BOOSTING BEHAVIORAL CHANGE IN RESIDENTIAL ELECTRICITY CONSUMPTION

DEMAND RESPONSE PROGRAMS AND FEEDBACK

Cajsa Bartusch

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School of Sustainable Development of Society and Technology
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Abstract

As part of realizing national and European climate ambitions, it is imperative to bring about increased energy efficiency and consumption flexibility in the residential sector of the Swedish power market. In addition to governmental policy instruments to this end, market-based measures play an important role in making behavioral change in domestic electricity use happen. In light of the prevailing lack of incentives for residential consumers to save electricity and cut peak demand at times of physical and financial market constraints, the research studies that form the basis of this thesis have the aim of adding to the body of knowledge on policy instruments for the purpose of boosting behavioral change in residential electricity consumption. The research has accordingly contributed to the general statistics on residential electricity consumption, which constitute the starting point for policy instrument development, and augmented knowledge on the merits of residential demand response programs involving hourly settlements in power trading and demand-based, time-of-use tariffs in power distribution as well as graphic feedback on individual households’ electricity use by means of a statistics service provided over the Internet.

The overall results have shown that household behavior, together with physical factors such as heating systems, help explain the sizeable differences in electricity consumption among homeowners. Statistical analysis of variance has in this context proven to be an effective method for identifying key indicators of policy development. Power suppliers and electricity consumers as well as society as a whole have been found to gain substantially from hourly settlements in retail. To suppliers, the greatest benefits are associated with risk management, while the major advantage to customers is that they are provided with an opportunity to reduce their electricity costs. It has also been empirically demonstrated that electricity users are willing to adjust their consumption to a demand-based, time-varying distribution tariff. Households generally have a favorable attitude towards this type of distribution tariff, seeing as they indirectly have a positive impact on the environment. Providing households with feedback over the Internet on their individual electricity use and demand has been shown to contribute to an increased awareness and lead to energy efficiency in homes. Easy accessibility and simplicity have proven to be key success factors in this context. Combining conventional bar charts, color symbolism and historic feedback is expedient in this respect.
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Summary in Swedish/Svensk sammanfattning

Att åstadkomma ökad energieffektivisering och förbrukningsflexibilitet i den svenska elmarknadens bostadssektor är ett nödvändigt led i realiseringen av de nationella och europeiska klimatmålen. Utöver statliga styrmedel för detta ändamål spelar även marknadsbaserade åtgärder en viktig roll för att få till stånd beteendeförändringar i samband med hushålls elanvändning. Mot bakgrund av den rådande bristen på bevekelsegrunder för elkonsumenter att spara el och minska effektuttaget när marknadens fysiska och finansiella begränsningar ger sig till känna har det övergripande syftet med forskarstudierna som ligger till grund för den här avhandlingen varit att bidra till den samlade kunskapen om styrmedel som främjar beteendeförändringar i hushålls elanvändning. Forskningen har således bidragit till den generella statistiken om elanvändning i bostäder, som utgör utgångspunkten för utvecklingen av styrmedel, samt ökat kunskapen om vinsterna med timavräkning inom elhandeln, effektbaserade tidstariffer inom eldistributionen i bostadsektorn och grafisk återkoppling på enskilda hushålls elanvändning med hjälp av en statistiktjänst som tillhandahålls via Internet.

De övergripande resultaten har visat att hushålls beteende, jämte fysiska faktorer såsom uppvärmningssystem, bidrar till att förklara de stora skillnaderna i elkonsumtionen bland villaägare. Statistisk variansanalys har i det sammanhanget visat sig vara en ändamålsenlig metod för att identifiera viktiga indikatorer för utveckling av styrmedel. Såväl enskilda elleverantörer och elkonsumenter som samhället i stort har visat sig ha mycket att vinna på timavräkning inom elhandeln. För elhandlaren är de största fördelarna förknippade med riskhantering, medan vinsten för kunderna består i ökade möjligheter att minska sina elkostnader. Det har även empiriskt påvisats att elkonsumenter är beredda att anpassa sin förbrukning till en effektbaserad tidstariff. Hushåll har generellt en välvillig inställning till den här typen av tariffer, eftersom de indirekt har en positiv effekt på miljön. Att tillhandahålla hushåll med återkoppling avseende deras individuella elanvändning och effektuttag via Internet har visat sig bidra till en ökad medvetenhet och leda till energieffektiviseringar i bostäder. Lättsillgänglighet och enkelhet har i det sammanhanget visat sig vara centraala framgångsfaktorer. Att kombinera konventionella stapeldiagram, färgsymbolik och historisk återkoppling är ändamålsenligt i det avseendet.
The research presented in this thesis was financed primarily by the Swedish Energy Agency and Elforsk AB, but it was also supported, financially as well as practically, by several other organizations, the most important of which are, in alphabetical order, Bostads AB Mimer, Eskilstuna Energi & Miljö AB, Eskilstuna Kommunfastigheter AB, Mälarenergi AB, Sala Heby Energi AB, Skånska Energi AB, Smedjebacken Energi & Vatten AB, Sollentuna Energi AB and the Swedish Union of Tenants.

