THINKING SMART ABOUT ELECTRICITY USAGE
how can advanced demand response programs affect consumption of electricity?

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Preface

This master thesis is a part of “Manage Smart in Smart Grid” and “IMPROSUME” projects at NCE Smart Energy Markets in Halden. I want to thank for being given the possibility to write in an always motivating environment and at the wonderful office at Storgata. Special thanks to Stig Ottesen for always being positive to me, open for discussions and willing to give good advice. A thank also to everyone at NCE Halden for nice talks and pleasant lunches.

Olvar Bergland has supervised this master thesis. He has been very accessible throughout the work process and has provided important feedback and materials, and comments on errors. I would like to express my great appreciation of his efforts and kindness. I would also like to strongly thank Hanne Sæle and SINTEF Energi Research for providing me with data from the pilot at Malvik Everk that tested remotely controlled load shifting. I should also thank Mikael Togeby and Kjell Vaage for giving me access to highly relevant for my thesis materials and to Hollie Orr for the help with sorting data from the REMODECE project.

Summary

Recent developments in the Nordic power system have shown some negative trends that relate to all actors in the market. Overall increase in prices and periods with extremely high prices are observed and operational problems are encountered. These facts question the reliability and security of electricity supply and challenge the development of a smarter grid through which problems can be mitigated.

Facing the situation described above the Norwegian Government has decided that advanced metering system (AMS) will be installed everywhere in the country by 2016. A main idea behind this action will be to stimulate energy savings and increase consumers' knowledge on their electricity usage. The desired consequence of the installation, however, will be to open possibilities for demand response (change in consumers' electricity usage patterns in response to price). This increased demand responsiveness can be a good solution to the existing operational problems.

This thesis analyzes the effect of a demand response program that involves time-of-use pricing and remote load control of household heating equipment and sets the analysis in the general concept of efficiency in the electricity market and all the benefits associated with it. The main focus has been to estimate the influence that automatic steering of waterborne space heating and electrical water heaters in combination with a tariff compiled of peak, off-peak and spot prices will have on Norwegian households' electricity usage based on a pilot testing remotely controlled load shifting at Malvik Everk. For this purpose I have used econometrics to estimate substitution elasticity and a price-elasticity equivalent measure and have tried to compare the extent to which electricity consumption has been reduced and moved to other periods throughout the day.

The estimation of substitution elasticity does not provide any statistically significant proof of shift from peak to off-peak usage as a response to prices charged. These results indicate that load reduction should be attributed specifically to RLC and not to price changes as prices and usage do not follow a particular correlation pattern during the hours neighboring the predefined peak periods. Price elasticity's estimates prove to be highly significant and show that load during hours of RLC has been reduced simultaneously with the customers being charged peak prices. The resulting elasticities equal to -0.47 and -0.10 account for a much higher extent of price-responsive behavior as compared to previous studies that analyzed price elasticities.

Results from demand response based pilots such as the one at Malvik Everk provide some important insights on what the opportunities for demand curtailment can be and on how load can be rescheduled. Estimation results indicate a big potential for RLC to contribute for reduction of consumption during hours corresponding with high-price periods. However, the true success of demand response programs will depend mainly on the introduction of adequate technological solutions, correct electricity pricing methods and a sound knowledge of the desired effects and their consequences.

Contents

List of Abbreviations

ADRS - Automated demand response system

AMR - Advanced metering reading

AMS - Advanced metering system

BEMS - Building energy management system

CPP - Critical peak pricing

PLC - Power line carrier

RLC - Remote load control

RTP - Real-time pricing

TOU - Time-of-use pricing

1. Introduction

1.1 Background

The Norwegian power system is dominated by hydro power and as such can offer the flexibility of shifting production from peak to off-peak periods. This feature leads to less peak price exposures and smoother intraday prices. However in the case of dry year huge seasonal variations in prices can be observed.

A look to the close past - winter 2010 – gives a clear view of an extreme situation where prices could reach unpredictable heights. Several facts were contributing to the extremely high prices in the beginning of that year. Besides dry and cold weather, the possibility of importing electricity from Swedish nuclear power stations was reduced and transmission problems were present. Such situations are also likely to be encountered in the future, indicating a possible need for an elaborative change in the power system.

The development of the future power system in Norway will be in correspondence with finding the optimal solutions for the existing operational problems and strengthening its reliability. A most probable scenario will involve more wind power and small scale hydropower as well as increasing number interconnectors to thermally based power systems elsewhere in Europe. In addition, the need for producing electricity from renewable energy sources will increase with the introduction of trade with green certificates from 2012. As a result the price volatility on seasonal and annual scale can be expected to decrease while the differences in prices throughout the day and week are likely to increase.

In a situation where electricity prices are dominated by daily fluctuations, the short term response to prices will be an important part of a well-functioning market. Currently, however, most customers do not face any incentive to respond to price changes as their meters account for accumulated consumption only and the hourly prices remain invisible due to lack of enabling technology and respective pricing methods. Yet, the fast development of innovative technologies and their decreasing prices can in close future contribute to a revolutionary change in electricity consumers' responsiveness. Norwegian Government has already decided that the implementation of advanced metering system will take place by 2016 and for Central Norway this deadline is shortened to 2013 accounting for the pending operational problems that this area is facing. Through this action the Norwegian Water Resource and Energy Directorate (NVE) presents its ambitious strategy to provide consumers with an option to use electricity in an economically optimal way.

Advanced metering system (AMS) that involves automatic meter reading through the technology known to the public as smart meters will not only make electricity users aware of their consumption habits, but will also open for the use of an additional resource: demand response. By the term demand response are meant programs and activities designed to encourage change in consumers' electricity usage patterns in response to changes in the price of electricity over time, or to incentive payments designed to induce lower electricity use at times of high wholesale market prices or when system reliability is jeopardized[1]. Thus demand response is any program that communicates with the customers and either enables them to lower or shift energy consumption. For the purpose of this document, I will focus only at the side of demand response that relates to the actions taken by residential customers in response to price signals. Incentive payments relate mostly to large industrial customers and will not be included in the analysis.

Customers can either respond to prices manually (for example with turning off some household appliances during peak price periods) or they can be a part of a program for automated demand response, in which case their consumption can be steered remotely, of course in compliance with their preferences. In this specific investigation customers are participating in a program for automated demand response but have also the possibility to respond manually.

Three main types of demand response determine the specific response action on a system level: peak clipping that decreases demand at critical hours when prices/costs are high due to contingences; load shifting which contributes to shift of demand from high-priced to lower-priced periods; and valley filling through which demand is increased in hours when prices are low. To achieve the specific load reduction and energy saving benefits related to the actions above a good knowledge on consumers' electricity usage pattern is needed. Figure 1 presents such a pattern for an average Norwegian household. We observe a morning and an afternoon peak period

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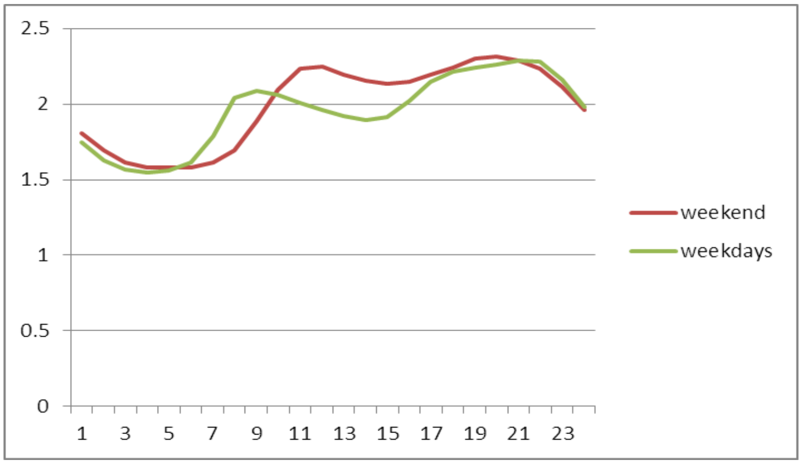
[1] Definition by US Department of Energy

associated with households' daily activities. Morning peak hours during weekends are met at somewhat later point.

Figure 1.1 – Estimated daily load curve for weekdays and weekend during the year 2006. Norwegian household customers at Skagerak Nett - 2006, kWh/hour



Source: Ericson and Halvorsen (2008), SSB

Referring to Norway's experience from periods with extremely high prices (for example: 17 December 2009 between hours 17-18, 8 January 2010 between hours 8-9, 22 February 2010 between hours 8-9) we can see that those hours are reasonably corresponding to the hours of households' peak consumption. Simulations to analyze these unfavorable situations have shown that even a small amount of increased demand flexibility could have substantially reduced the price peaks. The absence of response to price signals, however, prevented this from happening and market participants in some areas had to face prices that reached as high as 1400 Euro/kWh indicating the inability of the power system to provide enough transmission capacity to areas with scarce generation resources. An improvement in the ability to shift consumption from peak hours would bring significant market efficiencies as a result from better network utilization. Thus market clearing will be eased and consumers will face lower prices than they would otherwise do.

Multiple studies around the world have been aiming at capturing the size of potential benefits from demand response programs. More than 400 pilot tests have been performed worldwide testing various tariffs and types of enabling technology. And while AMS is a technology of an absolute necessity for accomplishing demand response activities, smart meters alone can contribute for utilizing the potential of demand response only to a certain grade. In a century where innovation and technology development are leading, there is much more to be discovered as a suitable technological solution for steering electricity consumption in accordance to price signals.

1.2 Purpose of research

The main goal of this thesis is to estimate the effect that advanced technologies for automated control of households' waterborne space heating systems and electrical water-heaters in combination with time of use pricing method will have on electricity consumption pattern in Norway. This is done through analyzing substitution and price elasticities and by estimating the potential for reduction and shift of peak load. With my thesis I will also try to present a state of the art review of possible demand response activities and outcomes and analyze those in tact with the benefits coming from market efficiencies and system reliability.

Increasing degree of price responsiveness in the market is expected to result in multiple benefits even in a hydropower dominated system as the Norwegian one. The main gains will be associated with mitigating extreme peak price situations, stimulating for more sensible electricity use, utilizing renewable power resources and better managing increasing consumption and grid capacities. For all these reasons demand response can prove to be an environmentally sound answer to the pending problems in the energy system and any effort to investigate its development is being worth.

1.3 Structure

The thesis starts by giving brief description of the Nordic power market and with providing the theoretical basis related to elasticity, demand response and their importance. The theoretical part is then followed by several sections describing some of the essential elements of demand response: controllable loads, technologies and economic tools (pricing methods). Next, some examples for pilots testing demand response programs are presented. Section 7 presents the core of this thesis: data, methods and results from data analysis are described. Finally, discussion and concluding remarks are given followed by reference to future developments.

2. Theory basis

2.1 Supply and demand in the Nordic power market

Norway is a part of a common power market - Nord Pool Spot - where also Denmark, Finland, Sweden and Estonia are members. As every other energy market, Nord Pool Spot determines the price based on supply and demand. Market actors (producers of power, suppliers, traders, large industrial companies) provide the market with bids to buy and offers to sell and price for each hour of the day is then set. This is the system price that functions as a reference price for financial contracts at the Nord Pool market.

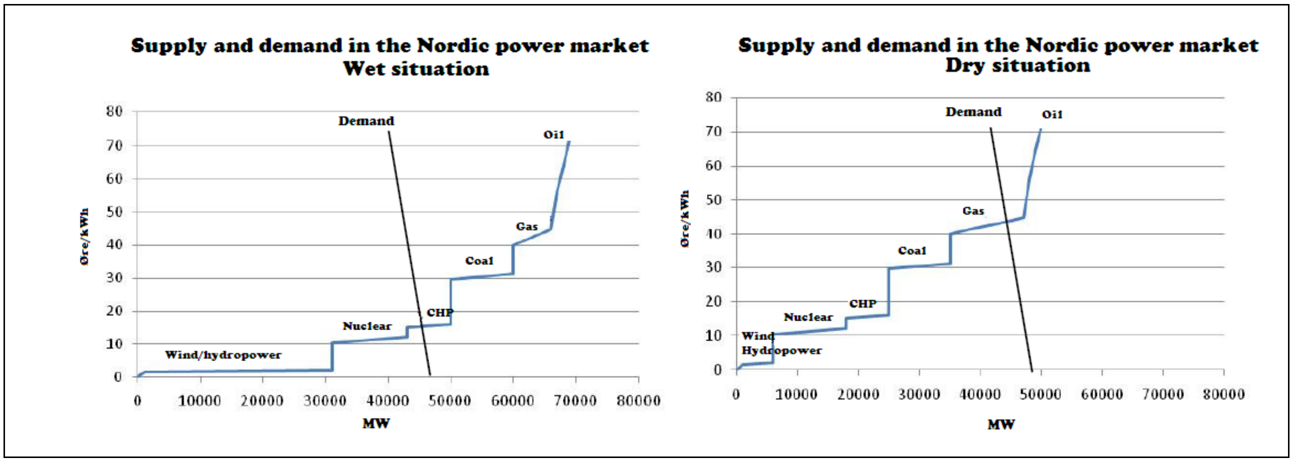
The quantity of electric power that can be exchanged at any time is determined by the transmission capacity of the grid. Yet, in a common power market, the electricity is streaming from lower-price to higher-price areas. And in the case when the desired amount of electric power to be exchanged between two areas is more than the actual capacity of the transmission lines between these areas, bottlenecks arise. Such bottlenecks are usually taken care of by price mechanism where the market is divided into separate Elspot areas. In this way the area with excess production gets a lower price compared to the area with insufficient production and this price differentiation continues until the transmission capacity is filled. Thus the market exchange of electricity is steered through price mechanism. Norway is currently divided into 5 price areas while in Denmark they are two. Market actors have to localize their bids and offers within the separate areas.

