AALTO UNIVERSITY SCHOOL OF ELECTRICAL ENGINEERING

ABSTRACT OF THE MASTER'S THESIS

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The primary objective of Smart Grid vision is to facilitate the integration of intermittent renewables with a high degree of reliability. Intermittent renewable energy sources (RES) are characterized by their variability and uncertainty which makes their integration in existing power system a very challenging task. The demand response (DR) is playing a crucial role in smart grid research today and there is a strong belief that DR is the only economical and feasible solution for making the RES integration on a large scale.

The vital aim of this study was to optimize the DR control of electric space heating with some degree of thermal storage in households under a smart grid scenario. The effect of degree of storage on flexibility of controlling the space heating load is compared by varying the size and initial level of thermal storage. The proposed model can easily integrate to the household level to allow a better exploitation of renewable energy sources and reduction of customer energy bill. The control methodology rests on the simple linear programming algorithm which fulfills certain objective without compromising on quality of service. The objective function was based on the dynamic pricing that follows power exchange prices. However this dynamic tariff can take any trend depending on the priorities (market, reliability) of retailer/aggregator.

The study also explored the space heating strategies by performing case studies whose objective was to reduce the peak to average ratio of grid with least loss of user comfort. Thermal model of house was constructed using Simulink to replicate cooling behavior and thermal inertia of the house. The simulation results quantify the flexibility they offer in terms of load shifting and load reduction during peak period and was assessed by observing the heating type load profile and considering the developed thermal model of house.

Keywords: Demand Response, Electric Space heating, Optimal DR Control

Preface

The work in this Master's thesis was carried out at Aalto University School of Electrical Engineering as part of the SGEM project under the supervision of Professor Matti Lehtonen.

There is no superior assistance than the assistance and guidance by Almighty ALLAH. Moreover, it is important to acknowledge the efforts and help provided to me by several individuals, without whom it would not have been possible to complete this Thesis.

I'm deeply indebted to my teacher Prof. Matti Lehtonen, whose help, stimulating suggestions and encouragement helped me in all the time of research. He has exposed me to unlimited potential of self-growth Thank you sir, thanks for having me here.

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Gigantic thanks to my parents for their support, encouragement and patience. They have always been by my side and provided me with firm support. Last but not the least, my special thanks to Fhd, Saqi, M.Ali, Laura, Nancy, Humayun, Farhan, Carlos and Adil for their never ending motivation.

Espoo, Finland. 22nd Oct 2012.

Mubbashir Ali

List of Symbols and Abbreviation

AMI	Advance Metering Infrastructure
AMR	Automatic Meter Reading
Appx.	Approximately
BAU	Business as Usual
C	Specific heat capacity of air
CPP	Critical Peak Pricing
DA	Day Ahead
DEH	Direct Electric Heating
DR	Demand Response
E	Energy stored
E_d	Energy (heat) demand
FI	Finland
Hr	Hour
K	Price signal
L-R	Load Reduction
M	Thermal mass of the house
Mins	Minutes
MWh	Mega-Watt hour
N	Air changes per hour
P	Charging speed
Q_{loss}	Total heat Loss
q_0	Initial level of storage

Qf	Fabric Heat Loss
q_n	Average demand of nth hour
Qv	Heat Loss through Ventilation
R	Thermal Resistance
RES	Renewable Energy Sources
RTP	Real Time Pricing
S	Realizable Storage potential
Temp	Temperature
TCA	Thermostatically Controlled Appliances
ToU	Time of Use
U	Coefficient of Thermal Conductivity
V	Volume of the building that is to be heated
W_{out}	Consumed heat energy
x	Degree of storage
X	Heating load (KWh/h)
$\Delta\theta$	Temperature rise
α	Duty Cycle
$\boldsymbol{\tau}$	Thermal Time Constant

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1. Introduction

As the deregulation and unbundling of electric utilities continues to soar, the role of DR is getting more and more important.