A vast number of individuals representing these organizations have, to a greater or lesser extent, taken an active part in the work it has involved, each and every one of them deserving to be individually acknowledged for their valuable contribution. However, seeing as mentioning no one means eliminating the risk of forgetting someone, these indispensable persons are hereby collectively, but nonetheless profusely, thanked.

A special thanks goes to my supervisor and very good friend, Professor Emeritus Lars Wester, for the effort he has invested in helping me complete my graduate studies and finish the thesis. I also wish to express my gratitude to my co-supervisors, Mikael Larsson, Thomas Porathe and Monica Odlare, all of whom I could not have done without in preparing the papers included in the thesis. As for my fellow colleagues, I owe my sincere thanks to many of them for having brightened my everyday life at the university, in which Runa Nordin has played the single most prominent part.

Finally, there are no words to express the deep gratitude and great affection I feel towards my beloved family - my dear parents, Siri and Dietrich, my darling sister Catrin, my lovely daughters Sandra and Malin, whose family pet names are Mylis and Mollis - for their never-ending love and support and, last but not least, the love of my life, Anders, to whom I owe everything. You all mean the world to me.
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List of papers

This thesis is based on the following papers, which are referred to in the text by their Roman numerals.


Reprints were made with permission from the respective publishers.

In compiling the above papers, all data collection, computations, analyses and writing has been carried out by the author. Except for Iana Vassileva, who took on the tedious task of extracting meter readings for the purposes of Paper III, the co-authors have merely served as sounding boards.
## Table of contents

Dedication ..................................................................................................... iii
Abstract ........................................................................................................ iv
Summary in Swedish/Svensk sammanfattning .............................................. v
Acknowledgements ....................................................................................... vi
A thought-provoking piece of art ................................................................. vii
Table of contents ........................................................................................... ix

### Defining the research mission .............................................................. 13
   Setting the scene ....................................................................................... 13
   Scientific challenges .................................................................................. 15

### Methodological approach ................................................................... 17
   Exploring variance in residential electricity use ..................................... 17
   Assessing the value of demand response in trading ............................. 17
   Estimating demand response in distribution ....................................... 17
   Designing and evaluating graphical feedback ..................................... 18

### Theoretical framework ....................................................................... 19
   Categories of policy instruments ......................................................... 19
   Demand response and its relatives ......................................................... 20
   The effect of demand response programs ............................................ 21
   Consumers’ need for feedback ............................................................. 23
   The effect of feedback ............................................................................ 24
   Designing feedback ............................................................................... 25
   Visualizing individual electricity use .................................................... 26

### Scientific contributions ...................................................................... 28
   Explanations of variance in residential electricity use .......................... 28
   Key figures for estimating trading risks ............................................... 28
   Assessment of trading risks ................................................................... 29
   Merits of hourly settlements in trading ............................................... 29
   Merits of charging demand in distribution ......................................... 29
   The design concept energiinfo™ ............................................................ 29
   Implications for the design of feedback ................................................. 30
Defining the research mission

Setting the scene

The commercialized version

Consequences in practice – a success story

The design concept in progress

User experience lab tests

Modifications of the design concept

Field trials

User acceptance

User categories

Perception of color coding

Units of feedback

Applications

Supplementary features

Units of comparison

The commercialized version

Conclusions

Acknowledgements

References

About the authors

Contact
Defining the research mission

This thesis deals with non-governmental instruments for controlling electricity consumption and managing peak demand in the residential sector of the Swedish power market, i.e. market-based means of promoting behavioral change in household electricity use. The focus of the research is on demand response programs involving economic incentives, in terms of electricity distribution tariffs and electricity supply contracts, for households to cut peak demand at times of limited distribution capacity and high spot prices on the Nordic power exchange, as well as graphical feedback on individual households’ electricity use and hourly demand by means of a statistics service provided over the Internet.

Setting the scene

Total energy use has remained constant during the last few decades in Sweden. Overall electricity consumption has, however, increased significantly since the seventies, the rise being particularly evident in the residential and service sector. The increase in residential electricity use is mainly explained by the growing proportion of electricity used for space and water heating and the growing number of electrical appliances in homes, workplaces etc. Electric heating has, in and of itself, declined since the nineties, but the need for electric cooling has on the other hand increased during the same period. Apart from two transitory deviations from the otherwise upward trend, which were occasioned by the oil crisis in 1973-1974 and a nationwide drive to reduce electricity use in 1980-1981, there has been a steady increase in household electricity consumption since the sixties (Swedenergy, 2010).

At the same time, alarming reports about the impact of energy use on global warming and thus climate change are taken more and more seriously by politicians and other decision makers. The world community is virtually unanimous in recognizing that global energy use has to decrease and become more efficient in order for internationally agreed-upon climate goals to be reached. Saving energy and improving energy efficiency are consequently top of the political agenda. There is, however, some difference in opinion as to how the responsibility for mitigating climate change should be allocated,
how such mitigation should be pursued as well as to who should pay for it among individual states. International agreements to these ends are, regardless of the negotiation outcome, to be put into practice by means of domestic legislation and policy instruments (Ellegård, et al., 2008).