Figure 2.1 – Elspot areas in the Nordic power market

Source: NVE and Nord Pool

In a hydropower based system, however, the bids related to supply can differ significantly from period to period. In Figure 2.2 is shown the distribution of loads being supplied with respect to different weather conditions. In wet situation more than 30000 MW of base load are covered by wind and hydropower production with the price being determined around the marginal cost of producing electricity in combined heat and power stations. In the case of dry situation prices are cleared at a much higher level - around the marginal cost of gas. The scenario presenting a normal situation gives a price around the marginal cost of coal and regulated hydropower production (Figure 2.3).

Figure 2.2 – Supply and demand in the Nordic power market

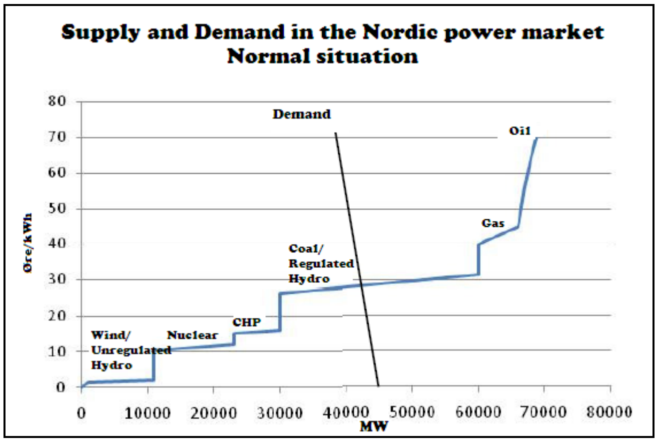


Supply and demand in the Nordic power market Wet situation

Supply and demand in the Nordic power market Dry situation

Source: Scenarios for price and volatility, Manage Smart in Smart Grid Workshop 2010, Bolkesjø T.

Figure 2.3 – Supply and demand in the Nordic power market



Supply and Demand in the Nordic power market Normal situation

Source: Scenarios for price and volatility, Manage Smart in Smart Grids Workshop 2010, Bolkesjø T.

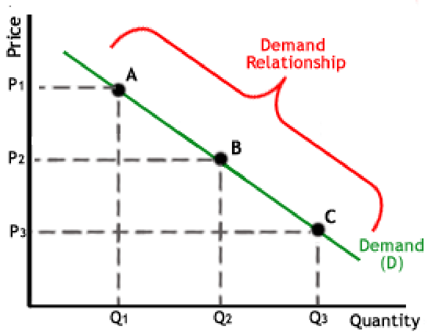
In the future the grade to which prices will clear around the marginal costs presented in the figures above or lower will depend on the amount of interconnectors to other European countries and the capacity being offered by renewable resources. More connecting cables to the main continent and more wind farms and micro hydropower stations will contribute to greater fluctuations in area prices on daily basis and present a challenge to the power system.

2.2 Price elasticity

The trends in future development of the power system will possibly bring about greater volatility in electricity prices. Thus it is natural to conclude that consumers might be to a higher extent willing to try to reduce costs by modifying their usage profile. This process will be both supported and accelerated by new technological solutions and pricing methods. For that reason it will be useful to investigate how consumers will respond to price changes and what difference with regard to response innovative technologies and economical tools such as various pricing methods can make (more on pricing methods in Section 5).

Through the Law of demand economic theory tells us that keeping all factors constant as the price of electricity increases, the quantity demanded decreases. And conversely - when price decreases quantity demanded increases. These relationships are presented in Figure 2.4.

Figure 2.4 - Graphical presentation of Law of demand



Source: Investopedia

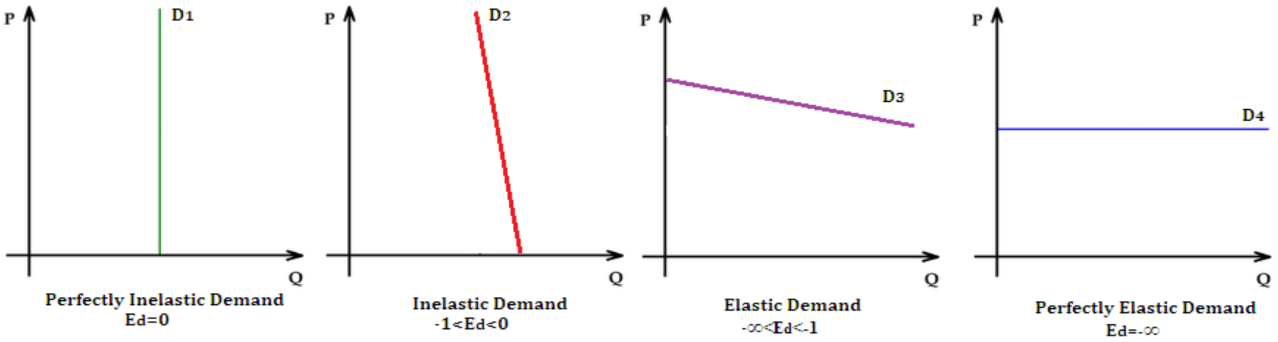
The grade to which consumers are sensitive to changes in prices can be estimated by the coefficient of price elasticity. With respect to electricity consumption, price elasticity will give a normalized measure of how electricity usage changes when price changes by one percent. Here normalized indicates that the measure concerns the relative price change. The basic formula for calculating elasticity coefficients is given below where E_d is the price elasticity of demand, Q_d - the quantity of electricity demanded and P is the price of electricity

$$E_d = \frac{\%\, change\ in\ quantity\ demanded}{\%\ change\ in\ price} = \frac{\Delta Q_d / Q_d}{\Delta P / P} \qquad (1)$$

The literature on economic theory reports two types of price elasticity - own-price and substitution elasticity (also known as cross-price elasticity). When related to electricity usage, the first type elasticity will present consumers' response to prices through the adjustment of quantity electricity they consume (as presented in (1) above). In this case the coefficients for elasticity will be negative accounting for the inverse relationship between demand and price.

Further on, own-price elasticity can be described as elastic, unit elastic or inelastic depending on the intensity with which consumption changes when price changes. For a proportional change in demand in response to price change the value of own-price elasticity will be $E_d = -1$. As a numerical example can be considered a 5% decrease in demand as a result of a 5% increase in price. This kind of demand is known as unit elastic. Next, elastic demand will be characterized by more than proportional decrease in demand in response to price increase. In the above numerical example a 10% decrease in demand when price increases by 5% will result in $E_d = -2$. Thus coefficients in the range $(-\infty, -1)$ are considered to present elastic demand. And last, inelastic demand is typical for situations where a price increase results in a less than proportional decrease in demand. For example a 2% decrease in the case of 5% price increase will give and elasticity coefficient $E_d = -0.4$. Coefficient in the range $(-1, 0)$ are thus representative for inelastic demand. Figure 2.5 gives outlook to the graphical presentation of demand curves with various elasticities.

Figure 2.5 - Price elasticity and demand curves



Perfectly Inelastic Demand Ed=0

Inelastic Demand -1<Ed<0

Elastic Demand -∞<Ed<-1

Perfectly Elastic Demand Ed=-∞

Substitution elasticity, on the other hand, gives an idea of how willing consumers are to substitute one good with another (or to substitute the consumption of a good from one period for a good from another period). With respect to electricity demand in a market where prices fluctuate throughout the day, such elasticity will account for users' willingness to move their consumption to lower-price periods by measuring the relative change in usage between periods with different prices. Thus substitution elasticity can be simply defined as the relative change in usage in the two periods (e.g. the ratio of peak to off-peak usage) for a one percent change in the relative prices in those periods (the ratio of the off-peak to peak price)[2]. Mathematically it can be expressed as:

$$E_{sub} = -\frac{\%\Delta\left(Q_p / Q_o\right)}{\%\Delta(P_p / P_o)} \tag{2}$$

Where E_{sub} is the elasticity of substitution, Q_p and Q_o are peak and off-peak usage and P_p and P_o are peak and off peak prices.

In contrast to the own-price elasticity, elasticity of substitution takes only positive values. Yet, when absolute values of the elasticity coefficients are compared, both types of measures give similar results. For example a zero value will mean no change in consumption and response will be increasing with higher absolute values for both elasticities.

However, due to the fact that own-price and substitution elasticities account for different adjustment in consumption on a conceptual level (with the one presenting response to price in one period and the other - to the relative prices in a couple of periods), it is important to distinguish between the circumstances identifying their proper usage. The best approach involves the use of own-price elasticity when adjustments relate to direct decrease in electricity consumption, while substitution elasticity can give best results in the case when adjustments are primary associated with shifting consumption from one period to another. In this document I will use only the concept "price elasticity" as a substitute for "own-price elasticity".

In general, the shorter the time for response, the less are the opportunities for any responsive action. Thus, in the "short-run" it is harder to realize any substitution or energy saving decision

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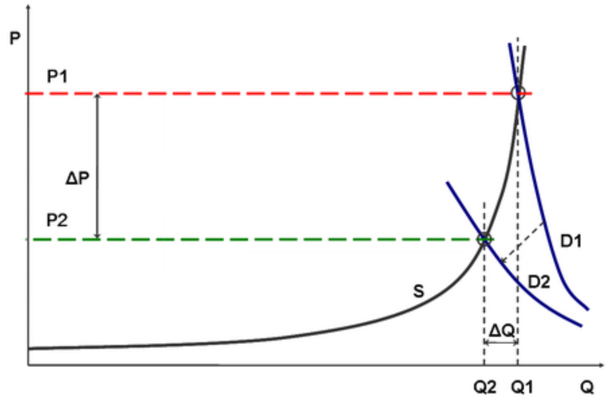
[2] Definition from Business and Economic Forecasting Unit, Monash University in South Australia

and the demand is rather inelastic. On the contrary, in the “long-run”, consumers facing price increase can switch to other energy sources and there is enough time for development of substitution technologies to take place. For these reasons demand is assumed to be more elastic in the longer term period.

2.3 Demand Response

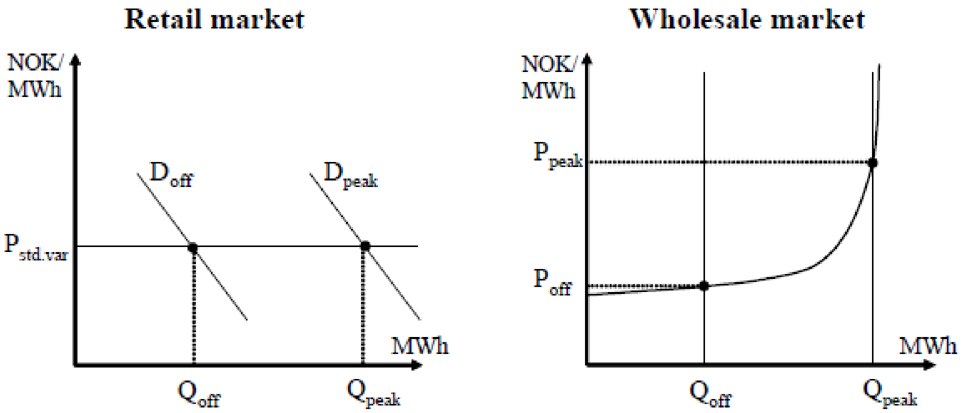
The basic purpose of demand response initiatives is to contribute for a more flexible demand. Flexibility in demand indicates that consumers are actively participating in the electricity market where they can observe and respond to prices that change over time. As it was mentioned above, by the law of demand, when price increases demand will decrease and vice versa. Greater price responsiveness will be presented by a flatter demand curve – D2 in Figure 2.6. We see how a more elastic demand curve contributes to lower prices and less quantity consumed.

Figure 2.6 More elastic demand (D2) gives a lower price (P2)



Currently the Norwegian electricity market is determined by low level of response to prices. Although the market price varies from hour to hour, most consumers are unable to respond to these price signals as they do not get any information on price variations and are accounted only for accumulated consumption. As a result consumers lack incentive to change their usage in accordance to price fluctuations and on the retail market the quantities demanded during peak and off peak hours are fixed, with the price being set according to a given standard variable tariff. The consequence for the wholesale market is retailers bidding inelastic purchase curves as presented on the right side in Figure 2.7 below.

Figure 2.7 - The disconnection between the wholesale and the retail markets

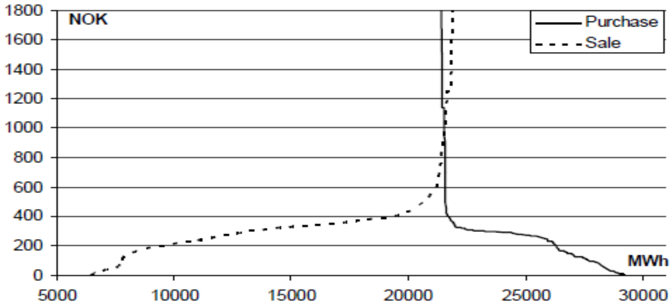


Source: Short term electricity price response, Torgeir Ericson (2007)

Even though consumers possess some elasticity of demand[3] (the peak and off-peak demand curves D_{peak} and D_{off} in the retail market are not vertical lines) and thus some willingness to respond to price signals, they are not offered the opportunity to do so and their short term consumption quantities in the wholesale market are presented as fixed.

