CHALMERS

Demand Side Management Potential in Swedish Households

A case study of dishwasher, laundry and water heating loads

Master's Thesis within the Sustainable Energy Systems Master Programme

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CHALMERS UNIVERSITY OF TECHNOLOGY
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MASTER'S THESIS

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ABSTRACT

With intermittent renewable power being integrated in the power system, which is targeted to increase in the future as countries attain their renewable energy goals, there has been increased concern over solving the problem of intermittency. Demand Side Management (DSM) is an energy management concept which targets the demand side of the energy system and has gained lot of attention in recent times because of its potential to solve the issue of intermittency. Load shifting is one of the DSM measures which intends at shifting the demand towards more favourable time periods. Electricity consumption in Swedish households holds a significant share of Sweden's total electricity consumption (around 29%). The possibility of getting charged for consumed electricity on hourly cost basis in Sweden has also opened an opportunity for electricity consumers to reduce their electricity costs by managing their loads. This thesis work investigates the potential for DSM in the form of load shifting common residential electrical loads in Swedish households. The loads examined are dishwasher, laundry and water heater loads. The possible effect on the load curve at a national level is also analysed. Further analysis has been made to estimate possible monetary savings that can be attained by consumers through load shifting.

An optimization model built on a GAMS platform is used to calculate a shifting of load in order to minimize yearly cost of consuming electricity. The model is based on linear and mixed integer programming which gives least-cost load curve as an output. The Swedish households are divided into various archetypes, and for each of these a monetary saving potential is calculated. The scaling up of the results from the model is done based on statistical data available for Sweden to calculate the load shifting potential on the national level. The results indicate a significant load shift potential with reduction in peak hours reaching 6% of the peak load. However, savings in monetary terms for individual households is quite modest (~100 SEK) pointing towards a low motivation for consumers to manage their loads. The results also show that the water heating load forms a large part of the load which can be shifted and this load shift is highly seasonal. Thus the overall potential depends upon level of hourly price fluctuation and the season.

Key words: Demand Side Management, peak load reduction, renewable energy, residential households.

Contents

Preface

In this study, the potential to shift common electric loads, i.e., dishwashing, laundry and water heating, in Swedish households has been investigated along with its impact on the electric load curve of the country. For the analysis purpose, an existing load shift model has been modified to handle the investigated loads. The project has been carried out at the Division of Energy Technology, Department of Energy and Environment, Chalmers University of Technology in Sweden.

I would like to start with acknowledging my supervisor Emil Nyholm for his patient guidance throughout the thesis work. Moreover, I would like to thank my examiner Mikael Odenberger who first of all made this thesis possible and has also given me much support. I sincerely thank Erika Mata Las Heras for her valuable inputs and help during the thesis work. Special thanks to Ulrika Claeson Colpier for helping me out in the report writing.

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Sanket Puranik

1 INTRODUCTION

In Sweden, the electricity use in households accounts for 29% of the total electricity use in the country. Within the household sector, space heating is the dominating use for electricity and contributes to about 60% of the total residential electricity use (Zimmermann, 2009). The second largest use is for water heating, with 20% of the total load. Electricity for appliances, lighting and cooking accounts for the remaining 20%. Electricity use in households depends on two factors: how energy efficient the energy-consuming equipment/appliances are; and how the household behaves. Energy efficiency potential in the residential sector has been explored (both for a EU and a Swedish level, see for instance Balaras et al. 2007, and Mata et al. 2013) and various energy efficiency standards have also been put into place, e.g. energy efficiency labels, and standards for appliances and equipment have been introduced. However, the other factor related to behaviour, i.e. the consumption pattern of the household needs further research. Electricity consumed during high renewable electricity penetration in a system results in less emissions compared to a time when conventional fossil based electricity is the primary producer. Moreover, renewable power, such as wind and solar, is intermittent and to use it efficiently one possibility would be for the load to adapt accordingly, if options such as storage does not exist.

Demand side management (DSM) is an approach which can be applied to govern the consumption in time, in order to adapt demand to supply. There have been studies on DSM which basically focus on peak smoothening, load shedding or efficient use of energy by reducing the energy consumption (see for instance Mata et al. 2009; Torriti 2012a; Torriti 2012b). The installation of smart meters in Sweden has allowed consumers the possibility to receive price signals on hourly basis. This dynamic pricing can be used by consumers to their advantage by reducing their monthly electricity costs. But, as Faruqui et al. (2009) point out in their study, the benefits of dynamic pricing can only be reaped successfully when consumers take advantage of it. Therefore, the consumers need to be informed that by managing their demand they can lower their electricity costs. Managing the electricity consumption could also contribute effectively towards improving the electricity system's stability, and reliability. This thesis aims at exploring the potential effect of load shifting by managing loads in Swedish households on the electricity system using hourly price signals as driver.

1.1 Previous studies

Several studies focussing on the application of DSM in buildings have been done. Finn et al. (2012) shows that a demand shift of dishwasher loads can be successfully used to integrate wind energy into the system. This study uses a bottom-up approach. Otherwise most the literatures available, for example Albadi and El-Saadany (2008), Papagiannis et al. (2008), Gupta (2012), Atzeni et al. (2013), have a top-down approach to analyse the effectiveness of DSM. This has the drawback of not considering how different users will react to DSM strategies. Thus, there is a need for using bottom-up approach in order to understand possible impact of DSM strategy. When it comes to analysis of DSM in buildings, most of the studies reviewed regard commercial buildings and focus on shifting cooling demands. For example, the studies by Klaassen et al. (2002) and Xu et al. (2004) show that by using a building's thermal mass and a simple pre-cooling strategy, cooling loads in commercial buildings can be shifted in time. For shifting heating loads, previous works mainly rely on thermal energy storage devices (see for instance Daryanian and Bohn 1993; Arteconi et al. 2012; Arteconi et al. 2013). All of the studies reviewed here in general show how much load that can be shifted, how much peak load that can be reduced and how high monetary savings that can be achieved; however, they do not show any effect on the load curve changes at the system level.

One of the most effective ways to make DSM successful is to implement Real Time Pricing (RTP) for the consumers (Borenstein and Holland 2003; Borenstein 2005). RTP here refers to the retail prices of electricity that changes frequently (on hourly basis for the Nordic market) in order to reflect the actual cost of generation for a particular time period. The electricity prices in Nordic market are available in advance in the day-ahead market. The RTP thus sends "real signals" to the consumers about the actual cost of generation offering them incentive to shift their loads to a time period when prices are lower. Some of the studies done using economic models, such as Aubin et al. (1995), Borenstein (2005), have shown that influencing demand using variable prices (like in RTP) increases the market efficiency as well as overall social welfare for all the consumers participating in the market. However using economic models, these studies do not take into consideration the technical aspects of the load shift. This present thesis has a bottom-up approach, and thus takes into consideration the technical aspects to find out the potential available for load shifting.

Additional work in this area (see for instance Klassen et al. 2002; Xu et al. 2004; Atzeni et al. 2012; Arteconi et al. 2013) focus on a single house level and on a time scale of a day or a couple of weeks. Studies have also shown that the loads in question can be controlled computationally (Ning and Chassin 2004; Lu and Katipamula 2005; Ning and Nguyen 2006; Olderwurtel et al. 2010). The electricity demand varies significantly with the seasons. Therefore, it is important to investigate the impact of DSM on the electricity system's load curve depending upon the season, especially when the electricity consumer start shifting their load in similar fashion to achieve cost savings. Thus a system perspective is needed to understand the effect of such load shifting. There has been no particular study done for Sweden that uses a bottom up approach to investigate the DSM potential of load shifting in Swedish households.

1.2 Aim and Scope

The aim of this Master thesis is to assess the potential to shift electrical loads in Swedish households, i.e. how much of the residential load is possible to shift, and whether there is any economic incentive for households in doing so. With installation of smart meters in homes and thereby the possibility to receive electricity bills on hourly consumption basis, it has become an interesting topic of research to assess how this will result in efficient managing of electricity.

The driving force behind shifting load is the economic gains in terms of reduced electricity costs due to shifting load to a low cost period. The loads investigated in this thesis are limited to loads for dishwashing, laundry (both washing and drying loads), and water heating.

The following research questions are investigated:

a. *Assuming rational consumer behaviour response to real time pricing: What is the technical potential of shifting electricity loads over time from dishwashing, laundry (both washing and drying), and water heating?*
b. *How would such a load shift affect the current load curve on a system level?*
c. *Is there any economic incentive for individual household to adopt DSM strategies if real time pricing is applied?*

Scope and limitations

- The work is based on price fluctuations presently observed in the system, i.e., a statistic price curve from 2012, whereas possible changes in price fluctuations, stemming from new configurations of future electricity generation systems, is not taken into account.
- The investigation is limited to analysis of the electricity system and will not analyse the effect on the energy system as a whole.
- Only the price differences decide the shift and no other constraint like transmission or distribution limitations are considered.
- The thesis will focus on single family dwellings except when analysing the dishwashing load where multifamily dwellings also are considered.

2 Background and Theory

2.1 Electricity consumption in Swedish households

Total electricity consumed in Sweden during 2011 was 125 TWh (Lundgren 2013). The main electricity consuming sectors are industries with a 43% share, households (generally also referred as residential buildings) with a 29% share and the commercial/public sector with a 14% share of the total electricity consumption.

The Swedish households can be broadly divided into two categories, namely single family dwellings (SFD) and multi-family dwellings (MFD). SFDs are residential buildings which do not share any inner walls with other dwellings. SFDs can be free standing or can have attachment to a neighbouring building via outer walls. Opposite of this are MFDs where multiple living units or dwellings are contained inside a single building or several buildings within a complex. Apart from constructional/architectural difference there is typically a difference in how these two types of dwellings are heated (both space and water heating). Most of SFDs have their own individual heating systems whereas most of the heating in, MFDs (92%) are served by a district heating system (Nilsson 2012a).

Figure 1 shows the division of electricity consumption in the Swedish households. Heating (both space and water heating) alone accounts to 50% of total electricity consumption in SFDs which corresponds to around 12% of total annual electricity consumption in Sweden. Figure 1 suggests that most of the electricity is consumed in SFDs alone as compared to MFDs and therefore the implementation of DSM within this building type could have highest impact on the electricity system.

Electricity is the major source for heating in SFDs (Nilsson 2012b). The average yearly electricity consumption is summarised in Table 1 below. The values here are taken from the report of the “End-use metering campaign in 400 households” conducted by the Swedish Energy Agency (Zimmermann 2009). This report is in this thesis hereafter referred to as the SEA campaign.

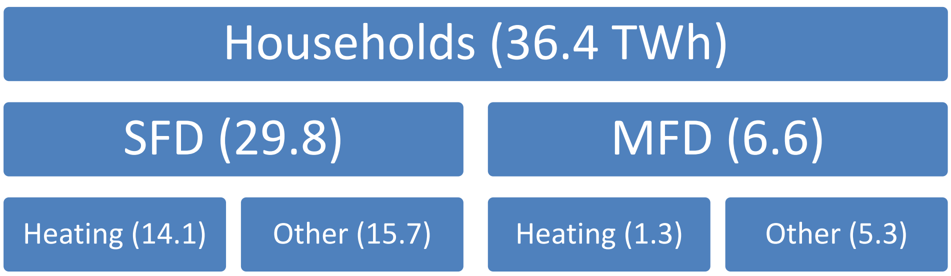


Figure 1: Electricity consumption (in TWh) in the two categories of Swedish households, divided upon main electricity use in the year 2011. Source: (Nilsson 2012a, Nilsson 2012b, and Lundgren 2013).

Table 1: Average electricity consumption in SFDs (single family dwelling) divided into different heating types and upon occupant category living in the households. Source: (Zimmermann 2009).

Household Type	**House**, *with direct electric heating(kWh/yr)*	**House**, *without direct electric heating(kWh/yr)*	**House**, *specific consumption only(kWh/yr)*
Family, 26-64 years old	18500	8400	4100
Couples without children, 26-64 years old	17100	10400	3360
Couples without children, 64 years old and above	13900	4800	2900

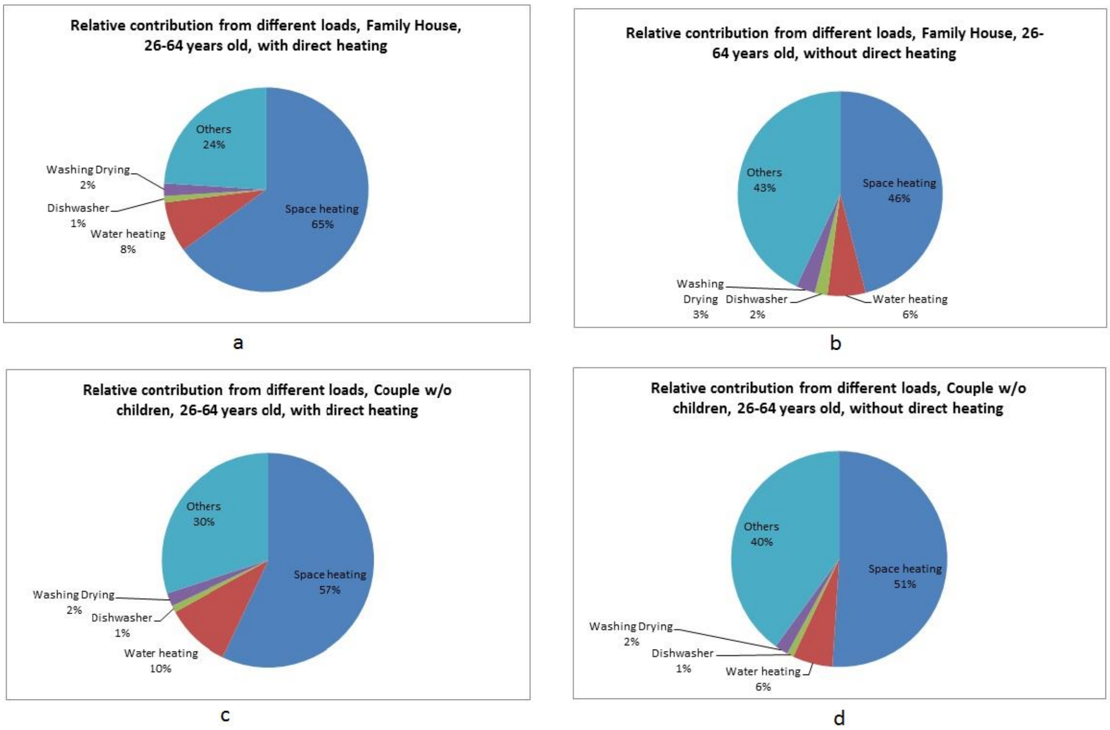


Figure 2: Contribution of investigated electrical loads and space heating in the household types Family and Couples without children households (SFD) in Sweden, Adapted from SEA report (Zimmermann 2009).

