NEW OPPORTUNITIES PROVIDED BY THE SWEDISH ELECTRICITY METER REFORM

Fredrik Wallin

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School of Sustainable Development of Society and Technology
NEW OPPORTUNITIES PROVIDED BY THE SWEDISH ELECTRICITY METER REFORM

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Akademisk avhandling

som för avläggande av teknologie doktorsexamen i energi- och miljöteknik vid Akademin för hållbar samhälls- och teknikutveckling kommer att offentligen försvaras onsdagen den 24 februari, 2010, 10.00 i Kappa, Mälardalens högskola, Västerås.

Fakultetsopponent: Professor David Natusch, Managing Director of Resource Development Ltd, Hunterville, Nya Zeeland
Abstract

The reduction of the impact of energy consumption is a priority issue and a major challenge that concerns every country in the world. This is a complex task that needs to be tackled from several angles in the search for areas where optimizations and savings can be made. In Sweden an electricity meter reading reform was fully implemented by 1st July 2009, including 5.2 million customers, and this created new set of circumstances in the Swedish electricity market. The main purpose of this thesis work has been to investigate the possibilities of increasing the use of remote meter readings. Two research questions have been: “How can the electricity market benefit from remote collected meter readings?” and “Where do barriers appear when utilizing meter readings?”. The work started in 2000/2001 to study Internet based applications that visualize electricity consumption patterns. Over these years the daily internet users have increased from approximately 40 % to 73 % and new markets for web-based applications have evolved. These solutions can be important in the forthcoming years as energy portals that hold new energy services. Experiences from new installations indicate that at least interested customers do submit information concerning building and household properties through internet. Still, it is challenging to enable the majority of customers to take part in these new solutions. It may therefore be important to remind customers on a regular basis in order maintain the frequency using the application and to make it habitual. Further the introduction of demand-based pricing allows electricity distribution utilities to achieve a stronger correlation between peak loads in the distribution network area and their revenues.
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To my family
Abstract

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Svensk sammanfattning


Detta arbetes övergripande syfte har varit att undersöka möjligheterna med de installationer av fjärravlästa mätsystem som nu genomförts i Sverige. Två forskningsfrågor är: ”Hur kan aktörer på den svenska elmarknaden tjäna på de genomförda installationerna av fjärravlästa elmätare?” och ”Var uppstår det barriärer när dessa insamlade mätvärden ska användas?”.


Vidare har analysverktyg för nya priser och tariffer föreslagits och utvecklats. Tre tariffer har utvärderats, varav två var effektbaserade. En av de effektbaserade tarifferna baserades på den

Vidare har två olika metoder föreslagits. En metod syftar till att återskapa timförbrukningsprofiler i elnätsområden med begränsad tillgång på timvärden medan den andra metoden syftar till att dela upp elförbrukningen ytterligare på deller som exempelvis värm. För att generera timprofiler på en övergripande nivå har energianvändningen och en tidsstamplad effekt topp använts, d.v.s. i stället för 24 timvärden per dygn utgår modellen från endast två värden. Resultaten var goda och det bedöms att med förfinningar kan noggrannheten förbättras avsevärt. Ett användningsområde kan vara att reducera insamlad förbrukningsinformation. I arbetet med att på individuell basis detaljbestämma olika typer av förbrukning har vi tittat på 14 hus där endast eluppvärmning har varit installerat. Resultatet visar att det efter analyserna går att se ett samband mellan husets aktuella värmehov och olika byggar. Detta ger en indikation på att metoden bör undersökas mot fler parametrar och med ett större urval av hushåll.

Acknowledgement

There are a number of people that I would like to thank for their contributions, discussions, help and encouragements over the years.

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Finally, to my family and friends for giving me love and support. To Jill, the woman in my life, for love, patience and understanding. To our children William, Kajsa, Ella and Martin for just being so important to me. To my mother Annelie, for support, lunches and always helping out when time is not enough. To my father Kenneth, Karin, my sisters Anna and Emma, my brother Alfred, and of course little Liam, who I am looking forward to meet.

To all those I should have mentioned…

Fredrik Wallin

Västerås, February 2010
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Part I
Thesis
Chapter 1

Introduction

This part presents the motivation and positioning of the work and the set of research questions that are addressed. Finally, there is a discussion of the methodologies used to address each research question and summary of related work.

1.1 Background

The reduction of the impact of energy consumption is a priority issue and a major challenge that concerns every country in the world. This is a complex task that needs to be tackled from several angles in the search for areas where optimizations and savings can be made.


- “The improvement of energy efficiency will benefit from an exchange of information, experience and best practice at all levels…”

- “Improved energy end-use efficiency can be achieved by increasing the availability of and demand for energy services or by other energy efficiency improvement measures…”

- “In defining energy efficiency improvement measures, account should be taken of efficiency gains obtained through the widespread use of cost-effective technological innovations, for instance electronic metering…”

- In order to enable final consumers to make better informed decisions as regards their individual energy consumption, they should be provided with a reasonable amount of information thereon and with other relevant information, such as information on available energy efficiency improvement measures, comparative final consumer profiles or objective technical specifications for energy-using equipment […]. In addition, consumers should be actively encouraged to check their own meter readings regularly.”
This work was started in parallel with the intensive discussions that initiated the Swedish electricity meter reform in 2001. The underlying drive for the meter reform was to improve on a previous reform, i.e. the deregulation of the Swedish electricity market. In the early years of the reformed electricity market (1996 – 1999), customers were forced to invest in measuring equipment themselves in order to take part in the deregulated market and replace their existing electricity retailer. The investment requirements for new electricity meter reading devices created an economic barrier for small and medium sized consumers and reduced the number of customers willing to be active in the new electricity marketplace. As a direct response to this barrier metering requirement was abolished in favor of a new profile-settlement system. A number of consumption patterns were applied in order to estimate the electricity consumption for each month. A total of 305 different consumption patterns were applied to different groups of customers within specific geographical areas [2].

Another important reason for the discussion about introducing more frequent meter readings was the fact that several studies indicated that there were potential energy savings to be made by improving customer feedback on energy consumption [3] [4] [5]. A major disadvantage of the profile settlement system is that there is no real connection between electricity consumption and the amount of electricity charged for during peak periods for small and medium sized customers. The Government also believed that more focus on electricity consumption could increase customers’ possibility to save energy [6].

The main purpose of this work has been to investigate the possibilities of increasing the use of remote meter readings, as many of the Swedish electricity companies initially focused only on providing monthly invoices based on actual electricity consumption. Improved customer information can lead to more active electricity users. Customer participation is believed to become an important feature in the future electricity system where variations in electric power output are expected to increase due to larger shares of distributed generation by renewable energy, such as solar and wind. To compensate for variable production from the alternative energy sources it is important to influence the consumption. New incentives for the customers could be new price models and a better understanding of the individual consumption patterns in order to decrease the imbalance between production capability and consumption demand.
1.2 Motivation and positioning of the work

The decision in 2003 to introduce more frequent meter readings is considered an important milestone in the development of the electricity market. The electricity distribution utilities were obliged to implement the regulations on hourly based metering and monthly meter reading by 1st July 2006 and 1st July 2009 respectively. As a result of the electricity meter reading reform the distribution utilities have made large investments in different remote meter reading systems with two main aims:

- To read and report consumer’s electricity meters at least once a month.
- To base customer invoices on actual electricity consumption.

During the initial discussions, meetings and seminars there was a strong focus on how to minimizing the investment cost. There were also concerns about which technical solutions that were actually able to fulfill the minimum requirements, and the authorities worked intensively to specify and improve the relevant regulations. At this time, in 2002/2003, the electricity market operators had very limited information and knowledge of the potential benefits of remote meter readings. Several activities were initiated at the time in order to create and assemble knowledge banks in different areas such as technologies, roll-out methods and business cases regarding added values that could be coupled to the forthcoming system installations. The increased requirements on electricity distribution utilities for improving meter reading indeed created new conditions for the electricity market. These corresponded well to the ongoing research and research strategy at School of Sustainable Development of Society and Technology at Mälardalen University, which became a natural discussion and working partner for the regional energy industry:

- “To develop innovative solutions and tools in the areas of energy, building and environment engineering.”

Excerpt from the research mission of the Process and Resource Optimization research group.
The work accomplished during the course of this project has been influenced by existing and emerging technologies. Current laws, regulations and other requirements have had to be considered and evaluated. The work began from the current state of knowledge and has applied methods and tools from the different existing fields of knowledge within the organization. Part of the work can be seen as a cross-fertilization of naturally related fields such as data mining and economics. The intersection of different subject areas is illustrated via the Venn diagram in Figure 1.

Figure 1. Positioning of the work.
1.3 Research questions

The research performed over this period can be summarized as a search for new possibilities at the intersection of a deregulated electricity market, regulated distribution utilities and a meter reading reform that is considered an important milestone for Swedish electricity customers. One reason to explore new solutions related to the meter reading reform has been to provide a broader and more comprehensive base to understand made decisions and to improve future ones.

A general question over this period has been how to maximize the use of detailed consumption data in order to increase the benefits of the investment in remote meter reading systems.

This general question can be divided into several important sub-questions that the individual efforts have each attempted to answer in some form.

RQ1: What are the primary applications possible using remote collected meter readings?

RQ2: How can the electricity market benefit from remote collected meter readings?

RQ3: Where do barriers appear when utilizing meter readings?

In order to identify individual pieces of the puzzle and to contribute answers to the questions above, parts of the work have been performed together with regional electricity distributors.

1.4 Methodology

Several processes of change were initiated when the Swedish meter reading reform was established by the Parliament. These processes are creating incentives and opportunities to implement new methods and tools in the electricity market. The outcome of thesis developments will involve several stakeholders, including energy companies, industry and residential customers.

An important part of the methodology has been to work with regional energy companies through discussions, meetings and workshops in order to identify knowledge gaps, future needs and critical issues in the areas affected by the reforms, such as the installation of remote meter reading systems and their integration into daily operations.
In the search for answers to the global research questions stated in Section 1.3 several methods and tools have been proposed, analyzed and implemented as a result of this work. A number of these solutions have been evaluated and discussed in the appended papers, and each individual effort has also contributed to a holistic understanding of problems, limitations and structural obstacles that exist in the organizations – both in daily routines as well from a long term perspective.

A bottom-up approach has been used in several parts of the work. In a bottom-up approach the individual base elements of the system are first specified in great detail. These elements are then linked together to form larger systems or software tools.

More specifically, different programming methods have been used to create the necessary software tools described in the papers. The implemented programming methods are considered as state-of-the-art (object-oriented and later component-based) and have been incorporated via the use of Visual Basic, VB.Net and C#, the latter two as a part of the Microsoft .NET framework. In order to implement more advanced mathematical solvers a number of FORTRAN libraries were used and routines wrapped in and made accessible via dynamic link libraries (dll). Databases were used to handle the large amounts of electricity consumption data. In the majority of work different versions of Microsoft SQL Server have been used in combination with related graphical user interfaces (Enterprise manager and Query Analyzer).

1.5 Scope and limit

The intended audience for the research described in thesis is researchers working on energy market questions and improved customer integration. As substantial parts of thesis deal with software applications related to remote meter reading and handling large amounts of consumption data it may also be of interest to workers in the area of computer science. The thesis presents an analysis of the effects of new electricity price structures, making it of potential interest to workers in the economics field.

Beyond the academic world the work is aimed to companies that operate primarily in the energy and metering fields, and also those involving future customer-oriented applications and other innovative solutions in the energy sector.
Five papers are included in the thesis. They are summarized below, including a description of my personal contribution to each paper.