Out of economic and environmental concern, it is against this background of great importance to improve market efficiency by increasing demand response, which in this particular context is defined as electricity consumers’ willingness to adjust demand to the current market price or time-varying tariff rates. Increased consumption flexibility in this respect is expected to ultimately result in reduced environmental impact, in that customers cutting peak demand in response to price signals would replace fossil fuelled peak load production. Increased demand response would also help stabilize the electricity price, mitigate the effects of power producers’ potential market power and avoid situations of load capacity shortage, which by extension will benefit end customers by way of competitive electricity retail prices (Lundgren, 2008; Gåverud, 2008). The International Energy Agency, IEA, consequently advocate a market-based approach for Sweden to maintain security of supply, since central intervention in market mechanisms, e.g. in the form of capacity reserves, runs the risk of penalizing investments and initiatives to promote demand response (IEA, 2008).

It is a known and established fact that increased consumption flexibility is a necessary condition for deregulated and thus competitive power markets to function effectively. Enabling customers to adjust their electricity use as prices fluctuate requires hourly meter readings, which in turn entails automatic remote meter reading. Swedish distribution system operators have made extensive investments in such smart metering systems, the main driving force of which has been the legal requirements for monthly meter reading. However, given that all market actors, including end customers, as well as society as a whole have a lot to gain from it, a vast majority of distribution system operators have invested in automatic meter reading systems that render registering and storing of meter readings by the hour possible. This in turn enables hourly settlements in electricity trading and demand-based tariff rates in distribution as well as improved statistics and feedback on electricity use and demand. In presenting and packaging these opportunities, it is essential that information is as condensed, yet accurate, and individually tailored as possible. Introducing the concept of demand has in this context proven to be a particularly delicate matter, seeing that customers find it hard to grasp the meaning of it (Badano, Fritz, Göransson and Lindén, 2007).
Scientific challenges

The Swedish Energy Efficiency Inquiry (SOU 2008:110), the main task of which was to propose how “the EC Energy Efficiency Directive”\(^1\) was to be implemented in Sweden, established among other things that improved statistics on energy consumption are an essential prerequisite to ensure the quality of policy instruments for promoting sustainable use of energy. Official statistics are essential for implementing and monitoring these measures, whereas general statistics are necessary for assessing the effectiveness of individual policy instruments. As part of the effort to improve domestic statistics on residential electricity consumption, an exploratory study, which set out to explain variance in electricity use among consumers living in single-family homes by means of variables relating to household features and building properties, was conducted (see also Paper I: Exploring variance in residential electricity consumption: Household features and building properties).

The results of this study showed that variance in electricity use among consumers living in single-family homes cannot be explained by household features and building properties alone, from which the conclusion was drawn that energy related behavior has a profound impact on residential electricity consumption. According to e.g. Darby (2006) and Santín, Itard and Visscher (2009), there are several studies supporting this finding in that they show that individual energy use, entirely on account of household behavior, may differ by a factor of two or more among households living in identical dwellings, irrespective of those being low-energy or not. Behavioral change that brings about energy savings and efficiency will not happen by itself, but requires some means of control to come about. This state of affairs implies that development and renewal of policy measures to that end, as well as further research on the effect of such policy instruments on behavioral change, is warranted (Lindén, Carlsson-Kanyama and Eriksson, 2006).

Automatic meter reading technologies have opened the door to novel approaches in developing superior electricity supply contracts for the purpose of controlling electricity use in an economically advantageous manner. As for electricity retailers, the major benefits of hourly settlements are reduced risk exposure and the prospect of offering customers innovative electricity supply contracts that bring about economic savings for consumers. Against this background, the Energy Efficiency Inquiry (SOU 2008:110) suggested that the Energy Markets Inspectorate be assigned to investigate the feasibility of introducing hourly settlements on a mandatory basis. To this end, an electricity supply contract involving hourly settlements, which is referred to

as “Fixed price with the right to return”, was evaluated in terms of its inherent incentive for residential consumers to reduce demand at times of high spot prices at the Nordic power exchange and its ability to reduce retailers’ trading risks. An additional objective of this study was to assess the magnitude of the physical as well as financial price and volume risk entailed in power trading (see also Paper II: Potential of hourly settlements in the residential sector of the Swedish electricity market: Estimations of risk reduction and economic result).

Seeing that smart metering also enables a more efficient utilization of power distribution grids, the Energy Efficiency Inquiry (SOU 2008:110) suggested that the Energy Markets Inspectorate is given the assignment to draw up proposals for imposing a requirement of demand-based electricity distribution tariffs in the Swedish power market as well as how this should be done. Given these policy objectives, an empirical study was carried out for the purpose of estimating the scale of residential demand response to a demand-based time-of-use tariff in electricity distribution as well as determining the economic consequences of implementing it and assessing domestic consumers’ view on being charged for demand as opposed to power supply (see also Paper III: Introducing a demand-based electricity distribution tariff in the residential sector: Demand response and customer perception).