It should be clarified here that, in Table 1, the ‘direct electric heating’ means houses which only use electric furnace (with hydronic system) for heating or electric radiators which directly converts electricity to heat. Whereas the category ‘houses without direct heat’ includes technologies like heat pumps (although these are powered by electricity) and other types of energy carriers. The values in the column ‘specific consumption’ reflect electricity use after removing heating demand.

Figure 2 presents more detailed distribution of electricity among the different loads which are investigated in this thesis. The figure only shows two types of households from the SFD category as the intention here is to give general idea on contribution from different loads towards total electricity consumption in household. The percentage distribution is fairly similar for other types of households. For MFDs the space heating and water heating loads are not included as they are, as mentioned above, mainly provided by district heating.

Figure 2 depict average values, within each house category, of the heating load (including both space and water heating), but it can easily reach up to 80% of total load for larger houses dependent entirely on direct electric heating (Zimmermann 2009).

The electrical loads in a household can be divided into two categories based upon whether they depend more upon behaviour of occupants or more on external climate conditions (Yao and Steemers 2005). The division is as follows:

1. *Behavioural loads:* This type of electricity consumption is highly related to the living habits of people living in the houses. These loads are independent of external factor like outside temperature, wind speed, daylight, etc. Loads falling into the behavioural load category are shown in Table 2.

2. *Physical loads:* This type of electricity consumption is highly dependent on climate and the consumption varies from season to season. Such loads have very low co-relation to occupant's habits.

Among all the loads, dishwasher and laundry loads are in comparison easy to shift by the consumers as it can be delayed or used early without causing too much of inconvenience for the users. The remaining loads listed in Table 2 are highly behavioural and are therefore more difficult to shift in time. For example, people cook when they are hungry, they will not wait for lower prices. There has already been a study on shifting the refrigerator loads and potential and savings have been quite comprehensibly researched (Zehir and Bagriyanik, 2012). Hence this thesis will not focus on such loads. Water heating having second largest share of electricity consumption after space heating load could have greater impact on the load curve and this makes them important to investigate. Thus, this thesis will concentrate on three loads namely: water heating, dishwashing, and laundry (consisting both of washing and drying loads).

Even though yearly electricity consumption by dishwasher and laundry is small as compared to space heating and water heating, the study by Finn et al. (2012) shows that these small loads can have significant impact on reducing peak loads and integrating more renewables into the system. These loads have high electricity consumption in hours when they are in use but as these loads run for a limited number of hours their yearly electricity consumption is small.

Table 2: The two categories of loads based upon their characteristics

Behavioural loads	Physical loads
Cooking	Lighting
Dishwashing	Cold Appliances
Washing Drying	Space heating
Audio/video	Floor heating
Computer	Water heating

2.2 Demand Side Management

Historically, demand has been considered to be inflexible and hence it was considered to be predetermined. However, with current changes in the electricity system, more intermittent renewable production being implemented, there can be a need for flexible demand. In such case, the electricity demand can no longer be treated as fixed and predetermined. Demand side management (DSM) intends to exploit the unused flexibility present in demand of power.

DSM in the simplest of terms can be described as those measures which are implemented to influence the behaviour of end user to achieve a required load pattern. Demand response is one of the DSM measures that aim at shifting of consumer's electricity demand from a given time towards more desirable time in response to changes in electricity prices on hourly level (Palensky and Dietrich, 2011). This concept is generally applied to electrical loads, which is why whenever DSM is discussed in this thesis work it is assumed that the target for shift is the electrical energy. The study by Palensky and Dietrich (2011) presents various incentives which can be used to implement DSM. Energy efficiency is another DSM measure. The basic motivation for DSM is cost reduction from electricity consumption (consumer), reduction in capacity margin (supply side balance), increasing reliability of electricity supply, attaining environmental goals and energy security (Gellings and Chamberlin, 1993; Strbac, 2008; Gupta, 2012).

The choice of implementing DSM strategy depends upon how the current demand curve looks like and what kind of demand curve that is the aim. Generally it is an intension to make the demand curve follow the supply curve. The DSM strategies as described by Gellings and Chamberlin (1993) are briefly presented here:

(a) *Peak clipping:* Under this strategy the peak load is reduced by using direct load control method (Figure 3a). In which utilities have direct control over customer load and can thus systematically cut of electricity supply for different regions during peaks.

(b) *Valley filling:* This strategy focusses on increasing the load during off-peak time periods. This is useful to manage the increasing load in a city or country by strategically placing new demand in the off-peak period (Figure 3b).

(c) *Load shifting:* In this strategy the load is shifted from peak to off peak period where production cost is low. This includes simultaneously peak clipping and valley filling (Figure 3c).

(d) *Strategic load conservation*: This basically involves either decreasing the load by cutting out power supply systematically or by energy efficiency measures (Figure 3d).

This work is limited to assess the effects of load shifting.

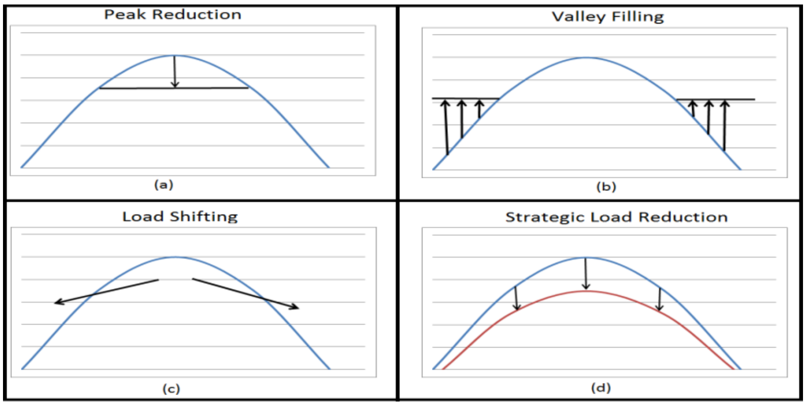


Figure 3: The four most commonly applied DSM strategies to adjust the load curve pattern. Adapted from Gellings and Chamberlin (1993).

3 METHODOLOGY

This chapter explains how the potential to shift and expected savings from shift are calculated for the investigated loads in the thesis. The loads have already been divided on the basis of their common characteristics (behavioural or physical load). To estimate the potential, a bottom-up approach is used in the study where the analysis is first done on individual household level and then scaled up to the country level. Figure 4 represents the methodology used for analysis in this study.

Data Collection

The data used in the study comes from three sources. First the SEA campaign (Zimmermann, 2009) which gives actual electricity consumption data for investigated appliances in various households. The electricity prices are taken from Nord Pool Spot for the year 2012 (Nord Pool Spot, 2013). The data regarding statistics of population of different households present in Sweden are taken from SCB (Nilsson, 2012a; Nilsson, 2012b).

Segmentation of households

The segmentation of buildings into archetypes is shown in Figure 5. The first division of households is based upon whether they belong to the SFD or MFD category and then upon type of occupants living, i.e. a family or couples without children (26-64 years), couples without children (64 years and older) or singles person. The later division is done because different types of occupants have different appliance usage pattern and different electricity demand.

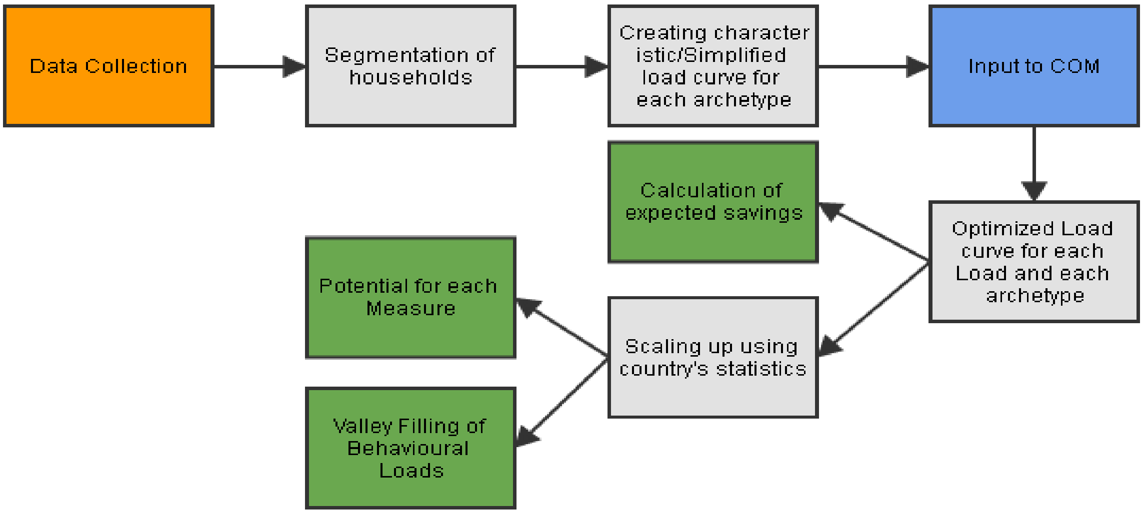


Figure 4: Step wise methodology as adopted in this thesis. The orange block represents input and the green blocks are the outputs. The modelling work is represented in blue block where COM stands for Cost Optimizing Model.

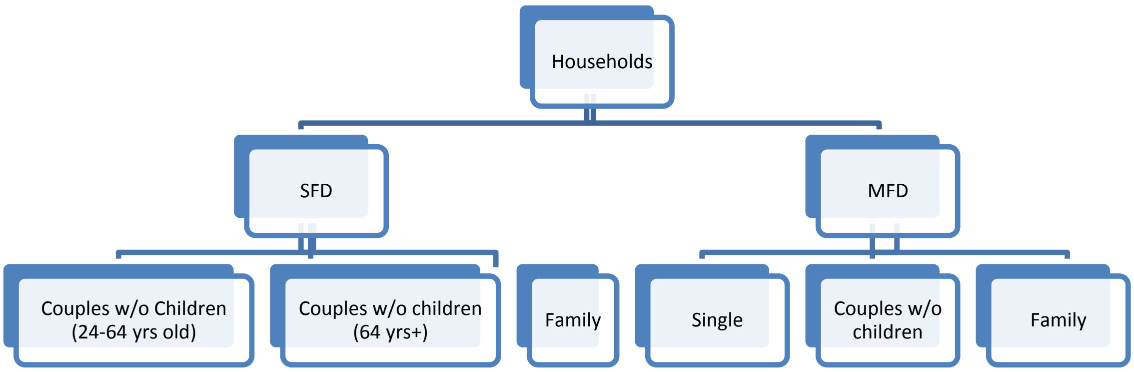


Figure 5: Division of households into different archetypes for the study.

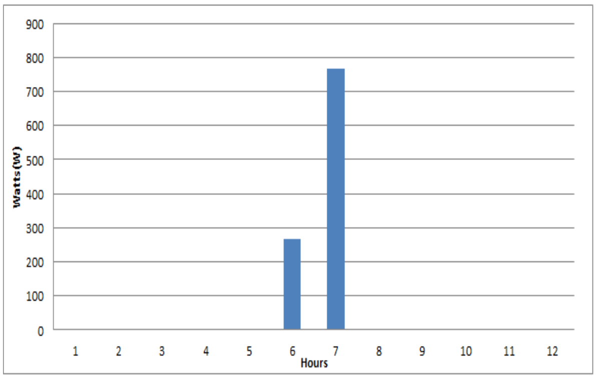
For laundry (both washing and drying) load only SFDs are considered along with dishwashing load from both SFDs and MFDs. The reason for omitting laundry load shift related to MFDs is that these households generally have common laundry space for the inhabitants. This creates hindrance in shifting of the washing load as a queue system is applied for common usage and people have to use it during their allotted time. SFDs households with only one inhabitant are few, and thus these types of households are not considered.

Only SFDs is considered for water heating because majority of the Swedish MFDs the energy for water heating is provided by the district heating network (Nilsson 2012a) and is thus out of scope of his thesis. From the SEA report no large load variation, in heating water, was observed within houses for couples of all age groups, and therefore, to simplify the analysis, these two groups are considered under same archetypes for water heating load. Thus there are only two archetypes, Family household and Couples without children households, for analysing the load shifting of water heating.

