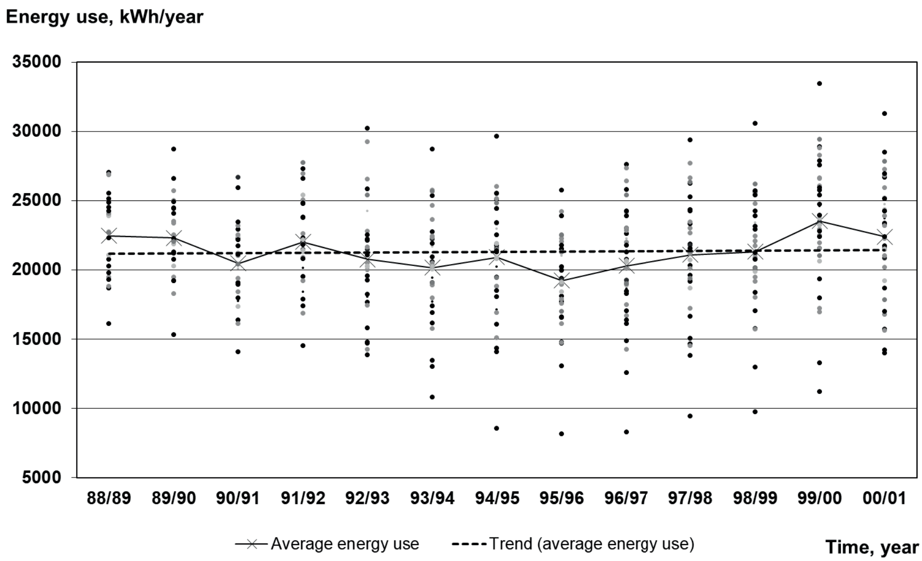

Figure 5 *Total annual energy use (corrected with degree-days) for 38 houses (kWh/year). Each dot corresponds to one house's energy use a particular year. The curve represents the average total energy use for all houses a particular year. The dotted line represents the trend for the average energy use.*

However, it is clearly shown that the energy use for different households differs greatly. That the energy use can vary significantly for nominally identically built houses has been acknowledged in previous studies (e.g. Värmekostnadssakkunniga, 1942; Gaunt, 1985; Lundgren, 1989; Lundström, 1982; Palmborg, 1986; Socolow, 1978; Jensen and Gram-Hanssen, 2000).

3.2 Step 2

In step 2 six house owners were interviewed according to a questionnaire regarding energy related activities/events that have occurred during the time period of interest. In general, it was difficult for the residents to remember *when* the different activities had happened. If evidence were available such as receipts, notes or other documentations presumed dates sometimes turned out to be some years from the actual dates. If there were more than one person present at the interview their views on when an activity took place could differ. Subsequently, the retrospective technique is not suitable for the purpose of the study in question.

If one disregard the uncertainty of some of the interview answers and make an attempt to interpret the results together with the households energy curves it can be found that definite conclusions are difficult to make due to that several activities might have happened simultaneously or very closely in time (for an example see Figure 6). Furthermore, the activities are of different nature. A change such as an extension has an immediate and lasting effect on the energy use. The installation of a heat source (e.g. a tiled stove) on the other hand can contribute to a decrease in the amount of energy bought, however, the effect depends on where in the house the source is installed as well as how frequent and how much it is used. Not even sudden changes from one year to another in the energy use can be given definite explanations.

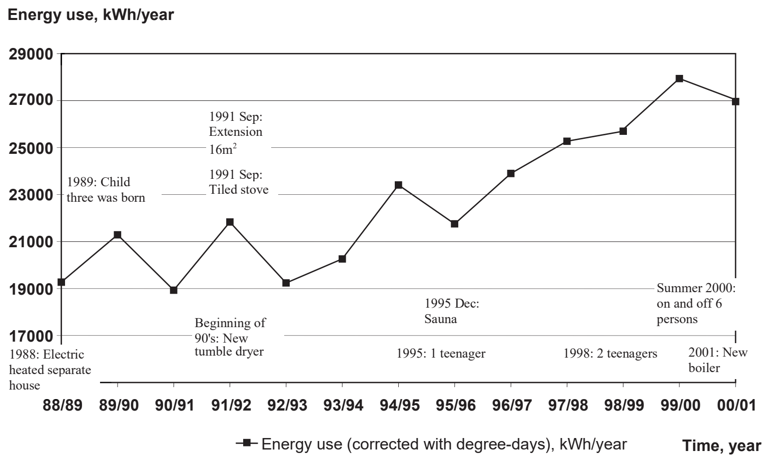

Figure 6 Energy related activities and annual energy use, house V

4. Conclusions and discussion

The main objective of the study was to verify or reject the hypothesis that the energy use increases with time in houses. On a group level it was shown that the energy use was stable over the years. The results from the study can be seen as a description of the appearance of the energy use for a group of modern detached single-family houses in Sweden. The key findings can be summaries as follows:

- Even though a number of energy related activities had occurred over the years, the average energy use for the group of houses had remained fairly constant.
- On an individual level the energy use could increase, decrease or remain on the same level.
- That the energy use can differ significantly between different houses have been confirmed.

Furthermore, a number of difficulties and uncertainties has been discovered such as the applicability of the degree-day method, sudden unknown changes in the energy use from one year to another and knowing when certain energy related activities have occurred in a house or household. These circumstances have subsequently made the analysis of the data and information gathered in the study more problematic.

The interviews highlighted the difficulties with using a retrospective technique, which meant that the appearance of the energy use in the house could not with certainty be related to individual changes of the house or changes of the users´ behaviour. More detailed and precise information about the activities/events that occurs in a house/household over the years as well as more frequent energy data had probably resulted in that more distinct relationships between activities and energy use could have been indicated.

The different levels of energy use between the houses have been investigated in step three of this project. Whether or not the difference is due to the residents are discussed in the above-mentioned paper *Sustainable energy use in Swedish houses - A study of energy data and energy performance.*

The consequence of the project is that in a continuation explanations to the energy curves will be sought. An attempt to link energy related activities with the appearance of the energy curves will be made. Special attention will be put on the residents' influence on the energy use. This will involve recording the residents' behaviours in journals as well as frequent energy readings. The result will hopefully lead to a better understanding of trends in the energy use.

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Appendix B

Paper II

Sustainable energy use in Swedish houses

– A study of energy data and energy performance

Carolina Hiller and Arne Elmroth (2005)

Published in *Proceedings of the 7th Symposium on Building Physics in the Nordic Countries*, Reykjavik, Iceland, 13–15 June 2005.

Note that the house codes in this paper are in accordance with their earlier denotation in the licentiate thesis. Turn to Appendix E and Table 8 for further clarification of denotations and detailed information about the individual households.

Sustainable energy use in Swedish houses

- A study of energy data and energy performance

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KEYWORDS: *sustainable energy use, single-family houses, changes over time, energy data, energy performance, specific heat loss, residents*

SUMMARY:
The energy use for more than ten years of a group of Swedish single-family houses has been studied in this project. The basis has been that it is of importance that the energy of a building is sustainable, i.e. that it stays on a low level even after that the building has been in operation for some years. The main objective has been to verify or reject the hypothesis that the energy use increases over time in modern single-family houses in Sweden.

This paper particularly describes the measurements of the specific heat loss carried out in two of the houses. The specific heat loss was used to measure the energy performance of the houses and their building services. The objective of the measurements was to investigate the difference in energy level between the houses and find out if the level of energy use could be linked to the building and its building services or the residents´ behaviours.

The findings were that no general trend over time of the energy use has been identified for the group of houses. Hence, the hypothesis could not be verified. The results from the measurements of the specific heat loss of the two houses showed that the house with the highest energy use had the lowest specific heat loss. This implies that the influences of the residents of a house are significant to the level of energy used.

1. Introduction

1.1 Background

The energy used by the residential, commercial service sector etc. stands for almost 40 % of the total energy used in Sweden. Moreover, the amount of energy used by this sector has remained quite stable over the last 30 years. However, factors having an impact on the energy use have changed over the years. The heated floor area has increased; for example, the number of residential buildings has increased with almost 40 %. A number of counteracting factors can be listed such as the change of energy sources – primarily from oil to electric heating for single-family houses, the increased number of heat pump installations, the introduction of energy saving measures and the increased usage of energy efficient household appliances (Swedish National Energy Administration, 2004).

Generally, the energy use of buildings is a burning issue, where the EU directive on the energy performance of buildings is one example (Commission of the European Communities, 2002). The implementation of the directive will focus on energy efficiency in buildings, which must be accounted for in e.g. a buying-selling situation. The building should have an energy declaration issued by an expert (will be labelled a declaration in Sweden - in other countries it might be recognised as a certification). The declaration should be accompanied by suggestions of different economic beneficial measures that can be taken in order to reduce the amount of energy used. The procedure of energy declaration of houses will need knowledge about the design of the houses and the influence of the residents´ behaviours. The present study hopes to be a valuable contribution to this knowledge.

1.2 Definition of problem

In Sweden there has been a number of energy efficient housing projects the last decades. In addition, energy saving measures have been made in many houses. Few of these houses have been followed up after some years in operation. From a sustainable viewpoint, an interesting question is if the energy use has remained on a low level.

However, three follow-ups have been found. The projects have studied the performance of low-energy single-family houses after some years in operation. The results were that after 7-10 years the energy use had increased with 13 % (corresponding to 1500 kWh) in one study (Weber, 1996). In another project the increase was after 10 years up to 40 % (corresponding to 4000-5000 kWh) (Berggren et al., 1997). In the final study the increase after 5 years was 5 % (corresponding to 900 kWh) (Nilson and Uppström, 1997).

The results from these studies give indication of that the energy use might increase or at least vary with time. This is of interest to study further in a group of normal houses.

1.3 Objective and scope

In the present project the energy use for a period of more than 10 years will be analysed. A housing estate with 38 houses, nominally identically built, is studied. The main objectives of the study are to highlight sustainable energy use in general and in particular to verify or reject the *hypothesis* that the energy use increases over time in modern single-family houses in Sweden.

The project as a whole is carried out in three major steps and is described in detail in a report from 2003, *Sustainable energy use in 40 houses – A study of changes over a ten-year period* (Hiller, 2003). This paper highlights the findings of step three (grey box in Fig. 1). The steps one and two are here only briefly described, but are further outlined in the paper *Sustainable energy use in 40 Swedish houses - A study of changes over a ten-year period*, which is being presented at the 2005 World Sustainable Building Conference in Tokyo, September 2005.

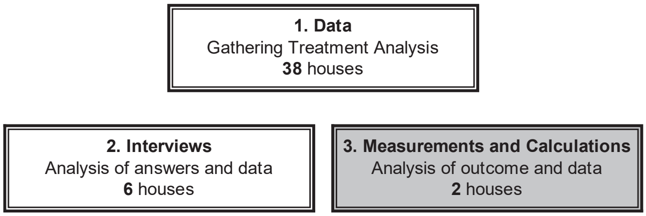

FIG. 1: The three major steps in the project

The objective of the measurements in step three is to further investigate the difference in energy level between different houses.

1.4 Description of the houses

A housing estate was chosen that consisted of modern houses erected in the mid-eighties. The houses are built in accordance to the Swedish energy codes prevailing at that time. The houses are detached with a single floor of 104 square meters. The houses have a wooden framework, a slab on ground as foundation and an unheated attic. The heating system consists of an electric boiler with a waterborne heat distribution system. The ventilation is provided by a mechanical exhaust system. After some years in operation alterations have been made to some of the houses, for example extensions have been made, heat pumps and tiled stoves have been installed.

The two houses included in the third step of the study are nominally identically built. However, in 2001/2002 the owner of one of the houses (labelled House VI) has made an extension of 27 square meters to the house. The extension has partly higher ceiling and more glass area than the rest of the house. Additionally, a cast iron stove was installed.

One of the major differences between the two households has been the number of persons living in the house. One of the households (labelled House II) has had a constant number of four persons over the years. The other household (House VI) has on and off mostly had one or two persons. At the time of measurements the indoor temperature differed significantly between the houses.

2. Methodology

As already mentioned, steps one and two are here only briefly described, but are further outlined in the paper *Sustainable energy use in 40 Swedish houses - A study of changes over a ten-year period* (Hiller, 2005).

2.1 Step 1 Data

In the first step energy data for 38 houses were gathered from the local energy supplier. The data were treated and analysed with the intention to identify any general trends for the group of houses. The data were corrected for the number of days in a year so that it corresponded to the energy use of 365 days. The data were also corrected for the outdoor temperature with the degree-day method in accordance to the Swedish Meteorological and Hydrological Institute (2004).

2.2 Step 2 Interviews

In order to relate changes that have occurred over the years to the energy use of the houses, structured interviews with six house owners were carried out in the second step. The questions concerned activities and events, having an influence on the energy use. The answers were thereafter analysed together with the house owner's energy use.

2.3 Step 3 Measurements and Calculations

The third step involved measurements of the specific heat loss in two houses. The owners of these houses were willing to participate in the measurements, which implied rather active roles for the residents. The purpose of the measurements in this project was to investigate the difference in energy level between the houses. The question of interest was if the house with the highest energy use also had the highest specific heat loss and vice versa. If this would be confirmed it would indicate that the level of energy use could be linked with the building and its building services rather than the residents´ behaviours.

2.3.1 Description of the method for the measurement of the specific heat loss

The specific heat loss, F_T, can be defined as the sum of the transmission and ventilation losses per degree of temperature difference between the indoor and outdoor environments. It is used to measure the energy performance of the house and its building services.

The transmission and ventilation losses are assumed to be equivalent to the supply of energy, obtained from the energy meter. Corrections were made for heat given off by the residents and heat storage of the building and interior (causing indoor temperature fluxes). The electric energy used by the fan was withdrawn from the energy read of the meter. Other energy demands that do not contribute in heating the house, such as heating the garage or an engine preheater, should also be withdrawn. The energy demand for e.g. the fridge and freezer is presumed to contribute to the heating of the house. The average power demand was calculated by Equ. 1 (Sandberg and Jahnsson, 1995).

$$Q_{average} = \left(E_{read} + E_{person} \pm E_T - E_{fan}\right)/t \quad \text{[W]} \qquad \text{(EQU. 1)}$$

where

$Q_{average}$ average power demand [W]

E_{read} energy read of the meter [Wh]

E_{person} energy given off by persons [Wh]

E_T energy correction for indoor temperature fluxes [Wh]

E_{fan} energy used for fan (mechanical ventilation) [Wh]

t length of measurement period [h]

In order to minimise the influence from the residents and the solar insolation the measurement period took place during the night. The average power demand was calculated for a number of nights and thereafter plotted against the average temperature difference between outdoors and indoors. The heat loss factor was calculated by linear regression analysis, which means that it is assumed that the heat loss to the ground is constant and that the transmission and ventilation losses are proportional to the difference in indoor and outdoor temperatures, Equ. 2 (Sandberg and Jahnsson, 1995).

$$Q_{average} = Q_{ground} + B_{losses} \times \Delta T \quad \text{[W]} \qquad \text{(EQU. 2)}$$

where

Q_{ground} heat loss to the ground [W]

B_{losses} factor that describes the other heat losses [W/K]

ΔT difference in indoor/outdoor temperatures (average) [K]

The specific heat loss, F_T, can be approximated by Equ. 3, where the heat loss to the ground is assumed to not vary with the temperature difference between indoors and outdoors. This is reasonable for houses with slab on ground and when the measurements take place in a limited period.

$$F_T \approx \frac{Q_{ground}}{\Delta T} + B_{losses} \quad \text{[W/K]} \qquad \text{(EQU. 3)}$$

The specific heat loss method is applicable for detached light, wooden-framed, houses with electric heating and mechanical ventilation. Due to long nights, limited solar heat gain and a large temperature difference between the indoor and outdoor temperatures, the method should be applied during the winter months (Sandberg and Jahnsson, 1995).

The advantage with the method is its simplicity, because no complicated or expensive equipment are needed as well as any specialised knowledge. Another advantage is that measurements can be carried out at normal conditions, that is, the house can be occupied, and the ventilation and heating system should operate as usual. A disadvantage is the limited accuracy. The measurement error, including the systematic and random errors, has been estimated to up to 10 % for the specific heat loss. One more drawback is that the residents have to do certain preparations and follow some restrictions. During the measurements some of the requirements are: no usage of other energy sources (e.g. cast iron stove), no usage of hot water and outdoor lighting, and no window opening. It is important that the influence of the residents´ behaviours is limited during the measurements in order to measure the performance of the house.

3. Analysis and results

3.1 Step 1 Data of 38 houses

Energy related parameters had changed with time but in spite of this no general trend over time of the energy use has been identified. Hence, the hypothesis that the energy use increases with time could not be verified. However, for individual households the energy use could both increase and decrease over the years and furthermore it could be noticed that the energy use differs greatly between the nominal identical houses. The last finding has previously been acknowledged in a number of studies (e.g. Värmekostnadssakkunniga, 1942; Gaunt, 1985; Lundgren, 1989; Lundström, 1982; Palmborg, 1986; Socolow, 1978; Jensen and Gram-Hanssen, 2000).

3.2 Step 2 Interviews with 6 households

The interviews with the questions regarding energy related activities that had occurred a few years back proved to be an uncertain method since the residents sometimes had difficulties with remember *when* activities had occurred. It was also learned that more detailed information is needed on how different activities really have influenced the energy use. As an example, the installation of a sauna can be mentioned. Obviously, it is not only of interest to know the installation date but also how frequent the sauna has been used over the years. Subsequently, the appearance of the energy use in the house could not with certainty be related to individual changes of the house or changes of the users´ behaviours.