**Paper A – A web-based dynamic simulator for applications in process industry and for education** – describes a web-based system architecture that encapsulates functionality in software applications situated on a server and makes it accessible to a user. One aim of this work was to present a system solution provide the following advantages:

- To minimize the need for locally installed software and expand the use of the Internet and web browsers.
- To streamline the maintenance and updating of software by using centralized installations.
- To reducing administration costs and license fees.

The author’s contribution to this paper has been to suggest and implement a general system architecture that is suitable for several purposes, to develop and implement the energy related work both in relation to both the energy simulator and to the information system dealing with electricity consumption data, and to evaluate and customize a graphical user interface. Together with staff from the AMR system provider HM Power, I suggested solutions to refine and recalculate the electricity consumption data and implemented the solutions. Staff from Mälarenergi, especially Andreas Forsman, implemented the web based ASP-solution in their environment. Erik Dahlquist has been a discussion partner.

**Paper B – The use of automatic meter readings for a demand-based tariff** – describes an implementation and evaluation of a flexible pricing tool. The economic consequences of demand-based time of use (TOU) tariffs, and particularly the effect of the demand-based tariff on revenues of the electricity distribution utility over the year 2003 were analyzed. The paper also includes a study of the impact on individual consumers, which has been made possible by the implemented bottom-up approach.

This work was mainly performed by me. I developed design and structure of the software tool, with inputs from Tobias Bäckström. I subsequently implemented and analyzed the new tariff structures in discussion with Cajsa Bartusch. In the electricity tariff evaluation phase, new tariffs were discussed with Bartusch. Eva Thorin and Erik Dahlquist assisted the work as discussion partners.
**Paper C – A method to refine electricity consumption data from automatic meter reading systems** – describes a method to extract new information from less detailed energy consumption series. One reason for the work was to overcome the problem of missing information on an aggregated system level when estimating the effects of new price structures. Some AMR systems were not designed or configured to handle hourly based meter series and in these cases we wanted to use measured data from a system that reported just two values, total energy and peak load, to describe each 27 h interval. A system that reports hourly based meter series would report 27 values for the same interval.

This work was performed mainly by me with some assistance on the validation from Eva Thorin. Andreas Kvarnström and Johan Kvarnström provided support with knowledge in the programming and database configurations used to implement the method. Erik Dahlquist assisted as a discussion partner.

**Paper D – Automatic Meter Reading Provides Opportunities for New Prognosis and Simulation Methods** – describes the possibilities of using meter readings to build bottom-up models for prognosis and simulation, and describes an approach to using meter readings for modeling and simulation. This article contributes with a discussion of how to breakdown meter reading series to identify heating properties. It also considers potential problems with the suggested methodology.

I was the main contributor to this work. Erik Dotzauer contributed with experience of statistical models that are useful for modeling household related consumption such as moving average (MA), weighted moving average (WMA), autoregressive moving average (ARMA). Eva Thorin and Erik Dahlquist assisted the work as discussion partners.
Paper E – Important Parameters for Prediction of Power Loads - A Bottom-Up Approach Utilizing Measurements from an Automatic Meter Reading System – is a continuation of Paper D. However, in this paper we shifted the focus to different parameters that could be used to disaggregate the meter reading series in order to extract additional information. Sections of previously performed surveys were included in the paper in order to discuss the usefulness of questionnaires when creating new prognosis models in order to obtain more accurate models.

The work was based mainly on my previous thoughts on bottom-up modeling. Cajsa Bartusch was main responsible for conducting several surveys, collecting household information over the past years, and in this work we have discussed how questionnaires could be used in a model structure. Bartusch contributed with her experience from surveys performed in the Mälarenergi, Smedjebacken Energi and Skånska Energi electricity distribution areas. I contributed to the discussions with Bartusch during the preparation and analysis part of the results from these surveys. Eva Thorin and Erik Dahlquist assisted the work as discussion partners.

![Image](image.png)

Figure 2. An illustration of the relationships between papers-papers and between the papers- research questions.
This thesis uses a relatively broad approach meaning that proposed applications have been suggested and evaluated in order to confirm the usefulness. The author is aware that some of the proposed methods can be further evolved and needs additional validation. This is a limitation. This thesis has partly focused on implementations in close cooperation with partners and on solutions that may be automated. Working with persons in various positions in the companies, and with different types of meter reading systems increased the probability to detect different barriers and to understand how these systems are used.

1.6 Related work

1.6.1 Europe

Sweden

There are several actors investigating the potential in applications and services related to remote meter reading in Sweden. Lund University has been one of the pioneers in this area and started early to investigate the potential of demand-side activities, this included both direct and indirect load control. They have performed related investigations into electricity use and control [7] [8], load demand activities and new price structures [9] [10]. Further the research has concerned presentation and customer perception of electricity consumption statistics [11]. The researchers have continuously used different statistical indicators, and also discussed how these contribute to the evaluation of specific consumption properties, such as coincidence factors, demand factors and load factors [12] [13].

One general experience based on years of work is concluded in the following statement [14]:

- “One general conclusion from this research is that there is a lack of knowledge and information on load demand variation and its consequences both on the demand (consumer) side and the supply (utilities) side. As the case studies show, consumers, especially residential consumers, mostly do not clearly distinguish between load demand (power, kW) and energy use (kWh)”
The Interactive Institute has been active in seeking new solutions in visualizing energy consumption in different ways and with innovative methods (see Figure 3). The research group Energy Design works with both design-related activities [15] and with new technologies to implement remote meter readings as input to applications such as energy mobile games and the energy aware clock [16][17].

Mälardalen University began early investigations into both technical and application-based opportunities coupled to remote meter reading, but the research group has also focused on more detailed metering of heat, warm water and electricity use in apartments. Questionnaires have been sent to approximately 600 apartments and the results have been used in order to compare tenants’ behavior to their consumption. Overall results showed a connection between higher salaries, higher interests in electricity savings and higher electricity and hot water consumption [18]. Different electricity price models have been investigated further, not only with respect to distribution utilities but also with respect to electricity reitals, e.g. fixed price with the right to return. The result indicates that households whose main heating system consists of a geothermal ground source heat pump may constitute the largest physical price and volume risk of suppliers [19]. Several activities have also been conducted related to customer feed-back on energy consumption data [20].

At Uppsala University the major part of the work has been related to how detailed energy metering can be used to create models of household consumption patterns that can be used to predict the potential for solar integration for residential energy consumers [21]. There have also been several joint publications with Mälardalen University [22] and Linköping University 0. At Linköping, the focus has been on behavioral aspects of energy consumption and especially on visualizing activity patterns [24] [25]. Activity pattern diagrams have been

Figure 3. Examples of energy design applications. (Pictures courtesy of Interactive Institute, Energy Design).
produced based on diaries to monitor people as they go about their business during the day. The entered activities have then been used to explain individual consumption patterns.

**Norway**

There have been several groups working on remote meter reading in Norway, where researchers at SINTEF have been active in this area for many years. There have been several publications in the area of direct and indirect load control. Estimates of economic benefits for different operators (national, regional and local) have been discussed, based on the assumption that load shifting actions of 1 kW over 9 hours can be achieved by residential customers [26]. It is concluded that distribution utilities, i.e. the local grid owners, have the largest incentives to promote customer participation and demand-side flexibility in order to preserve or lower the peak demand (see Table 1).

**Table 1. Estimated annual costs using different reduction techniques, i.e. load shifting or strategic conservation of load, versus expanding grid capacity.**

<table>
<thead>
<tr>
<th>Market role</th>
<th>Operational cost [USD/kW year]</th>
<th>Expansion cost [USD/kW year]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Supplier</td>
<td>3.6</td>
<td>--</td>
</tr>
<tr>
<td>National grid</td>
<td>2.0</td>
<td>7.7</td>
</tr>
<tr>
<td>Regional grid</td>
<td>3.2</td>
<td>9.7</td>
</tr>
<tr>
<td>Local grid</td>
<td>5.3</td>
<td>112.0</td>
</tr>
<tr>
<td>Total</td>
<td>14.1</td>
<td>129.4</td>
</tr>
</tbody>
</table>

At Norwegian University of Science and Technology the work has also concerned new estimations and prognosis methods. One model has been created that make use of meter reading information from both electricity and district heating to derive load profiles for different building categories. Load profiles are then aggregated in a bottom-up manner with a predetermined mix of building categories to create system load profiles [27].

**Finland**

In Finland the group at Tampere University of Technology has initiated work toward the smart grid area [28]. As integration and interaction between consumers and the market is an important feature of a smart grid, this work is highly relevant. They also identify market development at the customer level, e.g. to enhance market-based demand response and customer-oriented services, as a key issue for the future.
A concept for an interactive customer interface (ICI) that integrates both advanced meter reading technology and two-way communication has been proposed [29]. One important issue is the justification for increased cost of retrofitting and upgrading existing metering systems to next technical level. It is stated that added value services will probably be necessary to motivate increased investments in more advanced technical systems.

At Helsinki University of Technology has investigated the economic values if different groups of customers could act together in a deregulated electricity market. Meter readings collected from field tests in Helsinki have been used to analyze strategies on how individual customers could control their heating system to optimize the total cost for the cooperative [30]. They have also combined the use of individual meter readings and national statistics in order to implement a bottom-up modeling approach. Based on the national statistics probability factors were included in the model to simulate household use of electricity [31]. The accuracy of such models should improve when larger sets of customers are used.

1.6.2 North America

USA

An early investment into meter reading systems in the state of Washington was reported in literature several years ago. Puget Sound Energy contracted AMR services for 1.5 million customers including both billing functions and load management possibilities [32]. The investment included techniques for outage notification, incorporated home security systems, remote connection/disconnection, tampering alarms and additional integrated solutions for gas and water metering. The company has now incorporated a web-based interface for their customers, which offers analysis services as well as energy statistics [33].

The conditions in the US are similar to those in the Swedish electricity market, except that electricity prices are higher and more differentiated, creating larger economic incentives in many areas. Many demand side management (DSM) programs, including different pricing, were investigated and realized already in the eighties. In many cases the electricity market in US has, as in Sweden, undergone reforms towards an open restructured market with separate organizations for generation, trading and transmission and distribution. Previous DSM research is of course valuable, but the results of these early investigations must be used with care and cannot be implemented without complementary investigations.
1.6.3 Asia Pacific

Australia

In Australia a research group, including members from University of Sidney, has described estimation techniques using conditional demand analysis and direct metering to disaggregate the total energy demand into main end-uses. One purpose has been to determine the potential impact of demand-side activities [34]. They have also presented results from refined statistical methods in combination with direct metering used to forecast residential loads [35]. The results suggest that the detailed consumption patterns can be used with benefit to tailor marketing efforts for specific groups of electricity consumers.

Japan

In Japan an early investigation on direct consumption feedback was implemented. A project provided residential customers with devices to monitor electricity consumption in their dwellings. The information provided to the consumers was based on hourly updates [36] and provided the customers with graphs and tables visualizing the consumption on both hourly and monthly basis. The author suggests that the modest impact on the consumption could depend on how the information has been presented.
Chapter 2

Towards meter reading systems

2.1 The Swedish Electricity Act

This chapter presents a historical exposition focusing on the Swedish electricity legislation framework. Political intentions have driven several amendments of the Electricity Act and over the last 10 – 15 years these have created a completely new set of circumstances in the Swedish electricity market. The exposition ends with the decision to introduce more frequent meter reading to improve customer feedback on electricity consumption.