Lack of knowledge and information about individual energy use are the main reasons why energy efficiency measures, although profitable in themselves, do not happen. Automatic meter reading systems allow for fresh ideas in compiling information and statistics for residential electricity consumers (SOU 2008:110) and the Energy Efficiency Inquiry therefore put forward a number of suggestions involving enhanced and extended information on individual households’ consumption in energy billing. In light of political endeavors to increase the stock of information available to electricity consumers, a design concept for a statistics service intended for visualization of individual households’ electricity use over the Internet was developed and evaluated. The development has covered the user interface and functionalities of the statistics service, whereas the subsequent evaluation has involved assessing households’ perception and experience of the artifact and the services it provides. The overall ambition was to play an active role in boosting awareness among electricity consumers and thus promoting a more efficient use of electricity in households (see also Paper IV: Climate-smart information design: Visualizing residential electricity use over the Internet).

Methodological approach

A mixture of quantitative and qualitative research methods was employed to meet the widely different nature of the research questions which have been addressed over the course of the work toward this degree.

Exploring variance in residential electricity use

For the purpose of contributing to a further understanding of the scale as well as the source of variation in residential electricity consumption, conventional methods for statistical analysis of variance were employed using consumption and survey data on household features and building properties (see also Paper I: Exploring variance in residential electricity consumption: Household features and building properties).

Assessing the value of demand response in trading

In order to gain more knowledge about the merits of demand response, and with the aim of estimating the magnitude of the risks involved in power trading, a set of eight quantitative and monetary key figures was introduced, the calculations of which were carried out by means of computer simulations based on empirical consumption and survey data (see also Paper II: Potential of hourly settlements in the residential sector of the Swedish electricity market: Estimations of risk reduction and economic result).

Estimating demand response in distribution

As part of estimating the scope of consumption flexibility in power distribution, a demand-based, time-of-use electricity distribution tariff was implemented under a pilot project. The extent of residential demand response to the tariff was determined by comparing the values of a set of predefined parameters, the calculation of which was based on empirical consumption data, from the period of reference with those from the subsequent test period.
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As part of estimating the scope of consumption flexibility in power distribution, a demand-based, time-of-use electricity distribution tariff was implemented under a pilot project. The extent of residential demand response to the tariff was determined by comparing the values of a set of predefined parameters, the calculation of which was based on empirical consumption data, from the period of reference with those from the subsequent test period.
Customers’ view on, and experience with, the demand-based, time-of-use electricity distribution tariff were assessed by an in-depth interview study (see also Paper III: Introducing a demand-based electricity distribution tariff in the residential sector: Demand response and customer perception).

Designing and evaluating graphical feedback

The development of the design concept was characterized by reciprocal action between several phases of data collection, analysis and design. To put it simply, analysis of data provided ideas for advances to the conceptual model of the design in progress. At a late stage of the design process, user tests brought about inspiration for improvements and additions to the prototype. The development of the design concept consequently to a large extent took place in parallel with the evaluation of it (see also Paper IV: Climate-smart information design: Visualizing residential electricity use over the Internet).
Theoretical framework

This section gives the definition of relevant concepts and a general outline of state of the art knowledge in key areas for the highly interdisciplinary objectives of the various studies that are reported on in this thesis.

Categories of policy instruments

Policy instruments are introduced for the purpose of influencing developments so as to reach predefined goals or to correct the situation when developments are going in the wrong direction (Sterner, 2003). Lindén and Carlsson-Kanyama (2002) have identified four main categories of policy instruments for the purpose of promoting behavioral change, namely information, economic, administrative and physical instruments, the latter of which have subsequently also been referred to as design measures (Lindén, 2004 and Lindén, 2008). Policy instruments for the purpose of promoting energy efficiency and behavioral change differ in the type of influence exerted on electricity consumers and the pace at which the potential effects emerge (Lindén, 2001), which means that the efficiency of such measures may be improved by combining them in various ways (Jordan, Wurzel and Zito, 2003).

Information instruments seek to increase general knowledge of energy and environment issues or shed light on the consequences of individual behavior on energy consumption on a voluntary basis, using a wide range of media such as advertisement and labeling. The effect of information on behavioral change is gradual and comparatively slow. Economic instruments, such as discounts, subsidies, taxing and pricing, may have either a positively or a negatively motivational effect on households’ readiness to change their energy related behavior and choose environmentally friendly products. The short-range effects of economic measures are catalytic, in that they commonly involve increased awareness and further energy savings in other domestic areas. The influence of administrative instruments, i.e. laws and regulations, is immediate and forcing, in that measures come into effect on a preannounced date and apply to everyone who fall within the scope of its target group. Measures to limit carbon dioxide emissions and restrictions on trade
are examples of administrative instruments, the effects of which are middle-range. Design measures aim to facilitate behavioral change by way of designing products and services so as to support this particular end. Energy meters providing immediate feedback about the effect of behavior on individual energy consumption is a typical example of this kind of policy instrument, the influence of which commonly takes place repeatedly (Lindén et al., 2006; Lindén, 2008).