3.3 Step 3 Measurements and Calculations in 2 houses

3.3.1 Annual energy use of 2 houses

The measurements of the specific heat loss were carried out in two of the houses. The energy use of these households is shown in Fig. 2, where each marker corresponds the annual energy use of one house a particular year. The squares represent the energy use of house II and the circles represent the energy use of house VI. The unfilled markers stand for the energy use corrected so that it is equivalent to the use of 365 days and the filled markers stand for the annual energy use corrected with degree-days.

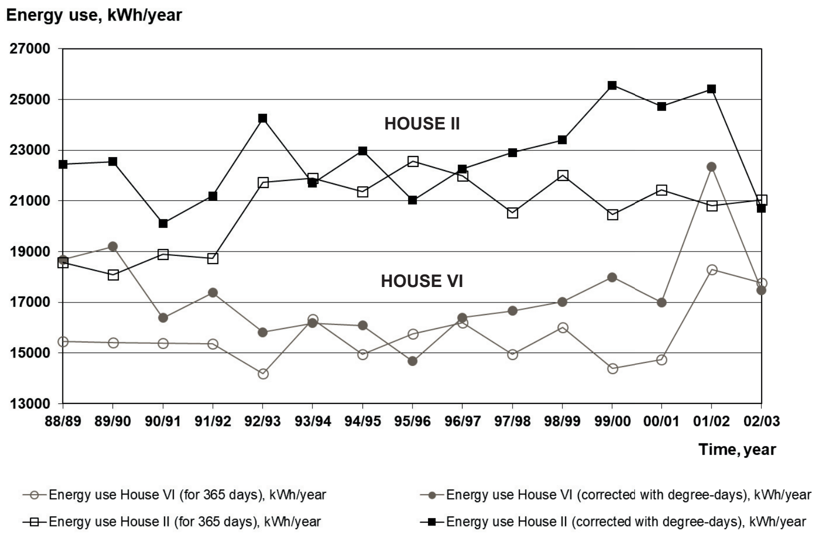

FIG. 2: Annual energy use of House II and VI for the time period 1988 to 2003. An extension was made to house VI in 2001/2002.

The energy use of the two houses differed quite significantly, on average roughly with 5000 kWh annually. One explanation could be the number of persons in the two households over the years. In house II there has constantly been four persons and in house VI the number of persons has varied, mostly between one and two persons. At the time of the measurements the indoor temperature of the households was approximately 23°C in house II and approximately 19.5 °C in house VI. If these values represent the temperatures for these two houses for the entire time period of 1988 to 2003 the temperature difference will of course serve as another significant explanatory factor. The extension made to house VI in 2001/2002 can explain the increase in energy use.

3.3.2 Specific heat loss of 2 houses

For each house the average power demand was calculated for each measurement period (each night), Equ. 1, and plotted against the average temperature difference between outdoors and indoors, Fig. 3. As can be seen the values are not spread around a line which makes the linear regression analysis somewhat uncertain. The coefficient of determination, which is a measure of how well a linear equation represent the values plotted, are in both cases very low, namely 0.37 for house II and 0.44 for house VI.

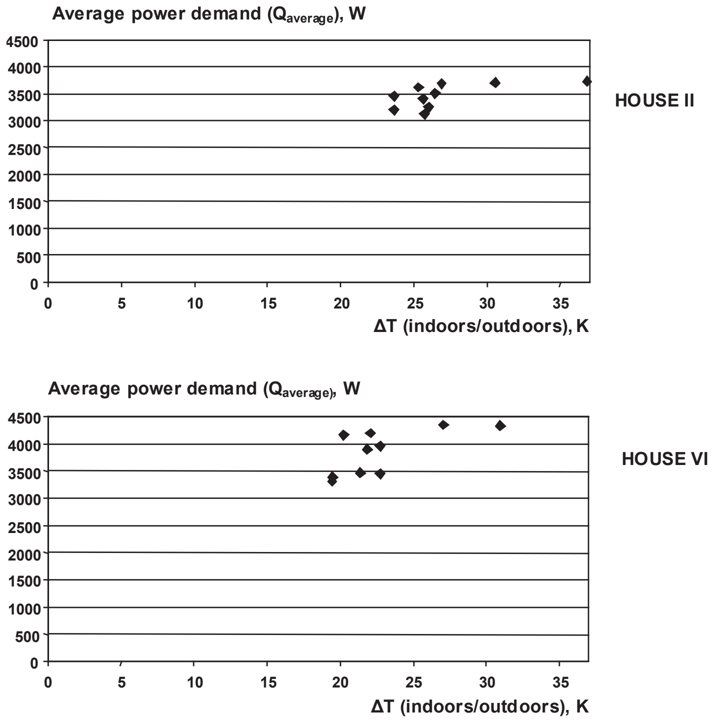

FIG. 3: Average power demand ($Q_{average}$) plotted against temperature difference (ΔT) indoors/outdoors for ten nights, House II and VI

Measures have been taken as an attempt to fit the linear model less arbitrarily. One measure entailed the exclusion of values that were obtained during nights that did not fulfil the requirements set up by the method. Another measure taken was to calculate the heat losses to the ground using the HEAT2 program (Blomberg, 2000), which simulates two-dimensional heat flows. Obtaining a fix value of this heat loss resulted in an increased value of the coefficient of determination.

These measures did surprisingly not have major impacts on the calculations of the specific heat loss and the following values given on F_T are representative values, regardless of measures being taken or not. House II has a specific heat loss of around 130 W/K and the value for House VI is around 170 W/K. The measurements have an accuracy of roughly 10 % which means that the results could vary between 117 and 143 for house II and between 153 and 187 for house VI.

4. Conclusions and discussion

The main objective of the project was to verify or reject the hypothesis that the energy use increases with time in houses. For the group of houses no general trend over time of the energy use has been identified. Hence, the hypothesis could not be verified.

The purpose of the measurements and calculations made in this paper were to investigate if the levels of energy use are due to the building and its building services or if it is due to the residents. A coarse measure of the energy performance of the house is the specific heat loss. The question asked is: Has the house with the highest energy use also the highest specific heat loss?

The results from the measurements of the specific heat loss showed that the house with the highest energy use had the lowest specific heat loss. This implies that the influences of the residents of a house are significant to the level of energy used.

As already mentioned, some of the major differences between the two houses are the indoor temperatures, the number of persons and, from 2001, the extension of house VI. Let us take year 01/02 as an example. The actual energy use of that year is for house II below 21 000 kWh and for house VI above 18 000 kWh. A general guideline is that if the indoor temperature is decreased with 1ºC this results in a 5% decrease of the energy demand for heating. This is a very rough estimation and originates from the temperature difference (between outdoors and indoors) in the middle of Sweden is around 20ºC during the heating season. This means that a decrease with 3ºC for house II would result in an energy use approximately the same as for house VI. Studying the previous year, 00/01, when the sizes of the heated floor areas are equal, an equivalent decrease in the indoor temperature of house II would not mean an energy use as low as that of house VI. Taking into consideration the estimations of the amount of energy for the hot water production of the two houses (2600 kWh respectively 1400 kWh), the difference is still more than 2500 kWh between the houses. Could the difference lie in the household electricity?

Regarding the method of the specific heat loss it has been shown that if the measurements take place during a period of small variations in the temperature difference between indoors and outdoors the uncertainty of the method increases due to that the linear model is fitted very arbitrarily. The method is very simple and can be carried out while the houses are occupied, but the relatively high measurement error and the problems highlighted in this paper makes it doubtful if the method is efficient to use on a larger scale. In addition, the energy related behaviours of the residents are also of interest to take into consideration.

5. Future work

To search explanations to the appearance of the energy data and to further investigate the influence of the residents would be of interest. In a literature survey (Carlsson-Kanyama and Lindén, 2002) the knowledge concerning the residents´ energy behaviour in their homes is highlighted. The authors point out that there is relatively little research regarding the household’s energy related behaviours in comparison with research regarding energy efficient technologies.

Consequently, the continuation of this project will engage both researchers with knowledge of behavioural science as well as researchers with technical backgrounds. The everyday habits (behaviour) of the residents in relation to their energy usage will be investigated. The energy use will be read frequently of the meter. The behaviour study will be completed with technical measurements and ocular inspections of the houses.

The aim is to investigate the trend of the energy use over time by describing and explaining it in a momentary study. Hopefully the project can be of value in energy planning and the design phase of buildings as well as for a better understanding of the relation between the technology and the behaviour of the users.

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Appendix C
Paper III

Influence of residents on energy use in 57 Swedish houses measured during four winter days

Carolina Hiller (2012)

Published in *Energy and Buildings*. *54*, 376–385.

Errata for Paper III

p. 191	In paper III: p. 384, left column, first paragraph	Misspelling: *cause* should be *because*

Energy and Buildings 54 (2012) 376–385

Contents lists available at SciVerse ScienceDirect

Energy and Buildings

journal homepage: www.elsevier.com/locate/enbuild

Influence of residents on energy use in 57 Swedish houses measured during four winter days

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ARTICLE INFO

Article history:
Received 1 March 2012
Received in revised form 13 June 2012
Accepted 21 June 2012

Keywords:
Energy use
Electricity use
Houses
Households
Homes
Residents
Occupants
Field measurements
Indoor temperature
Water use

ABSTRACT

The aim of this paper is to contribute to the knowledge about energy use in residential buildings. Field measurements were carried out in 57 electrically heated Swedish single-family houses, where the total energy use (i.e. electricity use for space heating, household electricity and electricity use for hot water production), indoor temperatures and water use were recorded during four winter days. Some of the findings were that differences for households' total energy use of similar houses were large. The characteristics of load curves clearly differ between weekdays and weekend days. The water use differs greatly for the households. This paper is part of a larger project where time use diaries were used in order to further link the energy use to residents' every day energy related behaviours. To get a better understanding of the energy use in our homes is a prerequisite to be able to both recognise the problems as well as the potentials of reaching energy goals of our society, leading to a decreased impact on the environment from the building sector.

1. Introduction

Approximately 40% of EU's total final energy use (i.e. delivered energy) stems from residential and commercial buildings, corresponding to 36% of EU's total CO_2 emissions [1]. In Sweden, during 2009, residential buildings and commercial premises (excluding industrial premises) accounted for around 34% of the Swedish total energy use [2].

In 2007, the European Council adopted ambitious energy and climate change objectives for 2020. The objectives imply that EU greenhouse gas emissions will be reduced by 20% (compared to 1990), that 20% of EU energy use will come from renewable energy sources and that there will be 20% improvement in energy efficiency [3]. In Sweden, the targets for the building sector are to reduce the total energy use per heated area by 20% by the year 2020 and by 50% by the year 2050 (compared to the use in 1995). The dependency of fossil fuel shall not exist and the share of renewable energy use shall increase continuously in the sector [4].

To decrease the energy use in the building sector, aiming for the energy targets, is an important contribution to the reduction of the negative impact on our climate. To implement technical energy efficiency measures in our homes is one important part, however in order to exploit the full potential of reducing the energy use, we need to broaden the perspective and complement technology development with studies of needs and behaviours of the end-users – here the residents.

In Sweden the energy demand for existing single-family houses can very roughly be divided into 60% used for heating including ventilation, 20% used for hot water production and 20% used for household electricity. Newly built houses usually have a lower heat demand due to increased insulation and better air tightness of the building envelope compared to older houses. Increased heat recovery and system efficiencies also contribute to a decreased need of energy. In addition, water saving armatures might be fitted to decrease the use of hot water and energy efficient white goods might be installed to decrease the household electricity use. In the next generation of houses the total energy use will be even less, especially in regards to the heat demand of the houses. This development is illustrated in Fig. 1.

The residents of a building influence to a great deal the household electricity and the hot water usage. They also influence the energy for heating to some degree by choice of indoor temperature and window airing habits. Considering the development in Fig. 1, it implies that in newer, more energy efficient houses, the residents' influence on the energy use will become increasingly important.

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http://dx.doi.org/10.1016/j.enbuild.2012.06.030

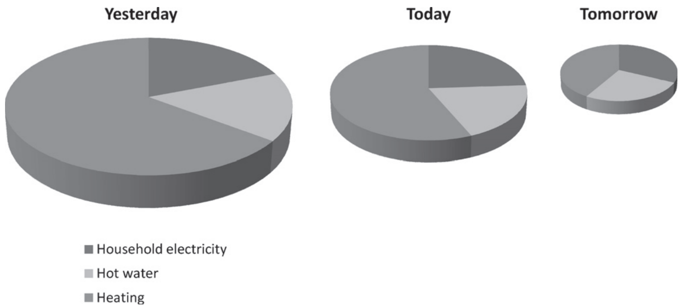

Fig. 1. Rough division of total energy use in single-family houses over time (estimation by [5]).

To get a better understanding of the real energy use in houses, field measurements are necessary. They are valuable in order to describe the reality and to find explanations to the general statistics. In order to better predict, simulate and calculate the energy use in houses, good input data is needed. Several field studies can jointly give a better picture of the reality, which this paper is contributing to.

In the overall project "Energy use in single-family houses – The significance of residents' behaviour", 57 households are participating in a time use survey. During the survey, the energy use in the participants' homes is measured. The overall goal is to use the knowledge derived to contribute, long-term, to the reduction of energy use in the residential sector. For example, the knowledge can be used to design the energy saving measures to various user profiles. This paper presents the field measurements of total energy use – including electricity use for space heating, household electricity and electricity use for hot water production – as well as measurements of indoor temperature and water use in the participating households.

1.1. Objectives

The objective of this paper is to describe, exemplify and gain knowledge of the characteristics of energy use in a number of common houses. How the energy use differs between different households in similar houses is highlighted. Measurements/readings of energy use, indoor temperature and water use are reported, which are also linked with the family composition of the households.

2. Questions

Questions that will be answered in this paper are:

- What are the characteristics of the energy and temperature curves during the measurement period for individual households?
- How does the energy use of the households differ considering that the houses originally have the same construction and building services?
- Are there any distinctions in the pattern of the load curves (mean power per hour) for weekdays and weekend days?
- How does the households' water use differ for the different households?
- Can any relationships be found between energy use and different parameters, e.g. different types of households?

2.1. Limitations

The study includes houses built on housing estates with many similar houses. The overall project was designed with both the measurements and the time use diaries in mind, which means that the measurement period was kept to four days. The measurements were made during three different periods due to personnel capacity.

3. Method

In the project, similar Swedish houses on three different housing estates have been chosen so that the constructions and building services of the houses does not differ too much. By choosing houses that originally are alike, the technical differences between the houses are limited; hence the energy use associated with the residents will become more apparent. However, changes that have been made in the houses since they were built, more than 25 years ago, still need to be considered. 57 electrically heated detached houses have been included in the project and the measurements took place during four days in the winter period – two weekdays and a weekend.

3.1. Measurements

A short description of parameters measured is given in Table 1.

Since the houses are electrically heated, the total electricity supply could be measured by connecting pulse meters to the houses' electric meters. Measurements have been feasible thanks to cooperation with the three energy companies in question. An indoor temperature sensor was set up on the entrance floor and in houses with two floors a sensor was also placed on the upper floor. The sensors were set up at centrally located walls, at about 1.1 m height from the floor. Proximity to heat source has been avoided as well as

Table 1
Summary of measurements.

Parameters measured	Description
Total energy use[a]	Measured in individual houses, presented every hour (registered every minute)
Indoor temperature	Measured for individual houses (one or two measuring points), registered every hour
Water use	Measured for individual houses, total use during the measurement period
Outdoor temperature	One measuring point per housing area, registered every hour

[a] This means the electricity use for space heating, household electricity and electricity use for hot water production.

walls that are exposed to intensive solar radiation. A sensor measuring the outside temperature was mounted on a pole, on 2–3 m height, in each housing area. The sensor was protected so that it was not affected by solar radiation, wind and rain. The use of water during the four days has been recorded by reading the water meters in each house. One reading was made at the start of the time use survey and one at the end of the survey.

3.2. Measurement uncertainties

The measurement uncertainty for the temperature measurements carried out was estimated to be better than ±0.5 °C for the sensors used, including calibration performed at the Energy Technology Department, SP Technical Research Institute of Sweden. This measurement uncertainty concerns only the temperature at the position where the sensor has been placed. The uncertainty regarding the mean temperature on an entire floor of a building is larger and can be estimated to ±1 °C [5]. The measurement uncertainty of the measurements of the energy use was estimated to approximately ±4%[1] [6]. The measurement uncertainty for common water meters in residential buildings is around ±4% at normal usage[2] [7–9].

3.3. Selection of houses

The three groups of houses included in the project were considered to represent "common houses". Electrically heated houses were chosen so that their energy use would be easy to measure. The houses were built in the 80s after the Swedish building regulations on energy use came into force after the so called oil crisis 1973–74. The findings can therefore be considered legitimate for modern houses. In addition to these criteria, the three housing areas were selected due to that there existed 30–40 houses of the same type, which were nominally built in the same way, within each area. Thus, the households' energy use could be compared without taking into account the buildings' design. The houses were also detached so that their energy use could be associated with an individual household. Some changes have occurred in the houses over the years which nevertheless have to be taken into account. The houses were located in western parts of Sweden with a relatively mild climate. The geographic location has to do with the proximity for the researcher to the housing areas, which was necessary considering the number of visits made to the areas. Consequently, in this project, no random selection has been made but rather the factors mentioned above have been taken into consideration when choosing areas. The aim has been to show the characteristics of energy use in ordinary houses.