Creating Simplified/Characteristic load curves

The next step is to create characteristic or simplified load curve, which would show usage pattern of loads, for each archetype which will be given as input to the model. The dishwasher and laundry loads are based upon cycles, i.e. each of these loads run for a specified period of time depending upon washing cycle selected by the user. These loads are discrete in nature. On the other hand the water heating load is not based upon cycles and is not discrete. Thus these two types of loads require different modelling approaches. *Simplified load curves* are used for dishwasher and laundry loads which are created to avoid unwanted shifting of partial loads. The *Characteristic load curve* is the actual load curve of the water heater of a selected household from an archetype as monitored in SEA campaign.

The time resolution applied in this work is one hour, thus each DSM load can only be dispatched on an hourly basis. An additional simplification is done on the basis of number of cycles for an appliance over a year. The appliance's annual number of cycles is obtained from the SEA campaign and electricity consumption for every cycle is assumed to be equal to average cycle consumption (this assures that the total electricity consumption by the appliance throughout the year remains same after simplification), which is obtained from the report by Richter et al. (2011). Figure 6(a) shows load curve of a dishwashing cycle as it occurs in one day (not all the hours are shown). The cycle is spread over two hours which is then simplified to one hour cycle (see Figure 6b) having same energy consumptions as one actual cycle has. The cycles of each appliance (dishwasher and laundry) are then extrapolated over a week, depending on their weekly frequency, and ultimately over the year to give yearly load curve. This provides the simplified load curve that is needed as an input for the model.



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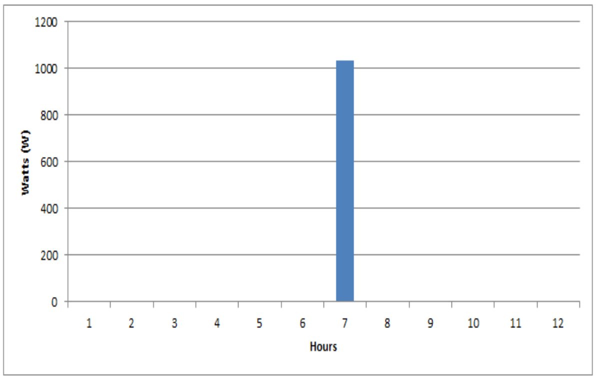


b

Figure 6: Dishwasher load curve (a) before simplification, (b) after simplification.

Cost Optimization Model

The cost optimization model dispatches investigated loads based upon constraints, and thus, gives a new optimized load curve.

The platform used for developing the model is General Algebraic Modelling System (GAMS) which is a high level modelling system used for mathematical programming and optimization. The load shift model used for the thesis is a linear optimization formulation. The model is implemented in GAMS and then solved using a Mixed Integer Programming (MIP) solver, which is required while dealing with dishwasher and laundry loads as these appliances can be either off or on with cycle dependent load. The model applied in this work builds on a previous model by Nyholm et al. (to be published). The earlier model aims at shifting load based upon solar power available while this has been modified to shift loads based upon only day-ahead electricity prices. This modified model used in this thesis hereafter will be simply called "COM" (Cost Optimization Model).

The COM optimizes the dispatch of investigated loads to minimize the cost of electricity (z) for the consumer. The objective function is:

$$z = \sum_{h=0}^{8760} [el\_price(h) * el\_demand(h)]$$

Where,

z = annual electricity cost for electrical heating (SEK),

el_price(h) = final electricity price (including VAT, transmission charge, & energy tax) for consumer at hour h (SEK/kWh),

el_demand(h) = electricity demand at hour h (kWh).

The el_demand is the simplified load or characteristic load curve obtained from the previous step. For each category of loads different constraints are put into the model and are explained later in this section.

For dishwasher and laundry loads the COM dispatches the cycles over the year in order to minimize electricity cost. The constraints are based on the appliance usage pattern observed in the monitored households in SEA campaign and are as bellows.

Constraints for dishwashing and laundry loads in the COM:

- The number of cycles for each appliance and each archetype should be constant for weekdays and weekends depending upon their individual behaviour. The model obtains this behaviour from the simplified input curves.

$$cycles = \sum_{App=1}^{3} [DSM\_load\_weekday(app) + DSM\_load\_weekend(app)]$$

Where,

cycles = number of cycles in a week,

DSM_load_weekday = number of cycles in a weekday (Monday-Friday),

DSM_load_weekend = number of cycles in a weekend (kWh),

app = Investigates loads, i.e. Dishwasher, laundry (washing appliance + drying appliance).

- A day can have maximum one cycle of each appliance. This constraint is given to prevent model to shift the entire demand of a particular load to the cheapest hour of the whole week.

$$daily\_demand \leq \sum_{App=1}^{3} DSM\_load(app)$$

Where,

DSM_load = electricity consumption in a cycle of a load (kWh),

daily_demand = maximum electricity demand for a day (equal to the sum of electricity consumption in one cycle of all three investigated loads).

- A dryer load has to be followed by a washing machine load.

The approach applied to shift the water heating load is by storing the energy in the storage tank. Each household is assumed to have a separate storage tank where hot water is stored for later use. The size of this storage usually lies between 15 litres and 500 litres. The recommended minimum size (by major water heating equipment provider: Nibe) for a house to fulfil its basic needs is 100 litres . Hence it is reasonable to assume a tank capacity of 100 litres for the study. Also the power rating of the water heaters available today basically falls into three categories, i.e. 1.5 kW, 3 kW or 6 kW. Due to lack of data on exact water heating system in the houses monitored (in SEA campaign) it is assumed that all houses have a 3kW heater installed. To prevent the Legionella bacteria from developing, water has to be maintained at a certain minimum temperature and 50 ^{0}C recommended by the equipment provider Nibe. The maximum output water temperature is assumed to be 80^{0}C . The heat capacity (C_p) of water is used to store the heat energy.

The aim is to shift the load without shifting the actual usage of hot water. Thus the water needs to be preheated before actual use. There are heat losses from the tank. The heat losses are assumed to be 1% of the stored heat for every hour (losses are for the equipment provided by Nibe). This is also the main constraint for the COM in this case. The further the load is advanced in time, the higher the losses. The characteristic load curve, which is the actual water heating load curve of a selected household, is given as an input to the model. The model is allowed to shift the load to reduce the cost of electricity used for heating the water. For calculating savings characteristic load curves are optimized and for scaling-up purpose average load curve belonging to each archetypes are optimized.

The minimizing function is same as that used for the behavioural loads where characteristic load curve for water heating is used to determine the parameter '*el_demand(h)*' instead of applying a simplified load curve.

To summarize, the constraints for water heating applied in the COM are:

- The maximum heat which can be stored in an hour is 3.5 kWh (calculated according to size of the tank and heat capacity of water which is stored)
- The heating capacity is 3 kW (the rating of the heating element)
- With shift in energy there is a loss of 1% per stored hour and this amount of energy has to be additionally supplied.

Calculation of expected monetary savings

The savings for each archetype is calculated by subtracting optimized yearly cost from the non-optimized cost. The optimized cost of an archetype is given by the COM and non-optimized cost is calculated using the actual non-optimized load curve.

A range of expected economic savings is calculated by running the model for different households. For all the archetypes load data from two different households are used find the range of savings, one representing the high consumption category and one representing a low consumption range. This range is also an indication on how the saving potential may vary between a household having a high consumption and household with low consumption.

Scaling-Up of Results & Potential to Shift

For scaling up and to analyse the effect of shift, a week from every season is chosen. The scaled-up results are then compared with total load of Sweden. As 2012 prices are used for the optimization for all the investigated loads, the electricity load curve (on a country level) of the year 2012 is taken into consideration. The winter week selected is the week with highest consumption of electricity for the whole year (week six). The spring (week 16), summer (week 29) and autumn (week 42) weeks investigated consume average electricity (on weekly level) for the corresponding season.

The load curves are up-scaled using the formula:

$$P\ (hour) = \sum_{i=1}^{5}\left(\sum_{j=1}^{3} Load(j) * p\ (j)\right) * N(i))$$

Where,

P = up scaled load on hourly basis (h),

Load (j) = Optimized or average load for individual loads (Wh/household),

j = number of different loads (three in this thesis, i.e. Dishwasher, washing machine, Dryer)

i = Number of archetypes

p(j) = penetration level of loads in each archetype,

N(i) = population of different archetypes (households).

N(i) is calculated using the date from SEA survey which gives the spread of various archetypes in the country and two other reports from SEA (Nilsson 2012a; Nilsson 2012b) which gives overall population of households. All the behavioural load curves (both optimized and non-optimized) are scaled-up together and water heating load curve is scaled up separately and are analysed separately.

The scaled up non-optimized average load gives the load curve of investigated loads without shift on the country/system level. The scaled-up average load curve of the investigates loads is subtracted from the total electricity load curve of Sweden, as obtained from Nord Pool Spot, to give *Base Load* curve. Thus base load curve includes all the loads which are not investigated. Then the scaled-up optimized load curve on country level is added to *Base Load* curve to give *New load curve* after load shift.

The sum of all shifted energy in the investigated weeks is determined and provides an estimate on the potential for load shifting.

Valley filling of dishwashing and laundry loads

As there is no feedback in model available on how the prices will vary with load shifting, the model always shifts the load to the cheapest hour. With the scaled-up results, this implies that the loads of all the households are being shifted to the cheapest hour for the whole country. This leads to a steep increase in load for the particular hour to which the load has been shifted. This could create problems like converting off-peak into peak, create congestion in the system or change the marginal electricity generating technology. To avoid such situations, a valley filling technique has been used in this thesis. This technique implies that the load shifted to one particular hour is divided among other off-peak hours having similar electricity prices and to create smoother load curve.

This valley filling technique is only performed for dishwasher and laundry loads as dividing the shifted load among other off-peak hour just results in shifting of cycles to those hours. This is in reality is possible to achieve and would not have too high impact on the economic savings as the prices in off-peak hours are very similar. Moreover, the shift does not result in increased electricity use. However, for physical measures, load cannot be simply divided as it can only be shifted before the actual consumption and cannot be postponed. This would, however, increase the heat losses from the storage tank and customer may end up paying more to compensate for the losses. Therefore, no valley filling is performed for water heating loads.

4 Input Data

The main source of input data for this thesis comes from SEA campaign (Zimmermann 2009). The campaign monitored consumption data for every electricity-specific appliance in a large number of investigated households, and the data are provided on an hourly basis. The campaign was carried out during three years, from 2005 to 2008. In total 400 households, of which 200 were single family dwellings (SFD) and 200 multifamily dwellings (MFD), were monitored. In each SFD and MFD category, 20 houses were monitored for an entire year. The other 180 households in each category were monitored during a period of a few months (1-3 months). Their monitored loads were then extrapolated to represent a whole year based on the pattern seen for the yearly monitored households.

The number and location of houses chosen in SEA campaign represent the existing households in Sweden as closely as possible. The characteristics of sample data collected are shown in Table 13.

Table 3 indicate that families dominate the SFD archetype whereas the household composition is more evenly distributed in MFDs. There is no further division on the basis of age groups for couples (in case of MFD) and single person (in MFD) households because there were no significant differences observed in their load curve for the different appliances. Table 3: Number of households belonging to different archetypes as covered in SEA campaign. Source: Zimmermann (2009).

	Number of households			
	Family 26-64 years old	**Couple without children 26-64 years old**	**Couple without children 64 years old and above**	**Single person**
SFD	125	46	21	7
MFD	81	56		52

4.1 Dishwashing load

The average yearly load of a dishwasher in a SFD is 236 kWh for family archetype and 157 kWh/year for “Couples without children (26-64 years)” houses. For “couples without children of 64 years and above” the average value is 146 kWh/year. The range of load varies from 143 to 236 kWh/year for the SFD category. For the category “MFD Dishwashing”, the load varies from 74 kWh/year to 214 kWh/year. From these yearly consumptions, the total number of cycles for an appliance and an archetype are calculated. The analysis of consumption pattern is done by examining the individual dishwasher load curves of each house based on when the load is occurring, i.e. on a weekday or on a weekend day, and frequency of cycles during a week.

The SEA campaign conducted in year 2005 reveals that average cycle consumption for dishwashing in Sweden is to 1.035 kWh (Richter 2011). In the present thesis, the recent average value is used so as to give better representation of the country and also serves useful to scale-up the results. The pattern for loads during a week for different archetypes can be summarized as:

- *Family*: Dishwashing is done five times a week. One cycle each on both weekend days (Saturday and Sunday) and the remaining three are distributed on weekdays. Average number of washing cycles are 260 cycles/year. The pattern is the same for a family living in a SFD or a MFD.
- *Couples without children*: Dishwashing is done three times a week with one cycle on the weekends and remaining two on any weekday. Average number of cycle for this

category is 160 cycles/year. This trend is common for all the age groups and for both SFD and MFD. For this reason the couple's archetype is not divided further.

- *Single*: Most single persons live in MFDs and use the dishwasher on an average twice a week, once during a weekday and once during a weekend. Average number of washing cycles for single person living in MFD is 104 cycles/year. The number of single person households in the SFD category is low and hence not considered in the scope of this this investigation

The general behaviour gives average number of cycles for a house with average consumption. The SEA campaign survey provides ranges of yearly electricity consumption by each appliance, i.e. gives upper and lower limits of yearly consumption. This upper and lower end values are used to give the number of cycles for higher and lower consumption households.