Yet, some electricity consumers (predominantly large ones with annual consumption of more than 100 MWh) have the possibility to respond to prices through time-differentiated tariffs, that some flexibility in the wholesale market already exists and the actual purchase curve is not vertical but extremely steep for high prices. An example of such situation for the year 2003 is presented in Figure 2.8. Inelastic demand contributes to a high clearing price of NOK 981,14.

Figure 2.8 - Elspot purchase/sales curves. Hour 17:00-18:00, 6 February 2003



Source: Nord Pool Spot AS

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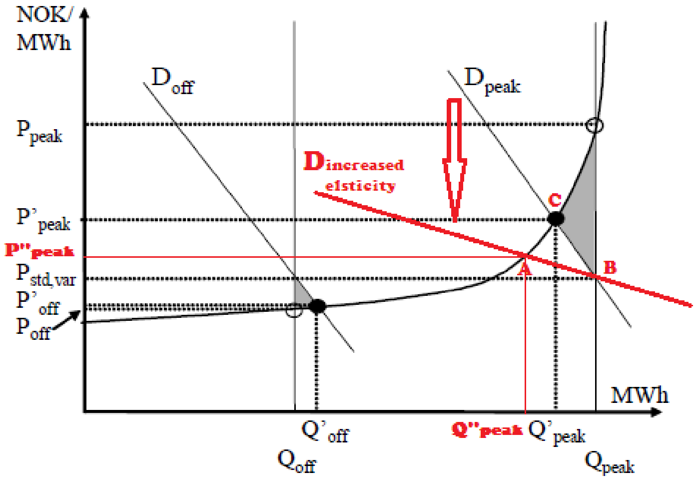
[3] Figure 2.7 gives a simplified model of demand curves. In reality consumption varies significantly and is not determined only by peak and off-peak periods.

Introducing of two-way communication through AMS as well as other innovative technologies will provide consumers with the possibility to face marginal prices of production and consequently exhibit price elastic demand. In a situation where consumers are facing and responding to an hourly spot price and are not restricted by fixed in the short run contract types (e.g. standard variable tariff that is based on the market price but price swings are less visible compared to the spot price contract and is thus presented as fixed in the short run), the peak and off-peak consumption quantities and prices to clear the market will be different compared to the case with vertical demand curves. New values are determined by Q'_{peak}, P'_{peak} and Q'_{off}, P'_{off} in Figure 2.9. The intersection points between supply and the elastic demand curves determine the efficiency gains presented by the grey areas (Ericson, 2007).

Figure 2.9 - A connected market with demand responsive consumers with time-differentiated tariff and increasing price elasticity in peak hours



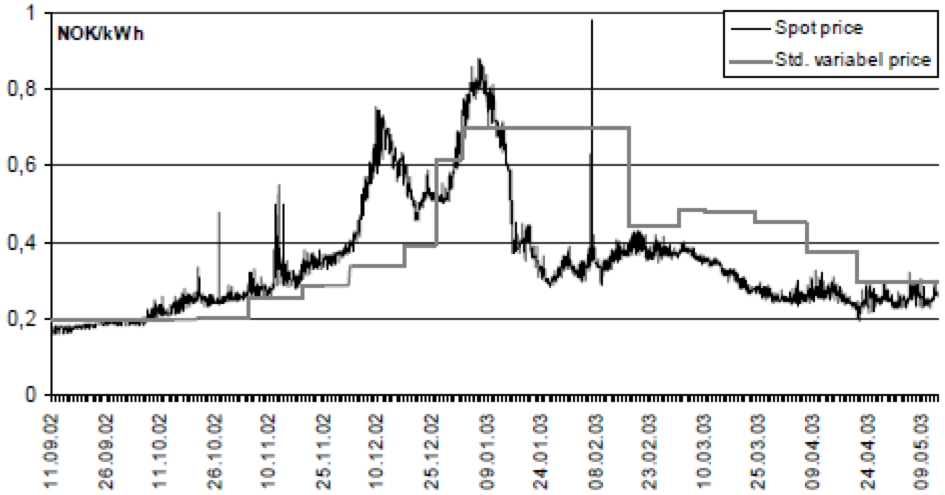
Source basic graph: Short term electricity price response, Torgeir Ericson (2007)

But new technology can not only facilitate visibility of price signals to end users. Advanced equipment providing additional functionalities such as automatic load control, building management, etc. (more on the issues related to technological development - in Section 4) can additionally enhance the shift to a flatter demand curve. In the case of a peak period this is presented by the thick red line in Figure 2.9. As a result lower price P''_{peak}, lower quantity Q''_{peak} and an additional efficiency gain by triangle ABC is achieved.

2.4 The importance of demand response for the power system and the market

Due to price inelastic demand the gap between end user price and spot price is present indicating market inefficiency. Increased short term price response will increase the economic efficiency of the market through a better integration between the spot and end-user market. In todays' system end users do respond to prices but there exists a time lag. This can be illustrated by comparing the spot and standard variable price for a given period. Figure 2.10 presents the fluctuations for the two prices during winter 2002/2003. It is visible how the changes in spot prices after some period are reflected in the standard variable price contract offered by the supplier. The correlation between the two prices is comparatively high when the spot price is stable but when it experiences big changes, the difference between the two increases.

Figure 2.10 – Hourly spot price for the Oslo region and the price offered by supplier Hafslund Energi through a standard variable price contract

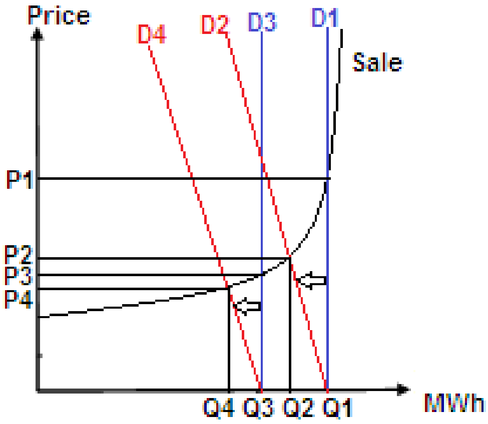


Source: Nord Pool Spot AS and Hafslund

Thus it is natural to conclude that in a longer term perspective the Norwegian wholesale and retail market are comparatively well integrated while in the short term (from hour to hour or day to day) they are almost separated and there is a limited number consumers that can directly respond to the spot prices (Ericson 2008 and 2009). Currently variable price contracts are less common and most customers choose to sign a fixed price contract or a spot price contract. While the fixed price contract is associated with one price throughout the whole contract period and is independent from the spot market, the spot price contract takes the average of the spot price for a given period, usually one month. These two highly common types of contracts, however, do not reflect the momentary fluctuations in market price and cause the deviations from the real time wholesale price to increase. As a result the disconnection between the wholesale and the end-user market is enhanced. Introducing contracts based on real time hourly spot prices and supporting those with respective level of technology that can instantaneously provide the necessary information could ensure a better functioning market with lower prices during peak hours and somewhat higher during off-peak ones (in Figure 2.9 P'_{off} is above P_{off}).

In the case when inflexible demand is close to capacity, bidding elastic purchase curves in the spot market can lead to large decrease in prices. In Figure 2.11 D1 shifts to D2 and price with elastic demand decreases from P1 to P2 and quantity from Q1 to Q2. Decrease in price and quantity is also observed at a lower demand level and shift from D3 to D4. The reductions in demand quantities from Q1 to Q2 and from Q3 to Q4 can in certain occasions be a valuable solution to the pending operational problems in the grid.

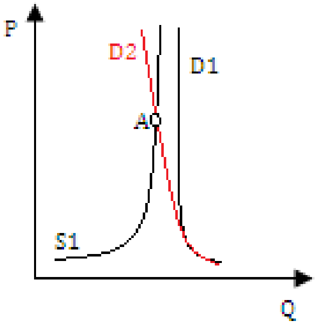
Figure 2.11 – Bidding responsive purchase curves in the spot market



In the Norwegian hydropower dominated electricity system, the importance of better integration between the spot and retail markets will be large in periods of shortages and when managing bottlenecks is critical for its reliability. With occasionally steep bid curve in the spot market determined by unfavorable circumstances (a combination of such was described in Section 1), a small price dependent reduction in load can result in significant price decrease and securing initial balance (Grande et al 2008).

In addition, a more elastic demand curve will help preventing an extreme situation where market clearing does not take place due to low flexibility. Such a case is presented in Figure 2.12 where both demand and supply are illustrated by steep curves (D1 and S1) that do not intersect. If demand is more elastic (D2) the market will be able to clear at point A and a number of costly emergency actions undertaken by Nord Pool Spot can be prevented[4].

Figure 2.12 - Market clearing with more and less elastic demand curve



3. Electricity usage and controllable loads

The need for DR and its opportunities evolve from consumers' electricity usage profile. Thus, in order to show where and how demand response actually can take place, consumers actual profile has to be presented. A recent study performed by Norwegian partners in the frame of the European REMODECE (Residential Monitoring to Decrease Energy Use and Carbon Emissions in Europe) project (2006-2008) aimed at specifying the electricity use per hour for a large number of household appliances, standby appliances were also monitored. Heating was not included in the study assuming that people will not be willing to sacrifice their warmth comfort for the benefit of reduced carbon emissions or load reduction in the system. The technological solution "Power Detective" was used by SINTEF for metering the consumption of separate appliances.

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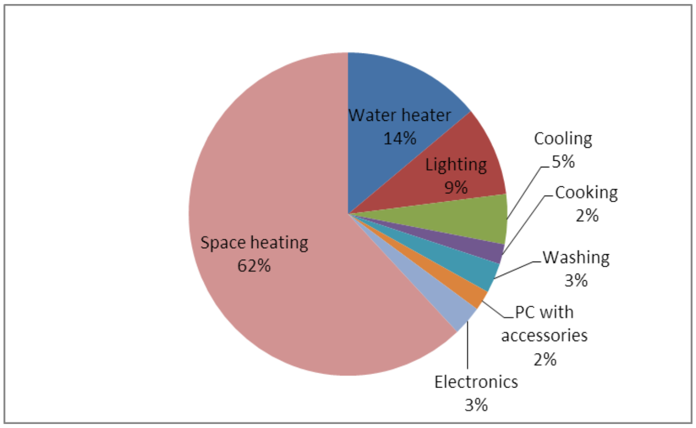
[4] A detailed description of actions taken by Nord Pool Spot when market clearing does not take place is available at www.nordpoolspot.com

Figure 3.1 – Power Detective technology used for measuring the appliances' consumption under the REMODECE Project

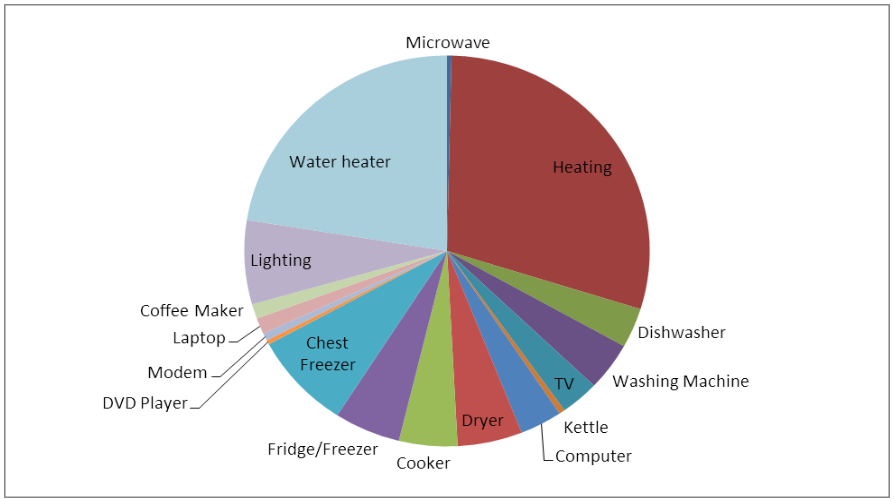
As a result of the measuring the shares of households' end uses could be estimated. In the process of estimation data was adjusted to respond to households' type (size and structure).

Figure 3.2 – Norway share of end uses by an average Norwegian household for year 2007 according to REMODECE Project



Based on the data[5] collected within the REMODECE project the daily consumption load shares for the various household appliances have been found (Figure 3.3). Then the daily load curves for those household loads that represent major shares of consumption (the four largest) are shown in Figure 3.4.

Figure 3.3 – 24-hour consumption load shares divided by sources



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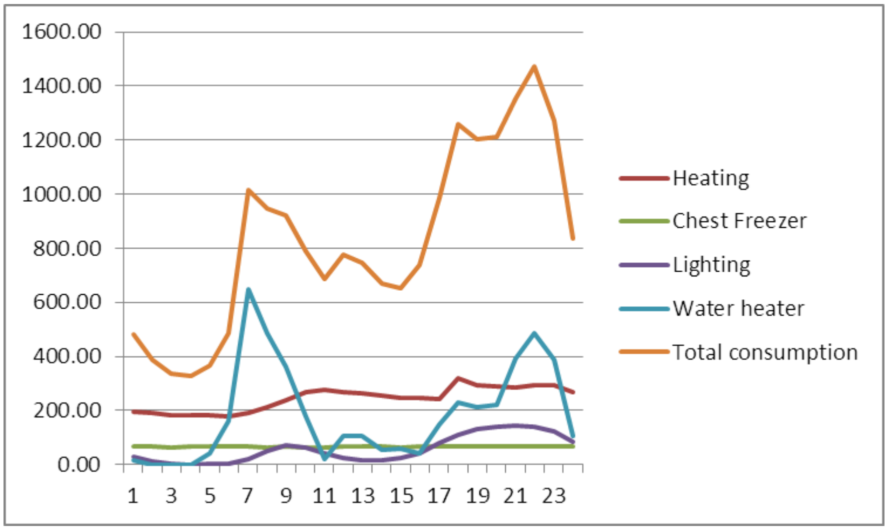
[5] Access to the European database is available through the project's website http://remodece.isr.uc.pt/

Figure 3.4 - Daily load curves by major consumption sources (Wh/hour)



A shape of total load curve (upper orange line) resembling the one in Figure 1.1 can be observed and we see from the strong similarity in the shapes of orange and blue lines that water heater constitutes a main determinant of total load profile. Thus water heaters are of specific interest as an important demand response resource and the possibilities for and the effect of exercising control over them will be further investigated in my thesis.