3.4. Procedure

In the overall project a number of steps were carried out with the intention to improve the response rate and the quality of the study. The steps included introduction letters, phone calls and home visits in order to inform residents about the project, ask for participation and to give instructions. Anonymity was guaranteed for the participants. Two more home visits were made prior to the measurement period to set up temperature sensors and to read the water meters. After the diary survey, the participants were asked to give additional information about their house and household as well as to discuss uncertainties in the diaries.

3.5. Measurement period

The survey was conducted over four days during the heating season. In order to study energy use both weekdays and weekend days, the measurements were carried out from Wednesday evening to Sunday evening. The survey was conducted during three different periods in each housing area, namely in November 2005 in area A, in December 2005 in area B and in February 2006 in area C.

3.6. Non-response analysis

In area A there were 41 houses, of which 22 participated in the project (corresponding to a response rate of 54%). In area B there were 31 houses, of which 19 participated in the project (61%). In area C there were 33 houses, of which 16 participated in the project (48%). The plan for the survey was to get as many households as possible to participate in the selected areas. Only one household out of a total of 105 potential households in the sample was not reached. It should be noted that the participation described, relates to the project as a whole, including both measurements and time use survey.

A response rate of an average of 54% for the three housing areas in the current project can be regarded as on similar levels as in other studies [10–12]. It may be emphasized that this figure refers to household level, i.e. everyone in the household must participate, and that this diary study was carried out during four days, which meant that the burden for the participants were quite large. Furthermore, there is no significant bias between those participating and those not participating in the study, when considering family composition.

4. Description of the houses and the household types

The houses within each area are shortly described in Table 2.

The original heated areas of the houses are stated in Table 2. Over the years some households have extended their houses. When the energy use per square meter is presented in this paper, the definition of A_{temp}[3] [13] in the Swedish building regulations has been used. For some houses additional spaces (areas) are heated to 10 °C or more. This additional area has been added to A_{temp} because the energy use for this heating is registered on the same electric meter.

In Table 3, the different types and numbers of households based on family composition is presented. The categorization is based on the report "End-use metering campaign in 400 households in Sweden – Assessment of the potential electricity savings"[4] [14] to allow a comparison of data. It may be clarified that the category "Families" includes couples with one or more children as well as a single parent with one or more children. Only in a few cases, are households not belonging to one of the stated categories.

[1] This figure is based on oral communication with SP Measurement Technology Department concerning general requirements for the electricity meters used in Sweden. The maximum allowable error is ±8%, but based on experience of calibration of electric meters, and considering that a large proportion of the measurement error is temperature dependent and greatest at extreme temperatures – which was not the case at the time of these field measurements – ±4% is a reasonable assessment of the measurement uncertainty for a large variety of meters. The measurement uncertainty for some individual meters/brands may be less, maybe down to ±2% [6].

[2] 4% is in accordance to the Swedish regulations and guidelines concerning periodic inspections of water and heat meters in field [7], which is based on the EU directive on measuring instruments [8]. Experiences of water meters and related reasonable figures have been discussed with Åke Eriksson [9].

[3] A_{temp} is the "floor area in temperature-controlled spaces intended to be heated to more than 10°C, enclosed by the inside of the building envelope (m^2)" [13].

[4] The Swedish Energy Agency's study on improving energy statistics for dwellings and commercial buildings included an end-use electricity metering campaign of 400 Swedish households, of which 199 lived in single-family homes.

Table 2
Short facts about the houses in area A, B and C.

Houses of area	A	B	C
Type of house	Detached one-storey single-family houses	Detached 1½-storey single-family houses	Detached 1½-storey single-family houses
Construction	Wooden framework. Foundation is concrete slab on ground	Wooden framework. Foundation is concrete slab on ground	Wooden framework. Foundation is concrete slab on ground
Heated area	104 m^2 (22 houses)	130 m^2 (13 houses), 132 m^2 (6 houses)	122 m^2 (9 houses), 121 m^2 (6 houses), 120 m^2 (1 house)
Year of construction:	Middle of 1980s	1980/1981	First half of 1980s
Heating system[a]	Waterborne electric heating (electric boiler)[b]	Direct electric heating[d]	Waterborne electric heating (electric boiler)[e]
Ventilation system	Mechanical exhaust ventilation system[c]	Mechanical supply and exhaust ventilation system with heat recovery	Mechanical supply and exhaust ventilation systems with heat recovery
Windows	Triple-glazing	Triple-glazing	Triple-glazing
Thermal insulation:			
Walls	170 mm mineral wool	145 mm mineral wool	170 mm mineral wool
Foundation	70 mm cellular plastic	50 mm mineral wool	70 mm mineral wool
Attic	120 mm + 230 mm glass wool (loose fill)	220–250 mm mineral wool	250 mm mineral wool

[a] Heating system equipped with central control system with the ability to regular temperature setbacks.
[b] An air to air heat pump has been installed in one house and an exhaust air heat pump for both heating and hot water heating has been installed in another, according to the house owners.
[c] One house owner stated that heat recovery has been installed.
[d] One house owner stated that an air to air heat pump has been installed. One house owner stated that an exhaust air heat pump for hot water heating has been installed.
[e] Two house owners stated that air to air heat pumps have been installed. Four house owners stated that exhaust air heat pumps have been installed.

Only one "single-person" household and only five retired couples are represented in the project. The majority of households were families. The distribution of households in each type is similar to that in [14].

5. Results

Results from measurements of energy use, temperatures and water use are presented in this section.

5.1. Energy use in the houses

In Fig. 2 the total energy use per square meter heated area (A_{temp} is described in Section 4) are shown for the measurement periods (four days and nights from 18:00 Wednesday to 18:00 Sunday). Note that the field measurements took place during different months of the winter 2005/2006 in the three areas – namely during four days in November for area A, four days in December for area B and four days in February for area C.

The energy use for four days was on average for the houses in area A 2.7 kWh/m^2, for area B 1.8 kWh/m^2 and for area C 2.7 kWh/m^2. Fig. 2 shows that the energy use differed a lot among the households within each area. In area A and B it differed by a factor of two between the highest and lowest usages. For area C, the difference was even greater – the maximum energy use was three times larger than the lowest.

In Table 4 the total energy use for each household type in the three areas are given (expressed as averages).

Table 3
Categorises of participating households.

Household types		Housing area A	B	C	Sum
I	Single persons, 26–64 years	1	0	0	1
II	Single persons, 65 years and above	0	0	0	0
III	Couples without children, 26–64 years	7	3	4	14
IV	Couples without children, 65 years and above	0	5[a]	0	5
V	Families	14	11	12	37
	Total number of households	22	19	16	57
	Total number of persons	66	52	53	171

[a] One couple has been categorized as household type IV, although they are not 65, because they are close to retirement age and because one person in the household is retired (disability pension) and the other person was unemployed at the time of measurements.

5.2. Temperatures

5.2.1. Indoor temperatures

The average indoor temperature in the three housing areas were relatively similar, namely 21.0 °C for area A, 20.7 °C for area B and 20.6 °C for area C. 15 houses had an average temperature of 20 °C or below. The lowest temperature of just above 18 °C is found in household B1. Six houses had an average temperature of above 22 °C, of which three households had close to 23 °C (A5, A6, and B12). The measurement uncertainty of the temperature measurements carried out should be kept in mind when interpreting and comparing the results. Temperature differences of less than ±0.5 °C at the point of measurement are not significant. The measured temperature can be seen as an indicator of the temperature of the house. However it cannot be seen as an average temperature of the house.

5.2.2. Outdoor temperatures

During the three measurement periods the outdoor temperatures were on average −2.7 °C for area A, 3.2 °C for area B and −2.7 °C for area C. Hence, the outdoor temperature was significantly higher during the measurements in area B.

5.3. Energy use and indoor temperature

5.3.1. Energy use and average temperatures during four days

In Fig. 3, the total energy use (per unit area) during the measurement period has been plotted against the mean indoor temperature for each household in the three areas.

Fig. 3 shows that there are no strong correlation between energy use and indoor temperature even though the correlation is different for the three areas. For area B there was no correlation at all. It should be emphasized that it is the total energy use that has been

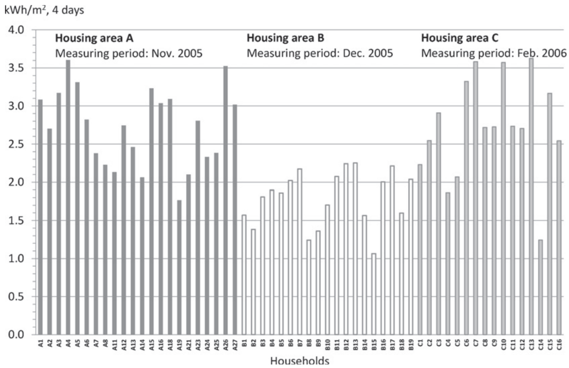

Fig. 2. The total energy use (kWh/m^2, 4 days) of the households during the measurement period (which was four days from Wednesday 18:00 to Sunday 18:00). The outdoor temperature was on average −2.7 °C for the measurement period in area A, 3.2 °C for area B and −2.7 °C for area C. The total energy use includes the electricity use for space heating, household electricity and electricity use for hot water production (the energy use has not been corrected for different outdoor temperatures).

Table 4
Total energy use (kWh/m^2, 4 days) expressed as average use for each household type during the measurement period. The total energy use includes the electricity use for space heating, household electricity and electricity use for hot water production (number of households within each subgroup are stated in brackets).

Total energy use (kWh/m², 4 days), given as average use for each group		Housing area		
Household type		A	B	C
I	Single persons, 26–64 years	2.7 (1)	0	0
III	Couples without children, 26–64 years	2.8 (7)	2.1 (3)	2.3 (4)
IV	Couples without children, 65 years and above	0	1.8 (5)	0
V	Families	2.7 (14)	1.7 (11)	2.8 (12)

measured for electrically heated houses, which means that the electricity use for space heating, household electricity and electricity use for hot water production was included.

5.3.2. Energy use and indoor temperature curves of individual households

When curves for energy use (mean power per hour) and indoor temperature of individual households were studied, some observations were made:

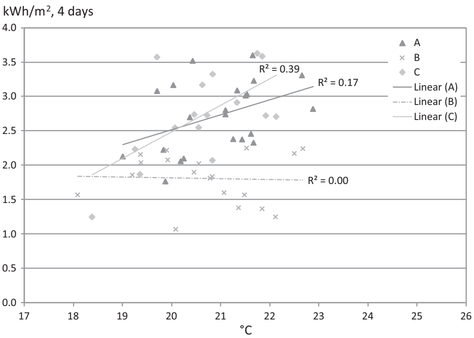

Fig. 3. Total energy use (kWh/m^2, 4 days) and average indoor temperature (°C) during four days for each household in areas A, B and C. The total energy use includes the electricity use for space heating, household electricity and electricity use for hot water production. The coefficients of determination, R^2, are given in the graph.

- 12 houses had very uniform indoor temperatures during the measurement period – both on the bottom and the top floors. Four of these houses had nearly constant indoor temperature with variations less than 0.5 °C. This was e.g. the case for household A15, see Fig. 4.
- Varying indoor temperatures were found in 11 houses. Varying energy usages were found in all but one of these houses as well. This was e.g. the case for household B9, see Fig. 5.
- For a few houses, sudden changes in indoor temperature and/or in the use of energy could be observed.

Furthermore, regular temperature setbacks were apparent in some houses. However, the setbacks were generally not very large, which may contribute to that houses with regular temperature setbacks did not stand out as households with low energy use.

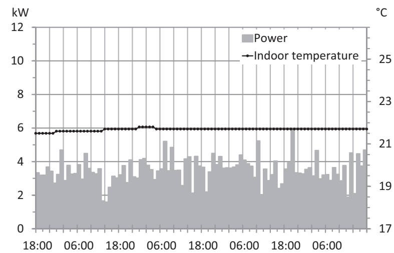

Fig. 4. Mean power per hour (kW) and indoor temperature (°C) during four days for household A15.

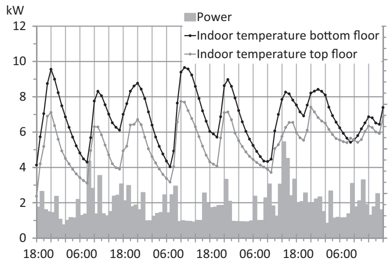

Fig. 5. Mean power per hour (kW) and indoor temperature (°C) during four days for household B9.

In many houses, the energy use seldom or never fell below a certain basic load. For several houses in area A this level appears to be around 2 kWh. For households in area B, it varies a bit from 1 to 1.5 kW and over. In area C there are a number of households that had a base load at around 2 kW and over.

5.4. Load curves on group and household level

The graphs in this section show the characteristics of load curves during the measurement period, presented for the different days (Thursday, Friday and Saturday). Data are aggregated on housing area level as well as for different household types in order to show the power peaks for these groups. Examples are also given from individual households.

5.4.1. Load curves on group level

The load curve for all houses in area A, from Thursday to Saturday, is shown in Fig. 6. The graph shows the mean power per hour of the 22 houses in area A.

Fig. 6 shows that there were power peaks in the morning and in the evening during weekdays (here Thursday and Friday) for area A. These kinds of morning and evening peaks were most pronounced for area A. However, the difference in the load curves characteristics between weekdays and weekend days (here Saturday) was very clear in all three housing areas.

Related to family composition the patterns described above are clear for household type Families, which is also represented by the most households.

5.4.2. Load curves on household level

In Figs. 7 and 8, examples are given of the characteristics of load curves of individual households in area A.

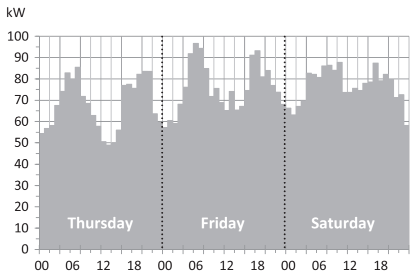

Fig. 6. Mean power per hour (kW) of 22 households in area A, Thursday–Saturday.

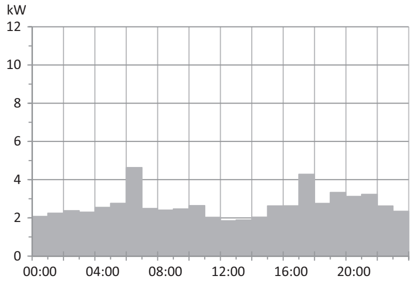

Fig. 7. Example of the characteristics of a load curve of one household (A2) in area A on a weekday (Thursday), expressed as mean power per hour (kW).

Regarding the load curves of individual households, there were some peaks "here and there", as for the household (A2) shown in the figures. It is difficult to see clear patterns, or any distinction between weekdays and weekend days, for individual houses of all three housing areas in this project.

5.5. Energy use and household size

There was no correlation between the energy use per unit area and the number of persons in a household. As has already been pointed out; it is the total energy use that has been measured for electrically heated houses, which means that the electricity use for space heating, household electricity and electricity use for hot water production was included. The number of people mainly affects water use and household electricity.

5.6. Water use during the measurement period

Average uses of hot and cold water were similar for the three areas and the mean value for all households was 330 l per day. If one takes into account the number of people in the households, the average was 116 l per person and day. There are households that had very low water use during the measurement period, down to 126 l per day (equivalent to 47 l per person and day). Several households used close to 600 l per day. Calculated per person, a household with 290 l person per day was in top. This household is a single person household. Other households with high usage used 186–195 l per person and day. The graphs in Figs. 9 and 10 show

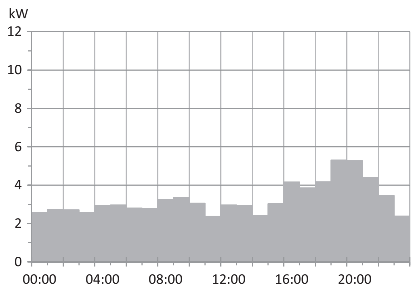

Fig. 8. Example of the characteristics of a load curve of one household (A2) in area A on a weekend-day (Saturday), expressed as mean power per hour (kW).

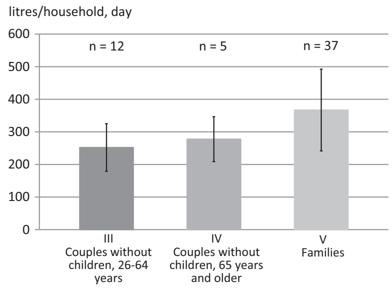

Fig. 9. Water use during four days of the households in areas A, B and C, shown as average usages for different household types expressed in litres per day. The number of households for each type is stated in the figure, as well as the standard deviation.

average water use for all households in area A, B and C of a given household type.

In the case of average water use for the different household types, the results are different dependent on if the data is presented as litres per day (Fig. 9) or litres per person and day (Fig. 10). It should be noted that the number of households within each household type was very different and for household type IV it was only five households. Families (household type V) were those that on average used most water per household, Fig. 9. This category had the largest standard deviation in its group, with a minimum use of 130 l per day and a maximum usage of 590 l per day. For household type IV the lowest use was 200 l per day and the maximum was 380 l per day. The corresponding figures of household type III was 130 l per day, respectively 370 l per day.

When instead the number of persons in the households was considered (the presence at home during the measurement period was however not taken into account), it was instead seniors (household type IV) that had the highest average water use, Fig. 10. The lowest use of this group was 102 l per person per day and the maximum was 189 l per person per day. The lowest use of household type III was 130 l per person per day and the highest was 186. The minimum and maximum usages for household type V were 47 and 195 l per person per day. The spread was about the same for the three categories reported.