2.1.1 A transmission and distribution infrastructure

It has been more than 100 years since the first Swedish Electricity Act was established. In 1902 the main purpose was to reduce the barriers and support a rapid expansion of the electricity transmission infrastructure. The objectives were to secure the use of Swedish hydro generated power based on industrial needs and for future national welfare. Swedish power production expanded, but problems began to appear, for instance due to technical differences. For example, the cities were often electrified via direct current systems while industries often invested in alternating current equipment. This conflicted with the idea of an effective and well planned expansion of the electricity system and showed the need for improvements in the regulations. In 1938 the low voltage parts of the grid were included in the concession application process as an amendment to the Electricity Act [37]. The electric power system was investigated from 1943 – 1954 in order to improve the systematic expansion of the grid and to comply with the growing electricity demand, e.g. from Swedish farmers in the countryside. Based on this investigation the Swedish Parliament decided in 1957 that concession rights should encompass both geographical areas and specific transmission lines. This amendment in the Electricity Act increased the possibilities for the authorities to ensure a functional expansion of the distribution system according to the plan for electrifying the countryside. One of the first recommendations for a more open electricity market was suggested in 1968 when the Government initiated investigation on rationalization of the distribution system delivered its official report [38]. The Government disagreed with several of the activities suggested in the report and a new investigation was opened in 1971 to analyze the organizational structure for distribution and production of electricity. The electricity investigation recommended a more regional approach and the reintroduction of preemptive
rights based on the request for bigger distribution entities. The power industry criticized the compulsory legislation ideas although there was agreement on the need for larger and more viable distribution entities. The Government proposed guidelines for a continued structural transformation of the Swedish electricity distribution system, including new regulations, also increased the ability to assess and control future ownership of distribution utilities [39]. These changes were incorporated into the Electricity Act in 1976. Between 1977 and 1991 several amendments were made where other legislation, e.g. concerning the use of natural resources, had an indirect impact on the Electricity Act.

Many of the decisions described above focused on encouraging formation of larger and more viable entities, important prerequisites for properly maintained distribution systems. Figure 4 shows the development of the number of electricity distribution companies in Sweden between 1943 and 2008.

![Figure 4. The number of distribution system operators/utilities/companies (DSO) has decreased over the years through acquisitions and mergers [37][40][41].](image)
2.1.2 Deregulation and towards improved customer information

It is unclear exactly when the move towards a deregulated Swedish electricity market was initiated. The decision in May 1991 to convert Vattenfall to a Government-owned limited liability company separate from the ownership of the national power system by a Government bill was a milestone [42]. The decision of Parliament decision was followed by a report to the Department of Industry analyzing the future organization structural of the national power system [43]. The results were included in a proposal from the Government that presented new goals and strategies for reform of the electricity market [44]. The market was deregulated in 1996.

Since 1996 there have been different prerequisites for Swedish customers to participate in the deregulated electricity market. Initially, in the first two years of the reformed market era, customers had to invest in costly metering devices in order to change to a new electricity retail company. This was considered a major barrier restraining customer mobility. In practice, the Government had imposed a fee that was far too high for any small or medium size customer to benefit from a change of electricity supplier. A maximum price of 2500 SEK was introduced for the necessary equipment in 1997 [45], but the customer take-up was still very low. The introduction of the new profile settlement in 1999 removed the financial obstacle and opened up the electricity market for residential customers [46]. Different consumption patterns, valid for customers in specific geographical areas, were then applied estimating the customers’ electricity consumption [47]. This partial integration of smaller electricity consumers into the electricity market produced several disadvantages; in particular the reduced coupling between energy consumption behavior and simultaneous pricing of electricity. Under this market construction, small and medium size end-users had no economic incentives to reduce or minimize electricity consumption in on-peak or high-peak periods.

An early declaration of the future intentions of the Government was apparent in the supplementary directive to the investigation evaluating concession contracts for electricity supply (LEKO-investigation) [48], to consider appropriate intervals for reading of electricity meters and including invoices based on real, and not estimated, electricity consumption. The final report [49] particularly stressed three advantages of introducing more frequent electricity meter readings: i) the accuracy in profile settlements would be improved, ii) the electricity customers would only be charged for real consumption, iii) increased awareness of electricity consumption would strengthen customers’ willingness to save energy. The investigators did not recommended any structural changes of the existing routines of debiting electricity customers’ accounts on a preliminary basis. In 2002 – just two years later – the Swedish
Energy Agency recommended the introduction of monthly meter readings, lowered the limit for hourly based metering, and introduced additional recommendations on e.g. automatic registration of electricity disruptions to the Government [50]. The energy industry organization Swedenergy, together with several major energy companies, expressed concerns over initiating monthly meter readings for all electricity customers and instead suggested meter readings quarterly meter readings for consumers of more than 8000 kWh. They also argued that the meter reform would imply higher costs than the Swedish Energy Agency estimates had indicated. However, in 2003 the Government followed the recommendations of the Swedish Energy Agency on introducing monthly meter readings at minimum for electricity customers and proposed a lower limit for hourly based metering that included all customers with fuse sizes above 63 A (> 43 kW) [51]. The recommendation for automatic disruption management was not included in the bill. The distribution utilities were instructed to provide customers with electricity consumption information once a month.

The Swedish electricity meter reading reform had begun and would finally include 5.2 million customers and total investments of 15 billion SEK [52].

2.2 Remote electricity meter reading systems

This chapter presents an introduction of the systems handling remote meter reading. The systems can be used to monitor consumption of electricity, district heating, gas and water. The chapter aims to explain differences between frequently used technologies and communication infrastructures.

2.2.1 Different names - what’s the difference?

Automatic meter reading

An automatic meter reading (AMR) system automatically collects consumption, diagnostic and status data from meter points (electricity, heat and water). The utility therefore does not need to have physical access to the meter in order to perform the meter reading. In principle, all AMR systems have the same basic structure. The meter point is typically situated at an electricity customer site and has an installed meter node that continuously registers consumed electricity. The meter node is connected via a communication interface (C.I.) to the central system though a communication infrastructure (see Figure 5). The infrastructure can be based on one or several communication technologies where different information carriers are used.
depending on the physical conditions, desired functionalities and the performance requirements.

The meter readings are stored and accessible through the central data storage, a database managed by e.g. the distribution system operator. There are several other systems that need access to the information in the data repository. These systems provide functionalities related to billing, customer information, demand forecasting, demand-side management, flow monitoring, etc.

![Figure 5. Schematic overview of an AMR system. Illustration based from report by Johnson [53].](image)

**Advanced metering management**

The term Advanced metering management (AMM) refers to an extension of the AMR system. The term indicates that the AMR system consists of a two-way communication solution, meaning that there is a bi-directional flow of information between the central system and the meter node, creating the possibility to control or influence energy consumption of customers. An optional functionality in several of the remote meter systems would be remote connection/disconnection and remote changes in contracted power or price schemes. This functionality enables a potential to realize and involve more advanced price models and actions related to demand-response measurements discussed in several papers [29] [54]. It should be stated that despite the existence of the term AMM many of utilities and researchers refer to such a system as an AMR system with two-way communication.
Advanced metering infrastructure

Advanced Metering Infrastructure (AMI) includes more features and expands the functionalities of an installation. AMI refers to both hardware and software installations and includes advanced metering devices, communication, advanced metering management and customer oriented systems. To collect and distribute energy information are central features of AMI and that can contribute to improved electricity market mechanisms and to increased interaction between different stakeholders such as customers, electricity suppliers and distribution utilities. AMI opens up for service providers that could offer new price constructions, demand-response initiatives and other supportive services that encourages lower energy usage.

2.2.2 Communication infrastructures

Topology

Different network topologies are used depending on the physical situation in the distribution system, the chosen technology and the preferred communication method. Figure 6 shows six different types of topology. The star network (a) is most commonly used when single meters send data directly to a concentrator/hub/multi-point. In the bus (b) and tree structure (c) data is typically transmitted though a wired access network. The major difference between these two topologies is that the tree structures are used when transmitted data is forwarded by additional nodes, i.e. repeaters, to a higher level in the hierarchy. In a tree topology the nodes do not communicate with other nodes within the same hierarchy level. The reason for use of repeaters is to extend coverage of a particular part of the AMR system. The topology is therefore used in situations where connectivity between meter nodes/central system or meter nodes/multi-point needs to be improved in order to increase the reliability of the communication infrastructure. The mesh topology is mainly used in conjunction with wireless technologies and will be discussed more in detail further down. It is an upcoming technology and used in several European countries, Canada and USA.
Power line communication (PLC)

Power line communication (PLC) can be divided into two main categories, Narrowband Power Line (NPL) and Broadband Power Line (BPL). Both technologies are used to transfer consumption information between two points via the power distribution system. The terms narrowband and broadband refer to the frequency range used to transmit data over the grid. The frequency range for NPL is regulated between 3 kHz and 148.5 kHz in Europe but in other parts of the world there are commonly accepted standards up to 450 kHz. For utility related services the CENELEC Band A applies, that is between 3 kHz and 95 kHz. The equivalent range for BPL would be between 2 MHz and 30 MHz depending on the manufacturer [56].

The main differences between the two different techniques can be summarized as follows:

- Operating frequencies
- Information capability
- Required power
- Attenuation

One of the latest techniques in the higher broadband range is the HomePlug AV developed by the HomePlug Power Alliance. The technique was primarily developed to transfer audio and
video, but is also usable for example to control thermostats and other load management applications [57]. End to end communication enables devices to discover other devices and create bindings with them. A control and event layer enables the ability to control remote devices. These types of control devices will be important features of the future smart grid.

The Telegestore project of the Italian energy company ENEL is an example of a large implementation of NPL in Europe. It is a proprietary NPL solution at a center frequency of 131.579 kHz. Today, more than 31 million meters are operated via the AMR system in Italy.

Radio frequency networks

The unlicensed radio bands were originally reserved for radio frequency (RF) electromagnetic waver for industrial, scientific and medical (ISM) purposes and not for communications purposes. Due to differences in national regulations the use of the radio bands in specific countries may differ. Commonly used unlicensed radio bands are 433 MHz, 868 MHz, 915 MHz and 2.4 GHz [58].

Two well-known proprietary radio solutions are EnergyAxis and OpenWay. The EnergyAxis solution operates in the 915 MHz level meanwhile OpenWay uses the 2.4 GHz band. These solutions are provided by Elster and Itron, respectively.

Mesh network

A mesh network represents a technique where nodes can be considered as independent devices and every node can use nearby nodes as independent routers to pass on information. If a used path is blocked or broken the system automatically reconfigures and the nodes identify new paths to reach its final destination by “hopping” from node to node. Mesh networks are self-healing and are typically considered as reliable as there is often more than one path between a source and a destination. A fully connected network is a notation for a mesh network whose nodes are all connected to each other.

ZigBee is one standard protocol that provides the network infrastructure required for wireless sensor network applications using mesh network. ZigBee network are used in metering applications because of their inherent redundancy, self-configuring and self-healing capabilities [59].
2.2.3 About standardization

CEN, CENELEC and ETSI

On 25 September 2008 the Competitiveness Council encouraged stakeholders from European standardization to be actively involved in development of world-wide standards and to promote European standards [60].