Demand response and its relatives

Demand response is another central concept that appears frequently in this thesis, hence warranting a particular focus of attention. The concept of demand response originates from the economic literature on peak-load pricing of public utility goods and services (Faruqui and Sergici, 2009), which are most commonly characterized by non-storability and demand fluctuations (Crew, Fernando and Kleindorfer, 1995). Demand response, which is commonly used synonymously with the concepts of load management and demand side management, is a multidimensional concept, in that it covers a number of technical, economical and legal aspects. Thus there is a wide variety of definitions to be found in the literature (Abaravičius, 2007), one of which reads:

“Changes in electric usage by end-use customers from their normal consumption patterns in response to changes in the price of electricity over time, or to incentive payments designed to induce lower electricity use at times of high wholesale market prices or when system reliability is jeopardized”.

U.S. Department of Energy, 2006, p. 6

Hence the term demand response program is defined as follows:

“A company's service/product/tariff related to changes in electric usage by end-use customers from their normal consumption patterns in response to changes in the price of electricity over time, or to incentive payments designed to induce lower electricity use at times of high wholesale market prices or when system reliability is jeopardized”.

FERC, 2008, p. 3

There is a wide range of different demand response programs, which are also referred to as demand-side participation programs (Tan & Kirschen, 2007). Demand response programs are generally categorized into incentive- and

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2 See Crew, Fernando and Kleindorfer, 1995, for a review of research on peak-load pricing.
price-based programs (U.S. Department of Energy, 2006; Albadi and El-Saadany, 2007), which have also been referred to as emergency- and economic-based, system- and market-led, stability- and economic-based as well as reliability- and price-based programs (Tan and Kirschen, 2007).

Incentive-based demand response programs, which are established by utilities, load-serving entities and regional grid operators, provide economic incentives for customers to reduce demand at times of capacity shortage or exceptionally high electricity prices. These payments are usually separate from, or additional to, customers’ electricity retail rate, which may be fixed, i.e. based on average costs, or time-varying. For the purpose of increasing providers’ confidence that demand reductions will materialize when needed, these programs typically involve rewarding participants according to their performance in terms of demand response during critical periods and sometimes penalize customers that fail to fulfill their contractual commitments (U.S. Department of Energy, 2006).

Price-based demand response programs, which are of greater interest for the purpose of this thesis, involve dynamic tariff rates that promote changes in patterns of electricity use. Prices vary from hour to hour or between pre-defined time periods and customers may on a voluntary basis respond to these price differences by adjusting the timing of their electricity use accordingly. The major price-based demand response programs in use involve time-of-use, real-time-pricing and critical peak pricing tariff rates (U.S. Department of Energy, 2006).

Time-of-use tariffs involve different unit prices within different blocks of time and reflect the average cost of utilities during these periods. Real-time tariff rates reflect the hourly wholesale electricity prices, which are typically notified to customers on a day- or hour-ahead basis. Critical peak pricing is a hybrid approach combining the merits of time-of-use and real time pricing tariffs. Under normal circumstances, customers are charged according to a time-of-use rate, but in times of system reliability being compromised or wholesale electricity prices being very high, the normal peak price is replaced with a much higher retail price (U.S. Department of Energy, 2006).

The effect of demand response programs

Several studies have found conclusive evidence that households respond to high electricity prices by reducing peak demand. An extensive, but briefly reported, review of research on experiences with demand response programs, covering most of the EU-15 countries, Slovenia, the U.S., Canada and Aus-
tralia, has shown that the average effect of such measures in terms of demand response ranges from 20-50 percent. Studies that have been conducted in North America and Australia are in general more large-scale and commonly involve more enabling technology than those that have been carried out in European countries, which for the most part have tended to focus on demand response as a means of controlling security of supply. Research undertaken in Northern Europe (e.g. Lingskoug, 2006; Grande, Sæle and Solem, 2007) has typically involved small-scale studies on active, i.e. including no enabling technology, demand response programs in order to raise awareness and inform behavior related to electricity use (Chardon, Almén, Lewis, Stromback and Château, 2008).

The results of a recent survey, including mainly U.S. pilot studies, experiments and full-scale implementations of demand response programs, show that the magnitude of demand response varies from modest to substantial. The extent of demand response has proven to depend on, among other factors, the scale of the economic incentive, the availability of enabling technologies, such as remote control of individual end-uses and the study design. The overall results of the study suggest that time-of-use tariffs bring about a drop in peak demand by 3 to 6 percent, whereas critical peak pricing tariffs induce a drop in peak demand that ranges between 13 and 20 percent. When accompanied by enabling technologies, critical peak pricing tariffs lead to reductions in peak demand ranging from 27 to 44 percent (Faruqui and Sergici, 2010).