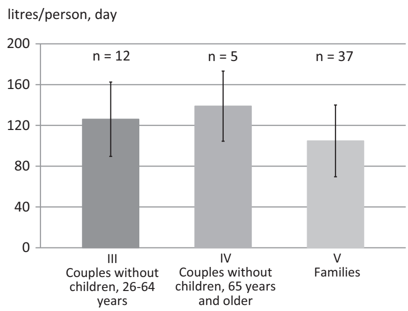

Fig. 10. Water use during four days of the households in areas A, B and C, shown as average usages for different household types expressed in litres per person and day. The number of households for each type is stated in the figure, as well as the standard deviation.

When the water use and the number of people in each household were studied, no strong correlation between water use for households and the number of persons were found. The relationship was slightly larger than that for total energy use and the number of persons (see Section 5.5). It should be noted again, that no account was taken to the presence at home during the measurement period for the people who live in the households.

6. Discussion

The results of the measurements of this paper are here summarised and discussed.

6.1. Differences between households' energy use

Differences between households' energy use within an area were found to be large. There was a factor two to three between the highest and lowest use in the houses in the three studied areas. These differences could not be explained by differences in the indoor temperatures, number of persons nor regular temperature setbacks. For the three areas the energy use revealed no correlation to household type (based on family composition). The measurements showed that families generally do not use more energy than other categories, which seems a bit surprising. Differences in residents' behaviours that influence the energy use can be assumed to be a reasonable contributing explanation for the differences in energy use, in addition to other contributing factors, such as socio-economic factors. These factors have not been evaluated in this paper. It can be added, that houses where building services have been changed according to the owner, such as the installations of heat pumps, have not on a group level shown to have lower energy use than other houses.

There are some old national and international studies that have studied differences in energy use between identical houses. A factor of two between the highest and lowest use of total energy is found [15,16]. This is also the case for gas consumption in an American study from the 70s [17]. Even earlier in the Swedish Government Official report about heat costs in rental apartments [18], the investigators state that there are great differences in energy use. Other investigations that find great differences between households' energy use are [19,20]. Some "reasonable" explanations to some part of the differences are found but they cannot fully explain them. Two recent studies show differences of 2.5 and 3 between the highest and lowest use for heating and household electricity, which cannot be explained by heated area or the number of persons in the households [21,22]. The significant role of the residents' choices and behaviours in relation to their energy use is shown in studies where the energy use of houses that have changed owner is compared before and after the change [15,16,23].

6.2. Comparison of energy use between three housing areas

The level of energy use in the three areas cannot be explained by the indoor temperature since the temperatures on average were relatively similar (between 20.6 °C and 21.0 °C). The outdoor temperature is however important, as evidenced by the lower energy use of the area B with significantly higher outdoor temperature during the measurement period.

That the energy uses on average were equal in areas A and C cannot easily be explained without studying the houses and residents in more detail. The outdoor temperatures were on average similar for the different measurement periods in these areas. The houses with mechanical supply and exhaust ventilation system with heat recovery did not show better performance than the houses with only mechanical exhaust ventilation system. A plausible explanation can be poor performance of the heat recovery units due to low temperature efficiencies from the beginning and which most likely also have deteriorated over time. The airtightnesses of the houses are not known. This is another crucial factor for the performance of the heat recovery balanced ventilation system. Another known factor that distinguishes the houses from each other is the shape; the houses in area C are two-floor houses with larger heated area, compared to the houses in area A.

6.3. Indoor temperature

The indoor temperatures were on average similar in the three areas, namely between 20.6 °C and 21.0 °C. This could be compared to the Swedish BETSI[5] study, where the measured and estimated average indoor temperature for the entire Swedish housing stock of single-family houses is found to be 21.2 °C during the heating season [24]. These results are pretty much in line with other recent Swedish field studies with measured indoor temperatures of 20.9–21.1 °C [25,26]. Preliminary, unpublished, results from the Swedish Energy Agency's study on improving energy statistics show a somewhat higher average indoor temperature of 21.9 °C during the heating season (October–April) for 98 detached single-family houses [27]. Older Swedish studies show results between 20.4 and 21.2 °C [16,28–30], which indicates that there have not been any significant change in indoor temperature over the last decades with the exception of the preliminary data from the Swedish Energy Agency's study. (It should be noted that some of the older studies include measurements performed during months outside the heating season). Examples of international measurements are two small studies of UK houses that reveal lower temperatures of 19.7–20.1 °C [31,32]. An older study in US households measured average temperatures of around 22.0 °C during the winter season [33].

6.4. Characteristics of energy and temperature curves

The energy and temperature curves had very different characteristics for the different households during the measurement period. Some houses had nearly constant indoor temperature while others had a varying indoor temperature and energy use. It is not always known whether the temperature was regularly lowered in some houses or not. For those households, where this occurred, the temperature decreases varied and were usually not very large. This could explain why the houses do not have lower energy use. One can therefore wonder what the benefits are of the temperature setbacks in the studied houses.

6.5. Load curves

Regarding load curves for groups of households, the patterns of the curves clearly differed between weekdays and weekend days. The characteristics of load curves for individual households looked very different, i.e. general patterns were only obtained on an aggregated group level. Knowledge of load curves' characteristics is very important for future smart grid applications/users where users may need to adjust their energy use so that it better agrees with the capacity of electricity production.

In the Swedish Energy Agency's study on improving energy statistics and specifically regarding the measurements carried out in single-family houses, it is seen that for families with electrically heated homes and for couples without children, 26–64 years, there are some differences in the pattern between weekdays and weekend days – there are notably more distinct power peaks on weekdays. For retired people there are no differences in household load curves between weekdays and weekend days and there are not as clear power peaks in the evening as for the other categories [14].

Generally many methods and models to produce load profiles are suggested in literature. In [34] load curves for direct electrically heated single-family houses are presented (produced by Svenska Elverksföreningen). Regardless of different outdoor temperatures and total energy use, the peaks in the mornings and evenings are clearly shown during working days, while the weekend profile is characterized by a more general increase in use during the day, reaching its highest point in late afternoon/early evening.

In two old American monitoring projects/programs, load shapes for single-family electrically heated houses are included. In one of these projects, the HVAC load shapes show distinct diurnal patterns, with heating having a distinct peak in the morning as well as a second peak in the evening [20], which are even more emphasized when the total electrical loads are studied in the other project [35]. Additionally it can be said that there are a number of publications focusing on load profiles for household electricity use. In the REMODECE database[6] the results from household electricity campaigns carried out in some European countries are found.

6.6. Water use

The water use varied greatly for the households. The average value of the total water use, i.e. including both hot and cold water usage, for all households was 330 l per day during the measurement period. This represented an average of 116 l per person daily. The maximum and minimum uses were 290 l per person and day and 47 l per person and day, which is a difference of a factor 6.2.

These values can be compared with the measurements of water use that was made in the Swedish Energy Agency's study on improving energy statistics, where the measurements in 35 single-family houses show averages of 438 l per day and 130 l per person and day [36]. The highest and lowest use is 235 and 53 l per person, which means a difference by a factor of 4.4. In older Swedish studies the daily consumption per person is found to be 154 [15], between 127–164 [37], 148 [16] and 185 [38].

Comparing to statistics compiled by Eurostat of "Use of water from public water supply by services and private households", the 2007 figure for Sweden is 142 l per person and day (52 m^3 per person and year)[7] [39,40]. Note that this figure includes the entire domestic sector, which means single- and multi-family houses as well as some services. Examples of water consumption in other countries published by Eurostat is the Norwegian figure of 214 l per person and day (78 m^3 per person and year) and German figure of 121 l per person and day (44 m^3 per person and year) [39]. The completely different figures are difficult to comment on as the facts behind the figures are not known. Figures for the US are found in the "Residential End Uses of Water Study" of 1999 which was carried out in 1188 single-family homes across the US. A rather high consumption, compared to Swedish figures at least, of 262 l per person and day is measured. This excludes outdoor water consumption but the leakages are found to be quite substantial for some houses [41].

That the water consumption can differ a lot between different households are also confirmed in other studies. The differences

[5] BETSI, stands for *Byggnaders Energianvändning, Tekniska Status och Innemiljö* (can be translated as Buildings' energy use, technical status and indoor environment) and was a project that was carried out by the Swedish National Board of Housing, Building and Planning.

[6] http://remodece.isr.uc.pt/database/login.htm.

[7] The Statistics Sweden states in a description to their latest report "Energy statistics for one and two-dwelling buildings in 2009 (ES 2011:01)" that the measurement uncertainty is too large for reported water usage and is for that reason eliminated in the national public statistics [40].

between the lowest and highest consumption (expressed as litres per day and household) of some studies is a factor of 5–6 [15,16,42] – this is when an extremely low consumption of one study has been excluded cause it lead to an extremely high factor [42]. In a UK field measurement study, a factor of 7 is found when considering the consumption in litres per day and person [21]. The average consumption of the households of this UK study was 91 l per person and day which is rather low compared to the UK national statistics which states a consumption of 146 l per person and day of English and Welsh households in 2008 [43].

Examples of studies that have analysed any relationship between water use and the number of persons in households are [15,38]. A certain, not very strong, correlation is found, which is at least a bit stronger than between energy use and number of persons. This was also the case in the present paper.

6.6.1. *Household categories and water use*

Families with children have the highest use on average per household and also the largest differences within the group. If instead the use per person is studied, families with children had the lowest use on average, while seniors represent the highest average use. The advantage of being a larger "unit" probably plays a role for the lower use for families with children and a greater presence at home also plays a role for the elderly people's higher use. However, no strong correlation with the number of people and water use was identified.

Compared with a study of the Swedish Energy Agency [36], families with children is also found to have the highest use on average (expressed in litres per day) and the largest spread is also found in this group. If one instead expresses use per capita, the use is comparable to or lower than the other categories (the division between the different household categories are similar to the distribution of the study in this paper). In the Swedish Energy Agency's study, the relationship between the number of people and water use is somewhat stronger than in the current paper.

6.7. *Application of the results*

When drawing general conclusions from the results of this paper, one can argue that only studying houses built on housing estates, with many similar houses, can be of some significance in terms of socio-economic and demographic aspects. It can also be difficult to know whether the four-day measurements were representing "normal" days in the lives of the participants. Since quite a number of households participated in the project, any exceptional events were of less significance when the material was analysed than if only a few households had participated. Finally, to measure and to understand energy use in our homes is a prerequisite to be able to both recognise the problems as well as the potentials of actually reaching energy targets, leading to a decreased impact on our environment from the building sector.

7. Conclusions

The main conclusions from the paper are:

- The differences between households' total energy use of similar houses are large, which confirms results from previous studies. That the choices and behaviour of the residents play a significant role are shown.
- The energy and indoor temperature curves have very different characteristics for the different households during the measurement period.
- The patterns of load curves for groups of households clearly vary between weekdays and weekend days.
- The water use differs even more than the energy use for the different households. In this paper a difference of a factor 6.2 is found.
- Families with children have the highest total water use on average and also the largest differences between lowest and highest use within the group. However, if the water use per person is studied, families with children have the lowest use on average, while seniors represent the highest average use.

Acknowledgments

The work is part of the project "Energy use in single family houses – The significance of residents' behaviour", which is a multidisciplinary project carried out in collaboration between the Departments of Building Physics (Professor Jesper Arfvidsson and Professor Emeritus Arne Elmroth) and Environmental Psychology (Associate Professor Thorbjörn Laike), both at Lund University, Faculty of Engineering, LTH, and the Department of Energy Technology at SP Technical Research Institute of Sweden (Ph. D. Ingemar Samuelson and M.Sc. Svein Ruud). I would like to thank all of the above mentioned supervisors for their great support. Further, I express my sincere gratitude to all the homeowners who participated in the project. It has been incredibly generous of them to open their homes so that the measurements could be carried out. The project is funded by The Swedish Research Council Formas, Region Västra Götaland and SP.

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Appendix D
Paper IV

Factors influencing residents' energy use

– A study of energy-related behaviour in 57 Swedish homes

Carolina Hiller (2015)

Published in *Energy and Buildings*. *87*, 243–252.

Errata for Paper IV

p. 199	In paper IV: p. 246, second column, last paragraph	Clarification: *Cluster* 3_n is intended with *Cluster 3*
p. 201	In paper IV: p. 249, Table 5	Misspelling: *DVD/VHC* should be *DVD/VHS*
p. 204	In paper IV: p. 251, footnote 3	Misspelling: *lightning* should be *lighting*

Energy and Buildings 87 (2015) 243–252

Contents lists available at ScienceDirect

Energy and Buildings

journal homepage: www.elsevier.com/locate/enbuild

Factors influencing residents' energy use—A study of energy-related behaviour in 57 Swedish homes

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ARTICLE INFO

Article history:
Received 10 July 2014
Received in revised form
30 September 2014
Accepted 4 November 2014
Available online 11 November 2014

Keywords:
Energy-related behaviour
Residents
Time use
Diary
Energy measurement
Cluster analysis

ABSTRACT

The aim of this work has been to study everyday energy-related behaviour in homes. All residents in 57 Swedish homes, living in three housing areas, have recorded time diaries over a period of four days, during the same time period in each area. The technical differences between the houses are limited, as the building designs within each housing area are the same. On an aggregated level, the diary data has been analysed with and without typical power data of appliances as well as in relation to measured total energy use, indoor temperature and water usage. Cluster analyses have been performed in order to find characteristics of groups of residents with regard to their energy-related behaviour. Some of the findings were that residents report long time use/operating time for activities related to electronic equipment (45% of total reported time). Residents which used energy to a greater extent than others were characterised by performing activities with long operating times, in combination with high, and fairly high, typical power ratings. The majority of residents showed many different energy-related behaviours, which indicates that a number of strategies to influence the behaviours – not just one – will be required.

1. Introduction

On the global level, the residential sector dominates energy use in the building sector, with use having increased by 32% between 1990 and 2009 (measured in joules) [1]. The equivalent figure for OECD countries is 18%. This includes a rapid increase in electricity use in all regions. At the same time, world population is increasing, and the number of households is predicted globally to grow even more, as there is a trend of fewer persons per household. Larger floor area per household is another trend in the residential sector [1].

Improved energy efficiency is one of the most important ways of reducing the negative effects of these trends, and has been so over the past decades. The energy-related behaviour of households plays an important role in realising energy-efficient measures in an effective way. This behaviour can be related to implementation and acceptance of new technology, maintenance of equipment and the use of energy. To a great extent, energy-related behaviour influences the gap between potential and actual energy efficiency levels [2].

Households' energy-related behaviour can be categorised as illustrated in Fig. 1, with different kinds of behaviour sorted by frequency and cost. It can be seen that some improvement actions occur relatively infrequently, such as replacing traditional light bulbs with low-energy bulbs or installing new seals around windows and doors. Such measures are relatively inexpensive, but their effect can be significant. Other decisions relate to more substantial improvements, usually with higher costs, and need more consideration. Examples include the purchase of refrigerators and freezers, televisions, computers or new heating systems. These purchases are usually made when the old equipment is worn out and discarded. Then there are habits and behaviours that occur on a daily basis and that often become routine. Small changes in daily activities can eventually make a big difference in energy use, often with no cost associated with these changes. Examples of this type include how laundry is dried or for how long people take in a shower. This article is mainly concentrated on these daily activities. Strategies to influence energy-related behaviour should be designed with these categories in mind [2,3].

It is generally difficult to put a specific figure on the potential savings from changed energy-related behaviour. A general estimate, often seen, is approximately 20%—however, the reference for this figure is not completely clear. In an American study, a number of common energy-saving actions related to behaviour in the 'No/low cost' category amounted to potential savings of approximately 12% [4]. In another American study, the savings are estimated to similar figures, but included transportation behaviour as well [3]. Older studies, e.g. Palmborg [5], estimate the potential

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http://dx.doi.org/10.1016/j.enbuild.2014.11.013

	Infrequent	Frequent
No/low cost	Stocktaking behaviour Energy-efficient lighting (e.g. LED) Temperature set backs Draught proofing	Habitual behaviour and lifestyles Turn off computer and other devices Air-dry laundry Take short showers Use energy-efficient washing programs
Higher cost /investment	Consumer behaviour Energy-efficient white goods/ appliances Energy-efficient windows Additional insulation Heat pumps	

Fig. 1. Households' energy-related behaviour, focused on some examples in single-family houses [3].

savings of total energy use to be about 10%. Various studies also show great variations between similar houses that cannot be explained by technical differences alone; energy behaviour is thought to contribute to the substantial differences [6–15].

This paper is part of the overall "Energy use in single-family houses—The significance of residents' behaviour" project, where 57 households participated in a diary study of everyday behaviour. The diaries recorded the time used for everyday activities in the households. In parallel with the diary keeping, energy use in the houses was measured. The overall goal is to use the knowledge derived to contribute, long-term, to the reduction of energy use in the residential sector. This paper focuses on the results from the diary study, and relates these data to measurements of total energy use in the participating households. The objective is to find out what kinds of activities characterise households' energy use. In [15] details of the measurements are presented including households' energy use, indoor temperature and water use as well as load profiles.