As it is easily perceived, some of the loads in the home are such on which consumers are unable or highly unwilling to exercise specific usage control – refrigerators are such an example. On the other hand, part of the loads gives possibilities to be controlled without the consumer noticing any discomfort. These could be water heaters, smart appliances, heat cables, electrical vehicles. In order to achieve increased demand elasticity and a greater potential for demand response, the aim should be to increase consumers' responsiveness to prices through managing the controllable loads they possess.

The concept of controllable loads leads to the idea that a certain components of the end electricity usage, presented as a percentage share in figure 3.2 above, can be used as areas where responsive action can be taken. Even if the share of space heating is excluded as an option for DR, a significant share of potential load shift/load reduction areas remains. Water heating and washing, for example, account for 17% of the end use in Norwegian households which, on aggregated level, could present a significant amount responsive load.

4. Technological development in the field of DR

Demand response technologies have in recent years been both used and developed. What concerns households' participation in programs achieving demand flexibility - development has been mainly aimed at facilitating communication of hourly price signal to the house and encouraging response through various automation technologies. For this purpose multiple factors have been taken in account and various technological solutions have been examined. I will briefly describe those that are most important and relevant for my thesis.

4.1 Smart meters

So far conventional meters have only been providing measure of aggregate consumption and no incentive has been given to users to steer they consumption behavior. However, a main prerequisite for enabling demand response is the provision of frequent and correct metering and facilitation of two-way communication. Such functions will be provided by "smart meters" which, as it was already mentioned in the introduction, will be installed everywhere in Norway by 2016. The new meters will be able to record consumption frequently (hourly or in shorter periods) and then to communicate this information instantly.

Smart meters have been already installed in all Swedish homes but the actual demand response functionalities of those meters are not yet identified. In Norway 140 electricity distributors will have to install smart meters to their customers and experience from other countries will be used under the choice of type of metering equipment. As a result of the implementation of AMS there will be a number of possibilities offered to end-users in order to manage their consumption and the opportunities for participation in demand response activities will increase considerably. Main drivers for resulting benefits will be the opportunity to read the new devices remotely and provide time-of-day information on prices and usage.

In addition smart meters can provide a number of complementary advantages that will strengthen the reliability of the system and improve market's efficiency. New tariffs and offers from electricity retailers will help increasing both intensity of market competition and the effective follow-up of market signals from users. Further on, the new meters will encourage households to take part in distributed generation (such as micro-windmills and solar panels) for which the accurate and timely measuring is a basic requirement. Last but not least important - by installing smart meters distributors will, to a much higher extent, be able to help detecting grid faults and reconnections after power outages and measurement of quality of supply at the connection point as well as calculation of loss coefficients or reactive power will experience increasing precision.

4.2 Automation and communication technologies

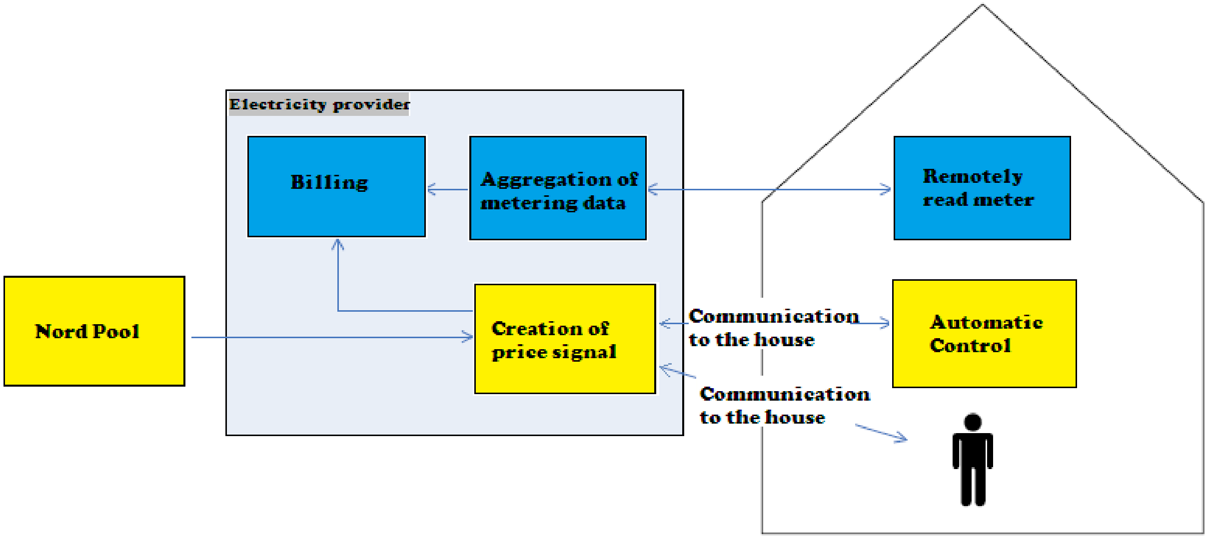
In order for “response” to take place smart meters should be linked to communication platform that will allow the transmission of price signals. In this way hourly prices from Nord Pool will reach households and communication between the meter and an established for the purpose data managing center will help optimizing consumption habits and eventually ease peak load situations in the system. With respect to enabling communication various technological alternatives have been developed and some of them include communication through SMS text messaging, internet, radio as well as directly through the electricity network in the form of power line carrier (PLC). .

Under various pilots (see examples in Section 5) it has been tested and confirmed that modern home automation technologies can be successfully integrated with AMS. The result of such synergy is a possibility to efficiently program certain types of demand. Moreover, the tests prove that automation technologies not only “can” be included when scheduling demand responsiveness to peak loads, but their implementation is rather a “must” in order to achieve desired results.

With the purpose to provide the necessary communication and automation equipment for demand response activities, multiple technological vendors are currently developing (and some already delivering) technological solutions to enable demand flexibility, steering and transfer of information. Examples are different energy management systems, based on various software and hardware combinations.

As a part of the Danish project “Price-Sensitive Electricity Usage in Households”, SIEMENS came out with a simple model of how communication of price signal to the house can actually take place. Figure 4.1 presents the basic flow of the price signal. The price from Nord Pool with added transport costs and taxes has to reach the user (or her automatic managing system). This could happen through various wireless connections - mobile net (GSM, GPRS, etc.), radio or TV signals, broadband connections (ADSL, optical cables, analogue modem, etc.) or technology that uses the electricity grid itself for data transfer.

Figure 4.1 - Engineering communication to the house



Source: Price-sensitive energy use in the mass market, SIEMENS

As we can see in the figure above after the price signal has been created it can go to both the consumer and to her system for automatic control. Although it has been proved in various pilots that automatically steered response produces highest reduction values, it will be still usefull to mention some of the various message-carriers that enable communicating the price signal to the end-user. In-home displays, E-mail, SMS, MMS, Tekst-TV, websites, el-buttons are among the information-providing solutions tested in relation to demand response trials[6]. Moreover, in an environment where mobile and internet connections develop rapidly, the control or simply follow up of energy consumption through iPad or iPhone might be a reality in recent future.

4.3 Smart thermostats

Thermostats are devices which role is to operate a given system in relation to temperature level. By introducing microprocessors that open for remote control temperature adjustments throughout

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[6] A summary of some European demand response pilots and technologies used is presented in the report Demand Response: A decisive breakthrough in Europe by Capgemini, VaasaETT and Enerdata

different time periods, the functionality of these devices widens and we refer to them as smart thermostats.

Many smart thermostats operate through a home wireless network or a special “wifi” center which opens for a variety of remote control actions on the users’ side. For this reason the installation of smart thermostats constitutes a basic approach to decrease consumption in peak price hours. Additional software applications included in the thermostats’ configuration will allow for controlling all heating/cooling and water temperature related appliances via easily-comprehensible visual display programs.

Along smart meters and technologies for automation and communication, smart thermostats are a leading solution for increasing demand flexibility. As we can see in figure 3.2 a total of 81% of Norwegian end-users’ electricity consumption is temperature-related (water and space heating and cooling included). This is a huge part of usage and indicates great possibilities for smart thermostat regulation that can reduce consumption at peak hours. However, actions on such regulation should be undertaken without causing any noticeable discomfort at consumer’s premises. Thus greatest potential for thermostat based regulation that does not reflect on users’ comfort will be offered by water heaters and waterborne space heating in which case water can be heated previously to high price periods with a consequent reduction in the water temperature when these periods are present. The effects from exercising control over this kind of water-based equipment will be further investigated in Section 7.

4.4 Smart appliances

The Association of Home Appliance Manufacturers (AHAM) in the USA defines the transition to smart appliances as “a modernization of the electricity usage system of a home appliance so that it monitors, protects and automatically adjusts its operation to the needs of its owner”[7]. Smart appliances are generally connected to an energy management system and use a combination of the automation and communication technologies described in part 4.2 to optimize usage in accordance to fluctuating price signals. The key features related to smart appliances are described under the following points:

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[7] Defined in “Smart Grid White Paper” published by AHAM in December 2009

- Information on dynamic electricity prices reaches consumers and gives an incentive to adjust demand of electrical energy use.
- An option to respond to these signals and contribute to load curtailment and energy savings by either providing reminders to move usage to low-price hours, or automatically. In the second case usage is reduced on the basis of consumer‘s predefined guidelines or manual adjustments.
- Integrity of smart appliances is maintained in simultaneity with their automatic usage adjustment in response to emergency power situations. In this way system failures such as brown- or blackouts can be prevented.
- When connected through an internal building area network and/or energy management system, smart appliances open for possibilities to create an electricity usage profile specific for each consumer. According to this profile consumption might be utilized so that certain levels of comfort and savings are satisfied.
- The time of usage of smart appliance can be automatically synchronized with the generation from renewable resources (e.g. generation from solar panels or wind power generation).

The smart appliances it is most often referred to are dryers, washing machines, refrigerators, freezers. Other appliances could also provide the “smart” functions described above but the extent to which these will be integrated in the energy management system of a consumer will depend on the technological development of demand response solutions in the years to come.

5. Economic tools for demand response

As it was mentioned on several occasions so far, the trends in technological development, and specifically smart meters in combination with automation and communication technologies, will considerably enhance consumers’ awareness of efficient price signals. So far various tests have been performed in order to find the best way for increasing users’ involvement in demand management. These tests involve combinations of different innovative tariffs and pricing methods and in general their aim is to give customers a better incentive to modify consumption in compliance with the electricity market. In particular, some dynamic pricing schemes are being used for this purpose and they often rely on the following pricing methods:

- Real-time pricing (RTP) - based on hourly fluctuations in electricity prices that reflect changes in the price at the wholesale market
- Time-of-use (TOU) pricing - reflects the average costs for electricity generation and delivery throughout different periods; special unit prices for usage during separate time periods are set.
- Critical peak pricing (CPP) - a combination of the above pricing methods where a higher CPP event prices are charged under specific trigger conditions (usually when the system reliability is being threatened).

The more such types of pricing plans have been developed and implemented in demand response activities, the higher the effective integration between wholesale and end-user market and the reliability of the power system have proved to be. Some examples of relevant pilots performed are provided in the next section.

However, it should be noticed that the difference between RTP and the other two pricing methods has some important implications for retail customers' response to prices. While RTP enables electricity retailers to send to end users signals that reflect the current situation at the wholesale market, TOU and CPP account for expected peak loads and emergency situations. Thus the first pricing method is assumed to give the most efficient market solution as all movements in the wholesale prices could be followed by respective changes in consumption. TOU pricing, on the other hand, does not allow for optimal demand-side participation because higher wholesale price signals will be reflected in the customers' tariff only to a certain grade and the response to high prices that are out of the range of the predefined peak hour prices of the TOU tariff will be limited. Yet, if no large and unexpected fluctuations in prices occur, TOU pricing can be adjusted so that it well matches high prices at the spot market.

6. A look towards demand response testing pilots

The pilots described below present some of the most important issues related to demand response programs. Generally, tests that concern demand response, aim at assessing the possibilities for load reduction, the potential for economic savings and customers' satisfaction and attitude. Here I will briefly describe relevant examples of such tests. Results are presented in correspondence with the main purpose of the respective pilot and while some show economic effects in Norwegian currency, others give the effects on consumers' load profile. The difference in results also reflects the variance in demand response tools used (pricing method and technology) under the specific pilot.