Table 4 summarizes the number of dishwashing cycles for the different archetypes and for different levels of consumption. Empty cells in Table 4 indicate insufficient data and therefore are not included in the study. For high consumption households, the higher electricity consumption per cycle is used, as well as a higher number of cycles per week. The high consumption per cycle was observed in some of the high consuming households and thus has been used as upper limit of the same (same reasoning is true for laundry loads).

Table 4: Distribution of dishwashing cycles in various archetypes during a week to create simplified load curves.

Archetype		Dishwashing			
		Consumption Level	*No: of cycles*		*El consumption per cycle (kWh/cycle)*
			Weekdays	Weekends	
SFD/MFD	Family house	Low consumption	2	1	1.035
		Average consumption	3	2	1.035
		High Consumption	5	2	1.5
	Couples without children, 26-64 years	Low consumption	-	-	-
		Average consumption	2	1	1.035
		High Consumption	3	2	1.5
	Couples without children, 64 years and above	Low consumption	-	-	-
		Average consumption	2	1	1.035
		High Consumption	3	2	1.5
MFD	Single person	Average consumption	1	1	1.035

4.2 Laundry loads (washing and drying)

The highest consumption of electricity for laundry is for family household archetype which has an average annual consumption of 213 kWh, this is followed by archetype without children (26-64yrs) with an annual consumption of 151 kWh. The analysis of consumption is done similar to dishwashing load. General patterns are:

- *Family*: Laundry is done four times a week out of which two are done during the weekends and two on weekdays.
- *Couples without children*: Households of age group 26-64 do their laundry three times a week once on a weekday and twice on the weekends. Households of age group of 64 years and more do their laundry once a week.

The average washing cycle energy consumption in Sweden is 0.95 kWh and for the drying cycle it is 1.2 kWh (Persson 2007).

Table 5 shows the number of laundry cycles for different archetypes and for different level of consumption. There is no other consumption level considered for couples without children (64 years old and above) as their consumption is already low and the number of houses monitored was not sufficient to determine higher range of consumption.

Table 5: Distribution of Washing and drying cycles for various archetypes during a week to create simplified load curve for laundry.

<table>
<tr><th colspan="2" rowspan="3">Archetype</th><th colspan="4">Washing & drying</th></tr>
<tr><th rowspan="2">Consumption Level</th><th colspan="2">No: of cycles</th><th rowspan="2">El consumption per cycle (kWh/cycle)</th></tr>
<tr><th>Weekdays</th><th>Weekends</th></tr>
<tr><td rowspan="9">SFD</td><td rowspan="3">Family house</td><td>Low consumption</td><td colspan="2">Once a week</td><td>2.2</td></tr>
<tr><td>Average consumption</td><td>2</td><td>2</td><td>2.2</td></tr>
<tr><td>High consumption</td><td>5</td><td>2</td><td>2.2</td></tr>
<tr><td rowspan="3">Couples without children, 26-64 years</td><td>Low consumption</td><td colspan="2">Once a week</td><td>2.2</td></tr>
<tr><td>Average consumption</td><td>1</td><td>2</td><td>2.2</td></tr>
<tr><td>High consumption</td><td>3</td><td>2</td><td>2.2</td></tr>
<tr><td rowspan="3">Couples without children, 64 years and above</td><td>Low consumption</td><td>-</td><td>-</td><td>-</td></tr>
<tr><td>Average consumption</td><td colspan="2">Once a week</td><td>2.2</td></tr>
<tr><td>High consumption</td><td>-</td><td>-</td><td>-</td></tr>
</table>

Due to confidentiality agreement between the occupants living in the monitored households and the SEA it is difficult to differentiate (on the basis of age) among couples without children households. Thus some assumptions are made while taking the base case load curve. For example, 213 kWh is the average yearly consumption for laundry in couples without children (26-64 years) archetype, thus the household with two occupants which consumes similar amount of electricity yearly for laundry are considered to belong to this archetype.

4.3 Penetration level of appliances

In order to scale-up the result and calculate the load shifting potential, it is required to have the penetration level of the investigated appliances. The penetration level gives the number of appliances per households for a given archetype, i.e. the average possession of appliances. The penetration level is presented in Table 6. These are the values observed from the SEA campaign (Zimmermann 2009) results and are very close to values found in the study conducted on EU level (Stamminger et al. 2008). The variation is mainly because the EU study focuses on overall penetration whereas in the campaign the values are divided upon the SFD and MFD categories.

Table 6: Penetration level of dishwasher, washing machine and dryer in Swedish households as obtained from SEA report (Zimmermann 2009).

	Washing Machine	Dryer	Dishwasher
SFD, Couples without children, 26-64 years old	1	0.57	0.91
SFD, Couples without children, 64 years old and above	1.05	0.48	0.76
SFD, Family, 26-64 years old	1.01	0.64	0.93
SFD, Single person, 26-64 years old	0.67	0.33	1
SFD, Single person, 64 years old and above	1	0.25	0.75
All SFD households	*1.01*	*0.59*	*0.9*
MFD, Couples without children 26-64 years old	0.49	0.15	0.6
MFD, Couples without children, 64 years old and above	0.43	0	0.47
MFD, Family, 26-64 years old	0.63	0.21	0.64
MFD, Single person, 26-64 years old	0.39	0.1	0.34
MFD, Single person, 64 years old and above	0.4	0.00	0.33
All MFD households	*0.52*	*0.15*	*0.51*

5 RESULTS

The different electricity load curve names used in graphs in the following section of results are:

- *Base load*: The electricity load profile on country level without including loads of behavioural measures.
- *Old Curve*: Load curve of all behavioural measures summed up together on country level before load shifting.
- *New Curve*: Scaled-up optimized load curve of all behavioural measures.

5.1 Dishwashing and Laundry loads

Potential for Load shift

Figure 7 shows the resulting load curve for the Swedish national level after the load shifting in the winter week. The loads are shifted to off-peak time resulting in new peaks, yet these peaks are never higher than the current peaks. There is a load reduction of around 300 MW (maximum) from peak during the observed week, see Figure 7, and a load addition of about 2-3 GW in off-peak hours of a day. During the week the loads are shifted to off peak hours except for one day during weekend where load is shifted in between peak and off-peak hour (see hour 127 and 128 in Figure 7).

In a spring week (Figure 8) a similar trend as seen in the winter week is observed. During the weekend, a peak is formed over the old peak indicating that prices are lower even when consumption is high (see Figure 8). The maximum load reduction taking place during a spring week is also around 300 MW. This load shifting during peak hours is only observed for the spring week and other analysed weeks of the summer and autumn season follow same trend as seen for the winter week.

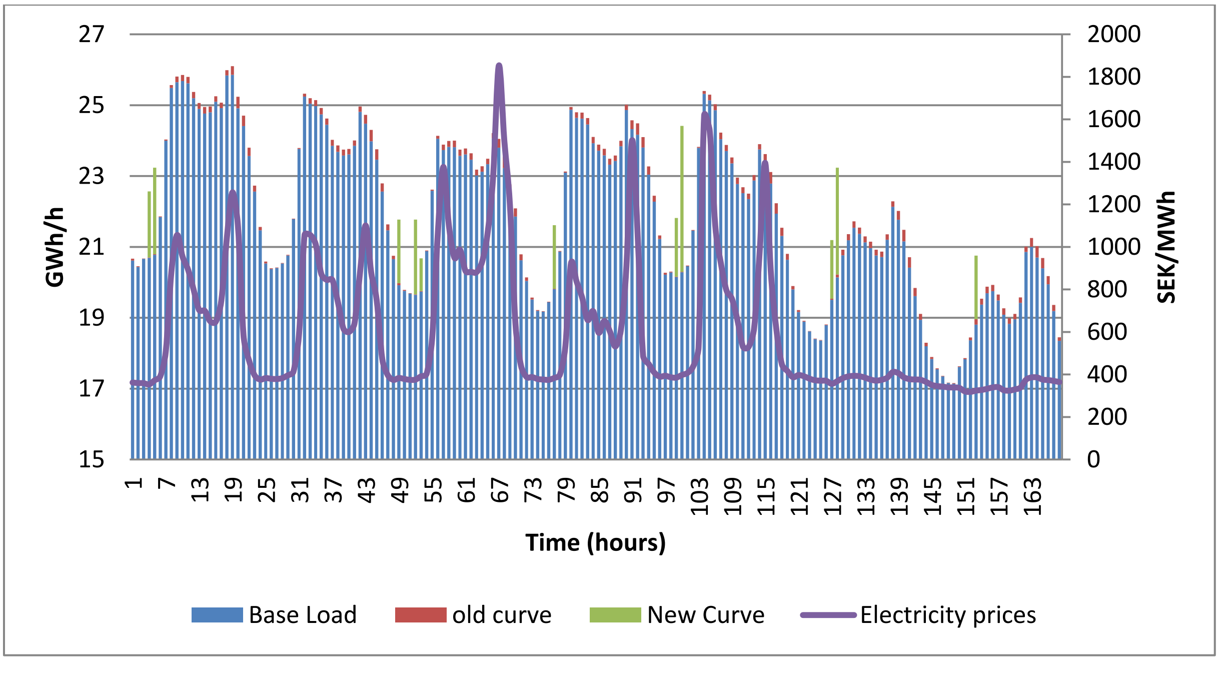


Figure 7: Effect of shifting behavioural loads on system electricity load during winter week (week six of year 2012).

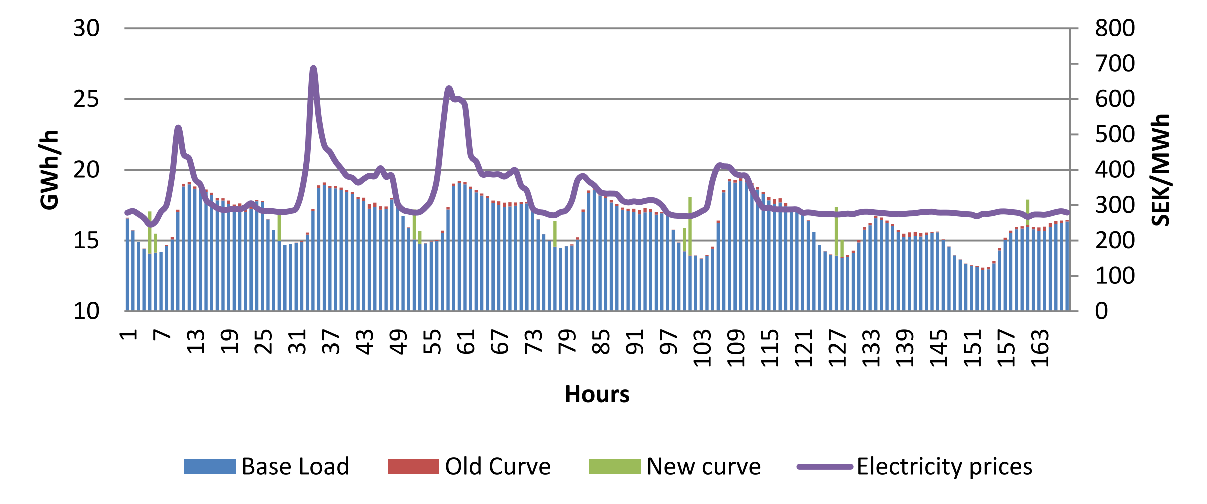


Figure 8: Effect of shifting behavioural loads on system electricity load during a spring week (week 16 of year 2012).

The total load shifting potential for different appliances is summarized in Table 7. The results show how much electricity, from the observed loads, is available for shifting on a daily basis. Thus, the load shifting potential of dishwasher is expected to be between 0.6 - 1.7 GWh/day. As generally seen, there are some days which have higher electricity prices than others and as the cycles of investigated loads are not run every day, there are some days which have no load shifting. As the use of these appliances are independent of seasonal changes the peak reduction in absolute terms remains same and is between 150 MW to 300 MW and increment in off-peak load also remains the same all of the year. In relative terms the peak load reduction is 1.1%, 1.5%, 2.3%, 1.6% respectively in winter, spring, summer and autumn season.

Table 7: Potential to shift for Behavioural loads on daily level for Sweden.

Appliance	Daily Potential
Washing Machine	0 -1.9 GWh
Dishwasher	0.6 -1.7 GWh
Dryer	0 -1.3 GWh

Expected Monetary Savings

The results shown in Table 8 are the monetary savings range for the different archetypes. The maximum savings are observed for the Family households, while the smallest savings are for Couples without children, 64 years and above. The high savings in family households can be attributed to fact that they have high load demands.

Table 8: Expected savings range for behavioural loads in Swedish Households.