Another recent review of North American studies into the effect of demand response programs has drawn similar conclusions. The results show that critical price pricing programs, which involve enabling technologies for automatic curtailment of loads, are most effective in terms of demand response. There is little to suggest that automatic control of individual end-uses causes inconvenience to households. This is particularly true for customers having an override option and access to information about which loads are being controlled as well as how this is done. Under these circumstances, critical peak price programs have proven to bring about peak demand reductions of at least 30 percent. Time-of-use tariffs have, however, been found to generate decreases in peak demand by no more than 5 percent (Newsham and Bowker, 2010).

An analysis of residential customers’ response to critical peak pricing tariffs in California may provide some clue as to what role enabling technologies play in achieving demand response. Households without automated end-use control technologies have proven to use up to 13 percent less electricity during critical periods than they do under normal circumstances and customers that are equipped with these enabling facilities have been found to use 25
and 41 percent less electricity during critical periods that last two and five hours respectively (Herter, McAuliffe and Rosenfeld, 2007).

Demand responsiveness is expressed not only in percentage changes, but more commonly in terms of the own-price elasticity, which is usually simply referred to as the price elasticity, and the elasticity of substitution, which is a common normalized measure of customer response to time-of-use tariffs. The own-price elasticity is defined as the quotient of the percentage changes in demand and price, whereas the elasticity of substitution is defined as the quotient of the percentage changes in the ratio of peak to off-peak electricity use and price (Møller Andersen, Grenaa Jensen, Larsen, Meibom, Ravn, Skytte and Togeby, 2006; Ericson, 2007).

Based on data from time-of-use programs, the U.S. Department of Energy (2006) estimated the average elasticity of substitution among residential and small commercial customers at 0.14, ranging from 0.07 to 0.21, and the average own-price elasticity, including data from critical peak pricing programs, at -0.30, ranging from -0.10 to -0.80. An elasticity of substitution of 0.17 is, according to King and Chatterjee (2003), consistent with an own-price elasticity in the region of -0.30.

The results of yet another U.S. study, which was based on a representative sample of 1300 California households, suggest that the distribution of household electricity price elasticity is strikingly skewed, which implies that only a small fraction of households accounts for a large part of aggregate demand response in the population (Reiss, White, 2005).

Consumers’ need for feedback

Electricity is an abstract utility, which is generally used subconsciously. Feedback on individual electricity use is in this respect very important. Households’ access to feedback on their electricity consumption is, however, commonly restricted to the meter and the bill. The latter is moreover perceived as being very difficult to understand (Fischer, 2008; Bartusch, 2009) and, in Sweden, the industry has, despite years of joint efforts, not succeeded in providing an electricity bill that is adequate to supply the need for easily comprehensible feedback (Bartusch, 2009).

Kempton and Layne (1994) have also drawn the conclusion that traditional billing is inadequate in that it lacks the detail that would allow customers to make sense of the bill:
“For readers whose familiarity with current energy billing has dulled their appreciation of its absurdity, we ask them to contemplate parallel examples. [...] consider groceries in a hypothetical store totally without price markings, billed via a monthly statement like 'US$527 for 2362 food units in April'. How could grocery shoppers economize under such a billing regime?”

Kempton and Layne, 1994, p. 857

Households living in apartment buildings are particularly unfortunate in the sense that their electricity meters are commonly placed in rooms to which they do not have admittance. Moreover, there are still households, whose electricity use is included in the rent. These households are obviously neither confronted with feedback nor with the economic incentives, which the electricity bill entails. These circumstances are completely at odds with political endeavors to obtain a decline in electricity use (Directive 2006/32/EC).

There are, according to Lundell, Ilistedt and Moen (2007), three distinguishable motivations for households to save electricity. These are related to economy, environment and habit. When the main reason for saving electricity is of an economic nature, being in control of the electricity consumption is very important to households. “Knowledge is power” and feedback on individual electricity use allows households to take control over their electricity bills. Households’ ability to reduce their electricity consumption, and hence the costs it entails, is in other words highly dependent on the feedback they have access to.

A number of empirical studies and live situations have, according to Lindén et al. (2006), shown that feedback on individual energy consumption is a fairly efficient instrument in striving for increased energy efficiency. In fact, the more targeted the information, the more efficient it becomes (Abrahamse, Steg, Vlek and Rothengatter, 2007; Ek and Söderholm, 2010).

The effect of feedback

Fischer (2008) conducted an exhaustive meta-study, covering five review studies (Darby, 2001; Darby, 2006; Roberts and Baker, 2003; Abrahamse, Wokje, Steg, Vlek and Rothengatter, 2005; IEA, 2005) and a sizeable number of primary source papers, into the effect of individual feedback on residential electricity consumption. The overall results of this study show that feedback on individual energy use bring about savings ranging from 1.1 to

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3 The example of a grocery store without prices originally derives from Kempton and Montgomery (1982) and Merrilee Harrigan completed the analogy by suggesting monthly billing.
more than 20 percent, whereas typical savings vary between 5 and 12 percent. The differences between the results of individual studies are attributed to context, methodological approach and more particularly to design features of the feedback per se.