6.1 "Market Based Demand Response Research Project" - Norway

This project was performed by SINTEF during the period 2005-2008 and engaged several companies for which customers the pilots were performed. The main objectives of the tests included in the project have been to explore customers' acceptance and the load curve impacts from using hourly based price signals and automatic load control schemes. The tests focused on both residential and commercial customers[8]. The overall pilot structure is shown in Figure 6.1 where each pilot from the project is presented by a separate sector and the electricity company at which premises the pilot was performed is denoted just outside the sector. The inner part of the sectors presents the type of customers that have been tested; the middle part refers to technology used while the outer one illustrates the specific price signal applied. For the purpose of my research I will further describe only the tests performed at Skagerak Nett and Malvik Everk where new technologies for metering and automation in combination with hourly spot prices were used.

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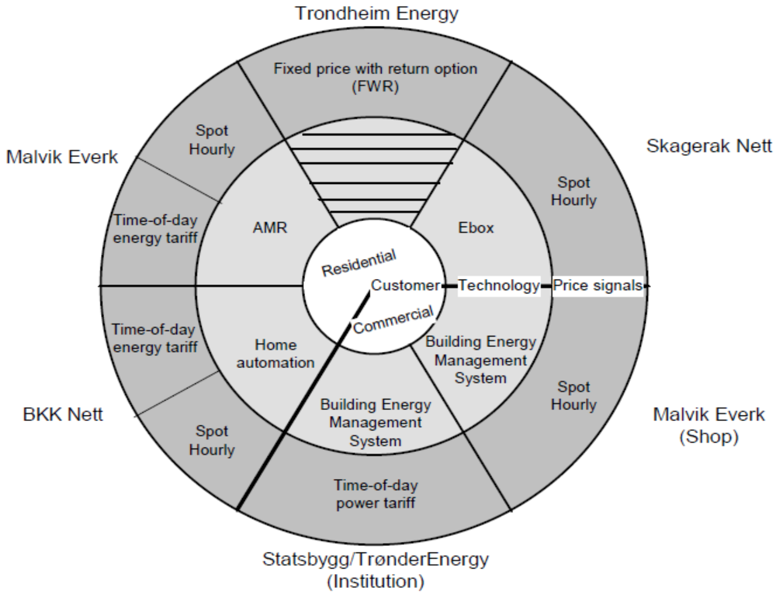
[8] Description from Market Based Demand Response Research Project Summary

Figure 6.1 – Organization of customer types, technology and price signals in pilots



Source: Market Based Demand Response Research Project Summary, SINTEF Energy Research

The test performed at Skagerak Nett aimed at residential customers (single houses) that were equipped with meters measuring hourly consumption. Each customer had an Ebox RLC Unit[9] attached to the water heater socket in the house and the device was controlled by radio signals that were separated from the advanced metering reading system installed. As a criterion for disconnection were determined the two highest-priced hours in the periods 7:00 to 11:00 and 16:00 to 20:00. An example is shown in Table 6.1 below.

Table 6.1 – Hours chosen for load control with reference to the highest spot prices (NOK/MWh)

Date \ hour	00-08	07-08	08-09	09-10	10-11	11-16	16-17	17-18	18-19	19-20	20-24
15.06.2005		237,56	244,77	245,76	245,7		232,82	230,87	228,87	228,34	

Source: Market Based Demand Response Research Project Summary, SINTEF Energy Research

The results from this test indicate significant response during morning hours while in the afternoon the response was of lower scale. Consumption was significantly decreased in hours

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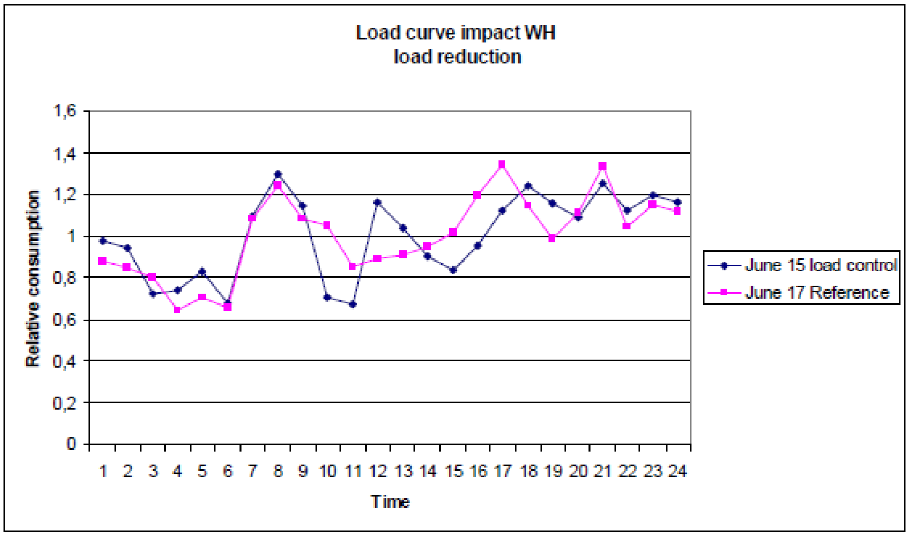
[9] The Ebox Unit in no longer produced. However similar devices have been developed recently by other manufacturers (Siemens, GE Energy and others)

8:00 to 10:00 but then a new peak was observed in hour 11:00 This trend is presented in Figure 6.2.

Figure 6.2 – Load curve impact: disconnection of water heaters. Demand response pilot at Skagerak Nett

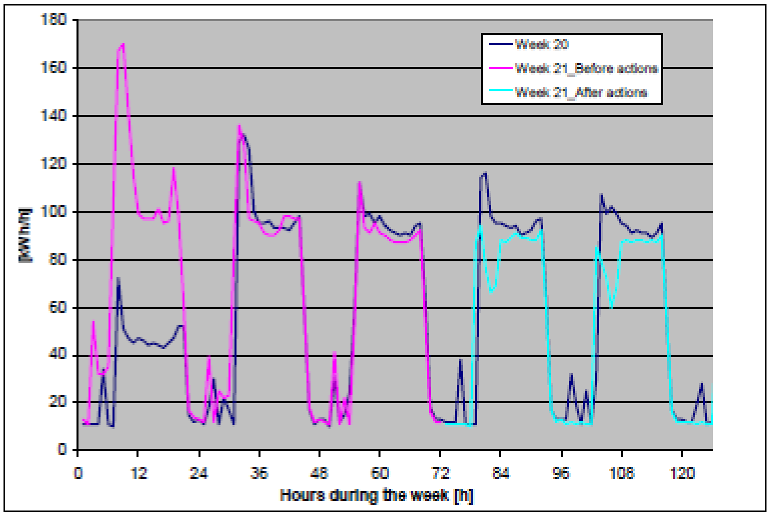


Source: Market Based Demand Response Research Project Summary, SINTEF Energy Research

A test at Malvik Everk - a Norwegian electricity distributing company in a district close to Trondheim aimed at testing the possibility of demand response facilitated by AMR and a specifically designed building energy management system (BEMS). In this pilot the customer chosen was a shop and its consumption was utilized via the BEMS that adjusted electricity usage to the varying spot prices throughout the day. A graphical representation of results can be seen in Figure 6.3. With reference to the graph it is important to know that the first day of week 20 was a holiday and the shop was closed and results only for weekdays are presented. There was no control during week 20 and the first 3 days of week 21.

As we can observe in the figure below, there is a significant decrease in high demand during morning hours after the implementation of demand responsive action (Thursday and Friday during week 21). In this specific test the BEMS ensured that heating appliances were started earlier than before and then switched off when other appliances started working.

Figure 6.3 – Electrical consumption before and after actions for demand response. Demand response pilot at Malvik Everk



Source: Market Based Demand Response Research Project Summary, SINTEF Energy Research

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In order to analyze the potential change in consumption pattern under a specific pricing and technology combination, I will use data from the other pilot performed at Malvik Elverk as a part of the project - the one that aimed at residential customers (see Section 7).

6.2 "Price Sensitive Electricity Usage in Households" - Denmark

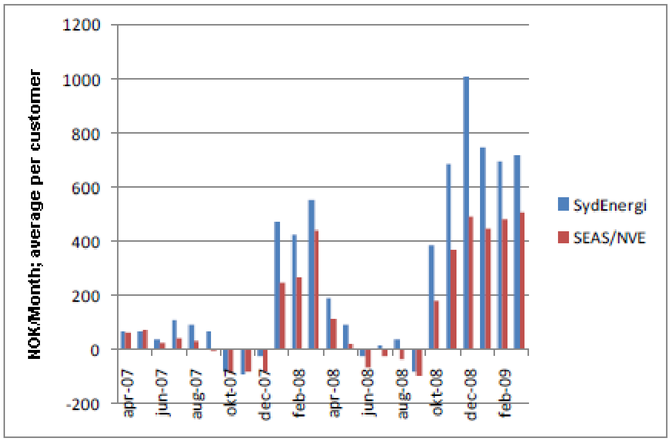
This project was conducted in cooperation of several Danish actors - DI-Energibranchen, SydEnergi, SEAS/NVE, Siemens, Danfoss and Ea Energianalyse and the practical tests were performed during the period April 2007 – March 2008. The trials aimed at managing electrical heating and included testing four separate groups of totally more than 500 residential customers:

- Group that had installed automation technology which regulated the electrical heating in correspondence with in advance defined standards related to the spot prices.
- Group that had installed a technological solution called Electronic Housekeeper which could show the price signal at any time of day. The customers were expected to regulate the heating themselves.

- Group that daily received e-mail or SMS that announced the price changes during the day and the customers were expected to steer usage on their own.
- A control group that did not participate in the tests in any way.

The results from the tests show that providing customers with spot price signals on its own does not facilitate any significant levels of demand response. Only when there is installed automation technology that can steer the consumption according to the prices, the effect becomes visible enough and can be considered as a reducible load on an aggregate level. Thus just the first of the groups above achieved the desired results. Results for the most successive group are presented:

Figure 6.4 Average monthly savings for the customers with home automation



Source: Prisfølsomt elforbrug I husholdninger. Sammenfatning af resutater af forsøg med kunder med elvarme

6.3 Automated Demand Response System Pilot – California, USA

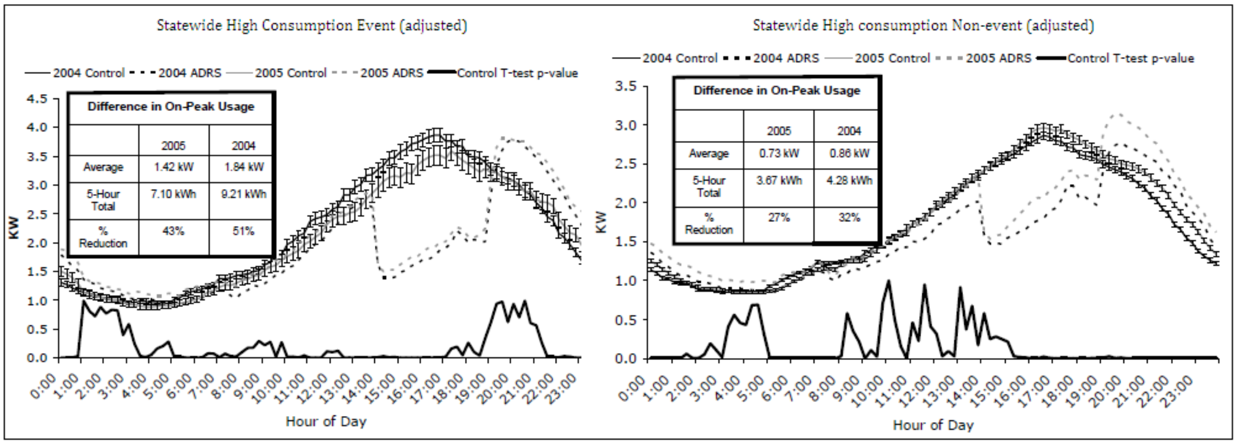
This pilot was performed during the summer months of years 2004 and 2005 by Pacific Gas & Electric (PG&E), Southern California Edison (SCE), and San Diego Gas & Electric (SDG&E) utilities and was aiming at identifying the potential for load reduction through automated demand response technology that steers the working regime of air-conditioning. At the same time the intemporary change in response and satisfaction of customers had to be evaluated and the effect of different pricing methods estimated.

The customers choosen for the pilot were owner-occupied, single-family homes and were served by specified television cable providers. The homes participating in the test were chosen regardless of their historical consumption but were screened for eligibility with respect to presence of central air conditioning. The possibilities for control over other reducible loads at their premises, such as swimming pools and spas were also investigated.

A specific feature of the Californian pilot was the use of a residential-scale, automated demand response technology for customers under a specified critical peak pricing tariff (a tariff that sets higher price during peak load events which may threathen the reliability of the grid). ADRS participants had the GoodWatts system, an Invensys Climate Controls product, installed in their homes. The GoodWatts device was an “always on” solution and provided customers with two-way communicating advanced home climate control system that included web-based programming of user preferences for control of home appliances. Climate control and pool or spa pump runtime preferences could be set via the Internet and the settings could be viewed and changed both locally and remotely during any time. Participants could also view additional information about their real-time usage as well as historical consumption.

Pilot results prove that customers with ADRS (dashed line in Figure 6.5) successfully managed to achieve load reductions compared to the control group. Reductions were observed for both 2004 and 2005 and for both event and non-event days and deviations from year to year were due to differences in temperature. A graphical representation of results is given in figure 6.5.