Archetype		Savings from dishwashing load shift (SEK/year)	Savings from laundry load shift (SEK/year)
SFD and MFD	Family house	18 - 124	10 - 143
	Couples without children, 26-64 years	15 - 24	10 - 110
	Couples without children, 64 years and above	15 - 24	10
MFD	Single person	14	N/A

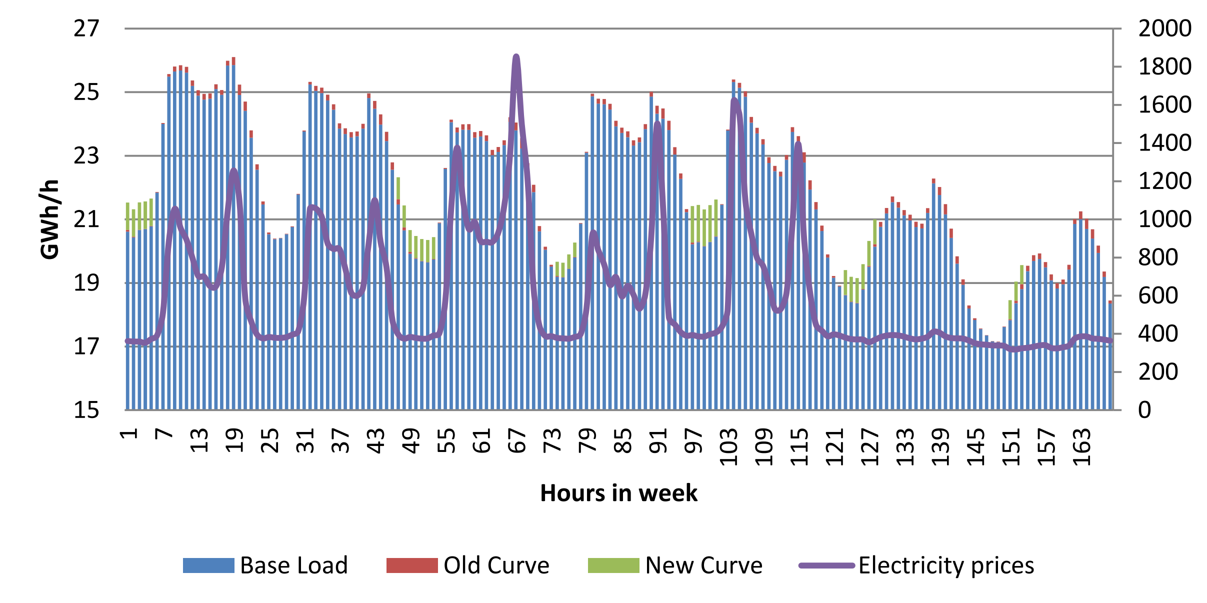


Figure 9: The resulting system load curve in winter after a valley filling strategy is applied to behavioural load shifting.

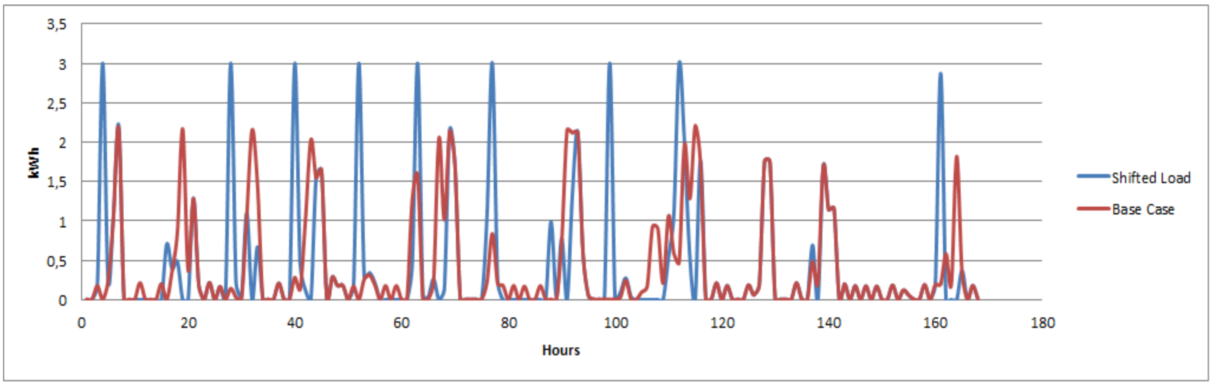
Results with valley filling

Figure 9 shows the load curve after distributing shifted loads to other nearby least cost hours. Only the analysed winter week is shown in the result and graphs of other weeks are available in appendix A. The previously seen load increase and spikes caused by the load shift (without smoothening) is reduced from 1-4 GWh/h to less than 1 GWh/h (depending upon number of off-peak hours available during the day) by valley filling operation. Thus the valley filling makes the system curve smoother by reducing sudden peaks occurring due to load shift in off-peak hours.

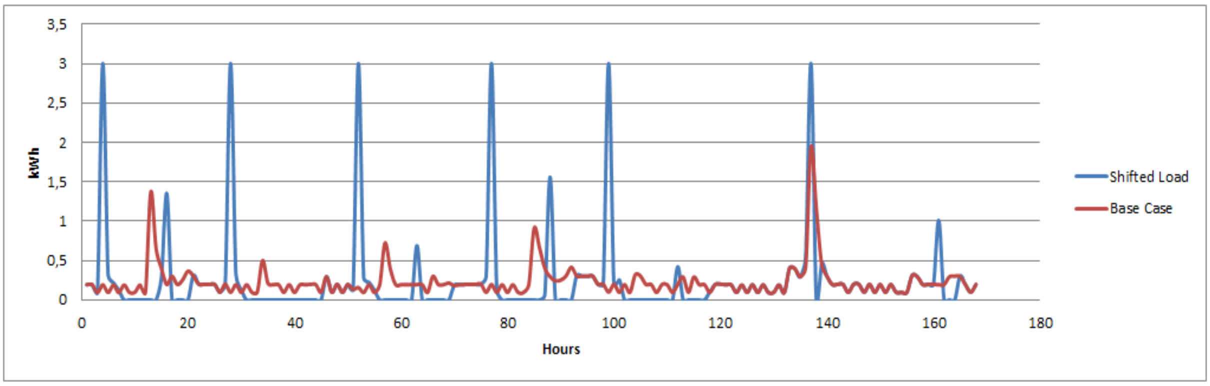
5.2 Water heating load

Figure 10 shows water heating load curve before and after load shift in a typical family household and for "couples without children" households. It is seen in Figure 10 that the new peaks formed in family house are around 1 kW more than the base case peak. This is due to fact that in the base case the load demand were recorded every 10 minutes thus giving average values over every 10 minutes. The peaks are considerably higher for houses with couples as compared to case where load is not shifted.

Figure 11 presents the results of when every household in SFD optimizes their water heating load and by doing this how the system load curve changes during a typical winter week. New peaks are seen during the former off-peak periods as well as for some peak hours. During the winter season the potential to shift on a weekday is between 8 and 9 GWh/day and on the weekend it is about 3 GWh/day. The peak load reduction varies between 0.95 GW to 0.43GW. The length of shifting period is governed by assumed losses and price fluctuation. Higher the differences in electricity price between peak and off-peak hours, more of the losses can be compensated for longer time making time of shift longer. The system load curve in this section only shows the base load and new water heater load. To see the old heater load with no load shifting curve refer to Appendix B. In the remaining part of this section only the scaled-up curve will be presented, while the load curve on individual household level is found in Appendix C.



a



b

Figure 10: Water heating load curve before and after load shift during winter for (a) Family archetype, (b) Couples archetype in SFD. Base case here represents water heating load without shift.

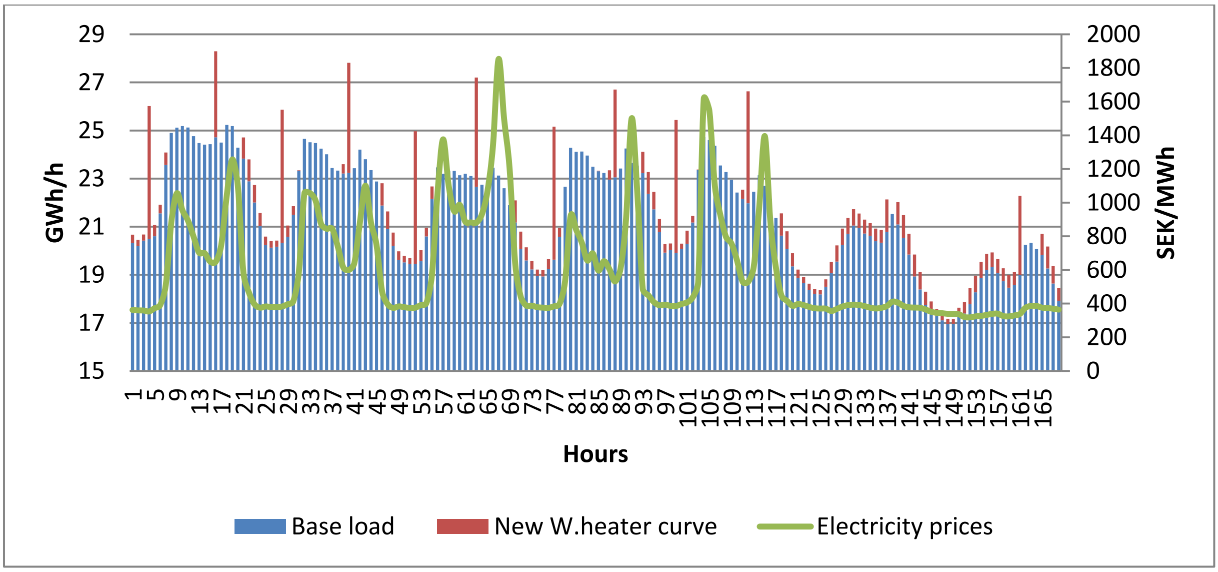


Figure 11: Effect of water heating load shift on system's electricity load curve in the selected winter week.

In a typical spring week a similar trend is observed as in the winter week. However, there is no load shift occurring during the weekend. The reason for this is the low price variations during the weekend which makes the economic saving from load shifting lower than the supplementary costs for compensating additional losses due to shifting. A similar trend of load shifting as seen in spring is observed during the summer and autumn week with load shifting potential decreasing for summer and again increasing in autumn.

The maximum peak load reduction observed in spring, summer and autumn week is 0.872 GW, 0.69GW and 0.9 GW respectively. This gives the peak load reduction of 4.5%, 5% and 4.7% respectively in spring, summer and autumn week. The maximum load addition to off-peak hours is 5.1 GW. 4.6 GW and 5.3 GW simultaneously in spring summer and autumn weeks.

The shifting of water heating load results in increase in electricity consumption. For family household this rise in electricity consumption is about 41 kWh/year which corresponds to a 1.35% increase. For couples without children household the rise in electricity consumption is 37 kWh/year corresponding to 1.8% increase in yearly consumption. On the system level this heat corresponds to increase in electricity demand by 75 GWh/year. The shift potential is summed up in the Table 9 below. The potential has been divided upon the different season weeks and within a week into weekdays and weekends.

With the assumption on capacity of storage tank, the duration for a load shift may be as long as nine hours. It is observed that couples without children have a longer time period for shifting (nine hours) as compared to family household (eight hours).

Table 9: Daily water heating load shift potential in Swedish SFD for different seasons.

Season	Daily Shifting Potential	
	Weekday	Weekend
Winter	8 - 9 GWh	0.8 - 2.7 GWh
Spring	3.3 - 5 GWh	0 - 3.7 GWh
Summer	2.5 - 5 GWh	0.7 GWh
Autumn	3 - 5 GWh	4 - 5 GWh

Cost savings by shifting water heating load

The cost saving range for family household is in the range of 55 – 81 SEK/year and for the couple's household it is 55 – 101 SEK/year. The saving range for the family is smaller than the couples. Also the lower range of savings is almost same for both archetype households. This low range can be because the water usage of monitored households falling in the family archetype occurred mostly during the off-peak hours during most of the year.

6 DISCUSSION

Dishwashing and laundry loads

For these loads, there is no effect of season on the potential of available load to shift nor is there any effect from price fluctuations (i.e. how big or small the fluctuations are) on the load shifting potential. This since for shift to occur only a price difference is required. The size of these differences does not matter because with current methodology it is always cheaper to shift load even if the price difference is only 1 SEK. What is not accounted in the study is the price reduction from peaks from where loads are removed and price increase in off-peak due to addition of peaks.

The assumptions made are crucial as they influence the results to a high degree. The cycle time is one of the important assumptions which can vary for each appliance and electricity consumed during that cycle varies depending upon the setting selected by the consumer. Hence it is not necessary that all the cycles are exactly one hour and consume same average energy per cycle as assumed in this thesis. Thus the shifting of load instead of taking place in one particular hour might actually be spread over two hours (or more) for each dishwasher, and laundry. This would result in distribution of load addition over couple of hours and thus reducing the possibility of off-peak getting converted into peak. The potential to shift on daily basis would still be the same as it is a summation of the entire load shifted in a day even when the cycle time is increased. Another assumption put in methodology regarding shifting is that there can only be one cycle in a day, so if the two lowest prices occur in two consecutive days then the model will allocate two cycles in row in two consecutive days. This would not be practical for many households, e.g. if laundry is done by couple on a day then they might only require to do it after two days, thus making allocation of laundry on two consecutive day impractical.

Assumptions on cycle size and cycle time also have an effect on the savings. For example, if instead of having one hour cycle there is a one and a half hour cycle along with higher energy consumption per cycle, this would affect the cost savings. Shifting such cycles from peak hours to off-peak hours would lead to higher savings.

In Figure 8 it is seen that during the weekend the loads are shifted to the peak hour. The possible reason would be that the demand is lower in the weekend which results in almost flat prices (fluctuations of about ±15 SEK). The marginal costs of electricity thus are very close to each other and the lowest happened to be during one of the peak hours. From a customer’s point of view it does not really matter if the load is shifted to the peak hours or to off-peak hour as price is the only signal for load shift. But for system operator it might create problems in balancing the system and pose threat to stability of system. Thus there is need to manage such situations where lower prices at peak hours would send wrong signal for load shifting.