Time diaries have been used and analysed in other studies, particularly in projects related to people's everyday behaviour conducted by Ellegård and colleagues at Linköping University in Sweden [16–19]. However, few studies have linked energy-related behaviour with direct measurements of energy use. There are examples of studies that have combined measurements and diaries with a focus on a few activities, such as dishwashing habits [20] or lighting patterns and presence in offices [21]. There are also examples of smaller studies where hot water usage as well as electricity usage in households have been studied together with diaries in order to identify usage and load patterns visually [22,23]. Other studies use national time-use data for modelling household profiles or to develop and validate models, e.g. [24–31]. There are also studies that relate time use data or diary notes to energy issues [18,32–34] and water consumption [35–37]. However, there is a lack of larger studies which connects actual behaviour with energy measurements. There are many questions to be answered regarding the residents and their activity patterns associated with energy use. Trying to describe and explain the residents' influence is important for energy planning and in order further to study different types of behaviour profiles. The project mainly complements previous studies, in which only a few households have participated, and focuses on differences between households where the construction and building services systems of the houses are similar.

1.1. Research objectives

The objective of this paper is to find characteristics of energy use in houses. How and in what way the energy use differs between different households in similar houses is specifically highlighted. The paper is focused on explanatory factors related to family composition, behaviour and other household-related factors.

Table 1
Categories of participating households.

Household types		Housing area			Sum
		A	B	C	
I	Single persons, 26–64 years	1	0	0	1
II	Single persons, 65 years and above	0	0	0	0
III	Couples without children, 26–64 years	7	3	4	14
IV	Couples without children, 65 years and above	0	5[a]	0	5
V	Families	14	11	12	37
Total number of households		22	19	16	57
Total number of persons		66	52	53	171

[a] One couple has been categorised as household type IV, although they are not 65, because they are close to retirement age and because one person in the household is retired (disability pension) and the other person was unemployed at the time of measurement.

1.1.1. Research questions

Questions that will be answered in this paper are:

1. What everyday energy-related behaviour is performed in homes? And for how long?
2. Can common characteristics be identified between different types of consumers?

1.2. Limitations

The main limitations of the study are:

- Only houses built on housing areas with several similar houses are included.
- Only total energy used is measured.
- The measurements are made during three different periods for the three housing areas.

2. Material and methods

2.1. Houses and residents

The three groups of houses included in the project were considered to represent "common houses", all built in the 1980s. Electrically-heated detached houses were chosen, so that their energy use would be easy to measure and could be associated with each individual home. Within each housing area, the houses were nominally built in the same way—thus the households' energy use could be compared without having to take the buildings' design into account. The houses are further described in [15].

57 households living in the three housing areas participated in the study. In total, the households comprised 171 family members, whereof 134 were 12 years old or above, and were asked to write individual diaries. In the end, 141 persons wrote diaries for four successive days (a number of children younger than 12 wanted to participate and two couples wrote only one diary instead of two individual diaries), which means 564 diary sheets were completed (four days and nights).

Table 1 shows the different types and numbers of households based on family composition. The categorisation is based on the report "End-use metering campaign in 400 households in Sweden—assessment of the potential electricity savings" [38]. It should be clarified that the category "Families" includes couples with one or more children as well as a single parent with one or more children. In a few cases, households do not belong to one of the stated categories.

Table 2
Diary sheet used in the study (translated).

Time start	Time end	What am I doing?	Use of equipment, lighting or hot water	Where?	Comments
			- Household appliances - Lamps (including number of lamps) - Other electronic equipment - Regulating temperatures (radiators) - Hot water usage	- Which room in the house - Garage - Storage - Garden	

One "single-person" household and five retired couples are represented in the project. The majority of households were families. The distribution of households in each type is similar to that in [38].

2.2. Measurement period

The study was conducted over four days during the heating season. In order to study energy use covering both weekdays and weekend days, the measurements and time diaries were carried out from Wednesday evening to Sunday evening. The study was run during three different periods in each housing area: namely in November 2005 in housing area A, in December 2005 in area B and in February 2006 in area C.

2.3. Time diaries

The diary used was designed as a structured diary, with headings as shown in Table 2. The headings were decided on after investigating previous time use studies [19,23].

The instructions were to write down everyday activities carried out while at home, and to do this over the course of the four days. This meant that each individual has recorded what activities they performed, how and when. Younger children's activities were recorded in their parents' diaries.

2.4. Measurements

While the participating residents kept diaries, each household's total energy use was measured continuously. The indoor and outdoor temperatures were recorded every hour during the four days. In addition, each household's water use was registered. The results from the measurements, including load profiles, are described in more details in [15].

2.5. Procedure

The approach, and specifically the use of time use diaries, is based on a number of sources, such as Ellegård and Wihlborg [19], Sernhed [23], Eurostat [39,40], Rydenstam and Wadeskog [41], and Japec et al. [42], Ellegård and Nordell [16], Sommer and Sommer [43], U.S. Census Bureau [44,45] and discussions with Statistics Sweden's Molén [46].

A number of steps were taken with the intention of improving the response rate and the quality of the study. They included introduction letters, phone calls and home visits in order to inform residents about the project, to ask for participation and to give instructions. During a first home visit, instructions were given orally and in writing to as many family members as possible. An example of an already filled-in diary was shown. Confidentiality was guaranteed for the participants and each person was given an individual code. Two additional home visits were made prior to the measurement period to install temperature sensors and to read the water meters. Before the diary study was started, the instructions and the diary sheets were tested on a number of persons of different ages to see if the method and the directives were user-friendly. After the diary study, the participants were asked during a final home visit to give additional information about their house and household, and also to discuss any uncertainties in the diaries.

2.5.1. Processing of diaries

The diary notes were sorted and categorised using a number of variables, representing certain energy-related behaviours. For each variable, the total time spent doing the activity for the whole household (i.e. all family members) was entered. For certain activities, the number of times that the activity was carried out was given instead, i.e. the frequency.

The variables were categorised under certain themes, related to previous literature (e.g. [47]). The themes were Cooking/Kitchen, Personal Hygiene, Clothes Care, Comfort and Electronics. There were also 'Others' and 'Presence at Home' categories. All uncertainties and missing values in the diaries were well documented and thereafter assessed and dealt with in a systematic way. Missing values were handled by using valuable information given at the home visits or by estimates from previous occurrences. In some cases, the uncertainties or gaps in the diaries were left and no data was filled in. This processing was carefully noted. Additionally, there were certain activities/information that could not be processed as the data quality was poor: these include lighting, stand-by electricity use and other constantly-plugged-in electronic devices, use of fireplaces, visits to toilets, etc.

It should be noted that in this paper the term 'Time Use' is used as a general term for the data derived from the diaries. In some cases, a more correct term would be to refer to the 'Operating Time' of appliances.

2.5.2. Interrater reliability test

An interrater reliability test was performed in order to evaluate interpretation of the diaries. The ordinary rater instructed the test rater in the procedures of interpreting the information in the diaries. Five cases have been tested and evaluated. The correlations of the results from the two raters were calculated using ReCal, which is an online interrater reliability web service[1]. The correlation values were in the range of 0.57–0.83 (Krippendorff's alpha [interval])[2]. This corresponds to agreements of 32–69% between raters. These percentages are satisfactory, meaning that the interrater reliability is acceptable, although the lowest value of 32% indicates only moderate agreement. The other values indicate substantial agreements.

2.5.3. Forming groups—Cluster and other analyses

A general description of the diary data has been compiled and presented for the three complete days—Thursday, Friday and Saturday. Cluster analyses were then performed in order to group residents according to their energy-related behaviour and explore similarities within a group as well as dissimilarities between groups. Data were used from 21:00 on Wednesday to 17:00 on Sunday.

In a first step, a hierarchical clustering was applied using Ward's method with the measure of Euclidean distances. In a second step, a *K*-means cluster method was used to see if the suggested hierarchical cluster solution could be improved. As the data for the different variables differ greatly the analyses were performed twice; once with non-standardised values (no data preparation), and once with

[1] ReCal can be found at http://dfreelon.org/utils/recalfront/ (October 2011).
[2] Krippendorff's alpha (interval) [48].

transformed values to a standardised scale (by z-scores). In a third step, one-way analysis of variance (ANOVA) was carried out in order to examine how the clusters differ. In addition to the 44 variables listed in Table 5, total measured energy use and energy groups (described below) were also tested. In a final step, the effects of background factors (here, housing areas and household types) on the cluster solutions were tested by performing chi-squared tests. The IBM SPSS Statistics (Version 21) software was used for the statistical calculations.

This procedure was then repeated for estimated energy data, which was obtained by using the diary data and converting this data to energy use by using typical power values and formulas, found in a number of Swedish references, such as [23,49–53].

Most of the variables previously tested were also included in this analysis. Exceptions were the use of printers (no power data found for actual usage, only standby mode) and washing clothes by hand. In addition, the Presence at Home, Number of Persons, Indoor Temperature and Water Use data variables were not converted to a standard energy use; they were tested separately for the suggested cluster solution.

Finally, another grouping was constructed from the energy usages of the households. The households were divided into three groups – low (1), medium (2) and high (3) consumers – based on a frequency analysis, where quartiles, median and typical values of energy use were considered. The sizes of the groups were roughly the same. This was done separately for each housing area, as the energy use had not been adjusted for different outdoor temperatures.

3. Results

3.1. Compilation of diaries—Obtained time use for different behaviours

Frequencies and averages are presented for a number of activities, which means a description of what energy-related behaviours are carried out and for how long (expressed in hours or minutes per day). Most of the data are presented as averages per household.

3.1.1. Time spent at home

The daily average time spent at home per person was 14.9 h on Thursdays and Fridays. On Saturdays, the corresponding figure was 17.8 h. Considering an entire week, the estimated presence at home was therefore 15.7 h per day.

3.1.2. Overall time use data related to energy use

Fig. 2 shows that the usages differed for the different days for the various categories (activities included in each category are listed in Table 5). There is an increase in activities on Saturday for all categories except for the Others category, where it was the opposite, having the most activity on Thursday instead. Fridays usually had fewer reported activities than Thursdays.

In Table 5, averages for a number of activities given in the diaries are listed. As can be seen, there were activities that were performed by several households. Others showed very low values, as they were performed for very short times and/or were performed by few households. Activities belonging to the Electronic category are illustrated in more detail in Fig. 3.

Fig. 3 shows that TV use was the dominant activity, mostly on Saturday, followed by Thursday and Friday. Other activities with long usage, included the use of computers, followed by stereo/radio. This equipment can be turned on for long periods without really being actively used all the time.

Table 5 shows detailed data for the other categories. It can be seen for the Cooking/Kitchen category that fans were the devices used for the longest time. As far as differences between days are concerned, the use of cooking stoves on Saturday stand out in comparison with stove usage on Thursday and Friday. Not much time was reported on activities to do with Personal Hygiene. Taking a shower was the most frequent activity related to Personal Hygiene. The opening of windows (airing) was one comfort-related activity that could be based on information from the diaries, but unfortunately this activity was irregularly reported. The time spent on Clothes Care that was related to energy was little in comparison with other activities. The tumble dryer was the appliance used the most, together with the washing machine. Finally, it can be seen that a substantial amount of time was spent on variables in the Others category.

3.2. Cluster analyses and ANOVA

The following cluster solutions are described in this section:

- Cluster solution with diary data (standardised values in minutes)
- Cluster solution with diary data (non-standardised values in minutes)
- Cluster solution with diary and power data (standardised values in Wh)

Last, a grouping based on low, medium and high energy use is presented.

3.2.1. Cluster analyses of diary data—Using standardised and non-standardised values

Three cluster solutions were identified, both in case of using standardised (Cluster 1_s–Cluster 3_s) or non-standardised (Cluster 1_n–Cluster 3_n) values, further specified in Table 3. Note that two of the households were not included, as their water usage data were incomplete.

The results for the analysis of variance are listed in Table 6—both for standardised and non-standardised values. 17 and nine of the 44 tested variables showed significant differences between the clusters (p-value ≤ 0.05). Presence at home, number of persons in the household and water usage (in litre/household, day) were variables that were significant in both the standardised and non-standardised analysis.

ANOVA results also showed that energy use differed between the clusters with the standardised values (p-values ≤ 0.05). This concerns both the total energy use – uncorrected for different outdoor temperatures (with values of 2.9 kW h/m^2 for Cluster 3_s, compared to 2.2 kW h/m^2 for both Cluster 1_s and Cluster 2_s) – as well as the three groups of Low, Medium and High usage (with Cluster 1_s having an average group value of 1.7, 1.8 for Cluster 2_s and 2.6 for Cluster 3_s). It was found that the average usage was higher for the eight households of Cluster 3_s. These households have reported a higher use of engine preheaters, electric clocks, fans, hair tongs, sewing machines and airing and hand-washing of dishes than the rest (Table 6). A number of activities included in the Others category were also performed by some of the households in this cluster, e.g. the usage of electric jigsaws, sandwich toasters, and extra electric radiators that were turned on constantly. As can be seen in Table 3, these households consisted, on average, of 3.3 persons per household, and many were families. They had an average indoor temperature of 21.0 °C.

The households of Cluster 1_s showed much lower values for presence at home, number of persons in the household and water usage (in litre/household, day) than the other two clusters (Table 6).

Energy use did not differ between the clusters with the non-standardised values (p-value >0.05). The households of Cluster 3 stood out as the cluster with generally longer usage time for a number of variables such as the use of TV, computer, electric kettle and dishwasher (Table 6). These households also spent longer

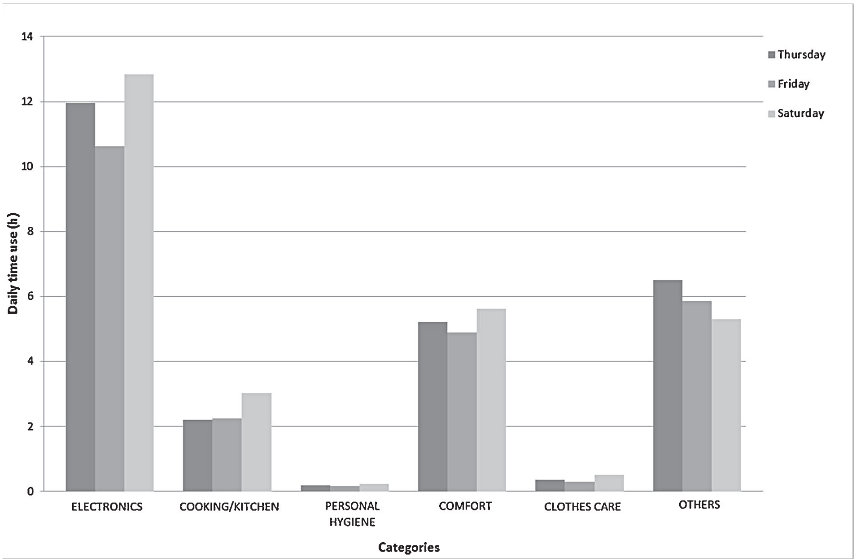

Fig. 2. Daily time use related to energy use for an average household, illustrated as total time use summed up for all appliances turned on or all activities performed. Data derived from diaries and expressed in hours. Shown for different categories of variables for three complete days–Thursday, Friday and Saturday.

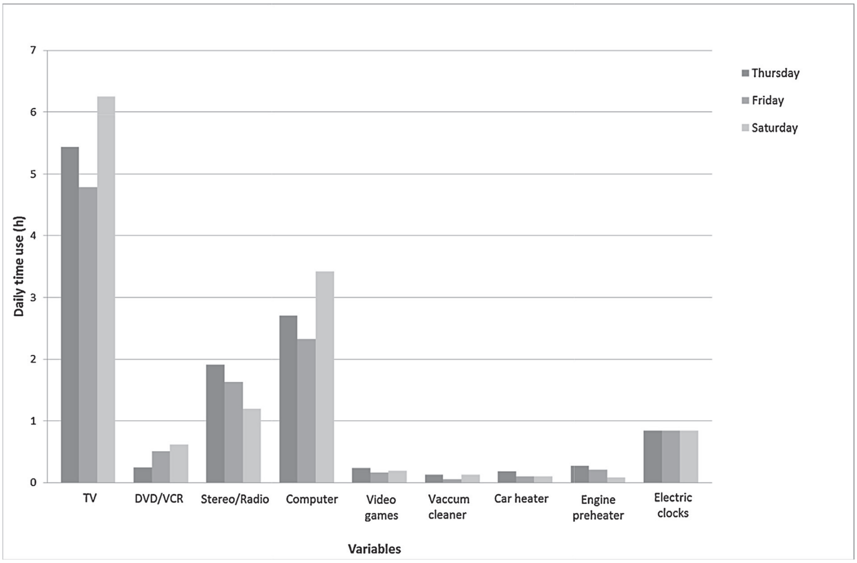

Fig. 3. Daily time use related to energy use for an average household, illustrated as total time use summed up for all appliances turned on. Data derived from diaries and expressed in hours. Shown for different variables for the Electronics category for three complete days–Thursday, Friday and Saturday (note different scale compared to Fig. 2).

Table 3
The characteristics of cluster solutions with standardised and non-standardised of diary data values.

Cluster solutions		No. of households	Average no. of persons	Household types (no. of households)					Housing areas (no. of households)			Average indoor temperature (°C)
				I	II	III	IV	V	A	B	C	
Standardised	Cluster 1_s	18	2.2	1	0	7	3	7	7	6	5	20.7
	Cluster 2_s	29	3.5	0	0	3	2	24	11	12	6	20.7
	Cluster 3_s	8	3.3	0	0	2	0	6	2	1	5	21.0
	SUM	55	–	1	0	12	5	37	20	19	16	–
Non-standardised	Cluster 1_n	24	2.1	1	0	12	5	6	8	10	6	20.5
	Cluster 2_n	23	3.5	0	0	0	0	23	10	7	6	20.8
	Cluster 3_n	8	4.5	0	0	0	0	8	2	2	4	21.1
	SUM	55	–	1	0	12	5	37	20	19	16	–

time on average on washing dishes by hand. Moreover, they spent more time at home (presence), they consisted of a greater number of persons per household, and they had higher water usage (in litre/household, day).