Figure 6.5 - Statewide high consumption event/non-event weekdays load curves for 2004-2005



Statewide High Consumption Event (adjusted)

Difference in On-Peak Usage		
	2005	2004
Average	1.42 kW	1.84 kW
5-Hour Total	7.10 kWh	9.21 kWh
% Reduction	43%	51%

Statewide High consumption Non-event (adjusted)

Difference in On-Peak Usage		
	2005	2004
Average	0.73 kW	0.86 kW
5-Hour Total	3.67 kWh	4.28 kWh
% Reduction	27%	32%

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Source: Automated Demand Response system Pilot – Final Report; Rocky Montain Institute, Colorado

Part of the load reductions attained were attributed to the pricing method used. However, technology appeared to be the main driver for load reduction in homes with high consumption level. Customers with the automated demand response technology installed achieved load reductions that were roughly twice as much compared to residential users who also participated in demand response programs but without automation technology.

7. Assessment of change in consumption

7.1 Sample

For the purpose of assessing the change in usage pattern will be used data from the pilot study performed at Malvik Everk. The test was performed as a part of the Market Based Demand Response Research Project and was carried out by SINTEF Energy Research. The data includes hourly demand for 39 residential customers in the period 1 Mai 2006 to 30 April 2007. The users in the pilot were equipped with smart meters that enabled hourly metering of consumption. 33 of the customers had a standard electrical water heater of 2-3kW while the remaining six used waterborne space heating system with an electrical boiler of 12-15kW.

The customers participating in the study were offered a TOU network tariff in combination with an hourly spot price energy contract. The periods for peak payment were hours in the morning and in the afternoon (8:00 to 10:00 and 17:00 to 19:00 during work days) and corresponded to hours with peak loads for both local DSO and the national grid. These were also the periods with highest expected spot prices. The TOU tariff consisted of firm, loss and peak payment parts which were 1500NOK/year, 0.07 NOK/ kWh and 0.63 NOK/kWh respectively. On average yearly basis the peak tariff is calculated to be 4 NOK 11øre per day and 0.7NOK per kWh consumed. While the firm part of the tariff aimed at covering at minimum the customer-specific costs related to metering, settlement, invoicing, etc., the loss component is used to cover costs of marginal loss (the loss that occurs when one extra kilowatt-hour is taken out, at a given load) in the network[10].

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[10] Norwegian Water Resources and Energy Directorate Description of electricity distribution tariffs, available at http://www.nve.no/en/Electricity-market/Transmission-Tariffs/Transmission-tariffs-to-households-/

Additionally, the customers were offered RLC as an option to reduce load in predefined hours. The remote control was performed via Power Line Carrier (PLC) system and relays connected to AMR system communication terminal. A special feature of PLC is that it combines the transmission of both power and communication signal through the same electric power cable. PLC presents a useful solution as it succeeds in integrating two separate applications of high importance in a single system.

7.2 Data

This study is based on four sets with data: consumption, price, temperature and wind. The data set for consumption consists of 8760 hourly measurements for each of the 39 sample households. Customers are divided in two pilot groups based on their consumption load source under remote control.

Table 7.1 Summary statistics for consumption for the two test groups of customers

Variable	Period	Number of observations	Mean	Standard deviation	Minimum	Maximum
Average hourly consumption - Space heating (kWh)	All hours	8760	3.15	1.68	0.4	11.42
Average hourly consumption - Water heater (kWh)	All hours	8760	2.87	1.21	0.75	7.21

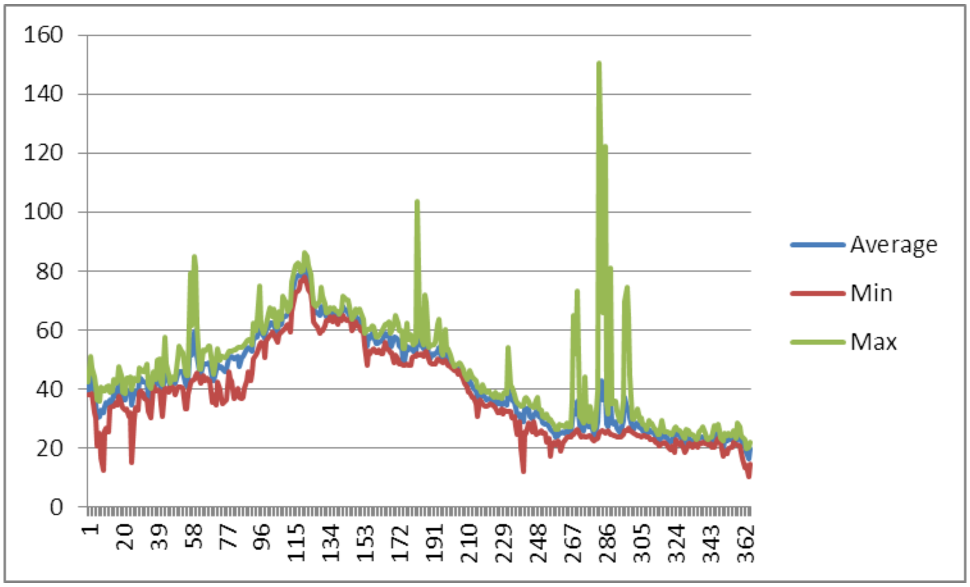
Table 7.2 Summary statistics for consumption for the two test groups of customers - Peak periods (with RLC) and off-peak periods during workdays

Variable	Period	Number of observations	Mean	Standard deviation	Minimum	Maximum
Average hourly consumption - Space heating (kWh)	Off-peak	5220	3.28	1.71	0.57	11.42
Average hourly consumption - Space heating (kWh)	Peak	1044	2.47	1.95	0.4	8.53
Average hourly consumption - Water heater (kWh)	Off-peak	5220	2.87	1.19	0.82	7.21
Average hourly consumption - Water heater (kWh)	Peak	1044	2.81	1.31	0.75	6.55

Peak hours (8-10, 17-19) and the remaining off-peak hours are related to TOU tariff with peak load payments and exercised remote load control on water heaters and space heating and are valid only for workdays. Thus the total number hours being steered throughout the whole period is 1044. A simple look at Table 7.2 reveals the basic impact of the pilot program. All values of mean, minimum and maximum hourly consumption during the off peak periods are higher than those in the peak periods for both customer groups, indicating that a reduction in load has been achieved.

Price data consists of hourly spot prices from Nord Pool for Central Norway. These are 8760 hourly prices that together with the data for the TOU network tariff charged and time series data for consumption will be used for estimating elasticity measures.

Figure 7.1 Average daily spot prices for the one-year test period (Euro/MWh)



Source of data: Nord Pool

As seen in Figure 7.1 the average daily spot prices experienced some periods of stability with the maximum difference between them in the first 56 days and last 67 days of the period being less the 26 EUR/MWh (or about 0.3NOK/kWh). The largest difference between hourly spot prices occurred on 6th of February 2007 when the minimum daily price was 125.32 EUR/MWh (or more than 1NOK/kWh) lower than the maximum price.

Table 7.3 - Summary statistics for Nord Pool spot prices for Central Norway during the test period

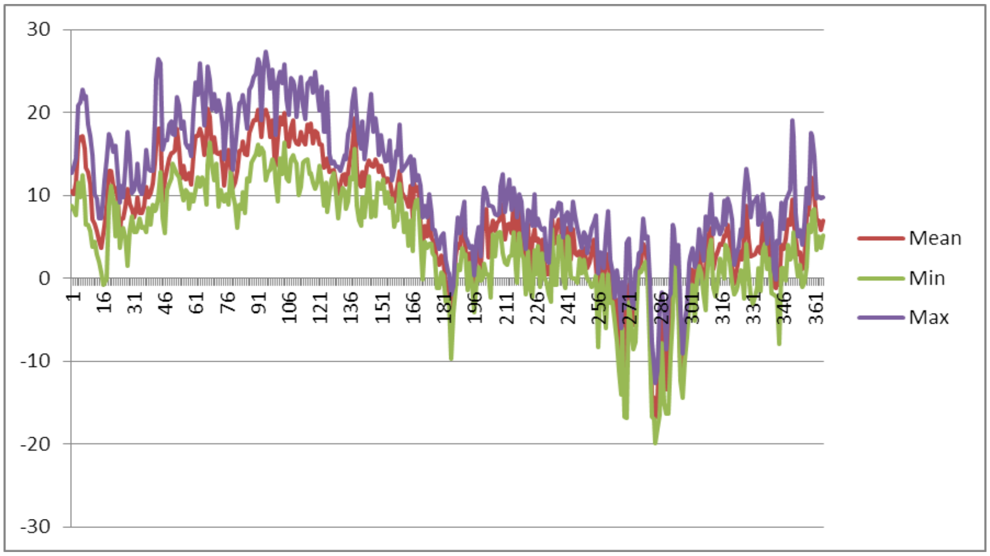
Variable	Period	Number of observations	Mean	Standard deviation	Minimum	Maximum
Price (NOK/kWh)	All hours	8760	0.338	0.126	0.083	1.202
Price (NOK/kWh)	Off-peak week hours	5220	0.341	0.127	0.095	1.202

The temperature and wind data sets are based on hourly observations from Værnes meteorological station, situated just a few kilometers east from the test area. Figure 7.2 below graphically presents the average, minimum and maximum values for the daily air temperature during the test period while table 7.3 gives summary statistics of the meteorological data.

Table 7.4 - Summary statistics for temperature and wind (hourly measurements for all days)

Variable	Number of observations	Mean	Standard deviation	Minimum	Maximum
Temperature(°C)	8709	7.4	7.6	-19.7	26.8
Wind (m/s)	8728	3.9	2.9	0	20

Figure 7.2 - Average, minimum and maximum daily temperatures from 01 May 2006 to 30 April 2007



Data source: Norwegian Meteorological institute

The variation in the meterorological variables throughout the one-year period was high with temperatures between -19 and 26 degrees celsius and wind speed varying from 0 to up to 20 m/s. The measurements represent some typical trends for the local area's weather conditions: strong wind and low temperatures in the winter months.

To ease the analysis of the data some simple changes to the datasets have been made. First, all prices have been converted to the NOK/kWh measure. Second, the temperature variable has been transformed to a heating degrees variable to avoid negative values. The heating degrees variable represents the number of degrees below 17 and has a minimum value of 1 for the values equal or above 17 degrees. And thirdly, the 32 missing observations for wind have been filled on the basis of predictions based on historical data.

7.2 Method and model

There have been conducted multiple analyses and experiments with the purpose to examine both the responsiveness to prices and the size of response related to shifting consumption from higher to lower price periods. The results vary widely reflecting the complexity of responsive behavior related to the specific program type (including communication of prices, personal characteristics of customers, level of technology, etc.). In this section I will examine the opportunities to assess substitution and price elasticity based on two different models.

7.2.1 Estimating substitution elasticity

The model I will use for estimating substitution elasticity will be based on microeconomics and the neo-classical theory of consumer behavior[11]. Consumers' utility function will be depending on three goods:

X - consumption of peak electricity
Y - consumption of off-peak electricity
Z - other consumption

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[11] Such model is used by Vaage K. (1995) with the purpose of estimating the effects of an experiment with time-differentiated prices.

E(X,Y) is defined as the aggregate electricity consumption. Then the utility function for a consumer can be expressed as:

$$U = U(X,Y,Z) = V(E(X,Y),Z) \tag{1}$$

Differentiation gives us the first-order conditions for utility maximization:

$\dfrac{\frac{\partial E(X,Y)}{\partial X}}{\frac{\partial E(X,Y)}{\partial Y}} = \dfrac{P_X}{P_Y}$ where P_X is the price in peak and P_Y is the price in off-peak hours. (2)

As it can be seen from (2), the marginal rate of substitution between peak and off-peak electricity consumption does not depend on the consumption of other goods but is determined by the price difference in the two periods. Further the Hicksian demand functions can be derived by looking at the dual optimization problem:

Minimize $P_Z Z + P_X X + P_Y Y$ subject to $U(X,Y,Z) = V(E(X,Y),Z) = U^*$ (3)

The solution of (3) will depend on U* which is a certain level of utility. Choosing E* and Z° so that Z° solves (3) gives the following optimization problem:

$$V(E^*, Z^\circ) = U^* \tag{4}$$

Now the Hicksian demand functions for X and Y can be found by solving:

Minimize $P_X X + P_Y Y$ subject to $V(E^*, Z^\circ) = U^*$

To estimate the Hicksian demand equations for X and Y, I use the approach of Vaage (1995) and specify the expenditure function in the form of a CES-function that will correspond to the function E:

$$C(P_X, P_Y, E) = \left[\alpha E^{\mu_X} P_X^{(1-\sigma)} + \beta E^{\mu_Y} P_Y^{(1-\sigma)}\right]^{(1-\sigma)^{-1}} \tag{5}$$

Applying Shepard’s lemma to (5) results in:

$$X / Y = (\alpha / \beta) E^{(\mu_X - \mu_Y)} (P_X / P_Y)^{-\sigma} \tag{6}$$

To make the function in a form suitable for estimation we take the natural logarithms:

$$\ln(X/Y) = \ln(\alpha/\beta) + (\mu_X - \mu_Y)E - \sigma \ln(P_X/P_Y) \qquad (7)$$

At this stage it is necessary to introduce into the estimation function other variables that will reflect meteorological conditions. Thus I will use temperature and wind variables to reflect shift in demand in correspondence to the weather pattern. Including two new shift parameters (T for temperature and W for wind) into the expenditure function will result in:

$$C(P_X, P_Y, E) = \left[\alpha T^{\gamma_X} W^{\delta_X} E^{\mu_X} P_X^{(1-\sigma)} + \beta T^{\gamma_Y} W^{\delta_Y} E^{\mu_Y} P_Y^{(1-\sigma)}\right]^{(1-\sigma)^{-1}} \qquad (8)$$

In logarithmic form this expenditure function can be presented as:

$$\ln(X/Y) = \ln(\alpha/\beta) + (\delta_X - \delta_Y)\ln T + (\gamma_X - \gamma_Y)\ln W + (\mu_X - \mu_Y)\ln E - \sigma \ln(P_X/P_Y) \qquad (9)$$

It is useful to briefly interpret some of the coefficients in equation (9) before they are estimated. The coefficients on E will be a measure of the influence from utility change on the peak/off-peak consumption ratio and is identifiable for the expenditure elasticity (Vaage 1995). Thus if $(\mu_X - \mu_Y)$ equals zero the peak and off-peak consumption will change proportionally to a change in E while a positive coefficient estimate will account for a peak period that is more expenditure elastic than the off-peak one. The estimate on σ will be measuring the size of change in the peak/off-peak consumption ratio that will result from change in prices in accordance with the applied pricing method. A deeper discussion on the significance and signs of the coefficients will follow the results from estimating (9) in the form of a regression model.