Monetary savings through shifting dishwashing load for the “couples without children” archetypes was observed to be small along with narrow range of savings. This low range can be attributed to two possibilities, one that the monitored houses did not use the dishwasher during the peak for most of the time in the year, thus not gaining much by shifting the load. This shows that the savings are also dependent on usage timing, i.e. households will save less if they are already using the appliances during low cost hours even though if they have high load consumption. Secondly some of the houses were monitored for one month and then their load extrapolated, so it is possible that during the monitoring period residents did not use it during peaks and this behaviour got extrapolated.

If people start behaving in a similar manner to minimize their electricity costs peaks will be seen in off peak hours, this will lead to increase in off peak prices and valley filling or other measures will be needed to tackle such problem. It is seen that the peak demand has been reduce through load shifting; this could lead to other benefits like lowering of capacity of reserves, reduced transmission capacity expansion and lowering of congestion.

Another way to look at this is that such loads can be planned depending upon availability of renewable sources. Different renewable source have different characteristics thus planning needs to be done accordingly. Shifting the loads during the period with high renewable electricity production in the system could provide people with better incentives as this would reduce marginal prices. People's demand on convenience and flexibility will have a great impact on actual potential. The potential calculated here is on assumption that all people behave in same rational way of minimizing electricity bills. Hence the potential calculated is the theoretical maximum which can be achieved but in reality it would be less. As seen from investment cost for smart technology(Seebach et al. 2009) it is clear that an average customer would either end up paying more for installing such technology or in best case end up paying all savings for the new technology. A simple way for people to save money without investing in expensive technology is to start using appliances at night (as the prices are usually lowest during night).

Water heating load

The time period within which load can be shifted for water heating is mainly limited by the energy losses. The variation in price during a day plays important role in determining the potential for shifting the water heater load. The price variation during weekends is lower thus there is a higher potential on weekdays than on weekends. This can also be verified from seasonal results as winter has the highest potential for shift and highest price variations. For the water heating load it is only during autumn that there is a high share of load shift during weekend, this is because during that selected autumn week the price fluctuations during the weekend was higher than other weeks.

As observed the maximum time period in which load is shifted is a 10 hour period observed in autumn for households of couples without children. For family households the corresponding value is nine hours. This difference is because of storage limitation, as family household have higher water heating loads the storage tank cannot store more heat than for the next nine hours. This leads us to assumption made in the thesis on storage tank and shows that the time periods as well as potential to shift are sensitive to storage capacity. Thus the potential of both amount of energy and the timeframe for shifting could vary if the assumption made in methodology is different. In fact different household have different sizes of tank and thus different potential and savings. Replacing assumed tank size with the country's average storage size might yield more accurate results on the system level.

During winter, the load is shifted within the peak hours (as seen in Figure 11). This behaviour is unique for the winter season but for the other seasons the load is only shifted to off-peak hours. The reason is that during winter peak hours there is very high price fluctuation even within the peak hours and it becomes more profitable to shift to nearby peak hours than in off-peak where higher losses have to be compensated. Another thing to consider here is that the winter week chosen in the study was "an extreme week", i.e. the week consuming the highest electricity in the whole year, and this might not a representative week as such weeks occur rarely during a year. Such situation of high load demand is potential enough to create problems in power system and this makes it important to avoid such shifting of load during peaks. With money saving as the only incentive and in absence of feedback on price change with demand change, such patterns would be hard to avoid. When the shifted water heating load is added with shifted behavioural loads then even valley filling of behavioural load would not help in preventing conversion of off-peak load to peak load. Simple valley filling in the case of water heating load will not be optimal from customers point because this would lead to increase electricity demand (due to higher losses) for certain customers whose demand is shifted further in time. These increased losses would then reduce the savings. Hence a smart system controlling load at regional or central level is needed to counteract this trend.

It seems correct to assume that higher-consumption houses have higher potential to shift and thus could achieve higher savings but as observed this is not true. The amount of load to shift and savings depends upon time of consumption, as houses falling in high consumption range did not always yield high savings. Thus a household using hot water more frequently during peak prices saves more from shifting load than the household which has higher consumption during off-peak hours. The methodology used here does not interfere with the actual usage of hot water. People use hot water in similar fashion as they did before shift; the water is only pre-heated before actual use. This does not cause any inconvenience. However, the problem here is with behaviour, the behaviour of people changes and people might not use hot water exactly the same way in another year. This thesis provides expected load which could be available for shifting. A smart technology which understands behaviour of people is needed to estimate future requirements and thus shift the load accordingly. What we are doing right now is looking back on how the consumption pattern was, but in reality we have to look into the future and shift the load to give the minimum cost.

All the potentials for different loads calculated in this thesis are the theoretical potential which is achieved when everyone follows the DSM strategies. Actual potential will be lower and needs statistics on percentage of people willing to take part in the DSM. As modelling approach used is simple and flexible, there are possibilities for further development in order to make the analysis more detailed. Like for example the peak load demand can be limited to certain value in order to limit new peak formation and transmission capacity constraints could be added to realize limitations of load shift. Further it should be interesting to put this type of results into a systems perspective by implementing potentials as realizable potentials in a dynamic techno-economic electricity systems model. This is believed to enable a more thorough analysis of DSM, e.g., price effects of load shifting and the value of these measures as to facilitate high deployment of intermittent power sources.

7 CONCLUSIONS

In this thesis a methodology is developed to assess the load shifting potential of dishwashing, laundry, and water heating (for hot tap water) loads at the national level. The cost saving from shifting such loads is also calculated. The work is performed to get a first-hand idea on how much load could be readily available to shift and to assess economic incentives from consumer's point of view under current market situations.

In Sweden, the shift able electricity load potential for the investigated measures is estimated to be up to 15 GWh on a daily basis. However, the potential is sensitive to electricity price fluctuation. For example, the potential is estimated higher during high electricity price fluctuation (during winter) than during lower fluctuations (during summer). The peak capacity shifted is 0.3GW from dishwashing and laundry loads, and 0.95 GW from shifting water heating loads. While the dishwashing and laundry loads can be shifted for any length of time as there is no technical limitation, the water heating load be shifted to maximum 10 hours (with current assumption on storage capacity). The load demand shifted to off-peak hour observed for water heating load is ≈ 5 GW and remains close to this value for all the seasons. For the dishwasher and laundry load the final load shift to off-peak hours have been reduced to below 1 GW using valley filling operation. The results from the modelling indicate that the individual household could save between 10 SEK/year to 140 SEK/year depending upon the load shifted. The reason for these low savings is low electricity prices as well as fluctuations in Sweden. The load shifting would, however, require the inhabitants of the households to change their behaviour and also to invest in different smart technology appliances in order to shift the water heating automatically. However, with the estimated low economic savings it is likely to be difficult to realize this potential. On the other hand there is good technical potential for shifting the loads. The results show that on a national basis, up to 5 to 6% of the peak load could be reduced. The cost savings for consumers depends highly on the usage pattern of appliances and hot water.

Another important conclusion of this work is that if the load shift is not managed on a regional or country level but the shifts are managed by the consumers on an individual basis, there is a risk that the load shifting will instead create new peaks on off-peak hours

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Appendix A

Results with valley filling for Behavioural measures

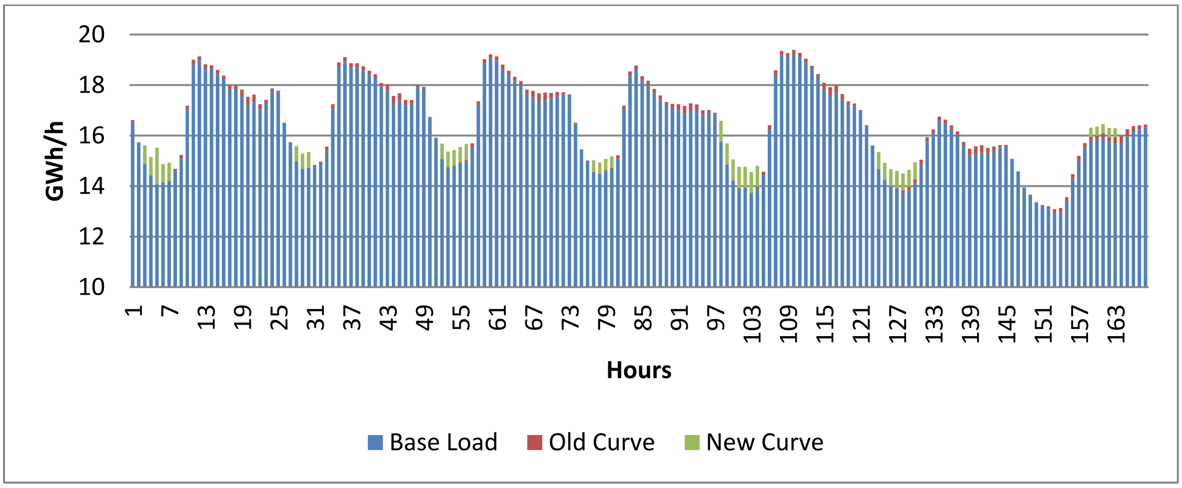

Figure A-1: System load curve of spring week after valley filling the shifted load in the spring week (Week 16 in year 2012).

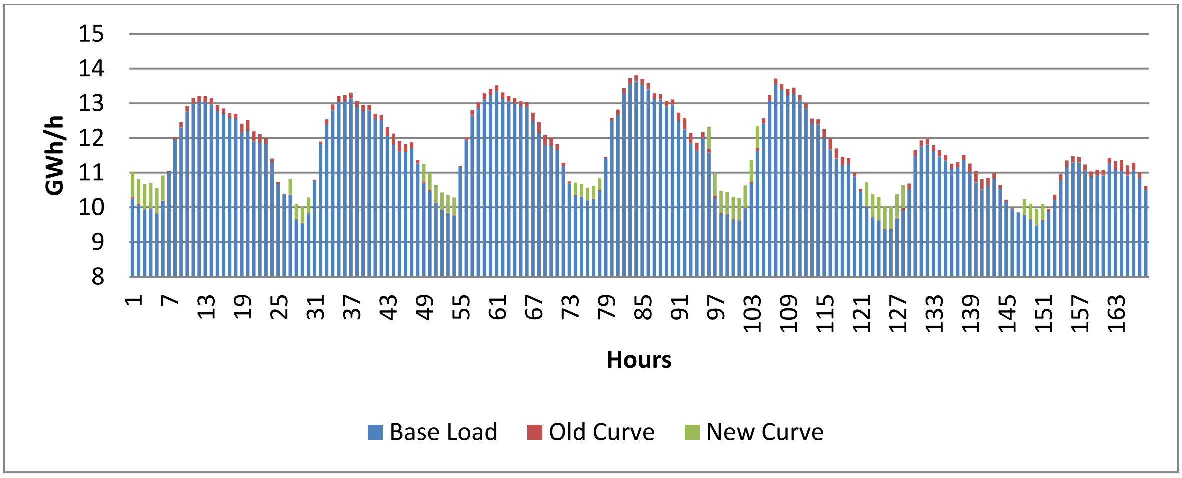

Figure A-2: System load curve of spring week after valley filling the shifted load in the summer week (week 29 in year 2012).

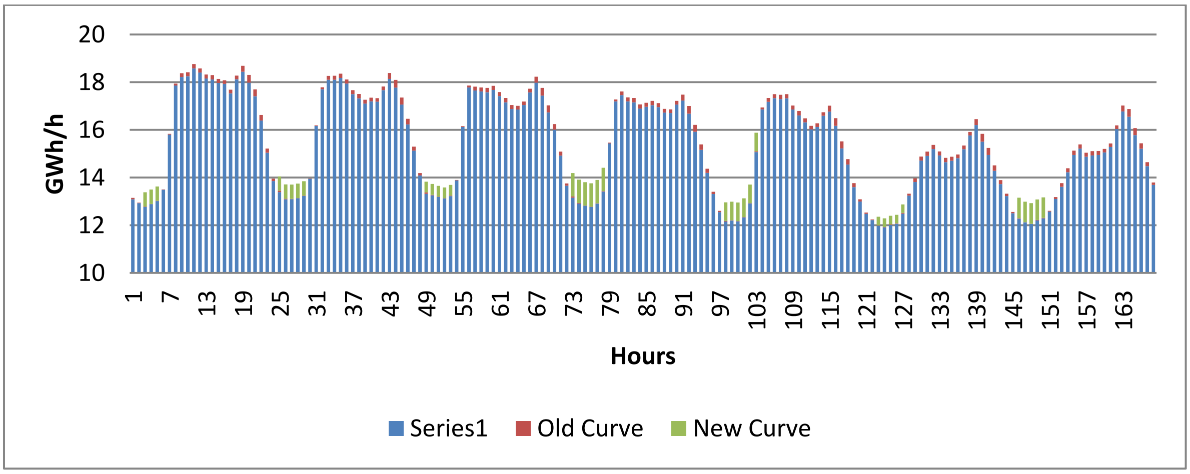

Figure A-3: System load curve of spring week after valley filling the shifted load in the autumn week (week 42 in year 2012).

Appendix B

Water heating load curves on system level without load shifting for investigated weeks.