With regard to the background factors of housing area and household type, no significant differences between the clusters were shown for the standardised solution according to the chi-squared tests (p-values >0.05). For the non-standardised solution, significant differences were found for household types (p-value <0.05), but not for housing area. Table 3 shows household types.

3.2.2. *Cluster analysis of diary data and typical power values—Using standardised values*

A three cluster solution was found using standardised power values (Cluster $1_{p,s}$–Cluster $3_{p,s}$), further specified in Table 4. The analysis with non-standardised values gave no relevant clusters.

The results of the ANOVA are shown in Table 6. Twelve of the 36 tested variables showed significant differences between clusters (p-value $\leq$0.05). These were TV, car engine preheater, car heater, kitchen fan and other fans, food processor, airing, floor heating, tumble drier and sewing machine. In addition, three variables belonging to the category of Others showed significant differences. Seven of these twelve variables showed a higher average for Cluster $3_{p,s}$ (Table 6). This meant that there was a small group of households (7) that had a substantially higher average usage of energy for heating their cars before driving (car heater and engine preheater), turning on fans and habits of airing. In addition, some of the households in Cluster $3_{p,s}$ used jigsaw, electric hedge trimmer, sandwich toaster, sauna and extra radiator, included in the Others category. In addition, the Presence at Home, Number of Persons and Water Usage (in litre/household, day) variables were significant for this specific cluster solution, where Cluster $1_{p,s}$ stood out with much lower values on average compared to the other two clusters.

The cluster solution differs regarding energy use – the variance analysis showed significant differences between the clusters (p-values $\leq$0.05). This regards both the total energy use – uncorrected for different outdoor temperatures – (with values of 2.2 kW h/m^2 for Cluster $1_{p,s}$, 2.3 kW h/m^2 for Cluster $2_{p,s}$ and 3.1 kW h/m^2 for Cluster $3_{p,s}$), as well as the three groups of Low, Medium and High usage (with Cluster $1_{p,s}$ having average group values of 2.2, 1.6 for Cluster $2_{p,s}$ and 2.6 for Cluster $3_{p,s}$). Cluster $3_{p,s}$ had the highest average usage.

With regard to the background factor of housing area, the chi-squared test (p-value <0.05) showed significant differences for this cluster solution. Table 4 shows the distribution regarding housing area. On the other hand, the household types did not show any significant differences between clusters.

3.2.3. *Grouping of low, medium and high usage*

The variance analysis showed that only the usage of food processors differed between Low, Medium and High consumers, both for standardised and non-standardised values (p-value <0.05).

4. Discussion

4.1. *Residents' energy-related behaviour*

The main findings of the studied residents' daily energy-related activities are that the appliances/activities that belong to the Electronics category account for the greatest time use (45% of total reported time), of which using the TV is the most common activity. It can also be seen that for most energy-related activities there is an increase in time use during the weekend compared to week-days. Personal Hygiene and Clothes Care are those categories on which less time is spent with regard to energy-consuming behaviour.

4.2. *Typical activities of energy consumers*

The main findings of the cluster analyses are here discussed. Based on diary data on time use or operating times, the eight households that have a higher average energy use are characterised by spending more time or longer operating time on car engine preheaters, airing and having extra electric radiators—to mention the activities using the most energy (referring to the solution Cluster 1_s–Cluster 3_s with diary data and standardised values in minutes).

Although there seems to be some influence of to which housing area the households belong, it can be seen, based on estimated energy data, that the seven households having a higher average

Table 4
The characteristics of cluster solution with standardised values of diary data and typical power values.

Cluster solutions		No. of households	Average no. of persons	Household types (no. of households)					Housing areas (no. of households)			Average indoor temperature (°C)
				I	II	III	IV	V	A	B	C	
Standardized	Cluster $1_{p,s}$	30	2.6	1	0	10	4	15	14	9	7	20.6
	Cluster $2_{p,s}$	20	3.6	0	0	2	1	17	6	10	4	20.9
	Cluster $3_{p,s}$	7	3.3	0	0	2	0	5	2	0	5	21.1
	SUM	57	–	1	0	14	5	37	22	19	16	–

Table 5
Average time (mean) for a number of activities, expressed as minutes or number of times (frequency) during a day[1]. The figures in brackets state the number of households performing the activity. Presentation for Thursday, Friday and Saturday.

Activity (variable)	Average time spent on a number of activities (minutes per day) *Note, for a number of activities, the frequency is stated (times per day)* In brackets: no. of households performing the activity		
	Thursday	Friday	Saturday
Electronics			
1 TV	326(55)	287(53)	375(53)
2. Computer	162(37)	140(32)	205(31)
3. Stereo/radio	115(24)	98(21)	72(26)
4. Electric clocks	51(2)	51(2)	51(2)
5. DVD/VHC	15(8)	30(12)	37(13)
6. Video games	14(4)	10(2)	12(3)
7. Engine preheaters	17(7)	13(8)	5(3)
8. Car heater	11(6)	6(6)	6(2)
9. Vacuum cleaner	8(17)	3(12)	8(18)
10. Printer (times per day)	0(1)	0(2)	0(1)
Cooking/Kitchen			
11. Kitchen fan and other fans	66(22)	60(19)	71(29)
12. Stove	22(36)	22(37)	45(48)
13. Coffee machine	21(31)	28(32)	30(42)
14. Oven	14(13)	17(13)	20(16)
15. Microwave	4(46)	5(37)	4(37)
16. Hand wash (dishes)	5(24)	3(16)	7(26)
17. Toaster	0(2)	0(3)	3(7)
18. Electric mixer	0(3)	0(0)	0(0)
19. Electric kettle (times per day)	0.7 (21)	0.6 (19)	0.5 (16)
20. Dish-washer (times per day)	0.4 (21)	0.3 (17)	0.4 (21)
21. Food processor (times per day)	0(1)	0(1)	0.1 (3)
Personal hygiene			
22. Shower	9(45)	8(39)	12(41)
23. Hairdryers	1(15)	2(21)	1(12)
24. Curling tongs or straighteners	1(5)	0(4)	1(3)
25. Bathing (times per day)	0(3)	0(3)	0(3)
Comfort			
26. Towel dryer	134(8)	137(8)	142(8)
27. Airing	101(20)	81(17)	120 (22)
28. Floor heating (comfort)	77(4)	76(3)	76(3)
Clothes care			
29. Tumble-dryer	16(10)	14(9)	21(14)
30. Iron	2(5)	3(7)	9(10)
31. Drying cupboard	16(2)	14(0)	21(1)
32. Hand washing	0(2)	0(2)	0(1)
33. Sewing machine	1(1)	0(0)	1(2)
34. Washing machine (times per day)	0.5 (22)	0.6 (24)	0.8 (30)
Others[2]			
35. Very low power (<100 W)	236(16)	192(13)	170(17)
36. Low power (100–500 W)	77(7)	79(11)	62(9)
37. High power (500–1000 W)	0(1)	0(2)	0(1)
38. Very high power (>1000 W)	77(5)	79(5)	86(9)
39. Changes (times per day)	0.3 (9)	0.2 (6)	0.2 (8)
Further variables			
40. Presence	–	–	–
41. No. of persons	–	–	–
42. Water use (l/household, day)	–	–	–
43. Water use (litre/person, day)	–	–	–
44. Indoor temperature (°C)	–	–	–

[1] Note that if multiple devices are used at the same time in a household, these are still entered for the same variable, which represents a certain device/activity and a certain hour of the day. This means that the number of minutes can be summed up to more than 60 min for a variable. For this reason, the number of minutes stated in the table can seem unreasonable if one forgets that they represent all devices that are used for a certain activity of a whole household.
[2] Others include four variables that are based on the possible power usage of the activities in question. There is also a variable called changes that include changes that have been performed during the diary period that might have an influence on the energy use, i.e. changing settings for boiler/water heater, heat pump, power cut, blown fuse.

energy use are characterised by using more energy on engine preheaters, car heaters, fans, airing and additional radiators than the other households on average. One can further see that these activities generally have long operating times, in combination with high power ratings (referring to the solution Cluster $1_{p,s}$–Cluster $3_{p,s}$ with diary and typical power data with standardised variables in Wh). It can be added that six households belonging to Cluster 3_s and Cluster $3_{p,s}$ are identical.

In addition, presence at home, number of persons in the household and water usage (in litre/household, day) are variables that stand out as characteristics of certain groups. Particularly those with lower values for these variables stand out (Cluster 1_s and

Table 6
ANOVA results showing significant differences (p-value ≤ 0.05) between the different activities performed by households in suggested clusters—shown for three different cluster analyses. Average values for each cluster are also shown.

Activity (variable)	Cluster analysis of diary data. ANOVA results, variables (activities) with p-value ≤ 0.05								Cluster analysis of diary data and typical power values, p. ANOVA results, variables (activities) with p-value ≤ 0.05. Standardised values, s			
	Standardised values, s				Non-standardised values, n							
	Significance level	Cluster 1_s	Cluster 2_s	Cluster 3_s	Significance level	Cluster 1_n	Cluster 2_n	Cluster 3_n	Significance level	Cluster $1_{p,s}$	Cluster $2_{p,s}$	Cluster $3_{p,s}$
		Mean of z-scores (−)				Mean values (units in left column)				Mean of z-scores (−)		
1. TV (minutes per day)					0.002	992	1409	1812	0.054	−0.25	0.43	−0.17
2. Computer (minutes per day)					0.007	325	811	1306				
4. Electric clocks (minutes per day)	0.001	−0.19	−0.19	1.16								
7. Engine preheaters (minutes per day)	0.004	−0.12	−0.20	1.07					0.000	−0.20	−0.27	1.61
8. Car heater (minutes per day)									0.001	−0.21	−0.14	1.30
11. Kitchen fan and other fans (minutes per day)	0.036	−0.11	−0.17	0.84					0.009	−0.06	−0.28	1.03
12. Stove (minutes per day)	0.019	−0.48	0.35	−0.05								
14. Oven (minutes per day)	0.004	−0.50	0.43	−0.33								
16. Hand wash (dishes) (minutes per day)	0.019	−0.49	0.14	0.59	0.020	15.0	20.8	49.0				
19. Electric kettle (times per day)					0.006	2.4	1.6	6.0				
20. Dish-washer (times per day)					0.006	1.2	1.9	4.3				
21. Food processor (times per day)									0.016	−0.34	0.47	0.12
22. Shower (minutes per day)					0.029	31.0	47.9	38.5				
24. Curling tongs or straighteners (minutes per day)	0.000	−0.32	−0.14	1.32								
27. Airing (minutes per day)	0.011	−0.15	−0.21	0.91					0.000	−0.09	−0.35	1.39
28. Floor heating (comfort) (minutes per day)									0.052	−0.23	0.43	−0.23
29. Tumble-drier (minutes per day)									0.003	−0.38	0.57	−0.00
30. Iron (minutes per day)	0.039	−0.33	0.34	−0.37								
33. Sewing machine (minutes per day)	0.024	−0.19	−0.12	0.90					0.009	−0.12	−0.19	1.05
34. Washing machine (times per day)	0.004	−0.50	0.41	−0.33								
36. Low power (100–500 W) (minutes per day)									0.035	−0.26	0.46	−0.18
37. High power (500–1000 W) (minutes per day)	0.005	−0.24	−0.12	1.05					0.000	−0.20	−0.24	1.52
38. Very high power (>1000 W) (minutes per day)	0.000	−0.22	−0.24	1.42					0.000	−0.23	−0.24	1.67
39. Changes (times per day)	0.001	0.72	−0.32	−0.43								
40. Presence (minutes per day)	0.000	−0.84	0.49	0.32	0.000	7805	12859	19321	0.003	−0.42	0.50	0.35
41. No. of persons	0.000	−0.81	0.50	0.24	0.000	2.1	3.5	4.5	0.002	−0.42	0.53	0.28
42. Water usage (l/household, day)	0.000	−0.83	0.47	0.17	0.000	262	372	431	0.039	−0.33	0.33	0.39

Cluster $1_{p,s}$). However, this is not clearly shown as the reason for low energy use.

4.3. Comments on the method used

Self-reported methods, such as diaries, are characterised by the fact that writers of the diaries will document what they think to be relevant, which will vary from person to person. There is therefore subjectivity in the actual data collection. The level of details given in the diaries also varies. The diversity of energy-related activities can be hard to capture and report in a diary format. One example is lighting, which can be of significance[3]. To minimise any obstacles of writing or misunderstandings, simplicity is prioritised in the design of the diary. If the diary study was to be repeated today, the use of digital tools would have been considered.

The question of standardising data or not has to be considered for data sets where variables that are to be compared are of different magnitudes or have very different variations. To use standardised scales can even out these differences. However, the drawback is that some variables can be given too much weight in the analysis. For that reason, analyses were made using both standardised and non-standardised values.

4.4. Application of the results

The study was performed over four days. In order to represent "normal days", a large number of households participated in the study, with the result that exceptional circumstances have lesser effect on the results than would be the case if only a few households had participated. To gather variations in activities over time, a large number of days would be preferable. However a greater number of days do not automatically mean more reliable data [54]. It is generally considered that a great number of days will decrease the quality of the diary data (less details and less accuracy) as the burden for the participants increases, leading to that the motivation decreases and hence the risk for non-response increases [40,43,55]. For large national time use surveys, two days are recommended and considered reasonable [40]. In this study a four day approach was chosen to gather enough information but without jeopardizing the response rate.

Although the houses in the study were not randomly selected, they can represent modern average houses, built in the 1980s after the Swedish building regulations on energy use came into force after the oil crisis 1973–1974. It should be noted that when a certain type of similar houses on housing estates is studied, socio-economic and demographic aspects may come into the picture.

4.5. Comparison with other studies

In the Introduction section some studies that use time use data were mentioned. However, it is difficult to compare the results from the different studies, as they have different objectives and perspectives and present the results in different ways. e.g. in Nordell [32], time use data is presented for two days and per person, and other activities in addition to energy-related activities are included. In addition, there are the large national time use studies performed in different countries [56]. The focus of these studies is on how people use their time in general, which is a much wider perspective than the focus of the present study.

To include two comparisons of "isolated" activities, one comparable figure can be mentioned related to airing, which was found in [57]. In this project, the options and potentials of energy diaries were studied, which includes investigating activities such as airing. The average number of times windows are open is 1 h and 30 min per day (on average, five windows per day). A remarkable difference in behaviour between the participating households is also noticed. In the present study the comparable figure is approximately 1 h and 40 min per day, although it must be borne in mind that this activity is irregularly reported.

The other comparison that can be made is for the daily estimated amount of time spent at home, which in this study is 15.7 h on average. This is similar to results in previous Swedish and international studies, with results of 15.6 h/day in Sweden [58], 15.7 h/day in Germany [59], 15.6 h/day in the USA [60] and 15.8 h/day in Canada [60]. This indicates that there is a certain extent of validity to the results of this study.

5. Conclusions

The main conclusions from the paper are:

- Regarding everyday energy-related behaviour, residents report on long time use/operating time for activities related to electronic equipment, such as the use of TV.
- More time is spent on energy-consuming activities in homes during the weekend than during weekdays.
- Activities with long operating times, in combination with high (and fairly high) power ratings, are typical for residents which use energy to a larger extent than other residents. This includes the use of engine preheaters, car heaters, fans and additional radiators, as well as airing habits.
- Those residents that on average spend less time at home and that have on average a smaller number of family members, also show a lower water usage (measured per household) on average. The study indicates that these are characteristics of households that can differentiate greatly between households.

This study has identified a number of characteristic behaviours of, primarily, those residents that use the most energy. However, this relates to a limited number of households. For the rest of the households, there are a number of activities that decide their energy use which could not clearly be pointed out. This indicates that there will also be a need for a number of strategies – not merely one solution – to influence energy-related behaviours.

Acknowledgements

The work is part of the "Energy use in single family houses - The significance of residents' behaviour" project, which is a multidisciplinary project carried out in collaboration between the Departments of Building Physics (Professor Jesper Arfvidsson and Professor Emeritus Arne Elmroth) and Environmental Psychology (Docent Thorbjörn Laike), both at Lund University, Faculty of Engineering, LTH, and the Department of Energy Technology at SP Technical Research Institute of Sweden (Ph. D. Ingemar Samuelson and Svein Ruud). I would like to thank all of the above-mentioned supervisors for their great support. Further, I express my sincere gratitude to all the homeowners who participated in the project. It has been incredibly generous of them to open their homes so that the measurements could be carried out. The project is funded by the Swedish Research Council Formas, Region Västra Götaland and SP.

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Appendix E

Information about participating households

Information about participating households

Table 8 shows information about the participating households at the time of the diary study and energy measurements. The information includes household composition, that is, the number of household members and their ages. The heated floor area, including extensions, for each house is listed, as well as changes made to the building services (information given by the households). Each household has a designated code. For the households that participated in the empirical studies of data analyses and interviews, and in the energy performance evaluations, the denotation was different – see notes under the table.

Table 8 Denotation of and information about participating households at the time of the diary study and energy measurements.