In 2008/2009 a major standardization work began. The three large European standardization bodies: The European Committee for Standardization (CEN), European Committee for Electrotechnical Standardization (CENELEC) and European Telecommunications Institute (ETSI) were asked to develop a European standard for an open architecture for metering, including secure bidirectional communication and appropriate data exchange formats. The task includes the difficult aspect of proposing a scalable architecture that supports a wide range of applications that can vary from the most basic solutions to highly advanced functionalities [61]. It is especially emphasized in the mandated work that European standards must allow innovation within the protocols to enable added value services for both consumers and suppliers. It is expected that the new harmonized European standards should be developed within 30 months via transparent processes that include consumers, distribution utilities and energy suppliers.

OPEN meter project

The main objective of the OPEN meter project is to remove barriers for a wide spread adoption of advanced metering. Project deliverables will be a set of draft standards for AMI, supporting electricity, gas, heat and water metering. The developed standards should be both open and public based on the agreement of all the relevant stakeholders in this area. The project should consider the real conditions of the distribution utilities and allow for full implementation of AMI [62].

The OPEN meter project is financed by the European Commission within the Seventh Framework Program. As an invited partner the work is coordinated with the European smart metering standardization mandate M/441 given to the European Standardization bodies mentioned above.
Chapter 3

Results and discussion

3.1 Architectures and related issues (Mainly Paper A and Paper B)

When we started this work in 2000/2001 our belief was that internet use would continue to increase dramatically. At this time improved customer feedback mainly meant more details on the electricity bill every month [3] [4]. The electricity companies had little or no experience on how to preprocess, calculate and present energy consumption data more frequently. The first papers (Paper A and Paper B) aimed to answer some of these questions; to present the results in scientific forums, to authorities and decision makers in order to provide new knowledge and make it more available. We were also interested how energy consumption data could be combined with other information sources to create added values. A structure or architecture suitable for this information handling was considered as an important first step.

3.1.1 Novel programming architecture for the energy sector

During the early 2000s we began to investigate the possibilities of interactions using different types of standard software applications, creating the simulators described in Paper A. Web-based applications were beginning to offer interesting opportunities for distributed calculations [64] but up to that there had, at this time, only been small cautious advances in the energy industry area [65]. Several advantages were identified in creating a flexible architecture in this way, both from the industry perspective and for education purposes. Handling user licenses and customized configurations still causes time consuming problems and waste of personal resources, resulting in increased overhead costs in the organizations.

Three reasons for implementing web-based interfaces are:

- Simulation software does not need to be installed on local computers.
- They enable user access to advanced solutions via regular web browsers.
- Administration fees and licenses may be reduced – this may also promote better usage of software applications.
The multi-tier architectures, based on client-server relationships, provide a flexible and modular approach that has been used in modern internet applications [66]. The most widespread of multi-tier architectures would be the three-tier client/server architecture (Figure 7) that has been used in various types of system, e.g. e-commerce applications. The three-tier structure promotes flexibility, maintainability, reusability and scalability [67]. The middle-tier could also be used as a load balancer to manage the performance of the application, both from a client-user perspective as well as from a server workload perspective in order to maintain optimal usage [68].

![Figure 7. Overview of three-tier architecture including a user/presentation tier, application tier and data tier.](image-url)
An extension of the three-tier architecture has been proposed in this work (Figure 8). The multi-tier structure includes an additional server that can be considered as a back-end calculation tier. An important contribution of the presented work is that the proposed solution uses a set of “off-the-shelf” software tools (Visio, Visual Basic, SQL Server) in order to achieve new functionalities for the energy sector that are accessible via web based interfaces. Two graphical user interfaces (GUI) were developed in order to provide options for graphical design and configuration of the energy process. When connected to the internet, the energy model is accessible via regular web browsers and has the ability to set input parameters, perform calculations and create simple graphs to display the result.

![Figure 8. Architecture of the connection of the energy model to the internet.](image)

The architecture was also shown to be useful for processing and visualizing electricity meter reading values via the internet. At this time a majority of the discussions on energy consumption feedback concerned information sent via the electricity bill. Different methods were evaluated, such as frequent bills based on readings plus historical feedback, frequent bills based on readings plus normative feedback, frequent bills plus disaggregated feedback, as summarized in [69]. In 1999, a PC based solution with manual input of individual consumption was described and evaluated and showed promising results [70], but it did not involve the interplay between AMR systems, processing and visualization over the internet. The original architecture was developed further in corporation Mälarenergi – the regional energy company, and HM Power – the AMR system provider. The graphical user interface in the back-end tier described in Figure 8 became redundant. Instead, improved mathematical
extensions were included on the application server. FORTRAN routines were then encapsulated in COM-objects in order to examine the possibilities for increased calculation performance in the otherwise relatively limited Visual Basic language. This concept also interested the ABB Pulp and Paper division, due to the fact that they would be able to combine the use of a straightforward programming environment like VB with more powerful mathematical software tools, such as the FORTRAN libraries.

Paper B describes an additional adaption of the architecture, which creates a flexible tool for energy price and tariff calculations that is used to evaluate three different types of tariff structures (result presented in Section 3.3). Two important outcomes from an architectural and programming point of view are mentioned here. Firstly, an adapter was introduced into the architecture to extract information from external databases (see Figure 9, tool for db extraction). There are several benefits to this approach, but the most important one is that it promotes a distributed means of handling and processing meter reading values. The adapter can easily be replicated and configured to transfer data from different types of databases without changing the structures in the calculation tool. Secondly, a bottom-up approach was introduced to deal with the energy data, which maximized the use of the information made available by the new meter reading systems. The bottom-up approach means that calculations are performed on an individual basis and thereafter aggregated to a system level. This generates valuable information for the energy company while still maintaining detailed information from the perspective of the customer.

Figure 9. An overview of the various components of the electricity price modeling tool. Tool for db extraction is an adapter that can be used to access different databases.
3.1.2 Advances in the architecture, improved functionalities and limitations

This subsection is justified because it exemplifies a case where applied research has been relevant to the business community and has resulted in the creation of new businesses, regional growth, and relevant and socially beneficial applications within a reasonable time. It is also stated in the Mälardalen University research strategy 2009 – 2012 [71]:

- “The University develops a model for researcher and postgraduates with purpose to increase the commercialization of research results”

Additional advances in the architecture have arisen at the intersection of research performed on distributed optimization in the pulp and paper industry (DOTS) and this work, on opportunities in large-scale installations of meter reading systems. The DOTS middleware model used a 3-tiers distributed architecture, resulting in a system based on three main layers, the optimizer, the simulator and the middleware. The middleware layer comprises of the middleware component, which handles the communication between the other two layers by interoperating with the adapters [72]

The positive experiences of using distributed optimization to integrate different simulator environments with optimization tools, together with the benefits of using the adapters for meter reading databases described above led to the development of a set of Web services to centralize information handling, processing and visualization of energy consumption data. The first steps towards a new computing environment (see Figure 10) were taken in order to develop and provide concepts that could be categorized as Platform as a Service (PaaS) and/or Software as a Service (SaaS). These types of applications are classed in the cloud computing category.

- “Clouds are a large pool of easily usable and accessible virtualized resources (such as hardware, development platforms and/or services). These resources can be dynamically reconfigured to adjust to a variable load (scale), allowing also for an optimum resource utilization [73]”
Figure 10. Advances in architecture of processing, handling and presenting information from meter reading systems (Courtesy by Svenska Energigruppen)

This structure is interesting because it has been implemented and successfully commercialized over the last few years through the Mälardalen University innovations program Idélab and the Västerås Science Park incubator program, and is now marketed as an independent platform by the name energiinfo™.
3.2 Implemented applications using remote meter readings

Two software applications have been implemented during this period to deal with information collected by the installed AMR systems (Mainly Paper A and Paper B). There have also been additional implementations of functions and methods and the evaluation of these are summarized in Section 3.4. It should be noticed that when Paper A was written in 2001, discussing structures, methods and visualization, not many scientific papers had been published in this area.

3.2.1 Visualizing energy consumption data (Mainly Paper A)

There have been several efforts to promote increased knowledge of individual energy consumption over the past few years. As previously mentioned, the most frequently reported experiments use the electricity bill as an information carrier. One of the first Swedish utilities to provide a web-based interface addressing the majority of their customers was Sollentuna Energi AB. The AMR system provider Senea AB included a module that enabled monitoring via internet in the Sollentuna area.

Complementary to the application above our early work focused on integrating more functionality in the visualization and making the information supplied to customers easier to understand. The performed work included an on-line calculation to show the relationship between outdoor temperature and energy consumption per day (see Eq. 1 and Eq. 2) and divided the total energy consumption (kWh/day), TC, into two energy components:

\[
TC = E_T \cdot (t_{in} - t_{eq}) + E_C \quad \text{(kWh/d)} \quad (t_{in} - t_{eq}) \geq 0 \quad \text{Eq. 1}
\]

\[
TC = E_C \quad \text{(kWh/d)} \quad (t_{in} - t_{eq}) < 0 \quad \text{Eq. 2}
\]

where \(E_T\) represents the temperature dependent energy consumption and \(E_C\) is the energy component representing the non temperature-dependent energy consumption during the year. The non temperature-dependent energy component must therefore be coupled to social consumption patterns. During warmer periods \(E_C\) alone accounts for the total energy consumption. The equivalent temperature \(t_{eq}\) represents a recalculated temperature that considers the influence of outdoor temperature, wind speed and solar irradiation. The equivalent temperature calculations were performed and reported by Swedish Meteorological and Hydrological Institute (SMHI) and included continuously in the database via routines that
scan e-mails automatically. According to a rule of thumb indoor temperature was set to 20°C. The assumed upper limit for heating demand was set to 17°C, as this limit has been used by SMHI when performing degree day summations. The difference of 3°C was assumed to be provided from passive energy sources such as solar irradiation and heat generated from people and electrical appliances [74].

The energy–temperature matrix was calculated using FORTAN solvers wrapped in COM-objects compiled as dynamic link libraries (dll). Each customer was represented by an individual linear equation that was used to estimate the temperature-dependent electricity. These individual equations can also be used to implement forecasting functionalities. The visualization of the customer electricity use was divided in three separate graphs, total consumption (see Figure 11), temperature-dependent consumption and non temperature-consumption. All graphs included the equivalent temperature plotted against used electricity.

![Image](image)

**Figure 11.** Web-based user interface with daily consumption statistics (red line) versus temperature (green line) over a period of time for a customer at Mälarenergi. The visualization is here integrated in a new environment by Mälarenergi.
The visualization interface was tested on customers at several occasions. At a house-owner fair the visualizations were presented and visitors interviewed. Inputs from residential customers together with our own experiences resulted in an extension of individual information. A feature to compare current consumption to previous consumption was included. The graphs were presented in a bar chart and data for the preceding 13 months became visible (up to 24 months are possible), enabling customers to see consumption through the whole year, and to compare the current month with the same month of the previous year (see Figure 12). Five years later, this concept for presenting energy statistics was adopted into the Swedish meter regulation STEMFS 2007:5 on how Swedish electricity customers should be informed about their electricity consumption. The thirteen months of energy statistics should also indicate the relative contribution of each month to the yearly energy consumption.

As well as the statistical summary, a calculation of the electricity bill and its different amounts were included in the work. The costs were here based on the actual consumption; meaning that the customers could continuously follow their actual energy consumption in terms of Swedish kronor (SEK). A pop-up window displayed the electricity costs in detail for the selected month, specified in retail, distribution and taxes.