The demand response can be best described as

> ***"Changes in electric usage by demand-side resources from their normal consumption patterns in response to changes in the price of electricity over time, or to incentive payments designed to induce lower electricity use at times of high wholesale market prices or when system reliability is jeopardized*** [1]***."***

The central task of demand response is to clip off the peak demand for maximum utilization of power system. The ability of DR is to change the amount and time of electric energy usage so that the best efficiency of consumption takes place in the peak interval [2]. The economical and feasible implementation of demand response program is a very challenging task therefore substantial research should be done to attain the desire goal. The issues such as quantification of DR potential and its duration and most important is that the customer incentives arrangement should be addressed adequately.

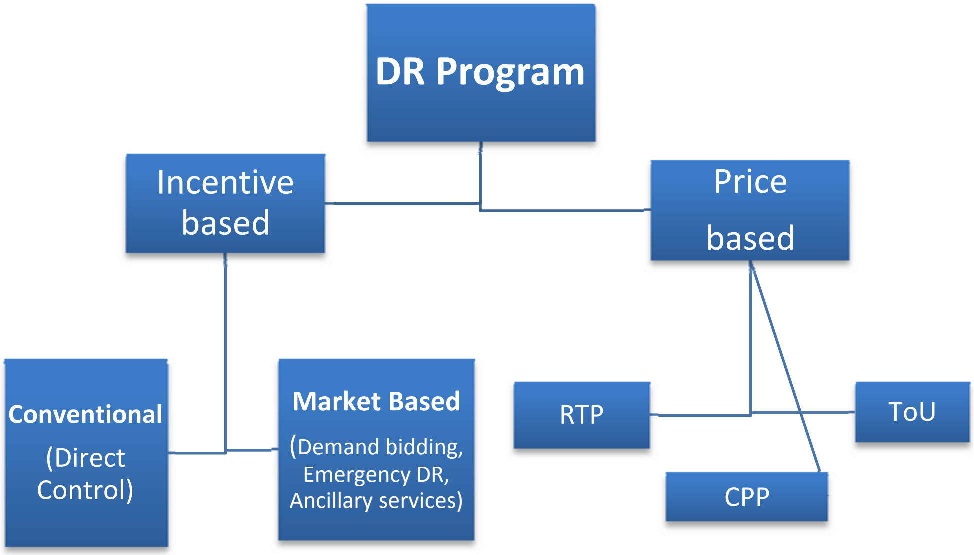

Fig 1.1: Classification of Demand Response Programs [3]

So Price based DR program are mainly classified into Real Time Pricing (RTP), Critical Peak Pricing (CPP) and ToU (Time of Use) Pricing. RTP refers to the dynamic tariff and are well suited program in view of the Elspot market. In case of ToU pricing, there may be peak period and off peak period tariff. Whereas in CPP, the peak price rate may be 3-4 times higher than normal rate and CPP are called during contingencies or in times of high spike in spot market.

All electrical loads are not suited for DR. In other words the potential of DR depend on the nature of load. The quantification of the DR of any load calls for the base load modeling. The load can be curtailed, reduced or postponed as long as the end use characteristic of such load is preserved. So making the load responsive and active requires some actions to be taken. The price can be a decisive factor in making load responsive. The introduction of price volatility will bring changes in the load shape and hence required targets can be achieved. Incentives can also mitigate the load dullness in terms of its response and allow them to participate actively. However these all actions must ensure that user comfort is not at all sacrifice and end user characteristics are not compromised beyond certain level, whatsoever.

Considering the household, load can be categorized broadly into 2 categories:

- Thermostatic load (AC, water heaters, space heater, heating oven etc)
- Non thermostatic load (lights, fans, washing machine, gadgets etc)

The thermostatic controlled appliances (TCAs) are more suited for DR applications as small shift or change in load wouldn’t be noticed by user while non thermostatic load curve alteration requires user acceptance and permission. Also few TCAs load are directly dependent on outside temperature and hence hourly load is somewhat predictable with good accuracy, while with the advent of smart metering penetration, the non-TCA load curve would also be known with higher accuracy. The aggregation of residential TCA loads can provide significant demand response scope.

1.1 Research Problem

The intermittent renewable energy sources (wind and solar) are penetrating in power system. However their unpredictability and variability puts the power system reliability at risk. Wind and solar generation poses certain operational challenges for the transmission grid such as balancing, additional ramping requirements [4].The aging infrastructure of power system further aggravates the problem.