House-hold code	**No. of persons**	**Age groups** 0–17 years	18–64 years	65+ years	**Heated area** incl. extensions (m^2)	**Changes** -in heated area -to building services
A1	4	2	2		104	
A2	2		2		104	
A3	3	1	2		104	
A4	3	1	2		104	
A5	2		2		104	Mechanical supply and exhaust ventilation system with heat recovery
A6[a]	4		4		113	Storeroom/shed (T_{indoor} >10°C)
A7[b]	3	1	2		115	Extension
A8	2		2		104	Air-to-air heat pump
A11[c]	4	2	2		142	Extension + separate small house (T_{indoor} >10°C)
A12	1		1		104	
A13[d]	2		2		130	Extension Exhaust air heat pump (space heating and hot water)
A14	5	3	2		140	Extension
A15	2		2		104	
A16	3		3		104	
A18	2		2		104	
A19	3	1	2		159	Extension (2nd floor)
A21	5	2	3		129	Extension

House-hold code	No. of persons	Age groups 0–17 years	18–64 years	65+ years	Heated area incl. extensions (m^2)	Changes -in heated area -to building services
A23[e]	4	1	3		130	Extension + separate small house (T_{indoor} >10°C)
A24	4	2	2		154	Extension (2nd floor)
A25	2		2		155	Extension (2nd floor)
A26	3		3		104	
A27[f]	3	1	2		119	
B1	2		2		130	
B2	3	1	2		132	Air-to-air heat pump
B3	3	1	2		130	
B4	4	2	2		132	
B5	2		2		130	
B6	2		1	1	134	Extension
B7	2		2		130	
B8	4	2	2		130	
B9	3	1	2		132	
B10	4	2	2		140	Storeroom/shed (T_{indoor} >10°C)
B11	4	2	2		132	Exhaust air heat pump (space heating and hot water)
B12	4	2	2		130	
B13	2		2		130	
B14	2			2	132	
B15	2		2		130	
B16	2		1	1	140	Storeroom/shed (T_{indoor} >10°C)
B17	2			2	142	Storeroom/shed (T_{indoor} >10°C)
B18	2	1	1		135	Storeroom/shed (T_{indoor} >10°C)
B19	3	1	2		130	
C1	4	2	2		122	Exhaust air heat pump
C2	2		2		120	
C3	5	3	2		122	
C4	2		2		121	Exhaust air heat pump
C5	4	2	2		121	Exhaust air heat pump

House-hold code	No. of persons	Age groups			Heated area incl. extensions (m^2)	Changes -in heated area -to building services
		0–17 years	18–64 years	65+ years		
C6	3	1	2		131	Storeroom/shed (T_{indoor} >10°C) Exhaust air heat pump
C7	5	3	2		122	Air-to-air heat pump Air-to-air heat pump
C8	2		2		122	
C9	3	1	2		122	
C10	2		2		122	
C11	4	2	2		121	
C12	4	2	2		121	
C13	5	3	2		121	
C14	2		2		124	Extension
C15	3	1	2		128	Storeroom/shed (T_{indoor} >10°C)
C16	3		3		122	

In the studies of data analyses and interviews, and in the energy performance evaluations (Paper I and II):

[a] household A6 was denoted house II.

[b] household A7 was denoted house III.

[c] household A11 was denoted house IV.

[d] household A13 was denoted house VI.

[e] household A23 was denoted house V.

[f] household A27 was denoted house I.

In addition to the definition of heated area (A_{temp})[149] stated in the Swedish building regulations (BFS 2011:6 – 2019:2), other areas are counted outside the main building envelope that is heated to more than 10˚C since energy for all heating on the premises is registered on the same electric meter. For example, heated storerooms and separate small houses, as listed in the table above, are included. Two households (C10 and C13) have stated that they heat their garages to more than 10˚C; these areas are, however, not included. The original areas are specified from drawings of the houses, while areas of extensions and the like are specified by the residents themselves.

[149] A_{temp} is the floor area in temperature-controlled spaces intended to be heated to more than 10˚C, enclosed by the inside of the building envelope (BFS 2011:6 – 2019:2).

Appendix F

Input data for energy calculations

Input data for energy calculations

In this appendix, the main data for the energy calculations for households A6 and A13 input into the Enorm software are accounted for. These input data are discussed in relation to regulations and recommendations on input data for energy estimations, primarily stated in earlier and prevailing Swedish building regulations, as well as the regulations determining the building's energy use under normal conditions.

Heated floor area

The heated floor area for the two houses was originally the same, namely 104.2 m^2, but in 2001 household A13 made an extension to their house which meant the floor area was extended by an additional 26.7 m^2.

Apart from being input data for the energy balance of the building, the Enorm program uses the area information for other estimations, including estimation of domestic hot water and household electricity (Svensk Byggtjänst, 1996). In the Enorm calculations carried out for this thesis, the floor area was defined as heated 'usable floor area',[150] but the definition has changed since then. In the building regulations of 2006 (BFS 1993:57 – 2006:12), heated floor area, A_{temp}, was introduced which meant a slight modification compared to the previous area term. A_{temp} includes the floor area measured from the inside of the building envelope, which is heated to a higher temperature than 10°C (BFS 2011:6 – 2019:2).[151] However, this change in area definition does not generally affect the results to any major extent, which was also found in the report of Antell (2013). After the definition change, the Swedish National Board of Housing, Building and Planning (Boverket) recommended that in existing buildings, where the area had been measured according to the older definition (BRA), the area could roughly be equalized to the new definition (Swedish Energy Agency, 2010). Generally, it is of great importance that the area is estimated correctly, especially as the energy performance in the building regulations is expressed per square meter heated area (BFS 2011:6 – 2019:2).

[150] Usable floor area is a free translation of the Swedish term 'bruksarea' (abbreviated as BRA).

[151] The English translation of the Swedish building regulations define A_{temp} as: 'The area enclosed by the inside of the building envelope of all storeys including cellars and attics for temperature-controlled spaces that are intended to be heated to more than 10°C. The area occupied by interior walls, openings for stairs, shafts, etc., are included. The area for garages, within residential buildings or other building premises other than garages, are not included.' (BFS 2011:6 – 2018:4). One difference between the old and new area definitions is that internal walls between units (e.g. apartments) are not included in the definition of BRA (SIS, 1989a).

Air leakage

The air tightness of the two houses was not known; instead, it was assumed that they complied with the building regulations prevailing at the time when the houses were built, that is, three air changes per hour at 50 Pa pressure difference (PFS 1980:1). This corresponds to 0.64 l/($m^2 \cdot s$) for household A6 and 0.66 l/($m^2 \cdot s$) for household A13.[152] Enorm then uses a simplified method to calculate the real air leakage (air leakage at operating pressure), with no consideration for pressure differences caused by wind and thermals. The air leakage flow is estimated at 4% of the air leakage flow at the pressure difference of 50 Pa for houses with exhaust air ventilation systems.[153] Another common percentage is 2.5% (Elmroth, 2012; LIP-kansliet, 2002).

The building regulations on air tightness have changed since the mid-1980s when the houses reported on in this thesis were built. Instead of being expressed as air changes per hour, it was later defined as air leakage flow per building envelope area[154] which is 3 $m^3/(m^2 \cdot h)$, approximately corresponding to 0.8 l/($m^2 \cdot s$) (BFS 1988:18). For one-floor houses, like the houses in these calculations, this change led to a somewhat increased airflow being allowed.[155] Since 2006, air leakage is part of the requirements of energy performance, which means that the building envelope shall be tight enough so that requirements for the building's energy performance (primary energy number) and installed heating power are met (BFS 2011:6 – 2019:2).

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[152] The air leakage is converted to a suitable unit by using the envelope area of the buildings (see definition in footnote 154 below).

[153] The air leakage through the building envelope is estimated in Enorm according to: $q_{operate} = q_{50}/d$ [$m^3/(m^2 \cdot s)$], where $q_{operate}$ is the air leakage at operating pressure [$m^3/(m^2 \cdot s)$], q_{50} is the air leakage at 50 Pa pressure difference [$m^3/(m^2 \cdot s)$], and d is equal to 25 in the case of exhaust air ventilation and 20 for balanced ventilation [–] (Svensk Byggtjänst, 1996).
However, in the Sveby guidelines for the Enorm program, the input value for the calculation of air leakage is recommended to be set at 0.5 l/($m^2 \cdot s$) for exhaust air ventilation, which would be applicable for the houses in question, and to 0.8 l/($m^2 \cdot s$) for balanced ventilation systems (at pressure difference 50 Pa) (Sveby, 2012). One reason for using these values is that Enorm does not actually differentiate between different ventilation systems, even though the manual says it does.

[154] The building envelope area is the total area of all surfaces of the building envelope, i.e. the area of the 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 (BFS 2011:6 – 2019:2).

[155] For two-floor detached single-family houses, with greater volumes in comparison to the building envelope area, the new definition usually means a stricter air leakage flow (expressed in the unit m^3/h).

Indoor temperature

The indoor temperatures were measured in February 2003 as 23.0°C for household A6 and 19.5°C for household A13. These values were higher and lower, respectively, than the 21°C stated in the regulations on determining the building's energy use (BFS 2016:12 – 2018:5). Other field measurements have found indoor temperatures of 20.9–21.2°C to be common in Swedish single-family houses during the heating season (National Board of Housing, Building and Planning, 2009b; Sjögren, Kronheffer, & Blomkvist, 2010).

Transmission losses

As mentioned in Section 2.2.2.2, Enorm was developed to check whether the building regulations were met, which meant, at the time, requirements for the average heat transfer coefficient (U_m) of the house.[156] Previous regulations prevailing at the time when the buildings were constructed had instead requirements for each building element (PFS 1980:1). From input data on materials and their thermal properties, U-values of the building elements were calculated in the program, so the requirements of the 1980s' regulations for the location in question (Borås) were met regarding the floor, windows and door, while they were just above the requirements for the roof construction and external walls.[157] From the U-values, the thermal transmittance through the building envelope was calculated by the program. A newer version of Enorm (Enorm 2004) included an adjusted definition

[156] Enorm 1000 relates to the Swedish building regulations BBR 94 (BFS 1993:57) and the national standard for thermal insulation SS 02 42 02 (SIS, 1989c). The requirement was expressed as $U_m = 0.18 + 0.95 \times (A_f/A_{om})$ [W/(m^2·K)], where A_f was the area of windows and doors and A_{om} was the envelope area of the building. For both houses in this thesis, this meant approximate requirements of 0.23 W/(m^2·K) compared to the Enorm calculated averages of the heat transfer coefficients of 0.30 W/(m^2·K) for household A6 and 0.28 W/(m^2·K) for household A13. Hence, the houses did not fulfil the requirements of these later BBR 94 regulations. (Note that, in reality, buildings should meet the requirements prevailing at the time when they were constructed – which in the case of the houses in housing area A was in mid-1980s.)

[157] The U-values of the two houses compared to the building regulations at the time of construction (PFS 1980:1) were:

- Floor: 0.13 W/(m^2·K) (extension of A13 0.10 W/(m^2·K)) compared to 0.30 W/(m^2·K) in the regulations.
- Windows: 1.9 W/(m^2·K) compared to 2.00 W/(m^2·K) in the regulations.
- Door: 0.8 W/(m^2·K) compared to 1.00 W/(m^2·K) in the regulations.
- Roof: 0.22 W/(m^2·K) (extension of A13: 0.16 W/(m^2·K)) compared to 0.20 W/(m^2·K) in the regulations.
- External walls: 0.32 W/(m^2·K) compared to 0.30 W/(m^2·K) in the regulations.

of the average thermal transmittance, which was a consequence of changes in the Swedish building regulations (BFS 1993:57 – 2002:18).[158,159]

However, the 2006 Swedish building regulations meant that new energy performance requirements were introduced, which were in line with the Energy Performance of Building Directive (BFS 1993:57 – 2006:12; Directive 2002/91/EC).[160] The requirement regarding the building's transmission losses remained, but it was in a somewhat changed and simplified form and with a clearer requirement that the building's thermal bridges shall be included in the calculation (National Board of Housing Building and Planning, 2006). The requirements on transmission losses are seen as an 'underlying requirement' of the overall requirement on a building's energy performance. That is, a well-insulated building envelope is one of the characteristics of the building that is required to meet the overall requirement of the building's energy performance.

Ventilation flow

The ventilation flows of the examined houses were measured to be 120 m^3/h for household A6 and 113 m^3/h for household A13, corresponding to 0.32 l/(m^2·s) and 0.24 l/(m^2·s), respectively. This was lower than the requirement of 0.35 l/(m^2·s) stated in the Swedish building regulations at the time (i.e. PFS 1980:1) and which still prevails in today's regulations (BFS 2011:6 – 2019:2). That the ventilation rate is typically lower than the requirement for single-family houses is found in other studies as well (e.g. Bornehag et al., 2005; Sundell et al., 2009).

Household electricity

Enorm calculates typical values of household electricity usage based on heated floor area.[161] These estimations would mean higher values for household A13 (with a larger floor area) even though it is a two-person household compared to household A6 with four persons. Hence, the Enorm estimations were adjusted manually, by decreasing the household electricity use of household A13 to that of household A6,

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[158] The regulations were changed to harmonise with the international standard *ISO 6946 Building components and building elements – Thermal resistance and thermal transmittance – Calculation method* (SIS, 2003).

[159] The calculation of the average thermal transmittance refers to calculation standards SS-EN ISO 13789:2007 (SIS, 2007) and SS 24230 (SIS, 1989b).

[160] In 2010 a recast of the directive was published (Directive 2010/31/EU) and in 2018 an amending directive was published (Directive (EU) 2018/844).

[161] Enorm calculates household electricity use according to *Household electricity = 6 + 0.06 × heated area* [kWh/day] (Svensk Byggtjänst, 1996).

namely 4472 kWh/year.[162] Other former recommendations of typical values of household electricity have included one part that is dependent on the number of persons in a household, such as previous recommendations connected to the regulations about energy performance certificates (BFS 2007:4 – 2012:9).[163]

According to the Swedish regulations determining the building's energy use, the annual household electricity shall be estimated to be 30 kWh per square meter heated floor area for residential buildings (BFS 2016:12 – 2018:5).[164] If this approximation had been used for the two houses in question, it would have led to lower values for both houses, that is, 3126 kWh/year for household A6 and 3927 kWh/year for household A13. The lower estimations might reflect the fact that there have been large improvements in the energy efficiency of white goods and lighting over the years. The floor area of house A6 is also smaller than the average Swedish house,[165] leading to a lower value.

Domestic hot water

Based on the actual water consumption of the two houses, the energy use for the domestic hot water was estimated to 2599 kWh/year for household A6 and 1368 kWh/year for household A13, which was used as input data in the Enorm calculations .[166] If no information about households' water consumptions is known, Enorm uses an estimation based on the heated floor area instead[167]. This would have

[162] In addition, Enorm compares input data on white goods with reference values in the program. If the actual appliances are more energy efficient than the references, a deduction is made for this; if they are more inefficient, an addition is made. For the houses in question, estimated values are entered for appliances based on brand, type, size, age, use and consumption (for more details, see the author's licentiate thesis (Hiller, 2003a)), which led to a decrease in the electricity consumption for household A6 with 911 kWh/year and an increase for household A13 with 114 kWh/year in the energy calculations.

[163] The estimation of household electricity use was then:
$Household\ electricity = (530 + A_{temp} \times 12 + B \times 690) \times 1.25$ [kWh/year], where A_{temp} is the floor area heated to more than 10˚C, and B is the number of people in the household.

[164] The estimate of 30 kWh per heated floor area for household electricity is used in the determination and verification of energy use during normal use. Household electricity is not included in the Swedish definition of energy performance, but its use contributes to the internal heat generation in buildings.

[165] The average Swedish house had an average floor area of 122 m^2 in 2019 (Statistics Sweden, 2020b).

[166] The actual water consumptions (hot and cold water) of the two houses were 190 m^3 and 100 m^3. A 30% hot water fraction was assumed, as well as a temperature rise of 38˚C.

[167] Enorm calculates the energy use for domestic hot water according to this formula: *Energy for domestic hot water = 5 + 0.05 × heated area* [kWh/day] (Svensk Byggtjänst, 1996).

resulted in estimated values of 3727 kWh/year for household A6 and 4214 kWh/year for household A13.

As outlined in Section 5.1.2, when verifying that the energy requirements in the Swedish building regulations are met,[168] a building's energy use for domestic hot water shall be determined by the following formula (excluding losses for hot water circulation): *Energy for DHW* = $A_{temp} \times 20/\eta_{tvv}$ [kWh/year], *w*here η_{tvv} is the yearly efficiency for the production of domestic hot water in the building (for electric boilers it can be set as one) (BFS 2016:12 – 2018:5). This is the normalised value for energy for domestic hot water in single-family houses; for households A6 and A13, this normalisation would have resulted in energy usage of 2084 kWh/year and 2618 kWh/year, respectively. If a building's energy use for domestic hot water is not measured separately, but the cold water volume is known, the regulations recommend that the following approximation is used before the normalisation is done: *Energy for DHW* = $0.35 \times V_{kv} \times 55/\eta_{tvv}$ [kWh/year], where V_{kv} is the measured cold water volume. For the houses in this thesis, this would have led to energy usage of 3658 kWh/year for household A6 and 1925 kWh/year for household A13.

The values presented in this section give a mix of estimates on the energy use for the domestic hot water of the two houses. For household A13 in particular, the estimates based on the heated floor area are rather high in comparison to values which draw on the actual water consumption.