Designing feedback

The way data is displayed is crucial for the perception of information. Inspired by Saul Amarel (1966), Herbert Simon (1996, p. 132) stated that “solving a problem simply means representing it so as to make the solution transparent”. The physician John Snow’s mapping of the 1854 cholera outbreak in London is, according to Tufte (1997), a case in point. A time-series seemed likely to give a clue to cause, but there was no temporal event in the days before the outbreak that shed any light on the reason for it. Snow’s brilliant idea was to use space instead of time as the explanatory variable. Based on their home addresses, he plotted each deceased person on a map (Figure 1). The pattern was striking: the cluster of victims around the Broad Street water pump was obvious.

![Figure 1](image_url). Mapping of the 1854 cholera outbreak in London by John Snow (1855).
Another example is the disastrous decision to launch the space shuttle Challenger in 1986 (Tufte, 1997). On account of leaking O-rings in the field joint of the right solid rocket motor, the spacecraft exploded only 73 seconds after takeoff. There had been several occurrences of leaking O-rings in the past owing to low temperatures stiffening the rubber so that it would no longer seal. The forecasted temperature for the takeoff was considerably lower than it had been at the time of any of the previous 23 shuttle launches. The rocket engineers nevertheless failed to convey the risks involved to NASA. Tufte later analyzed the 13 diagrams, combining previous experience and experimental data, which the launch decision was based on. In light of his conclusions he suggested an alternative visual representation of the 23 successful launches preceding the tragedy. By means of a simple graph, including the explaining variable field joint temperature and the dependent variable O-ring damage, he got the huge risk across (Figure 2).

Figure 2. O-ring damage index as a function of field joint temperature at the time of the successful shuttle launches preceding the Challenger explosion. Adapted from Tufte (1997, p. 45).

These introductory examples aim to highlight the importance of mode of presentation. Energy use may not seem as dramatic a context as that of the examples above, but against a background of global warming the task of designing feedback that serves the purpose of energy conservation is central.

Visualizing individual electricity use

There are, according to Wood and Newborough (2003) as well as Fischer (2008), surprisingly few studies into design issues when it comes to feedback on individual electricity use and, what is more, existing artifacts to this end disregard the social implications of design (Broms, Katzeff, Bång, Nyblom, Ilstedt Hjelm and Ehrnberger, 2010).
Holmes (2007) has suggested that one of the key issues in visualizing energy consumption is the sheer scale of numbers and has therefore put forth arguments for a new area of discourse called eco-visualization, which combines artistic and scientific information to create novel modes of data representation in providing feedback to electricity consumers. Eco-visualizations focus on promoting resource conservation and make obscure feedback, such as kilowatts and carbon loads, more visible and thus more readily comprehensible.

Comparing two separate studies (Egan, 1999, and Wilhite, Høivik and Olsen, 1999) testing the same set of four “on-bill” graphs representing normative, also referred to as comparative, feedback in the U.S. and Norway respectively, implies that residential electricity consumers’ preferences vary considerably between cultures. The graph design that ranked highest in the U.S. totally flopped in Norway, seeing as Norwegian electricity consumers found it both childish and hard to interpret (Figure 3).

![Figure 3](holmes_2007.png)

*Figure 3.* “On-bill” normative feedback using houses to represent the distribution of electricity consumption. Provided by courtesy of Harold Wilhite.

Another example supporting that there are culturally conditioned differences in preferences as to mode of presentation is the fact that British and Swedish electricity consumers favor historical feedback (IEA, 2005, and Sernhed, Pyrko and Abaravičius, 2003, respectively), whereas their Finnish and Japanese counterparts prefer normative feedback (Haakana, Sillanpää and Talsi, 1997, and Ueno, Inada, Saeki and Tsuji, 2005, respectively).
Scientific contributions

In the following, the published results of the research that led up to this thesis are briefly recapitulated.

Explanations of variance in residential electricity use

In terms of statistical significance, variance in electricity consumption per square meter of heated living space among households living in single-family homes are partly and to some extent explained by variables relating to residence location, means of water and space heating, household size and composition, year of building construction and electric underfloor heating. The impact of household behavior and the stock of domestic appliances on electricity consumption per square meter of heated living space are considered the main reasons for the poor explanatory power of household- and building-related variables in explaining variance in this respect. From this it has been inferred that policy instruments that bear upon household behavior are just as important as those relating to, for example, heating systems.