![Image](image.png)

**Figure 12.** In EnergiDialogen (2002) the customers were able to see monthly consumption. Data for the preceding 13 months is visible. A pop-up window presents detailed information of the costs that make up their electricity bill each month.
The application was available for around 1000 electricity customers in the Mälarenergi area from autumn 2003. From the recorded log files it is possible to see the usage patterns of the application (see Figure 13). Over the two years shown in the graph, the largest number of unique users to use the application in one month was 140. Mälarenergi promoted the application to the 1000 customers when it was launched in autumn 2003. Use of the application decreased when no special efforts were made to remind customers about it. It is therefore important to remind customers on a regular basis in order maintain the frequency using the application and to make it habitual. Nevertheless, in investigations made by the research group, it is possible to see that design concepts, including web-based statistics service more or less has proven to contribute to households’ enhanced awareness about their individual electricity consumption [20].

![Graph showing number of unique visitors to the web-based application EnergiDialogen from October 2003 to June 2005.](image)

**Figure 13.** Number of unique visitors to the web-based application EnergiDialogen from October 2003 to June 2005.

The decreasing number of visitors highlights an important problem that needs to be planned for already when the utility decides to invest in a presentation platform. Continuous development of the presentation and a communication strategy will probably maintain and increase usage of a platform, even though it is possible to see a variation of visitor that is related to the size of the latest energy bill.
In a survey from 2002 a question was asked about the customer interest gaining more specific information on the electricity bill or via Internet [75]. The results are interesting from several perspectives. 30 % of the respondents stated they were positive to information through Internet while 50 % had a negative attitude to the web-based solutions. At the same time 90 % are positive to warnings of unexpected changes in the energy consumption.

The results above should be interpreted together with the internet usage patterns in Sweden. It has been possible to calculate the percentage increase (see Table 2) based on data from Statistics Sweden, and their yearly investigations on internet usage [76]. The “daily” users have increased from approximately 40 % to 73 % meanwhile the “never” users have decreased from approximately 21 % to 7 % over the period 2003 to 2009. It must be emphasized that the acceptance of web-based solutions are wider today.

Table 2. Internet usage in Sweden over the years 2003 to 2009 for private persons at the age 16 to 74 years. Calculations are based on data from Statistics Sweden [76].

<table>
<thead>
<tr>
<th>Internet usage</th>
<th>2003</th>
<th>2004</th>
<th>2005</th>
<th>2006</th>
<th>2007</th>
<th>2008</th>
<th>2009</th>
</tr>
</thead>
<tbody>
<tr>
<td>Daily</td>
<td>39,9%</td>
<td>51,7%</td>
<td>56,7%</td>
<td>61,0%</td>
<td>58,3%</td>
<td>68,7%</td>
<td>73,0%</td>
</tr>
<tr>
<td>Every week</td>
<td>28,7%</td>
<td>23,6%</td>
<td>19,3%</td>
<td>18,8%</td>
<td>17,3%</td>
<td>14,9%</td>
<td>13,1%</td>
</tr>
<tr>
<td>Every month</td>
<td>5,4%</td>
<td>5,1%</td>
<td>4,5%</td>
<td>5,0%</td>
<td>3,6%</td>
<td>3,5%</td>
<td>2,8%</td>
</tr>
<tr>
<td>Less them every month</td>
<td>2,2%</td>
<td>1,1%</td>
<td>1,0%</td>
<td>1,4%</td>
<td>1,1%</td>
<td>0,9%</td>
<td>0,7%</td>
</tr>
<tr>
<td>Less them every third month</td>
<td>2,9%</td>
<td>6,2%</td>
<td>7,0%</td>
<td>4,2%</td>
<td>5,0%</td>
<td>3,5%</td>
<td>3,0%</td>
</tr>
<tr>
<td>Never</td>
<td>20,9%</td>
<td>12,3%</td>
<td>11,6%</td>
<td>9,5%</td>
<td>14,8%</td>
<td>8,6%</td>
<td>7,4%</td>
</tr>
</tbody>
</table>

3.2.2 An electricity price evaluation tool (Mainly Paper B)

The electricity price application was initially designed to be used for evaluations in the Smedjebacken area. Different operators have different prerequisites because they have different AMR systems installed. For example, Mälarenergi and Smedjebacken Energi had completely different AMR systems during the initial phase of AMR installation, when the software tool was developed. Smedjebacken Energi selected an hourly based metering system for their approximately 3500 customers, and was one of the pioneers when it came to complete full scale AMR installations. Mälarenergi, with almost 100 000 customers needed to consider a different path, and started with a system called Turtle, known to be slow but robust. With just these two utilities we had representative systems with considerably different properties. The first generating 24 meter readings for every 24 hour period and the second only generated two values to represent each 27 hour interval. The obvious differences in
AMR systems increase the requirement for a uniform solving method that can be used to make a generalized software tool, from a meter reading perspective that can also deal with different types of price structures.

A number of properties were therefore considered as important for the successful implementation of a price evaluation tool:

- Flexible handling of meter reading values
- A set of user levels suitable for different purposes; such as research, price strategies and customer services.
- An open structured cost function
- A web-based interface

The developed software was shown to be useful for evaluating of new price structures. Figure 14 (left) shows the different parameters of the cost function that can be created and saved both as one energy and/or load component. The different parameters of the cost function are saved in the database along with additional information (right), such as validity period of cost function.

Figure 14. Two screen-shots of the web-based software tool developed to evaluate new electricity price structures with input data from AMR-systems. The screenshot on the left illustrates parameter settings of the cost function and the screenshot on the right shows the possibilities for a dynamic setting of the time periods when the cost function could be applied.
The user is able to create adjusted price functions in order to accomplish new network tariffs for distribution utilities or new electricity price offerings (electricity retailers) according to the cost function defined in Eq. 3.

\[ p(E, L) = (k_e \cdot E^a \cdot C_e) + (k_l \cdot L^b \cdot C_l) \]  \hspace{1cm} \text{Eq. 3} 

where \( k, a, b \) and \( C \) represent variables that can be set through the graphical user interface (see Figure 14). \( E \) and \( L \) represent the actual metered energy consumption and the selected peak load respectively. The subscripts \( e \) and \( l \) define the variable dependency on energy and peak load parts of the cost function respectively.

A function was included to generate summary reports (see Figure 15) of the calculation set-up, presenting the outcome of the evaluated tariff or electricity price. The reports also compare the evaluated price structure with old ones when they are available. This enables the user of the price evaluation tool to see how and when revenues from different price models differ from each other.

Figure 15. An overview of the report functions in the developed application. Revenues can be evaluated by customer type, monthly distribution etc.
3.3 Result from economic evaluation of new price structures. (Paper B)

Several utilities have experienced increased peak loads in the electricity distribution system. One reason for the higher hourly peak loads is the combination of more frequent use of electrical appliances along with a higher density of appliances. Both Mälarenergi and Smedjebacken Energi also expressed concerns that a consequence of increased use of heat pumps in the electricity system could be higher peak loads (power) in the distribution system relative to consumed energy. During cold weather the coefficient of performance (COP) decreases and the heat pump operate at a ratio closer to 1:1. This implies that a high share of heat pumps in the system could reduce the revenues from the energy based tariff while causing higher system peak loads and increasing costs for the local distribution network to regional transmission and distribution utilities.

460 residential electricity customers were included in the study to evaluate new tariffs that included a peak load component. The customers in the subset are distributed over the three load levels 11.1 kW, 13.9 kW and 17.3 kW as follows: 56.5 %, 41.1 % and 2.4 % respectively (see Table 3). This corresponded well with the distribution of all residential customers in the area. The meter readings used are from the year 2003.

Table 3. Households included in the study to evaluate introduction of a peak load component.

<table>
<thead>
<tr>
<th>Fuse</th>
<th>Number of households</th>
<th>Maximum load</th>
<th>Total installed load</th>
</tr>
</thead>
<tbody>
<tr>
<td>16 A</td>
<td>260</td>
<td>11.1 kW</td>
<td>2886 kW</td>
</tr>
<tr>
<td>20 A</td>
<td>189</td>
<td>13.9 kW</td>
<td>2627 kW</td>
</tr>
<tr>
<td>25 A</td>
<td>11</td>
<td>17.3 kW</td>
<td>190 kW</td>
</tr>
<tr>
<td>Total</td>
<td>460</td>
<td>--</td>
<td>5703 kW</td>
</tr>
</tbody>
</table>
Three types of rates, decided in discussions with the utilities, were included in the evaluation (see Table 4). The existing tariff (from 2003) was a traditional energy tariff with a fixed part related to the fuse size (USD/month) and flexible part related to energy consumption (cent/kWh). The daily demand-based tariff is a tariff that depends both on the time of year as well as the time of day (USD/kW). The average of the three highest peak loads each month determines the final electricity cost for the customer. Finally, a seasonal demand-based tariff was also included in the evaluation. This alternative had no fixed part and was only operational during the winter months, from December to March (USD/kW). The exact levels of the flexible rates were not set initially, as one constraint to the calculations was to maintain the original total annual revenue. The reason for this approach is that the fairness of the electricity tariffs is reviewed after each year (ex post). Sweden will be the last country in Europe to abandon the ex post model in 2012, after which fairness of electricity tariffs will be evaluated continuously and in advance (ex ante).

Table 4. Different tariffs used in the study including customers fuse size. The costs for different tariffs are divided in fixed and flexible parts.

<table>
<thead>
<tr>
<th>Tariff type</th>
<th>Fuse fA</th>
<th>Fixed [USD/month]</th>
<th>Flexible rate</th>
<th>Time</th>
<th>Rate based on (No of peaks)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1a. Traditional</td>
<td>16/20</td>
<td>14.0</td>
<td>2.1 cent/kWh</td>
<td>All year</td>
<td>Energy (→)</td>
</tr>
<tr>
<td>1b. Traditional</td>
<td>25</td>
<td>21.5</td>
<td>2.1 cent/kWh</td>
<td>All year</td>
<td>Energy (→)</td>
</tr>
<tr>
<td>2a. Daily Demand-based Tariff</td>
<td>16/20/25</td>
<td>14.0</td>
<td>5.6 USD/kW</td>
<td>Nov - Mar 07-19</td>
<td>Load demand (3)</td>
</tr>
<tr>
<td>2b. Daily Demand-based Tariff</td>
<td>16/20/25</td>
<td>14.0</td>
<td>2.8 USD/kW</td>
<td>Apr - Oct 07-19</td>
<td>Load demand (3)</td>
</tr>
<tr>
<td>3a. Seasonal Demand-based Tariff</td>
<td>16/20/25</td>
<td>0</td>
<td>14 USD/kW</td>
<td>Nov - Mar</td>
<td>Load demand (3)</td>
</tr>
<tr>
<td>3b. Seasonal Demand-based Tariff</td>
<td>16/20/25</td>
<td>0</td>
<td>6 USD/kW</td>
<td>Apr - Oct</td>
<td>Load demand (3)</td>
</tr>
</tbody>
</table>

With the new seasonal based tariff 42% of the studied households will have increased electricity costs amounts to between 10 and 460 USD/year. 9% of the customers will not experience any change, and 49% of the customers will reduce their costs by 10 to 330 USD/year. The greatest reduction in terms of percentage is 14%.
This study has shown that there is a dependency between the characteristics of the usage profiles (described as load factors) and the calculated difference in cost when modeling a change of tariff type (see Figure 16). Customers with a lower load factor tend to have an increased electricity cost. As a result of the bottom-up approach, i.e. the use of consumption data from each customer, it has been possible to evaluate the tariffs both on a system level as well as on an individual customer basis.