Heat gains

Heat given off by persons, household appliances and domestic hot water production, as well as heat from solar insolation, contributes to cover the heat demand of a building during the heating season. Heat gains from persons are estimated in Enorm based on the heated floor area.[169] As the number of residents was known in the two households included in the calculations, the estimates were adjusted so that twice as much heat was gained in household A6 with four persons as in household A13 with two persons, namely 1146 kWh/year and 573 kWh/year, respectively. 100% of this heat is considered as useful heat in Enorm according to the instructions (Sveby, 2012).

In the Swedish regulations determining the building's energy use under normal conditions, heat given off by persons shall be estimated in the following way: *Heat given off by persons = no. of persons in household × presence at home × heat*

[168] Energy use for domestic hot water is included in the Swedish definition of energy performance but needs to be normalised before verification of the requirements is done, that is, the energy requirements shall be met during normal use of hot water.

[169] Enorm calculates the heat gains from persons according to this formula: *Heat from persons* = $0.024 \times$ *heated area* [kWh/day] (Svensk Byggtjänst, 1996).

generation [Wh/year] (BFS 2016:12 – 2018:5). The presence at home is fixed to 14 hours per day (all days of the week and all weeks of the year) and the heat generation per person is set to 80 W. Typical values for the number of persons in households, based on the size of the dwelling, are stated in the regulations. If this approximation had been used for the two houses in the thesis, it would have led to the same value of 1431 kWh/year.

Related to the household electricity described above, Enorm assumes that 80% is given off as useful heat, contributing to the space heating during the heating period of the building (Svensk Byggtjänst, 1996).[170] The corresponding figure stated in the regulations determining the building's energy use is 70% (BFS 2016:12 – 2018:5). Furthermore, Enorm considers 20% of heat given off by domestic hot water production as useful heat (Sveby, 2012). The regulations do not mention heat gains from the production of hot water.

Enorm considers useful heat from solar insolation by using solar data, glass areas in different orientations,[171] solar transmittance of the windowpanes and the solar shielding.[172,173] The solar transmittance was put at 1.0.[174] For the solar shielding, a solar screening factor of 0.75 was used, as recommended in the Enorm manual when there is 'normal' horizontal shielding and 'normal' window niches (Svensk Byggtjänst, 1996). The regulations determining the building's energy use state that when calculating a building's energy use, the building's design, location and orientation shall be taken into account, including outdoor climate and passive solar radiation. Data for the outdoor climate shall be representative for a standard year at the place where the building is located (BFS 2016:12 – 2018:5). No recommendations on how to estimate gains from solar insolation are given, only that the screening factor shall be put at 0.71 for adjustable solar shadings. Fixed solar

[170] Moreover, Enorm makes a reduction or addition in the heat given off by fridges and freezers if more efficient or inefficient ones are used than the reference ones in the program. In house A6, more efficient fridges and freezers were used, resulting in reduced useful heat gains of 519 kWh/year. In house A13, instead, somewhat more inefficient fridges and freezers were used, which led to increased heat gains by 185 kWh/year in the energy calculations.

[171] Glass areas in different orientations are listed in Table 6 (Section 2.2.2.2) for the two houses in question.

[172] The effects of the solar insolation are overestimated by Enorm, as no consideration is taken to the sun's position in the sky at different times of the year (Hagengran & Stenberg, 2005; Larsson & Nilsson, 2003).

[173] The method used by Enorm to calculate the energy use from solar insolation is not suited to buildings with great window areas and that are designed to make use of passive solar energy to a great extent. Except for the extension of house A13, the houses in this thesis do not have large window areas compared to the floor area.

[174] The solar transmittance shall be put at 1 for triple glazed windows without a low emission layer (Svensk Byggtjänst, 1996), which was the case for the two houses in the energy calculations.

shadings are not included in these regulations as they cannot be adjusted by the residents.

Airing

Enorm does not take airing into account in the energy calculations and this factor was therefore not considered for the two houses in the thesis (nor was any information available on the households' ventilation behaviours). The impact of airing on a building's energy use can be difficult to estimate due to a number of reasons, such as the size and duration of the window opening, the dwelling's exposure to the wind, temperature differences and the building's ventilation system. Although the impact of airing can be included in energy simulations through airing profiles, it is usually not calculated in most programs (Levin, 2012). In addition, there are possibilities to consider an increased air exchange due to airing by adding extra estimated energy use, increasing the air leakage or increasing the ventilation flow in the energy calculations (Levin, 2012). The regulations determining the building's energy use state that increased energy use due to airing should be taken into consideration and an additional heat energy use of 4 kWh/(m^2·year) is recommended (BFS 2016:12 – 2018:5).

Appendix G

Imputation to handle uncertainties and missing values in diaries

Imputation to handle uncertainties and missing values in diaries

All uncertainties and missing values in the diaries were carefully noted. Such data included the type of activity and time it occurred, which household it was in and for which resident it occurred. Subsequently, uncertainties and missing values were assessed and dealt with in a systematic way which will be explained in this appendix.

To start with, uncertainties and missing values were described in one (or several) of the following ways:

a. there was a gap in time when no activity was reported, or an activity was very vaguely described in the diary,

b. it was not noted *when* an activity occurred (it was just noted that it occurred) and

c. it was not known for *how long* an activity lasted.

Thereafter, the uncertainties and missing values were handled by imputation, that is, missing values were 'replaced' with suitable substituting values. As was mentioned in the section *Data handling of diaries* (Chapter 2), this approach was chosen because the aim of the diary study was to include as many energy activities as possible in the analysis. In some surveys, imputation is made for certain activities, such as in the Swedish national time-use surveys, imputation is made for sleep (Molén, 2011). However, imputation needs to be handled with great consideration and systematically, and be well documented (U.S. Census Bureau, 2019).

Before imputations were made, the diary writers were asked, during a home visit, if they could clarify any uncertainties and missing values in their diaries. For issues that remained, the imputations were carried out, by an individual assessment of each case, in one of the following ways (specified in order of priority):

1. A substituting value for an activity/time/duration was filled in with information from other diary data, with great certainty (in regard to uncertainties a, b and c above).
2. A substituting value for an activity/time/duration was filled in with information from other diary data, with some uncertainty, for example, by matching with the last time the activity was performed, the previous day's/days' activities, or other household members' diaries (in regard to uncertainties a, b and c above).
3. A substituting value for the duration of an activity was based on average data from the person's diary, from other household members' diaries, or from other households' diaries (in regard to uncertainty c above).

4. A substituting value for the duration of an activity was based on a general estimation for how long a certain type of activity would typically last (in regard to uncertainty c above).
5. No imputation was made due to very incomplete information; the uncertainties or gaps in the diaries were then left and no value was filled in (in regard to uncertainties a, b and c above).

In addition, there were certain activities recurring in virtually every diary that could not be processed at all as the data quality was generally too poor. These activities included lighting, standby electricity use and other constantly plugged-in electronic devices, use of fireplaces, visits to toilets, etc.

In Section 2.3.2.2, a brief compilation of the uncertainties and missing values are presented.

Appendix H

Typical power data used in cluster analyses

Typical power data used in cluster analyses

Below are typical power data and formulas listed, which were used for the cluster analyses presented in Paper IV (Appendix D).

Table 9 Typical power data used in cluster analyses (Sources: E.ON., 2007; Energirådgivarna, 2004; Levin, 2012; Lindell, 2005; Sernhed, 2004; Sydkraft, 1998)

Activity (variable)	**Power** (W)	**Comments**
TV	140	
Computer	125	
Stereo/Radio	45	
Electric clocks	3	
DVD/VHS	45	
Video games	200	
Engine preheaters	500	
Car heater	900	
Vacuum cleaner	1000	
Kitchen fan and other fans	200	
Stove (plate)	1500	
Coffee machine	800	
Oven	2500	
Microwave	1500	
Hand wash (dishes)	2740	A water temperature of 45°C has been assumed.
Toaster	1000	
Electric mixer	150	
Electric kettle	2200	The number of times kettles were used was obtained from the diary data. On each occasion, the kettle was estimated to be used for 2.5 minutes.
Dishwasher	1250 (Wh/cycle)	The dishwashers were connected to the cold water, with the heating of the water was done in the machine.
Food processor	300	The number of times food processors were used was obtained from the diary data. On each occasion, the food processor was estimated to be used for 3 minutes.
Shower	26,350	A water temperature of 38°C has been assumed.
Hairdryer	1000	

Activity (variable)	**Power** (W)	**Comments**
Curling tongs or straighteners	50	
Bathing	5490 (Wh/bath)	A water temperature of 38°C has been assumed.
Towel dryer (electricity)	80	
Airing	1557	The typical value was based on the following formula of energy use for airing: $Q_{airing} = q_{airing} \times \rho c_p \times \Delta T \times t$ [kWh], where q_{airing} is the air flow due to airing, ρc_p is the properties of air, ΔT is the temperature difference between indoors and outdoors and t is the duration of the airing. With q_{airing} put to a 'forced air flow' of 60 l/s and ΔT to 21.4°C, representing an average difference for all the houses during the diary periods, the typical value Q_{airing}/t was estimated to be 1557 W.
Floor heating, comfort (electricity)	340	In the houses there are small floor areas with comfort heating. An average of 4 m^2 was used.
Tumble dryer	2000	
Iron	1000	
Drying cupboard	2000	
Sewing machine	85	
Washing machine	1500 (Wh/cycle)	
Others – Very low power	50	
Others – Low power	250	
Others – High power	750	
Others – Very high power	1250	

Appendix I

Validity and reliability of the diary study

Validity and reliability of the diary study

Validity

To evaluate if the diaries actually reflected everyday energy-related activities, the (measurement) validity was investigated. This was done by studying a number of households and by comparing the estimated energy use from diary data to the measured energy use. The estimated energy use from diary data was calculated by using typical power data (found in Appendix H). Ten households' diary data and energy use were studied during two hours of the day; five households were studied at 18:00–20:00 on a Thursday evening and the other five were studied at 8:00–10:00 on a Saturday morning. The nightly measured energy use was subtracted from the daily measured energy use in order to remove the use that was most likely not related to the activities given in the diaries (as most people were asleep). Still the calculations were made with and without consideration of any ongoing night activities and was repeated during two different periods during the night.

The selection of households to be included in the validity test first meant an exclusion of households which had a large number of uncertainties in their diaries, houses where heat pumps were installed and houses where there were regular temperature setbacks. Subsequently, a proposed selection plan was drawn up considering representation of the three housing areas and the different household types (previously described in Table 5 in Section 2.1.3). The plan included an allocation of the households over the evening and the morning times examined. The selection plan was then matched with suitable households, after they had been checked for activities going on during the investigated two hours and that their energy curves did not vary greatly during night times.

The correlations were calculated for different comparisons between the estimated energy use from diary data and measured energy use, shown in Table 10 and Table 11. The correlation coefficients for the comparisons between the measurements of the two-night periods were also calculated as a control that the periods did not differentiate too much.

Table 10 Correlations for three different comparisons (for 10 households)

	Comparisons		**Correlations** (Spearman's rho[175])
	Estimated energy use (from diaries)	Measured energy use (night period 1)	0.69 ($p < .05$)
	Estimated energy use (from diaries)	Measured energy use (night period 2)	0.43 ($p < .05$)
Control	Measured energy use (night period 1)	Measured energy use (night period 2)	0.90 ($p < .01$)

Table 11 Correlations for three different comparisons with consideration to nightly activities (for 10 households)

	Comparisons		**Correlations** (Spearman's rho[175])
	Estimated energy use (from diaries)	Measured energy use (night period 1)	0.83 ($p < .01$)
	Estimated energy use (from diaries)	Measured energy use (night period 2)	0.82 ($p < .01$)
Control	Measured energy use (night period 1)	Measured energy use (night period 2)	0.98 ($p < .01$)

The correlations between the two measured night periods (the control) was very strong, which was expected. The tables show that there were fairly strong and strong correlations for the other comparisons – somewhat stronger correlations were shown when night activities were considered. To conclude, the validity test showed that the validity of the diary study was fairly good.

Reliability

To evaluate the reliability of the diaries, including the interpretation of the diary data, two types of reliability tests were conducted. The first test investigated if the

[175] Spearman's rho, or Spearman's rank correlation coefficient, is a measure of the correlation between two variables considering the ranking of the variables, whose values need not be normally distributed (Everitt & Skrondal, 2010). The coefficient ranges from –1 to +1.

results were consistent over the diary days (repeated). This was done by comparing the diary information from one day to another – that is, between two weekdays, between a weekday and a weekend day and lastly between two weekend days. However, between the weekday and the weekend day certain differences in activities are generally expected. The second test evaluated the interrater reliability, which is the degree of agreement among raters. In the performed test, two raters were compared with each other using Krippendorff's alpha.

Reliability test over the diary days

Four comparisons regarding days were made:

1. Comparison of a weekday with a weekday: Thursday (00.00–24.00) – Friday (00.00–24.00)
2. Comparison of a weekday with a weekend day: Thursday (00.00–24.00) – Saturday (00.00–24.00)
3. Comparison of another weekday with a weekend day: Friday (00.00–24.00) – Saturday (00.00–24.00)
4. Comparison of a weekend day with a weekend day: Saturday (00.00–17.00) – Sunday (00.00–17.00)

These comparisons were made, household by household, for each category of activity (introduced in the section *Data handling of diaries*, Chapter 2). The correlations are presented in Table 12.

Table 12 Correlations for the comparisons of diary information between different days, shown for categories of activities (using Spearman's rho[175]).

Categories / Comparisons	**Elec-tronics**	**Cooking/ Kitchen**	**Personal hygiene**	**Comfort**	**Clothes care**	**Others**
1 Thursday – Friday (00.00–24.00)	0.61[a]	0.26	0.03	0.88[a]	0.20	0.71[a]
2 Thursday – Saturday (00.00–24.00)	0.61[b]	0.03	0.15	0.81[a]	0.30[b]	0.69[a]
3 Friday – Saturday (00.00–24.00)	0.56[a]	0.27[b]	0.21	0.83[a]	0.40[a]	0.64[a]
4 Saturday – Sunday (00.00–17.00)	0.75[a]	0.34[a]	0.09	0.77[a]	0.00	0.59[a]

[a] $p < .05$

[b] $p < .01$

The category of ‘Comfort’ showed very strong correlations for all comparisons. This could probably be explained by the fact that once the activities were carried out (e.g. the towel dryer), this was usually done for quite some time. Hence, for this category it did not matter which day of the week that was considered.

Strong correlations were shown for the categories of ‘Electronics’ and ‘Others’. For ‘Electronics’ it was especially strong when comparing a weekend day with a weekend day. Moderate to fairly strong correlations were shown for the other comparisons. A somewhat weaker correlation between a weekday and a weekend day than on similar types of days was anticipated as it can be expected that people use their electronic equipment differently during these days due to different amounts of time spent at home, for example.

For ‘Cooking/Kitchen’ and ‘Clothes care’ there were weak correlations for some of the comparisons, while ‘Personal hygiene’ showed no clear relationships. This meant that there was no repetition (during four days) for these types of activities. ‘Cooking/Kitchen’ possibly showed lower regularity than foreseen. For ‘Clothes care’ and ‘Personal hygiene’, this was perhaps expected, considering activities such as showering and washing clothes may be performed irregularly.

In summary, the comparisons between different days showed, in most cases, that the diaries pretty much described what was expected concerning day-to-day patterns.

Interrater reliability test

An interrater reliability test was performed in order to evaluate the interpretation of the diaries. The ordinary rater (the author) instructed the test rater in the procedures of interpreting the information in the diaries. Five examples, including different diaries (concentrated to members of the same household) and a few variables, namely, presence at home (active and passive[176]) and the use of a stove, were tested and evaluated (Table 13).

The correlations of the assessments from the two raters were calculated using ReCal, an online interrater reliability web service.[177] Krippendorff's alpha was used, which is well regarded and considered one of the conservative indices, meaning that it does not overestimate the agreement of the raters (Freelon, 2010).[178] The correlation values were in the range of 0.57–0.83 (see Table 13), which corresponded to agreements of 32–69% between raters. These percentages were satisfactory, meaning that the interrater reliability was acceptable, although the lowest value of

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[176] Active means awake and passive means asleep.

[177] ReCal can be found at http://dfreelon.org/utils/recalfront/ (October 2011).

[178] More about Krippendorff's alpha (interval) can be found in the book *Content Analysis: An Introduction to Its Methodology* (Krippendorff, 2004).

32% indicated only moderate agreement, while the other values indicated substantial agreement.

One experience of the interrater reliability test was that the instructions to the test rater were very important. After the test, most of the interpretations from the ordinary rater were kept as they were.

Table 13 Examples that were tested in the interrater reliability test

Examples	**Diaries**[a]	**Variables**	**Krippendorff's alpha (interval)**	**Agreement**[b] **between raters, %**
1	A23a	Presence at home (active[176])	0.73	53
2	A23a	Presence at home (passive)	0.83	69
3	A23b	Presence at home (active)	0.57	32
4	A23c	Presence at home (active)	0.64	41
5	A23 all household members	Stove	0.67	45

[a] Individuals' diaries are indicated by lowercase letters.

[b] Agreement equals to the square of Krippendorff's alpha (interval).

Printed by E-husets tryckeri, Lund university, Sweden

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This doctoral thesis explores how energy use in single-family houses varies and how energy-related behaviours of households influence the use of energy.

Lund University, Faculty of Engineering
Department of Building and Environmental Technology
Division of Building Physics
ISRN LUTVDG/TVBH - 20/1023 – SE(235)
ISBN 978-91-88722-66-9 (print)
ISBN 978-91-88722-67-6 (pdf)
ISSN 0349-4950

LUND UNIVERSITY