Key figures for estimating trading risks

For the purpose of estimating the scale of electricity retailers’ physical and financial risk in trading, eight key figures, which are referred to as magnitude of physical price and volume risk, monetary value of physical price and volume risk as well as financial price and volume risk, monetary value of financial price and volume risk, were introduced. These key figures were found useful in assessing electricity suppliers’ trading risks as a whole and in various customer segments. Hence they may also serve as a guide for electricity retailers in developing innovative offers and targeting their marketing activities.
Assessment of trading risks

The risks associated with electricity trading proved to be greatest in the physical power market. In terms of magnitude and monetary value, the highest trading risk was found to arise from fluctuating market prices and the physical price risk is in this sense most severe in the customer segment of households that use a geothermal heat pump for space and water heating purposes.

Merits of hourly settlements in trading

Implementing hourly settlements in terms of the electricity supply contract “Fixed price with the right to return” proved to bring about economic benefits for both suppliers and consumers of electricity. As for electricity retailers, the economic gains of introducing hourly settlements are primarily the net result of reduced trading risks. By extension, hourly settlements are also expected to involve environmental benefits in that a large-scale implementation is expected to bring about a reduction in the use of environmentally adverse fuels in power production.

Merits of charging demand in distribution

Empirical evidence was found that demand-based, time-of-use electricity distribution tariffs are in general met with a positive reception from residential customers, the main contributory factor being that it has an indirect bearing on the environment. It was also empirically verified that households respond to price signals by cutting peak demand in periods, which by the distribution system operator have been defined as peak hours, and shifting electricity use from peak to off-peak periods. Another evident finding is the fact that residential customers, who are being charged according to a demand-based, time-of-use electricity distribution tariff, are in great need of feedback on their instantaneous demand.

The design concept energiinfo™

The design concept energiinfo™ was developed with the aim of designing intuitively available feedback on individual households’ electricity use and thus raising awareness and promoting behavioral change among residential
electricity consumers. The software proved to be adapted to its purpose in these respects and it was, moreover, established that individual feedback brings about a sense of being in control of one’s electricity use. The graphical user interface of the statistics service has, since energiinfo™ was first commercialized and Paper IV was published, undergone repeated changes in response to user needs (Figure 4).

Figure 4. Late version of the statistics service energiinfo™. Provided by courtesy of Svenska Energigruppen AB.

Implications for the design of feedback

The evaluation of the design concept energiinfo™ offered useful implications for the design of feedback on individual households’ electricity use. It was demonstrated that ease of access and straightforwardness are key factors in the development of web-based tools to this end. Combining conventional bar charts, color symbols and historic feedback proved to be useful in these respects. Finally, it was also established that residential electricity consumers perceive a great need for breakdown feedback, for the purpose of which existing statistical services have shown to be inexpedient.
Wrapping up

It has been established that energy-related behavior has a significant impact on residential electricity consumption. Political ambitions to increase energy efficiency in the domestic sector are high, but inducements for household behavioral change are deficient. This state of affairs calls for market-based policy instruments for the purpose of increasing efficiency in electricity use and promoting consumption flexibility. Automatic meter reading technologies have opened the door to innovative approaches to this end.

An example of such novel initiatives is the electricity supply contract “Fixed price with the right to return”, which has proven to make a win-win situation in that it substantially reduces the trading risks of suppliers and, on the assumption that they are prepared to respond to its price signals, considerably lowers the electricity expenses of consumers. It has also been empirically established that households are prepared to cut peak demand in peak periods and shift electricity use from peak to off-peak periods in response to a demand-based, time-of-use electricity distribution tariff.

Feedback on individual households’ electricity use, which is made available over the Internet by means of a statistics service, has proven to contribute to heightened awareness and behavioral change among residential electricity consumers. As for mode of presentation, a combination of conventional bar charts, color symbolism and historic feedback has shown its expediency in providing households with intuitively accessible visualizations of their electricity use.
Areas warranting further research

The results suggest that the design concept for a web-based statistics service, which was developed and evaluated within the framework of the research studies, helps boost awareness among electricity consumers and thus effects behavioral change. The scale of the observed energy efficiency gains is, however, yet to be quantified and, what is more, the question remains as to whether individual feedback brings about increased energy efficiency in the long term.

It was also established that there is a pronounced need for feedback on instantaneous demand among households that are charged according to a demand-based, time-of-use electricity distribution tariff. Further, previous field research has demonstrated the necessity of providing electricity consumers with direct feedback on the current market price when implementing hourly settlements in terms of the electricity supply contract “Fixed price with the right to return” in the residential sector. In light of these findings, development and evaluation of means that are fitted to these particular purposes stand out as being key areas for future research endeavors. So do investigations into the aptness of web-based statistics services in providing information about the long-term trend in the spot price on the Nordic power exchange. According to Stern (1999) and Uitdenbogerd, Egmond, Jonkers and Kok (2007), incentives and information have different functions, which means that efforts focusing on only one of these types of interventions may involve failing to secure their synergetic effects on behavior. This state of affairs further stresses the importance of such research efforts.

One of the most evident findings that were generated during the course of the research studies is undoubtedly electricity consumers’ perceived need for breakdown feedback. Given that access to such information is considered to be a necessary condition for households to be successful in increasing energy efficiency, this want should be supplied.
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Bibliography