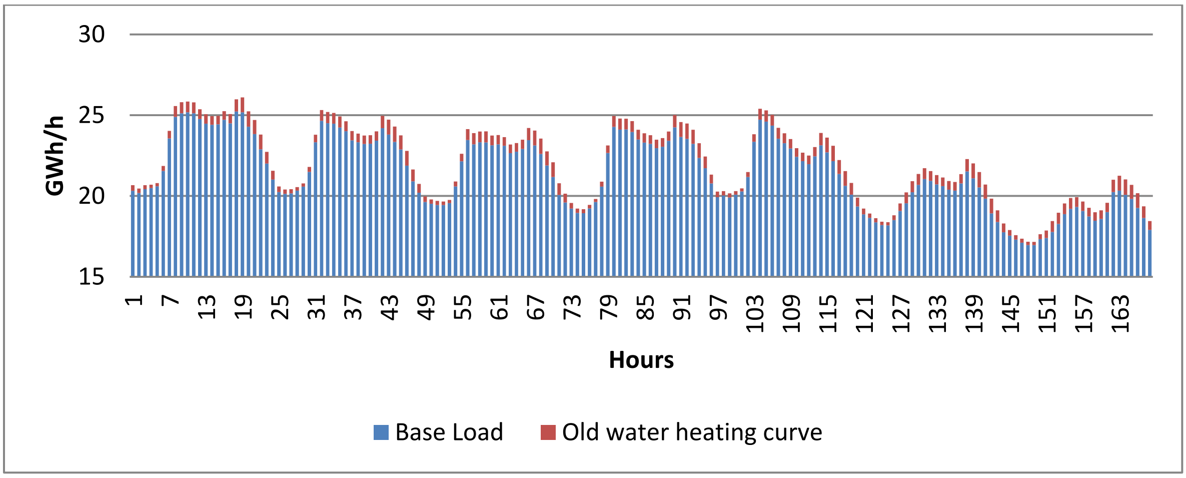

Figure B-1: Swedish electricity load curve with no water heating load shift in winter (week six in year 2012).

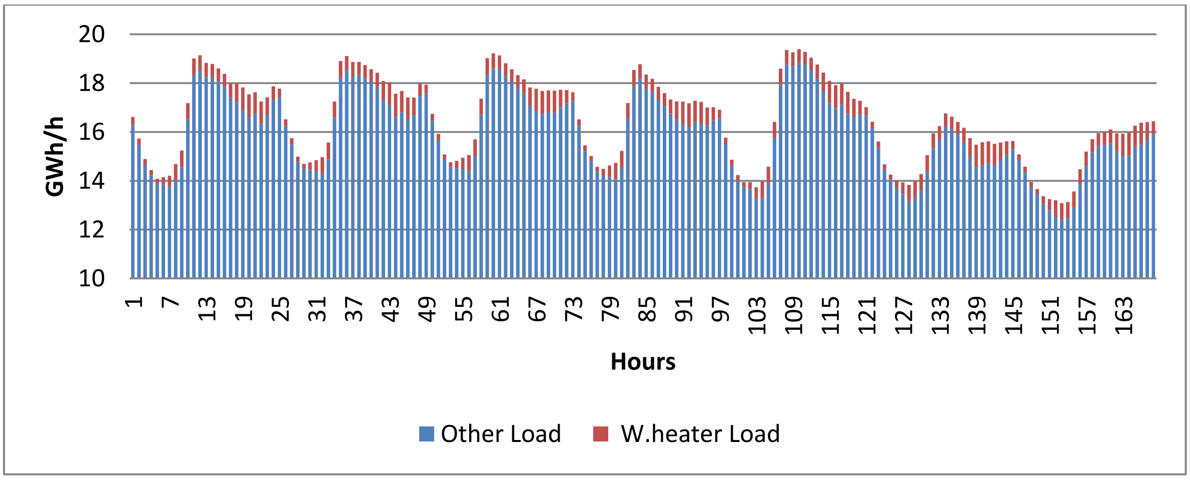

Figure B-2: Swedish electricity load curve with no water heating load shift in a spring week (Week 16 in year 2012).

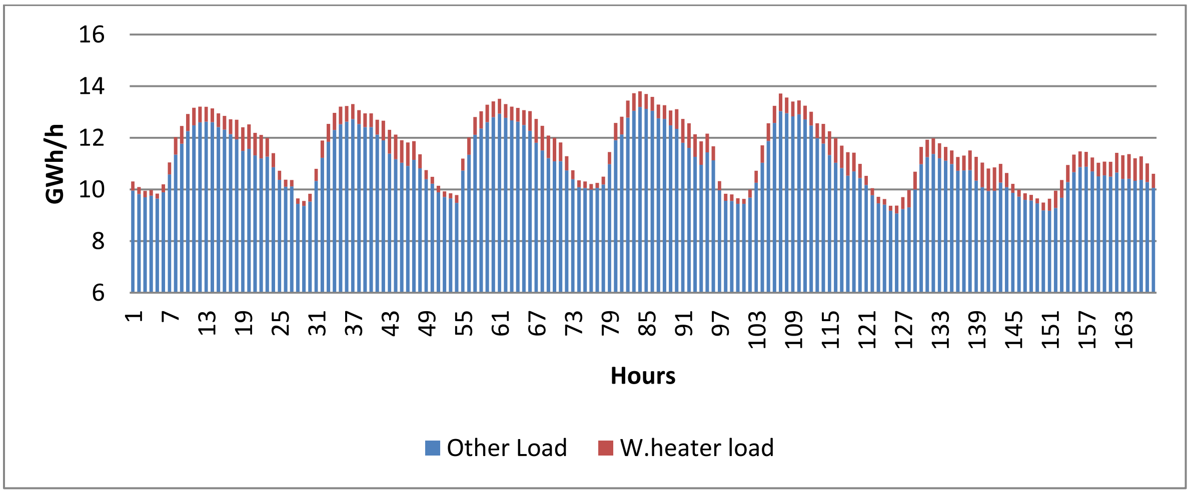

Figure B-3: Swedish electricity load curve with no water heating load shift in summer week (week 29 in year 2012).

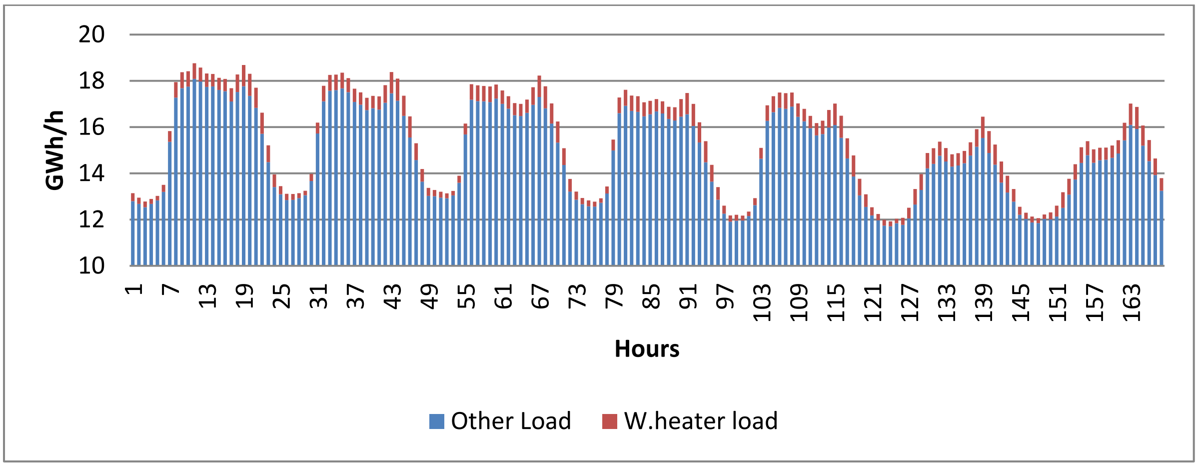

Figure B-4: Swedish electricity load curve with no water heating load shift in autumn week (week 42 in year 2012).

Appendix C

Results for Water heating load shift.

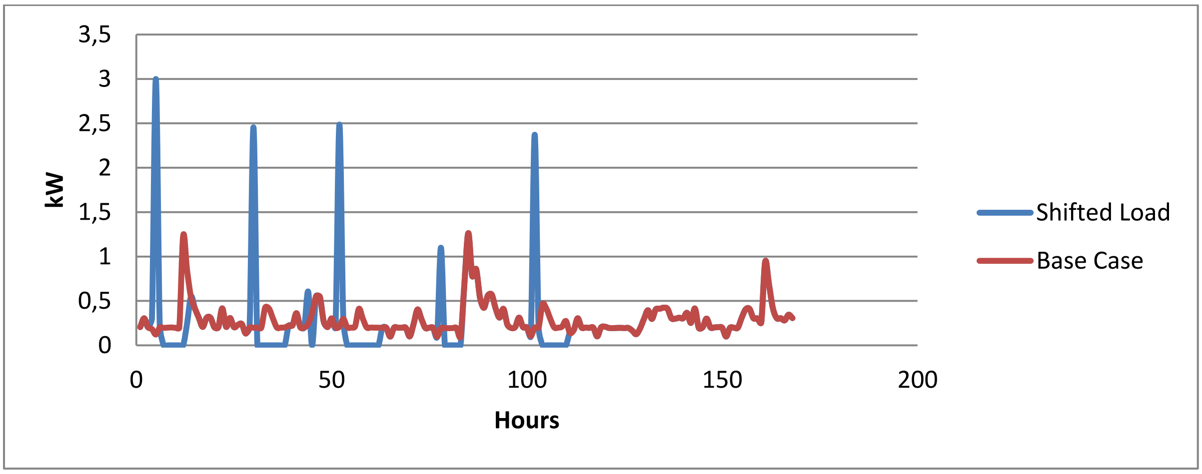

Figure C-1: Water heating load curve before and after load shift during the spring week (Week 16 in year 2012) for SFD with couples.

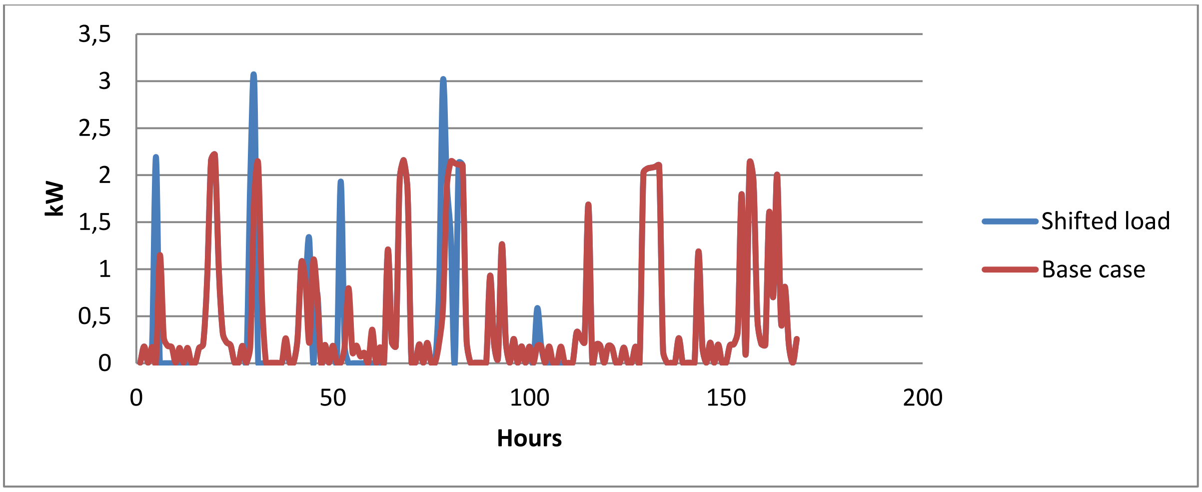

Figure C-2: Water heating load curve before and after load shift during spring (Week 16 in year 2012) for SFD with couples.

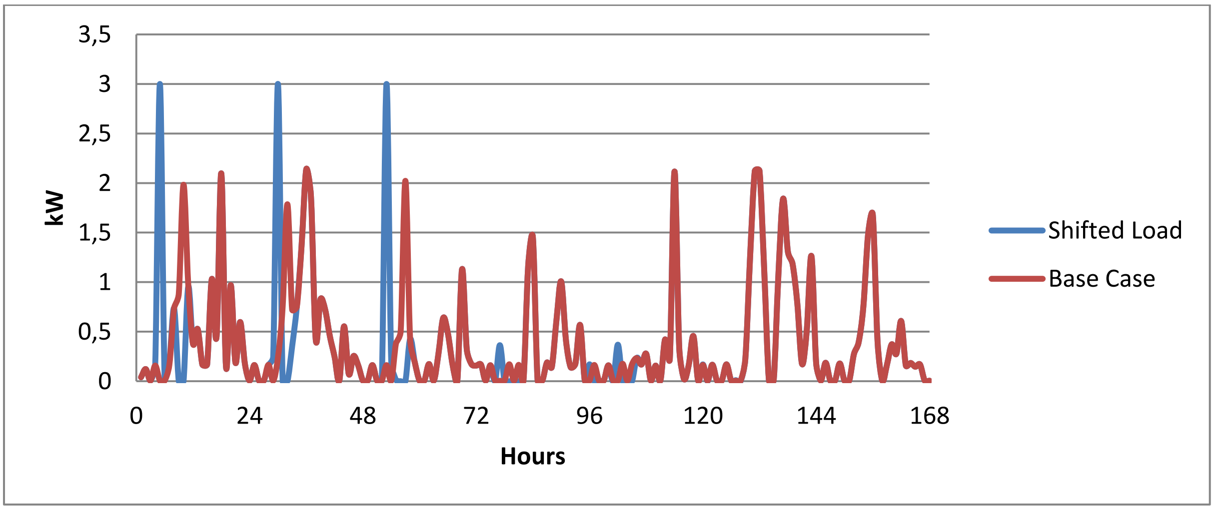

Figure C-3: Water heating load curve before and after load shift during summer (week 29 in year 2012) for SFD with family.