Table 7.5 - Results for customers with space heating

Variables	Estimate	St.Error	t-value	p-value
Ln Heating degrees	.0073029	.0086024	0.85	0.397
Ln Wind	.0131319	.0069094	1.90	0.058
Ln Total consumption	-.0519385	.0222542	-2.33	0.020
Ln Price ratio	.0106071	.0117035	0.91	0.366
Constant	.2900924	.077554	3.74	0.000
			Number of obs. =	261
			F(4, 256)	3.5
			Prob > F	0.0084
			R-squared	0.0518
			Adj R-squared	0.0370

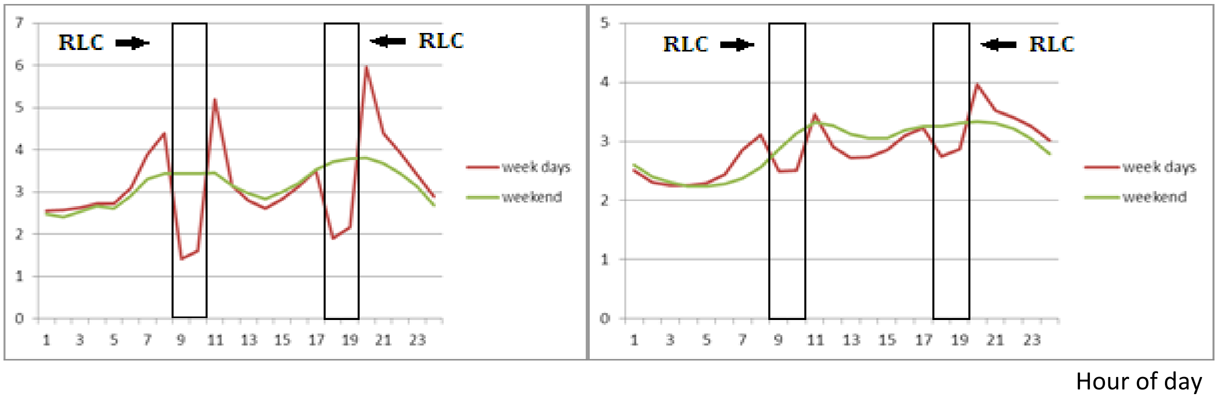
Table 7.6 - Results for customers with water heaters

Variables	Estimate	St.Error	t-value	p-value
Ln Heating degrees	.0106288	.0029795	3.57	0.000
Ln Wind	.0039394	.0025518	1.54	0.124
Ln Total consumption	-.0045759	.007698	-0.59	0.553
Ln Price ratio	.0009261	.0044858	0.21	0.837
Constant	.1723808	.0259798	6.64	0.000
			Number of obs. =	261
			F(4, 256)	15.75
			Prob > F	0.0000
			R-squared	0.1975
			Adj R-squared	0.1850

The above results show non-significant coefficients at the 5% level for all the variables except for heating degrees in the test for water heater customers (p-value 0.000) and for total consumption in the case of possessing space heating system (p-value 0.020). This outcome should not be surprising when the peculiarities of the pilot are taken into account. Most important - the test is focusing on experiencing RLC in combination with TOU tariff. This fact brings about the natural consequence that the peak to off-peak usage ratio is not significantly determined by the difference between peak and off-peak price. Referring to Figure 7.3 below, a sharp drop in usage during peak-price hours with RLC can be observed, with a peak usage taking place in the neighboring hours.

Figure 7.3 - Load profile for the two groups of customers (KWh/hour):

a) Households with waterborne space heating b) Households with electrical water heater



However, the sharp increase in usage in the periods just before and after RLC was exercised is not associated with a sharp momentary difference in the peak to off-peak prices. Thus it is natural to have insignificant coefficients on the price ratio coefficient. In addition, the fact that customers with water heaters have insignificant coefficient for total consumption indicates that it will be hard for them to find a substitute for the existing heating technology in use to help them be more expenditure elastic with respect to peak and off-peak periods.

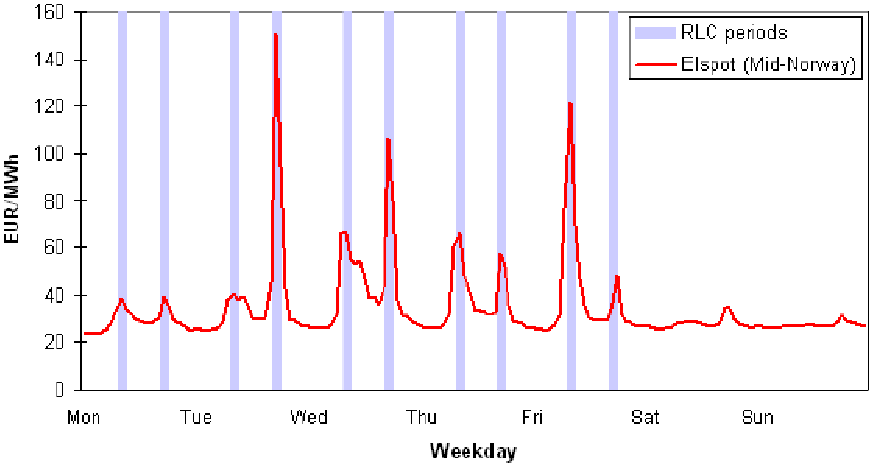
The negative coefficient on total consumption for the pilot group with space heating accounts for a more expenditure-elastic off-peak usage when compared to the peak one. The higher level of usage for those customers as well as the larger choice of existing space heating alternatives could be a reasonable explanation to that. In this case a high electricity bill will undoubtedly make that group more concerned about usage pattern. The significance of the heating degrees variable for the group with water heaters and the positive coefficient of 0.01 present the expected increase in consumption in response to lower temperatures.

As a general conclusion from the attempt to estimate the substitutability between peak and off-peak hours in response to peak and off-peak prices it can be pointed that the effects cannot be captured by a statistically significant trend. The main reason for that is the existence of RLC besides the TOU tariff - a fact that makes the actual peak-hour reductions much larger than they would have otherwise been if based only on price response. And although the project results[12] state that the response in this pilot has actually proved higher response level as compared to tests when only RLC was active, the additional price-related reductions are not sufficient to indicate a statistically significant measure of substitution elasticity.

7.2.2 Estimating price elasticity

As it was explained under the sample description and when analyzing substitution elasticity the pilot customers were subject to RLC during the predefined peak-price hours (Figure 7.3). This special feature of the test will bring about some model peculiarities that will affect the estimates for price elasticity. What we could expect to see is a high level of price response which in this case will not only reflect consumers' behavior but will be, to a great extent, artificially steered. Thus the model developed in this section will rather focus on assessing a measure for price elasticity-equivalent response.

Figure 7.4 - Spot Prices from Nord Pool for Central Norway and hours with RLC during the period 5-11 February 2007



Source: Market Based Demand Response Research Project Summary, SINTEF Energy Research

To estimate the equivalent price elasticity response I will apply an econometric model that defines electricity consumption as dependent on electricity price, temperature, wind. The hourly values for all the variables will be used with the price set to 0.75NOK/kWh in the peak hours (the

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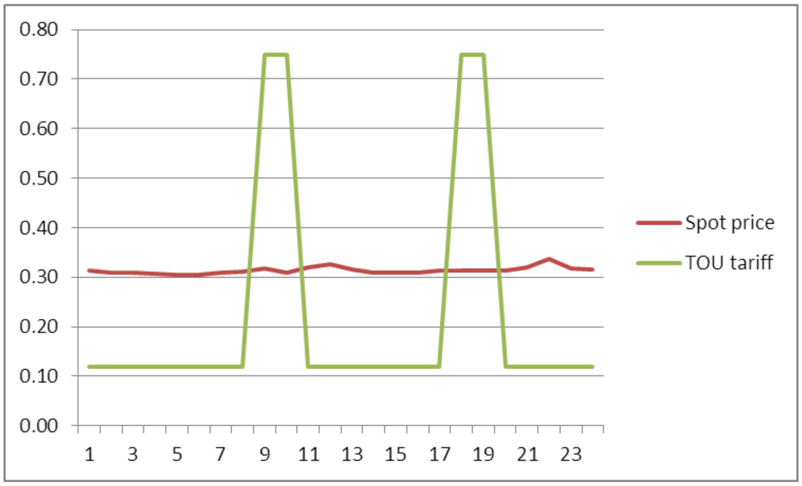
[12] Market Based Demand Response Research Project Summary, SINTEF Energy Research, p.20

sum of peak payment and loss part plus an additive of 0.05 NOK per kWh to cover the firm part of the tariff - 1500NOK/year). Figure 7.5 presents prices charged for the first day of the test period.

Figure 7.5 - Hourly spot prices and the time of use network tariff for 1st May 2006 , NOK/kWh



The estimation of demand for electricity during the test period will be restticted to the days of the week when TOU pricing and RLC are performed - i.e. Monday to Friday. There are alltogether 6264 hourly observations out of which 1044 are subject to the specific pricing and load control methods. The general econometric model defined is:

$$y_t = \alpha_1 + \alpha_2 H_t + \alpha_3 W_t + \alpha_4 P_t + \varepsilon_t \qquad (10)$$

Where:

y_t - Electricity demanded at hour t

H_t - Heating degrees at hour t

W_t - Wind speed at hour t

P_t - Price at hour t

ε_t - Error term, by assumption independently distributed over t and with constant variance

Table 7.7 - Results from estimating electricity demand for customers with space heating

Variables	Estimate	St.Error	t-value	p-value
Heating degrees	0.12589	0.0024485	51.41	0.000
Wind	0.0419158	0.0054438	7.7	0.000
Price	-2.96345	0.0903605	-32.8	0.000
Constant	2.91125	0.0581308	50.08	0.000
			Number of obs. =	6264.000
			F(3, 6260)	1877.000
			Prob > F	0.000
			R-squared	0.474
			Adj R-squared	0.473

Table 7.8 - Results from estimating electricity demand for customers with water heaters

Variables	Estimate	St.Error	t-value	p-value
Heating degrees	0.133388	0.0014925	89.37	0.000
Wind	0.046435	0.0033182	13.99	0.000
Price	-0.55523	0.0550778	-10.08	0.000
Constant	1.549743	0.0354327	43.74	0.000
			Number of obs =	6264
			F(3, 6260)	3424.38
			Prob > F	0.000
			R-squared	0.6214
			Adj R-squared	0.6212

Looking at the tables above it can be seen that all variables are statistically highly significant (p-values of 0.000) and the signs of the coefficients are the normally expected ones. An increase in the heating degrees related to decrease in tempearture will be associated with higher consumption (positive coefficient estimates of around 0.13 for both customer groups). The same will be true for the wind variable according to the coefficient estimates of which a one meter per second increase in speed will result into increase in consumption with 0.042 and 0.046 kWh for the customers with space heating and water heaters respectively. The coefficient estimates of highest interest - the ones for price - also possess the expected signs: negative signs indicating that an increase in price will be resulting in a decrease in consumption. A considerable difference between the price-response for the two separate customer groups can be observed with the one with space heating proving to be much more price elastic than the water-heater-possessing group. Thus a price increase by 1NOK/kWh will lead to on average 2.96 kWh/h decrease in consumption for customers with space heating and 0.56 kWh/h decrease for those with water heaters. As it was explained earlier these estimates account for no more than the price elasticity-equivalent rsponse and should be interpreted under the condition that participating households where exposed to RLC. In comparison the pure price-responsive effect for customers equipped with water-heaters from a similar pilot[13] was estimated to be 0.077kWh/h (Ericson, 2006). Thus a great amount of the response initiated should be attributed solely to RLC.

Price elasticities can be calculated based on logarithmic transformation of the econometric model. For this purpose I use Stata to estimate the model:

$$\ln y_t = \alpha_1 + \alpha_2 \ln H_t + \alpha_3 \ln W_t + \alpha_4 \ln P_t + \varepsilon_t \qquad (11)$$

Running the regression on (11) gives a coefficient estimate on $\ln P_t$ of -0.47 and -0.10 for the customers with waterborne space heating and water-heaters respoectively (all estimates are highly signifficant). These results present the price elasticity equvalent measures and indicate a significant increase in price responsiveness (although to large extent artificially generated) when compared to other studies that analyse price elasticity of electricity demand. As an example Ericson (2006) analyzed the price response of Norwegian households and concluded that price elasticity varies in the interval (-0.03, -0.02). He also estimated price elasticity value of -0.26 for customers on TOU tariff in combination with spot price contract. Stokke et al(2009) analyzed the effect of demand charge electricity tariff on the residential sector and ended up with price elasticity of approximately -0.02 (result similar to that of Ericson). This is a confirmation that RLC can to a great extent increase the opportunities for price-response resmbling behavior and induce all the benefits decribed in sections 2.3 and 2.4.