![Figure 16. Illustration of the difference of cost when replacing the energy based tariff with the seasonal based tariff. The outcome is related to individual load factors.](image)

A tariff or price with a peak component could be justified for several reasons, not only promoting customer having a more favorable load factor. As shown in Figure 17 it can be seen that an average 16 ampere customer has several peak loads that exceeds the dimensioned limit of the fuse size. The peak load 14 kW is registered several times, meaning that the fuse is overloaded with 27% every time this occurs. A demand-based tariff would compensate the electricity distribution utility for this behavior.
A tariff or price with a peak component could be justified for several reasons, not only to compensate the overcost due to the change of tariff type (see Figure 16). This study has shown that there is a dependency between the characteristics of the energy consumption for a 27 hour interval and the maximum peak load in the same interval. The technical performance varies between the different meter reading systems. The minimum requirement is monthly based meter reading, but a majority of all electricity utilities have invested in a system that are ready for hourly based meter readings. The main reason for this study has been to investigate the possibility of refining a meter series containing information of the energy consumption for a 27 hour interval and the maximum peak load in the same interval.

To refine the Turtle AMR series a set of functions have been implemented in a C# based software tool utilizing the Microsoft.NET framework. The database functionality is provided by a Microsoft Database Engine (MSDE 2000). The following methodology is applied to customer in the calculation (see Figure 18). First, the annual electricity consumption is determined. The annual consumption is used as an input parameter to the base load calculation irrespective of the selected base load approach. Furthermore, the base load is distributed over the hours in the interval. The next step is to distribute the registered peak load to the correct hour. The peak load sets the upper limit of the load values. The load factor

![Graph](image.png)

Figure 17. A frequency peak load (kWh/h) diagram – average hours at a certain load - for different customer groups (solid line = 25 A customer, dashed line 20 A customer and dotted line 16 A).

### 3.4 Implementation of methods and functions

#### 3.4.1 Refining meter reading series (Mainly Paper C)

The technical performance varies between the different meter reading systems. The minimum requirement is monthly based meter reading, but a majority of all electricity utilities have invested in a system that are ready for hourly based meter readings. The main reason for this study has been to investigate the possibility of refining a meter series containing information of the energy consumption for a 27 hour interval and the maximum peak load in the same interval.

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profile is used to distribute the remaining energy. The control of the peak load profiles is managed by a control function. If a load value exceeds the upper limit the surplus energy is removed and allocated to another time according to the load distribution profile. Hours exceeded the upper limit of load is locked for further allocation of electricity in the iteration.

Figure 18. A model to refine meter reading series.

The work presented in this article shows the possibility for refining an electricity metering series collected from an AMR system that only provide interval energy readings and a time stamped peak load value. The result shows that simple methods can be used to reproduce the load profile on an aggregated system level – that is the sum of all individual loads – with reasonable accuracy. The methods have so far been coarse so further improvements to the outcome should be possible.
In a survey financed by Elforsk it is shown that 77% of the Swedish distribution utilities have invested in system that can collect hourly meter readings [77]. However some of these will then need to be upgraded in order to collect hourly meter readings. The questions have been answered by 86 distribution utilities (54% of Swedish DSOs) and these utilities together represented 4,217,569 of the Swedish electricity customers which correspond to 81% of the customer stock up to 63 ampere (44 kW). When summarizing the customers that are covered by a system being able to collect hourly meter reading every day without any additional investments (see Figure 19) it is shown that 52% are included. This number represents distribution utilities that have bought functionality to collect hourly meter reading, however, not necessary meaning that the functionality are used or even has been evaluated at this stage.

![Figure 19. Share of Swedish electricity customers included in systems having technology to collect hourly meter readings every day [77].](image)

Based on the facts above it could be interesting to use the concept to refine meter reading series in Sweden. There are at least two areas where an implementation of the methodologies above could be useful. Firstly, generating more detailed consumptions series at an aggregated level would be interesting for utilities that need to evaluate distribution areas where no system load curve is available. Secondly, the approach could be interesting for distribution utilities searching ways of reducing size of metering value databases. If the methodology is developed further it could be possible to reduce the amount of values in the database only saving strategically important key data, such as interval peak load and energy.
3.4.2 Extracting information from meter reading series (Mainly Paper D, Paper E and new results)

There are a number of different methods in the literature for processing and extracting information from meter reading systems for different purposes. Artificial neural network models have shown to be effective in profiling, pattern recognition and load and thermal prediction [78]. A disadvantage to these methods is the limited ability to dynamically predict and determine new consumption trends, e.g. based on new technical trends [79]. Engineering methods are known to provide more accurate results in these cases. The quality of a linear regression analyzes and the linear dependency between heat load and temperature has been discussed by several authors and parts of the early works have been summarized by Pyrko [80]. Contributions from several authors have been categorized by results indicating a linear or non-linear relationship, respectively. Further, two different studies have been included that have had a linear regression approach and showing a low level of agreement. The first study, by Lundgren, T. 1989. “Bostäder som brukarstyrd energisystem” – Dwellings as consumer controlled energy system – (In Swedish), weekly average values have been used and the reported $R^2$ values shows on a degree of explanation between 0.64 and 0.75. The second study, by Finska elverksföreningen, 1986, “Elförrukningens belastningsmätningar” – Electricity load measurements (In Finnish), reports an average $R^2$ value for direct electric heating systems to 0.52. The thesis [80] concludes that a linear relationship between hourly meter readings and outdoor temperature has not been verified. An additional conclusion would be that the dependency seems to be stronger in untenanted buildings.

The purpose of our study has been to suggest methods and functions suitable as a complement to handling meter readings by electricity distribution utilities. General properties that are considered as advantageous and added value in long term are the possibility to automate the process and promote actions that not require extensive external data collection procedures in addition to the installed AMR systems. Together the two papers suggest a methodology for using electricity consumption data including different input parameters. Both measured data and data based on customer input can be utilized.
The suggested methodology is presented in Figure 20 that originates from Paper E. At page 4 in Paper E we also draw new conclusion based on previous work on important factors to consider when analyzing and processing meter readings. Also, new results are included in the section using the proposed methodology discussed in Paper D and Paper E, where 14 buildings are analyzed to determine the individual electricity heat demand.

![Figure 20. A schematic overview of how to combine meter reading values, external input data and customer inputs.](image)
Working with electricity series including space heating, hot water and social energy requires a strategy for isolating different characteristics of the consumption. Plotting the energy consumption during night hours has shown to be an interesting method to evaluate the dependency between of energy consumption on outdoor temperature (see Figure 21, right). The average load is calculated based on the consumption between hours 01:00 to 04:00. For normal customers, average load in these hours over the summer period indicates the base load $L_B$, which represents the contribution from appliances that are active over the whole year, such as fridges, freezers and ventilation systems. This assumes that no cooling devices are installed.

![Figure 21. Electricity consumption related to outdoor temperature. Hourly load values for one year (left) and average load based on consumption between hours 01 to 04 (right).](image)

The intersection of the base consumption line $L_B$ and the sloped line $L_T$ describing the energy demand for heating related to outdoor temperature indicates temperature limit $T_{\text{lim}}$ (i.e. balance temperature) for heating. For outdoor temperatures lower than the temperature limit additional heat from e.g. electric heating systems is needed.
By regression analysis it is possible to determine the slope for the temperature dependent load LT (see Eq. 4). In this case L_T corresponds to the total heat load for the building if assuming that no additional heat sources exist. The base load L_B is determined by evaluating the warmer summer nights and is calculated as an average of these night hours (see Eq. 5). It is also clarified in Eq. 6 that space heating demand covered by the electric heating system L_{T,el} is zero when outdoor temperature is equal or higher than T_{lim}. The subscript ‘el’ has been used to separate the two different types of heating loads.

\[
L_T = C_1 \cdot T_{out} + C_2 \quad (\text{kWh/h}) \quad T_{lim} > T_{out} \quad \text{Eq. 4}
\]

\[
L_T = L_B \quad (\text{kWh/h}) \quad T_{lim} = T_{out} \quad \text{Eq. 5}
\]

\[
L_{T,el} = 0 \quad (\text{kWh/h}) \quad T_{lim} \leq T_{out} \quad \text{Eq. 6}
\]

It should be clarified that the heat demand for the building, L_T (Eq. 4), is calculated based on the temperature difference T_{out} – T_0, where T_0 = 0 °C. When rewriting the equation to represent the heating supplied from the heating system, L_{T,el}, it is more suitable to base the temperature difference on T_{lim} – T_{out}. In Eq. 7 the building heat demand is first rewritten for the proper temperature interval.

\[
C_1 \cdot (T_{out} - T_0) + C_2 = L_B - C_1 \cdot (T_{lim} - T_{out}) \quad T_{lim} > T_{out} \quad \text{Eq. 7}
\]

Next step (see Eq. 8) would be to remove the base load in order to obtain the function for the heating supply from the electric heating system.

\[
L_{T,el} = -C_1 \cdot (T_{lim} - T_{out}) \quad (\text{kWh/h}) \quad T_{lim} > T_{out} \quad \text{Eq. 8}
\]

As a complement to the presented work describing the methodology and possibilities additional single-family houses from the Sollentuna electricity distribution area have been evaluated according to the described method. The building parameters have been calculated in order to show benefits and drawbacks with the suggested approach. It should be mentioned that identifying the slope of the line, L_T, has been the target of the evaluation since it will form a base for further analysis.
14 buildings were identified via a survey conducted by Cajsa Bartusch and the author in 2007 that covered the same distribution area mentioned above. The survey was directed to 800 households that have reported a ground source heat pump installation to the municipality in Sollentuna between the years 2002 and 2006. The total response rate was 40.3 % or 322 unique answers.

The survey addressed different parts, both technical and behavior related issues that affects the final energy consumption for a residential customer. The content of the survey can be dived in four main areas, and information related to the different types of categories can be extracted:

- Building/construction issues
- Household composition
- Stock and use of electric appliances
- Behavior patterns

The typical characteristics for a selected single-family houses in this analysis would be; electrical heating, no complementary heating installations, no energy efficient measurements actions have been taken before the year 2003.

The reason to identify houses with no energy efficient measurements taken and an electrical heating system in use was to see if there would be any correlation between year of construction and estimated coefficient describing the heating demand. Only 14 buildings remained after filtering respondents according to the specified survey answers and fulfilling the requirement of complete consumption series for the used time period.

In Table 5 the coefficients $C_1$ describing the specific heating demand and the estimated base load, $L_B$, are presented. Further, the temperature limit, $T_{lim}$, has been determined as the intersection of the base load line (Eq. 5) and the heating demand line (Eq. 4). Identifying the temperature limit could be described as a relatively coarse iterative process starting with an estimation of the temperature limit, followed by determination of base load and temperature dependent load. The process is finalized by calculating the correlations of each iteration in order to identity the best fit. Further, in each new iteration the estimated temperature limit has been lowered in steps of one degree. Additional important parameters such as building/customer identity (CID), year of construction, living area, number of persons in the household and indoor temperature are also presented in Table 5 below.
In Table 5 the coefficients \( C_1 \) describing the specific heating demand and the estimated base remained after filtering respondents according to the specified survey answers and fulfilling heating system in use was to see if there would be any correlation between year of electrical heating, no complementary heating installations, no energy efficient measurements. The typical characteristics for a selected single-family houses in this analysis would be:

- The final energy consumption for a residential customer.
- The load, \( L_B \), are presented.
- Further, the temperature limit, \( T_{\text{lim}} \), has been determined as the content of the survey can be.

The survey addressed different parts, both technical and behavior related issues that affects unique answers.