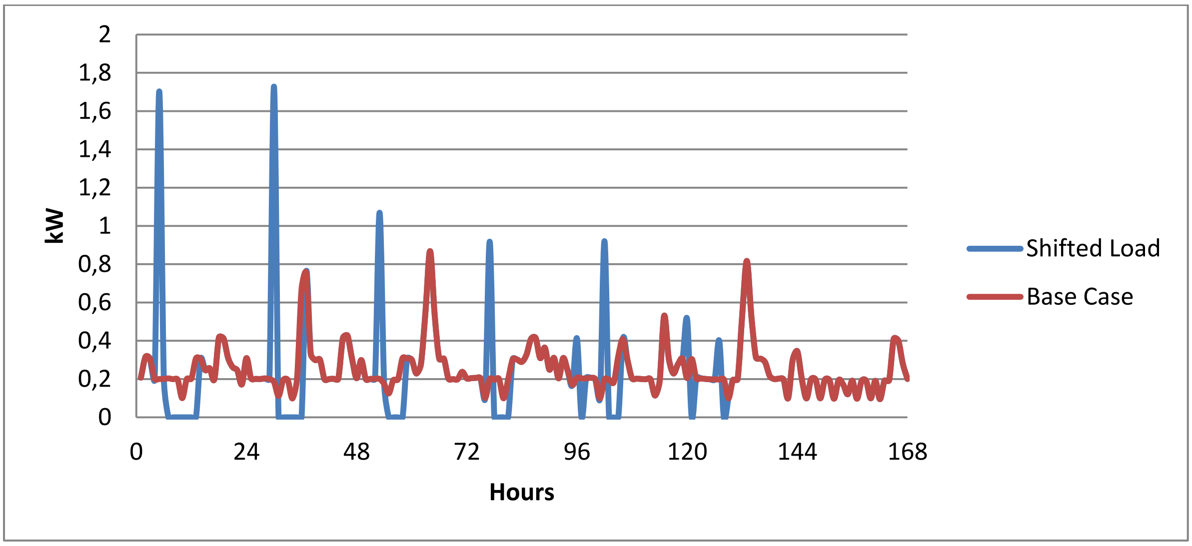

Figure C-4: Water heating load curve before and after load shift during summer (week 29 in year 2012) for SFD with couples.

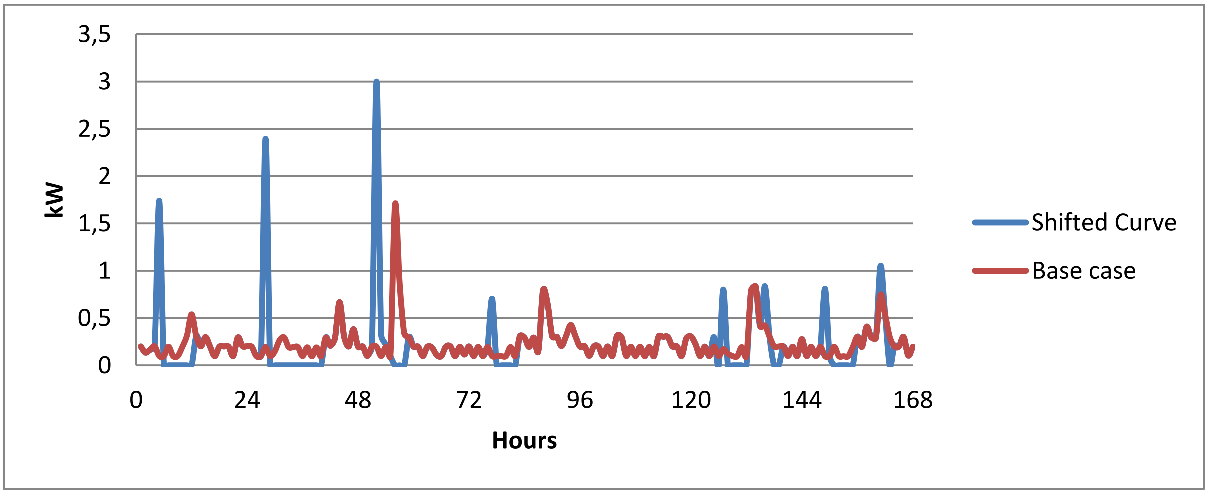

Figure C-5: Water heating load curve before and after load shift during autumn (week 42 in year 2012) for SFD with couples.

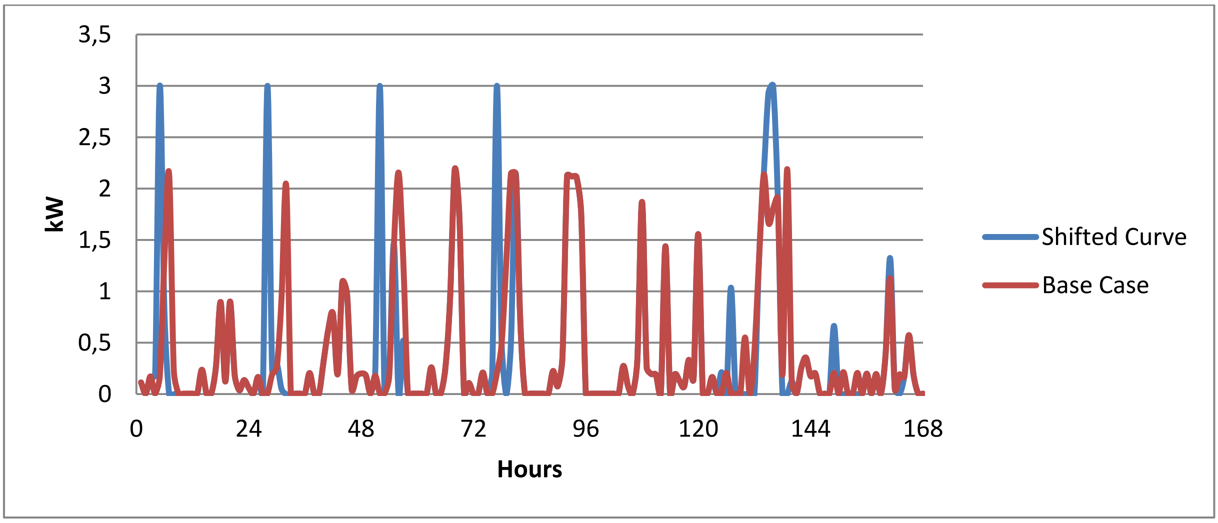

Figure C-6: Water heating load curve before and after load shift during autumn (week 42 in year 2012) for SFD with family.

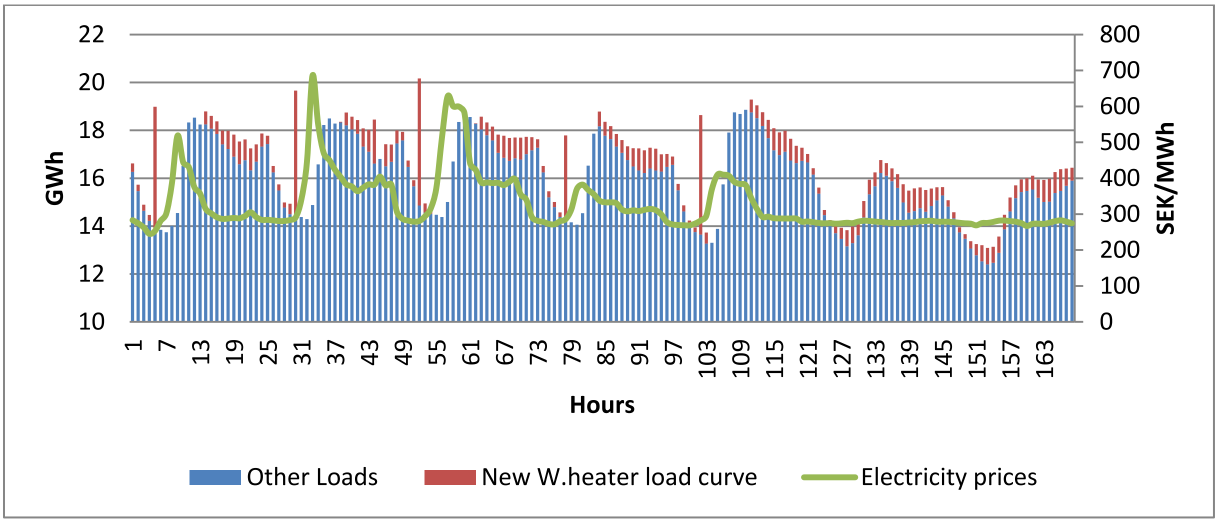

Figure C-7: Effect of water heating load shift on system electric load curve in the selected spring week (Week 16 in year 2012).

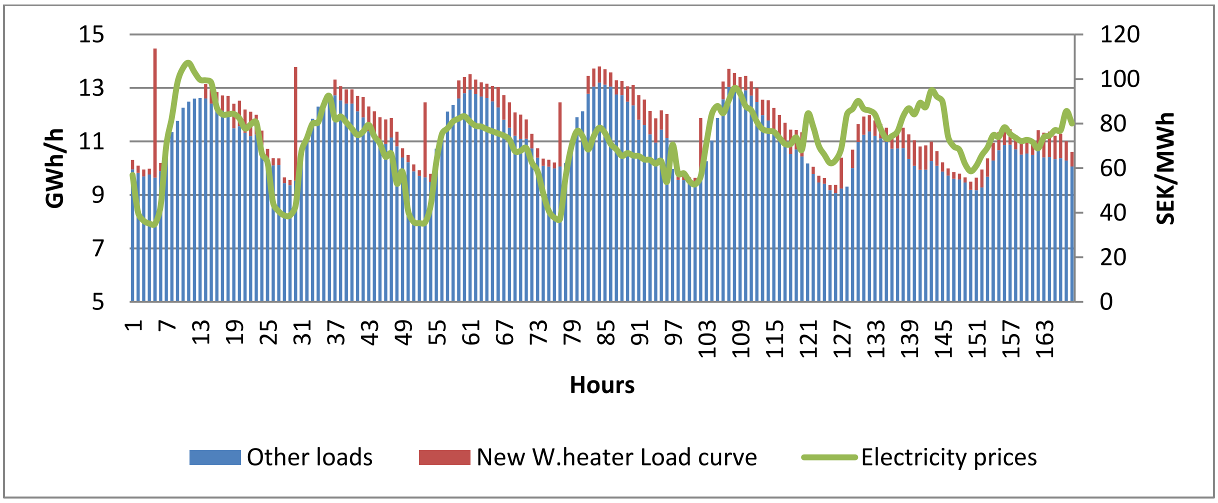

Figure C-8: Effect of water heating load shift on system electric load curve in the selected summer week (week 29 in year 2012).

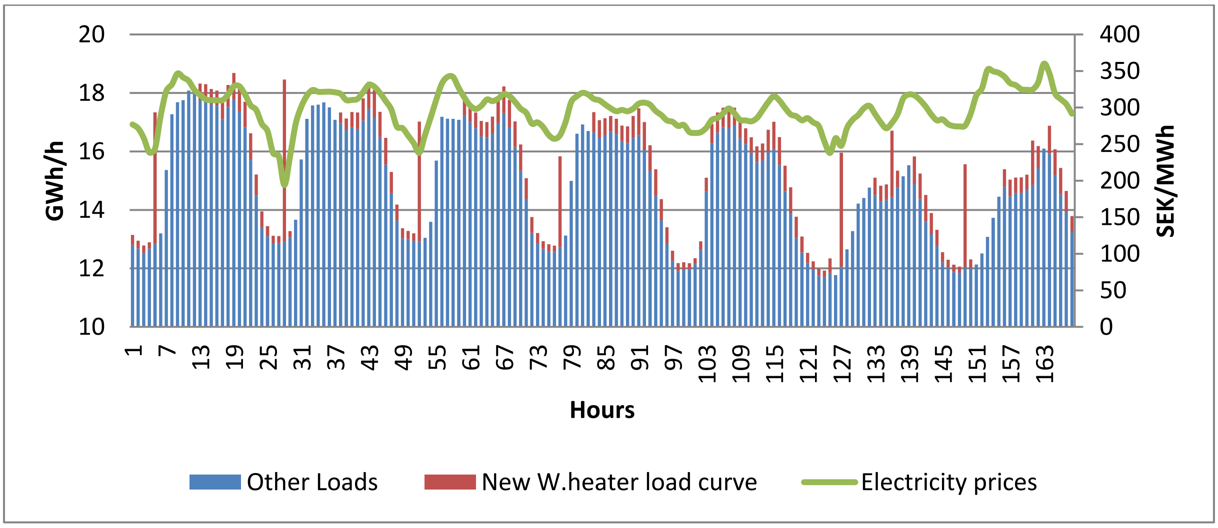

Figure C-9: Effect of water heating load shift on system electric load curve in the selected autumn week (week 42 in year 2012).