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[13] The Norwegian project “End-User Flexibility by Efficient Use of Information and Communication Technology” was run during the period 2001-2004 and encompassed developing and testing time-differentiated network and power tariffs and direct load control of water heaters.

The outcome of the above analysis is not corrected for potential endogeneity bias that can result from price being correlated with the error term. This is a natural consequence of an existing simultaneity: electricity consumption and prices are to a large extent jointly determined and higher level of electricity consumption drives the prices up. However, in this specific case only a very small sample group of customers (39) have been tested and it cannot be expected that their electricity usage will affect the price in the whole area of Central Norway. The issue on endogeneity could be a good starting point for further analysis under the condition that enough data for building an estimation model based on proper instrumental variables is available and that the sample of consumers is large enough to affect price. A good instrument for price should not be correlated with the error term but should be correlated with the price variable. In the particular test with peak and off-peak prices and RLC, the task to find proper instruments on price will be definitely a hard one. I will leave this problem open for future discussion under a separate topic investigation.

7.2.3 Reduction or shift in consumption?

Referring to Figure 7.3 it can be seen that customers with space heating achieve higher reductions (Figure 7.3 - a) compared to the ones with water heaters (Figure 7.3 - b). This is a natural consequence from the magnitude of the respective reducible load (2-3 kW for the water heater and 12-15 kW for the space heating system's electrical boiler). The results from the pilot as presented in the project summary report (Table 7.9) give the approximate size of load reductions achieved during the peak price hours.

Table 7.9 - Average demand response

Type of customers/Peak Hours	**08:00-10:00**	**17:00-19:00**
Customers with electrical waterborne space heating system	~2.5 - 3 kWh/h	~1.3 kWh/h
Customers with electrical water heater	~1 kWh/h	~0.5 kWh/h

Source: Market Based Demand Response Research Project Summary, SINTEF Energy Research

However these values do not indicate whether consumption is as a whole reduced or only moved to other hours of the day. In this section I will try to find out more on that issue.

Looking at figure 1.1 some general trends of weekly consumption can be observed. Peak loads during weekends occur at some later hour and the overall level of electricity is a bit higher in those days as compared to weekdays' consumption. I will estimate the daily consumption profile for weekdays based on the correlation between hourly usage during weekdays and weekends as shown in figure 1.1. Results for customers with water heaters are presented graphically.

Figure 7.6 - Average hourly usage - daily profiles for customers with water heaters during the test period, kWh/h

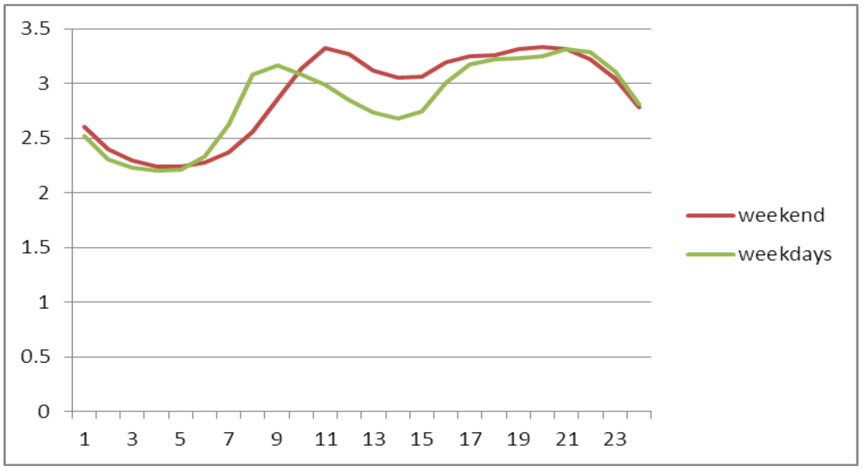
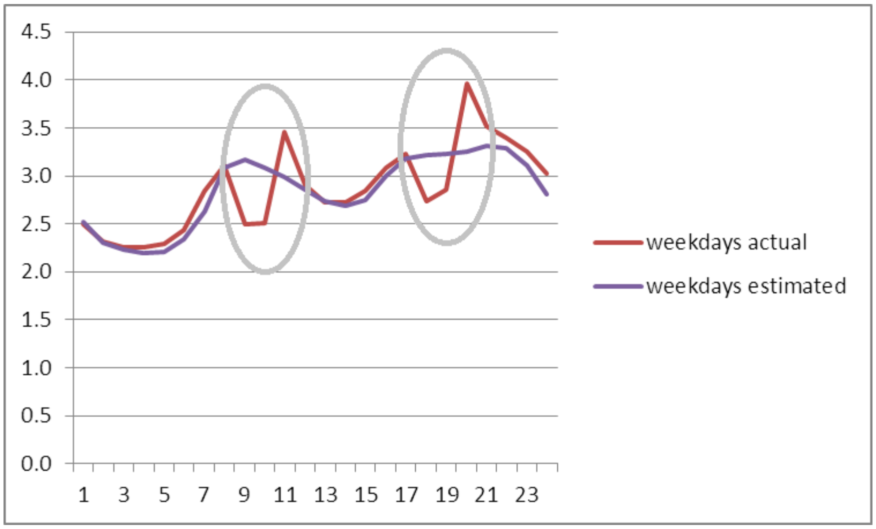


Figure 7.7 - Actual (with TOU/RLC) and estimated (without TOU/RLC)daily load profile for customers with water heaters, kWh/h



The estimated values point that on average daily consumption has increased by 0.59 kWh as a result from the test performed. Thus the peak load reductions in peak hours caused by this particular combination of TOU tariff and RLC does not account for an overall decrease in usage. On the contrary - consumption is even slightly increasing indicating that the usage in peak load neighboring hours is much higher than the usual for those hours. Results are similar for the customers with waterborne space heating. For this group the daily usage has increased on average by 0.86 kWh. A credible explanation for the observed effect of increase might be the higher electricity consumption associated with a temporary off-mode for the heating appliances under control and the consequent loss of energy. The turning off is followed by a certain heat recovery which then requires more energy. As a result new peaks can be observed with consumption under the new peak periods being above the initial ones.

8. Discussion and conclusions

The idea of demand response rests on two basic goals. One is to achieve reduction of load during peak hours and a second is to provoke price-responsive behavior in relation to market signals. Ensuring for these two will increase security of supply by strengthening the ability of the power system to cope with operational problems and will contribute to an overall decrease in price volatility. This thesis analyzes the effect of a demand response program that involves TOU pricing and RLC and sets the analysis in the general concept of efficiency in the electricity market and all the benefits associated with it. The main focus has been to estimate the influence that automatic steering of waterborne space heating and electrical water heaters in combination with a tariff compiled of peak, off-peak and spot prices will have on households' electricity usage. For this purpose I have estimated substitution elasticity and a price-elasticity equivalent measure and have tried to compare the extent to which electricity consumption has been reduced and moved to other periods throughout the day.

The estimation of substitution elasticity does not provide any statistically significant proof of shift from peak to off-peak usage as a response to prices charged. As it has been explained in Section 7.2.1 the results indicate that load reduction should be attributed specifically to RLC and not to price changes as prices and usage do not follow a particular correlation pattern during the hours neighboring the predefined peak periods. Price elasticity's estimates prove to be highly significant and show that load during hours of RLC has been reduced simultaneously with the customers being charged peak prices. The resulting elasticities equal to -0.47 and -0.10 account for a much higher extent of price-response equivalent behavior as compared to previous studies that analyzed price elasticities. Thus the option that advanced automation technologies give in order to efficiently steer consumption, can contribute to a revolutionary change in the way market actors think of electricity usage.

Moving usage load away from the peak hours will be beneficial for the electricity distributors if on a larger scale. The benefits will result from decreased necessity for investments in distribution lines and components as well as from reduced losses. It has been proved under multiple cost-benefit analyses that the unit costs for installation and control of the technological solutions significantly decrease when they are being widely introduced. Furthermore the inquiries conducted in relation to the testes in Norway and Denmark indicate that consumers are both willing and interested in changing their electricity usage behavior. The most important argument for test participants remains to be the economic incentives, in particular reducing costs, but a certain value is also attributed to environment considerations.

However, the actual economic benefits for customers are hard to quantify, especially in a system like the Norwegian one where prices seldom experience high fluctuations. With a higher level of response and better integration between the end-user and the wholesale market, prices are expected to additionally even out. Thus the profit from increased flexibility of electricity demand should not be referred solely to the increased economic savings[14] for the separate user but to the benefit for the electricity system as a whole (increased reliability, reduced need for new generation capacities and transmission lines, etc.) and to the environmental benefits.

The analysis hereafter can be expanded to correct for possible weaknesses. One such weakness will be the existence of endogeneity bias that results from price and consumption being

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[14] In the described pilot from Denmark customers with automation technology to control their space heating installed saved on average over 3000NOK yearly. In contrast a Norwegian household with an average consumption of 15000kWh/year can be expected to safe around 50NOK yearly if washing, drying and dishwashing machines are running during off-peak periods (Gjessing S., Teknisk Ukeblad). Thus the actual level of savings will be highly dependent on the specific demand response program and the technology and appliances involved.

simultaneously determined. However, this would be only relevant if the sample group under investigation is large enough to influence the price. The corrections may be done through the inclusion of instrumental variables for price in the model, given that sufficient data sources are available. Another potential improvement could be associated with discussion on other pricing methods and technologies for initiating demand response. In addition, the specter of investigation can be widened by developing possible market structures for efficient distribution of benefits from demand responsive actions. A good research question might be focusing on how the benefits resulting from reduction of grid losses, reduced need to invest in grid capacity and improved operational security will be distributed among market participants so that high motivation for end users to participate in demand response activities is maintained.

Currently many utilities around the world are testing and installing systems for automated electricity control that will enable the reduction of load under extreme conditions and multiple pilots exploring pricing methods have been conducted. In this respect Norway is not lagging behind with research in the demand response field having taken place for more than 10 years. The investigated pilot performed at Malvik Everk provides some important clues on the outcome from executing remote load control. While considerable reductions in load during peak hours can be achieved, the actual amount of electricity consumed can be slightly higher due to the increase in usage in the period subsequent to the peak one. Additionally, newly occurring peak periods will present a challenging problem for the grid if RLC is not performed at the time and scale most suitable and in compliance with good predictions on the size of consumption increase to follow. Thus RLC should be planned with caution to ensure that the desired demand response action does not end up as a simple shift in system peak load from one period to another, in the worst case accompanied by an overall increase in consumption.

Results from demand response based pilots such as the one at Malvik Everk provide some important insights on what the opportunities for demand curtailment can be and on how load can be rescheduled. As we have seen estimation results indicate a big potential for RLC to contribute for reduction of consumption during hours corresponding with high-price periods. However, the true success of demand response programs will depend mainly on the introduction of adequate technological solutions, correct electricity pricing methods and a sound knowledge of the desired effects and their consequences.

9. Prospects for future development

Information technologies being developed in order to enable the real-time communication between electricity providers and consumers and to facilitate the management of household devices present a part of a concept increasingly discussed in recent years - the “Smart Grid”. Smart Grid technologies (smart meters, communication platforms, management systems, home displays, distributed generation and storage, etc.) can increase customers’ incentives for a 24-hours/daily load control by allowing for an easily accessible observation of prices and consumption. As a result price elasticity of demand will increase and contribute to efficiency improvements in the electricity market.

Yet, the main benefits from extracting market efficiencies can be related to the immediate communication of a price signal from the wholesale market to the customers and the associated real-time pricing method. Allcott (2010) analyzes the first program in the USA to test the effect from charging residential customers with hourly real-time prices. His estimates show that households have statistically significant elasticities of about -0.1 and a total effect of reduction in electricity consumption is achieved for the households willing to participate in the program. And although results account for an increase in consumer surplus per year, this increase constitutes such a small percentage of users’ total spending on electricity that the gross cost for establishing the necessary metering and communication technologies cannot be outweighed and the main arguments for building the smart grid should be associated with the improvement in electricity market efficiency.

Knowing that RTP-based demand response program should provide the most efficient market solution, testing such program in Norway can be good starting point for future research. Despite the fact that prices in the Norwegian hydropower-based electricity system seldom experience big fluctuations, the periods with extreme prices and operational problems give a good reason for such investigation. Results from this type of pilot will differ considerably from the ones examined in the thesis so far where TOU pricing was the basic motivating factor and will show whether market efficiency can in reality be achieved through communicating a real-time price signal.

In addition there are answers to most important questions to be found if smart grids with their key instrument - demand response - are to be established in the country. One aspect to be questioned will be the behavioral response of Norwegian households - to what extent users will be willing to consume in accordance with price signals and what factors will give them the strongest incentive? In this respect their attitude towards both environmental benefits and economic savings can be addressed. A next issue of importance will be the identification of a response level at which the investment in technologies will be recovered. For this purpose costs and benefits related to the multiple sides of the demand response program should be compared. Further, if as a part of the program some household appliances are subject to RLC: What amount of load could be discharged without the customer noticing any inconvenience? And how the effect of increased consumption after disconnections can be mitigated?

There is much work to be done if the above and more related questions are to be answered. However, the vision of an energy world, where “Smart Grid” infrastructure centered around a responsive electricity consumer resigns, is gaining worldwide popularity. It seems that the optimal way to change the current power system is not yet found, but a change is undoubtedly coming and it will be a sophisticated, profound and revolutionary one.

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