Sollentuna between the years 2002 and 2006. The total response rate was 40.3% or 322 households that have reported a ground source heat pump installation to the municipality in that covered the same distribution area mentioned above. The survey was directed to 800 14 buildings were identified via a survey conducted by Cajsa Bartusch and the author in 2007 including.

### Table 5

<table>
<thead>
<tr>
<th>CID</th>
<th>Year</th>
<th>Area [m²]</th>
<th>Persons</th>
<th>( T_{\text{m}} )</th>
<th>( C_1 )</th>
<th>( L_B )</th>
<th>( T_{\text{lim}} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>-1940</td>
<td>8690</td>
<td>1926</td>
<td>235</td>
<td>2</td>
<td>-0,53</td>
<td>1,01</td>
<td>15</td>
</tr>
<tr>
<td></td>
<td>8745</td>
<td>1934</td>
<td>210</td>
<td>4</td>
<td>-0,42</td>
<td>1,00</td>
<td>17,5</td>
</tr>
<tr>
<td></td>
<td>8779</td>
<td>1938</td>
<td>115</td>
<td>4</td>
<td>-0,29</td>
<td>0,79</td>
<td>13</td>
</tr>
<tr>
<td>1941-1960</td>
<td>8645</td>
<td>1941</td>
<td>120</td>
<td>4</td>
<td>-0,36</td>
<td>1,47</td>
<td>17,7</td>
</tr>
<tr>
<td></td>
<td>8726</td>
<td>1946</td>
<td>240</td>
<td>1</td>
<td>-0,27</td>
<td>1,65</td>
<td>15,5</td>
</tr>
<tr>
<td></td>
<td>8707</td>
<td>1947</td>
<td>200</td>
<td>3</td>
<td>-0,28</td>
<td>5,72</td>
<td>15</td>
</tr>
<tr>
<td></td>
<td>8743</td>
<td>1959</td>
<td>133</td>
<td>2</td>
<td>-0,19</td>
<td>0,69</td>
<td>15</td>
</tr>
<tr>
<td></td>
<td>8752</td>
<td>1960</td>
<td>175</td>
<td>4</td>
<td>-0,26</td>
<td>0,83</td>
<td>17</td>
</tr>
<tr>
<td>1961-1975</td>
<td>8742</td>
<td>1966</td>
<td>200</td>
<td>2</td>
<td>-0,25</td>
<td>2,31</td>
<td>17,9</td>
</tr>
<tr>
<td></td>
<td>8763</td>
<td>1972</td>
<td>223</td>
<td>2</td>
<td>-0,27</td>
<td>1,02</td>
<td>19</td>
</tr>
<tr>
<td></td>
<td>8710</td>
<td>1973</td>
<td>140</td>
<td>6</td>
<td>-0,16</td>
<td>0,79</td>
<td>17</td>
</tr>
<tr>
<td></td>
<td>8513</td>
<td>1979</td>
<td>160</td>
<td>2</td>
<td>-0,19</td>
<td>0,68</td>
<td>15</td>
</tr>
<tr>
<td></td>
<td>8523</td>
<td>1980</td>
<td>240</td>
<td>4</td>
<td>-0,14</td>
<td>0,93</td>
<td>19</td>
</tr>
<tr>
<td></td>
<td>8672</td>
<td>1986</td>
<td>200</td>
<td>4</td>
<td>-0,19</td>
<td>0,93</td>
<td>17</td>
</tr>
</tbody>
</table>

A summary of the results for the 14 buildings coefficients is presented in Table 6. The average values of the slope, \( C_1 \), are sorted on four intervals representing different year of constructions. The used intervals originate from changes in Swedish construction directives over the years. These have also been used in several reports in the ELIB-study, a nation-wide study of indoor climate carried out over the years 1991 to 1992 [81]. When evaluating the magnitudes of the average slope in each interval it is possible to see that buildings from early parts of the last century have a relatively higher values then those buildings built more recently. This indicates that it could be a possibility processing hourly based meter readings in order to estimate the coefficients describing heat loss demand for individual buildings.

### Table 6

<table>
<thead>
<tr>
<th>Year</th>
<th>No. CID</th>
<th>( C_1 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>-1940</td>
<td>3</td>
<td>-0,42</td>
</tr>
<tr>
<td>1941-1960</td>
<td>5</td>
<td>-0,27</td>
</tr>
<tr>
<td>1961-1975</td>
<td>3</td>
<td>-0,23</td>
</tr>
<tr>
<td>1976-</td>
<td>3</td>
<td>-0,17</td>
</tr>
</tbody>
</table>
Based on the regression analyzes the coefficient of determination, $R^2$, has been calculated and presented in Table 7. The columns represent different average values for load and temperature, respectively. All calculations start at hour $t_i = 04$ and uses x-values back in time forming the average load value $L_x$ and y-values back in time forming the average temperature value $T_y$. The period $L_{4i}T_{12}$ represents the notation for an average load based on values between $01 – 04$ ($x = 4$ values) and average temperature based on values between $16 – 04$ ($y = 12$ values). The coefficients of determination, $R^2$, have been used in order get an overview on how correlation varies between different average loads and average temperatures (see Table 7). The $R^2$ value for each building is sorted on the building/customer identities (CID).

Table 7. How different average load values $L_x$ correlates to a set of average temperatures values, $T_y$. The subscripts X and Y denotes the number of hours back from time 04:00 used to calculate the average load and temperature, respectively.

<table>
<thead>
<tr>
<th>CID</th>
<th>$R^2(L_{4},T_{12})$</th>
<th>$R^2(L_{4},T_{24})$</th>
<th>$R^2(L_{12},T_{12})$</th>
<th>$R^2(L_{12},T_{24})$</th>
<th>$R^2(L_{24},T_{12})$</th>
<th>$R^2(L_{24},T_{24})$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1940</td>
<td>B690 0.84 0.89 0.88</td>
<td>0.89 0.92 0.92 0.92</td>
<td>0.93 0.93 0.91 0.92 0.94 0.95</td>
<td>0.64 0.75 0.79 0.74 0.82 0.82</td>
<td>0.78 0.82 0.82 0.82 0.85 0.86</td>
<td>0.83 0.89 0.90 0.86 0.91 0.90</td>
</tr>
<tr>
<td>1941-1960</td>
<td>B779 0.64 0.75 0.79</td>
<td>0.74 0.82 0.82</td>
<td>0.35 0.36 0.35 0.41 0.42 0.44</td>
<td>0.70 0.52 0.53 0.55 0.54 0.54</td>
<td>0.48 0.52 0.53 0.55 0.54 0.54</td>
<td>0.60 0.68 0.72 0.69 0.77 0.76</td>
</tr>
<tr>
<td>1961-1975</td>
<td>B726 0.83 0.89 0.90</td>
<td>0.86 0.91 0.90</td>
<td>0.35 0.36 0.35 0.41 0.42 0.44</td>
<td>0.48 0.52 0.53 0.55 0.54 0.54</td>
<td>0.60 0.68 0.72 0.69 0.77 0.76</td>
<td>0.60 0.68 0.72 0.69 0.77 0.76</td>
</tr>
<tr>
<td>1976-</td>
<td>B742 0.92 0.94 0.94</td>
<td>0.94 0.94 0.94</td>
<td>0.80 0.79 0.78 0.89 0.92 0.93</td>
<td>0.80 0.79 0.78 0.89 0.92 0.93</td>
<td>0.80 0.79 0.78 0.89 0.92 0.93</td>
<td>0.80 0.79 0.78 0.89 0.92 0.93</td>
</tr>
</tbody>
</table>

In Table 7 it is possible to see $R^2$ values showing that the regression analyzes are not “describing” the linear dependency between average load and temperature values in a perfect way. The coefficients are varying between 0.35 up to 0.95 and in general the linear dependency indicates a stronger correlation for average values based on 48 values back in time, both load and temperature. Looking at values $R^2(L_{4},T_{24})$ and $R^2(L_{48},T_{48})$ it is possible to see that 9 of 14 buildings are having a $R^2$ value showing a degree of explanation $\geq 0.75$ and $\geq 0.81$ for the values respectively.
Analyzing the two buildings, B510 and B707, with the lowest degree of explanation, 0.36 and 0.36 for $R^2(L_{4},T_{24})$, it is possible identify potential parameters affecting the outcome. In Table 5 it is possible to see that building B510 consists of 6 persons. As already concluded in [80] there seems be a possibility that occupied buildings could experience less degree of explanation. It could from this conclusion be reasonable to state that a household that consists of more family members also could experience a lower degree of explanation on linear regression analyzes. In Figure 22 (left) the consumption patterns for building B510 is presented. It can be seen that the average load values are forming two patterns for temperatures below 5 °C. This could represent one of several energy saving measurements such as lowering the thermostat in nighttime, household members could have been away or a complementary heating system. The household have not written anything in their survey answers that explains this consumption behavior. In Figure 22 (right) it is possible to see a wide spread consumption pattern for the building B707. The variation in average loads in the temperature range above 5 °C is very high. According to Table 5 the average base load based on values above 15 °C amounts to 5.72 kWh/h which must be considered as unusual. Assuming the meter reading system is working properly it is difficult to give reasons for such high base load consumption.

![Figure 22. Electricity consumption profiles from two buildings with lower $R^2$ values. Y-axis: Load (kWh/h). X-axis: Outdoor temperature (°C).](image)

Interesting input that complements the suggested methodology presented in this section is new data of usage of energy services via internet. With the previously discussed web-based architecture and interface, user statistics were collected from three new installations of such systems at Sala-Heby Energi, Smedjebacken Energi and Göteborgs Elförening. 21806 customers got access to a new web portal around 1st January 2010 and since then 1066 (4.9 %) customers have used the application. Of these 1066 active customers 43% have taken the
opportunity to add additional information regarding their building and household properties (year of construction, living area, heating appliances, etc.) This information can be used to improve and verify the suggested methodology further. The positive development of customer input in a one month period also suggest that the schematic overview in Figure 20 would not require inputs from expensive and time consuming methods like questionnaires. Instead, energy web portal should be considered as an interesting alternative to collect and store detailed customer information that later are used for new energy services. It should be mentioned that customers in Smedjebacken have had access to an older version over a longer period of time. However, user statistics have only been collected from the date when upgraded the system. The user frequency was lower in Smedjebacken.
3.5 Barriers to implementations

During this thesis work several sub-projects have been initiated and a large number of contacts and meetings with electricity distribution utilities have been performed. This section aims to summarize several years of experiences related to barriers accessing, handling and using meter readings. The barriers are categorized as technical and non-technical. Technical barriers refer to issues involving performance of the meter reading system and data quality. Non-technical barriers are more related to the people working with the collected data, available competence and contract formulations between companies.

3.5.1 Technical barriers

As shown, in Figure 19, 52% of Swedish electricity customers are represented by systems providing functionality to collect hourly meter readings series every day. 19% are situated in distribution areas were additional investments are needed to provide this functionality. This represents an obstacle for introducing new energy services based on hourly consumption data, e.g. the daily demand-based tariff evaluated in this work. However, there are energy services that could be provided with less detailed data than hourly meter reading series. The seasonal demand-based tariff presented in this work was not differentiated on a daily basis and it would be possible to implement the tariff with one peak load registration per day.

Absence of hourly meter series makes it more complicated to perform e.g. assessments of distribution losses, estimation of individual contributions to system peak loads, i.e. coincidence factors [13], and determine impact and soundness of new electricity tariffs and prices. The work presented in Paper C partly addresses a solution to this problem, but still require at least one registered peak load in every 27 hours consumption interval.

Quality issues using unexplored hourly based meter reading series should not be underestimated. In fact, this has been a central problem in almost every undertaken project during these years. A set of functions have therefore been established to pre-analyze the individual meter reading series in order to determine the overall quality (see Figure 23). Information from questionnaires is a useful input when searching for a specific type of customers, e.g. with electric heating systems. When pre-processing the values in the database it is important to keep track on the number of unique customer id (CID) and to compare the expected maximum number of values (theoretical value) with the actual available number of meter values.
Further, the measured values for each customer have been checked against the theoretical maximum values, identical repeated values and zero values in order to find deviations. The most common reason disqualifying customers in the pre-analyze phase would be missing values generating meter reading series with a low coefficient of fullness.

![Diagram of meter reading quality control process](image)

Figure 23. Overview of meter reading quality control process.

Meter series that have several identical repeated values or zero-values could indicate a meter system malfunction, but it could also be a natural consequence of storing values with low resolution. For various reasons electricity utilities today are collecting and saving consumption statistics in a wide range of accuracy. The resolution varies from decimal numbers, integers and up to hundreds of kilowatts (kWh/h). This will probably affect and restrain the future possibilities for several utilities to use meter readings in different energy services. In some cases it is possible to perform system updates from remote and the resolution can be improved with moderate costs. The higher costs occurs when the technicians needs to make system updates (software and/or hardware) on site.

3.5.2 Non-technical barriers

The electricity distribution utilities in Sweden have chosen a meter reading system based on several aspects. Some decision makers have had the belief that the authorities demand on more detailed energy information only causes higher costs for the electricity customers. Others have seen possibilities in more advanced metering system, both within the organization as well as towards the customers. A combination of attitudes, beliefs, experiences and future-looking ideas have naturally influenced the final outcome and on how potential opportunities may have been weighted towards the overall costs.
Organizational differences are also important to understand, e.g. the number of employees in the smallest distribution utilities are less than ten. One identified barrier is also related to the available competence in the utilities. The collected information is normally stored in databases and accessible via different user interfaces. Several of the small and medium sized utilities contacted during these years have often had limited knowledge on how electricity consumption data are processed in the databases. The technicians that handle the consumption information uses predefined interfaces provided by the supplier of the meter reading system and are not having adequate training to master direct access to databases. Knowledge gaps may have arisen between the persons who understand energy and the persons who have knowledge of what can be obtained through effective database management. In several small and medium sized distribution utilities the knowledge is, in worst case, not even included in the company organization, it is provided by external consultants.

The first barrier was related to the competence to access collected information, the second potential barrier concerns to legal aspects of accessing meter reading values in the databases. It is possible to divide data access rights in several levels:

- Full access for users and external software.
- Limited access for external software.
- Limited access for users via predetermined user interfaces.

Limited access to collected data can be explained by several factors. The suppliers of meter reading system have concerns guaranteeing full functionality of system and are not confident having the utility or third party working towards the databases. There are examples of utilities that have included this in the terms of the agreement for the system delivery, but this may become a future problem for parties were this issue has been overlooked and still remains unclear.

The last issue concerns the relation between the electricity distribution utilities and third-parties, e.g. providers of energy services and electricity retailers. Will Swedish electricity customer be entitled all collected consumption information both in theory and in practice? Voices for a Swedish national database for storage of hourly meter readings have been raised [77] similar to the suggested Meter Data Management / Repository (MDM/R) in the Ontario smart metering initiative [82]. It is an interesting initiative and it is necessary to evaluate the experiences from different perspectives, e.g. criticism from electricity distribution utilities in Ontario [54].
Chapter 4

Conclusions

The installations of new meter reading systems have opened up for an introduction of several applications based on the new information. Benefits arising out of these applications can be attributed to both customers and electricity companies.

RQ1: What are the primary applications possible using remote collected meter readings?

Using individual consumption series in order to create aggregated information may be interesting. Methods processing meter readings for economic, prognosis or simulation purposes could be incorporated in web-based portals. The implemented methods could create new individualized services such as determine insulation properties for a building as well as energy “consumption” patterns aside of this.

Architecture has been proposed for centralized energy information handling and its presentation for the users was implemented. Later this was also commercialized as a cost competitive method. Based on user statistics of an implemented web-based energy visualization tool it is possibly to see a continuous decline in the usage of a web-based information tool related to the year of introduction. This could be a potential problem for this kind of applications.

An evaluation tool for new price structures has been proposed and implemented. The bottom-up approach has proven to be valuable since it gives possibilities to evaluate impact on an individual basis as well as on an aggregated system level.

RQ2: How can the electricity market benefit from remote collected meter readings?

Introduction of demand-based pricing allows electricity distribution utilities to achieve a stronger correlation between peak loads in the distribution area and revenues. The economic evaluation indicates that customers with a more smooth consumption profiles, that is higher load factors, benefits from a demand-based tariff. Remote collected meter reading is necessary for the implementation of these.
The authority has accepted that legally acceptable energy information may be distributed through internet. This should promote the use of web-based services. A set of web-based tools can form new energy services based on collected meter readings. Some of those have been implemented and presented in this thesis work.

Internet based applications that visualize energy “consumption” patterns may be an important future tool in customer communication. Experiences from new installations indicate that at least interested customers do submit information concerning building and household properties. Still, it is challenging to enable the majority of customers to take part in these new services.

RQ3: Where do barriers appear when utilizing meter readings?

Problems to integrate, access and work with hourly meter readings should not be underestimated. Missing values is the most common reason for excluding customers from the evaluations in this work.

There are distribution utilities losing valuable consumption information by using coarse resolution for collection and storage of consumption data.

Knowledge gaps creating problems to utilize full potential of consumption statistics have arisen. The electricity distribution utilities may need to strengthen personal competence in order to resolve this problem.
Chapter 5

Future works

It would be interesting to implement the model proposed in the thesis to perform a declaration of the energy properties of apartments and buildings, as well as a means to show the overall consumption pattern for households as a function of time, as well as aggregated consumption. It would also be interesting to evaluate and develop new indicators from the data analysis of the collected meter readings combined with questionnaires or web-based interaction.

Implementations of different price models together with technical means to handle load control in an automatic way are other interesting areas.

Decision support methods could also result in different control strategies in order to give both companies and single users individualized recommendations on how to act based on present conditions.
References


www.pse.com (accessed 2009-12-01)


Appendix

List of acronyms

AMI  Advanced Metering Infrastructure
AMM  Automated Meter Management
AMR  Automatic Meter Reading
API  Application Programming Interface
ARMA  Autoregressive Moving Average
BPL  Broadband Power Line
CEN  The European Committee for Standardization
CENELEC  European Committee for Electrotechnical Standardization
CID  A unique customer/building identity
COP  Coefficient of Performance
COM  Common Object Model
DLL  Dynamic Link Libraries
DOTS  Distributed optimization in the pulp and paper industry
DSM  Demand Side Management
DSO  Distribution System Operator
Elforsk  The Swedish electrical utilities research and development company
ELIB  Swedish nation-wide study of indoor climate
ETSI  European Telecommunications Institute
FORTRAN  Formula Translation (a programming language)
<table>
<thead>
<tr>
<th>Acronym</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>GUI</td>
<td>Graphical User Interface</td>
</tr>
<tr>
<td>ICI</td>
<td>Interactive Customer Interface</td>
</tr>
<tr>
<td>ISM</td>
<td>Industrial, Scientific and Medical</td>
</tr>
<tr>
<td>LEKO</td>
<td>Governmental investigation of concession rights for supply of electricity</td>
</tr>
<tr>
<td>MA</td>
<td>Moving Average</td>
</tr>
<tr>
<td>MDM/R</td>
<td>Meter Data Management / Repository</td>
</tr>
<tr>
<td>MSDE</td>
<td>Microsoft Database Engine</td>
</tr>
<tr>
<td>NPL</td>
<td>Narrowband Power Line</td>
</tr>
<tr>
<td>OPEN meter</td>
<td>Open Public Extended Network metering</td>
</tr>
<tr>
<td>PLC</td>
<td>Power Line Communication</td>
</tr>
<tr>
<td>PaaS</td>
<td>Platform as a Service</td>
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<tr>
<td>RF</td>
<td>Radio Frequency</td>
</tr>
<tr>
<td>SaaS</td>
<td>Software as a Service</td>
</tr>
<tr>
<td>SINTEF</td>
<td>Norwegian foundation for scientific and industrial research</td>
</tr>
<tr>
<td>SMHI</td>
<td>Swedish Meteorological and Hydrological Institute</td>
</tr>
<tr>
<td>STEMFS</td>
<td>Swedish Energy Agency regulations (now The Energy Markets Inspectorate regulations, EIFS)</td>
</tr>
<tr>
<td>SQL</td>
<td>Structured Query Language</td>
</tr>
<tr>
<td>TOU</td>
<td>Time of Use</td>
</tr>
<tr>
<td>VB</td>
<td>Visual Basic</td>
</tr>
<tr>
<td>WMA</td>
<td>Weighted Moving Average</td>
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</tbody>
</table>
**List of notations**

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>C₁</td>
<td>Specific heating demand (kW/°C)</td>
</tr>
<tr>
<td>C₂</td>
<td>Heating demand at T\text{out} = 0°C (kWh/h)</td>
</tr>
<tr>
<td>Cₑ</td>
<td>Fixed price constant related to energy (USD)</td>
</tr>
<tr>
<td>C₁</td>
<td>Fixed price constant related to peak load (USD)</td>
</tr>
<tr>
<td>E</td>
<td>Energy consumption (kWh)</td>
</tr>
<tr>
<td>Eᵃ</td>
<td>Energy consumption value with non-linear adjustment (kWh)</td>
</tr>
<tr>
<td>Eₜ</td>
<td>Temperature-dependent energy constant (kWh/°C, day)</td>
</tr>
<tr>
<td>kₑ</td>
<td>Price constant related to energy (USD/kWh)</td>
</tr>
<tr>
<td>k₁</td>
<td>Price constant related to peak load (USD/kW)</td>
</tr>
<tr>
<td>p</td>
<td>Cost function (USD)</td>
</tr>
<tr>
<td>L</td>
<td>Load (kWh/h)</td>
</tr>
<tr>
<td>Lᵇ</td>
<td>Peak load value with non-linear adjustment (kWh)</td>
</tr>
<tr>
<td>Lₜ</td>
<td>Base load (kWh/h)</td>
</tr>
<tr>
<td>Lₜₑ</td>
<td>Temperature-dependent load of building (kWh/h)</td>
</tr>
<tr>
<td>Lₜₑ</td>
<td>Load supplied from heating system (kWh/h)</td>
</tr>
<tr>
<td>Lₓ</td>
<td>Average load value based on x number of hours (kWh/h)</td>
</tr>
<tr>
<td>R²</td>
<td>Coefficient of determination</td>
</tr>
<tr>
<td>T₀</td>
<td>Temperature, T₀ = 0 °C</td>
</tr>
<tr>
<td>Tₑq</td>
<td>Equivalent temperature (°C)</td>
</tr>
<tr>
<td>Tᵢn</td>
<td>Indoor temperature (°C)</td>
</tr>
<tr>
<td>Tᵢₗᵣ</td>
<td>Limit temperature or balance temperature (°C)</td>
</tr>
</tbody>
</table>
\( T_{out} \) Outdoor temperature (°C)

\( T_y \) Average temperature value based on \( y \) number of hours (°C)

TC Total energy consumption (kWh/day)