The power system will be more utilized if the fluctuations in demand are minimal. The existing power system around the world is facing continuing load growth and integration of intermittent renewable generation. Hence the capacity should be increased to meet all the challenges. That requires huge investment which is not feasible given the unbundling of power system. The feasible solution would be to make demand as responsive as it could in order to maximize the utilization of existing grid system. Load shaping rather the load following should be the strategy of future grids [4]. That will not only postpone the infrastructure investment but would make system more reliable and thwart any blackout or brownouts. The integration of intermittent renewables is challenging task. However with the introduction of these renewables, some additional reserve requirement is required for the sake of no compromise on reliability. The more station capacity is highly capital-intensive and thus cheaper option is DR. Given the low accuracy in predictability of these renewables, the renewables integration would put the system at higher risk unless some extensive measures are to be taken such as storage. However the storage technology is too expensive to be implemented.

Keeping in view of the situation, DR looks promising to provide safe passage to intermittent renewables [5] [6] [7] and can play an integral role in their integration. The loads like electric space heating and introduction of loads like plug-in electric vehicles can transform this challenge into opportunity. These loads come with certain storage and with the advent of AMR the load can be shaped to facilitate the operation of power system. The significant DR potential available at household level in the form of electric space heating storage is yet to be utilized. The obstructions in unleashing the DR potential of electric space heating are lack of smart grid infrastructure, vague consumer incentive program and issues related to quality of service, unawareness of the DR potential and optimal DR control methodology. One of the drawbacks of power market is the fact that most consumers are unexposed to price volatility. RTP programs are well suited program in view of the spot market these days. In Finland mostly customer pays 8 cents/KWh [8] even when prices are as high as 1000 euro/MWh. So, the flat rate is responsible for inactive response. However the major hindrance in implementing RTP is not communication infrastructure but the consumer mindset. Implementing RTP mean fluctuating energy bill and certainly consumer will be against such program. A possibility can be made if aggregator take the risk of RTP and implement some incentive based program down the line to the end user. This policy would be fruitful from power system reliability point of view. The dynamic tariff will help in flattening the load curve, reducing the price volatility in whole sale market, security of the power system in contingency and making the integration of renewables easy.

The thesis first evaluates the DR potential of electric space heating and then proposes optimal DR control which requires least infrastructure. It also throws light on how a market based DR using dynamic tariff can be achieved taking into account the occupant thermal comfort. In this way it stresses on the importance of bridging the hidden potential and performance gap.

1.2 Objective and Organization of the Thesis

The central task of the work is to analyze the DR potential of electric space heating in households under the smart grid scenario. The essential steps are fulfilled in order to achieve the desire goal. They are as follows and also indicate the flow of thesis.

- To develop a thermal model of a typical house in Simulink. The thermal time constant of house is determined using mathematical equations and existing literature. *(Chapter 2)*

- Analyze the Nordic electricity market scenario and variation in spot prices over the year. Case study is performed over the winter 2011/12 spot prices (FI area). To get idea about the impact of increased renewables on power market, a literature review of German electricity market and its comparison with Nordic market is done.*(Chapter 3)*

- Electric space heating strategies are developed and case study of different type of space heating is performed to analyze the DR potential of such load using the type load data for different type of heating customers.*(Chapter 4)*

- Developing a model of thermal storage using mathematical equations/expressions. *(Chapter5)*

- Finally, optimal DR control of electric space heating with some degree of storage is proposed using dynamic pricing as a signal. The control algorithm complies with the developed mathematical model of thermal storage. Case study is performed for different degree of storage and comparison with BAU case is done using simulation results.*(Chapter 5)*

2. Developing Thermal Model of a Typical Finnish House

2.1 Electric Space Heating in Finland

Finland has the highest energy consumption per dwelling thanks to the extreme weather and high living standard. On an average, the consumption is 14000 KWh/ year per dwelling [1]. Approximately one quarter of households in Finland utilize some form of electric heating, which accounts for around 40% of all electricity consumed by the household sector. Electrical heating is used for space heating of homes and cottages (including full storage heating, partial storage heating and direct heating) as well as for domestic hot water, car heating and for electrical saunas, which are found in many homes in Finland [9].

Households account for 12.2% of electricity consumption in Finland, and together with residential electric heating, the share is 21.6%

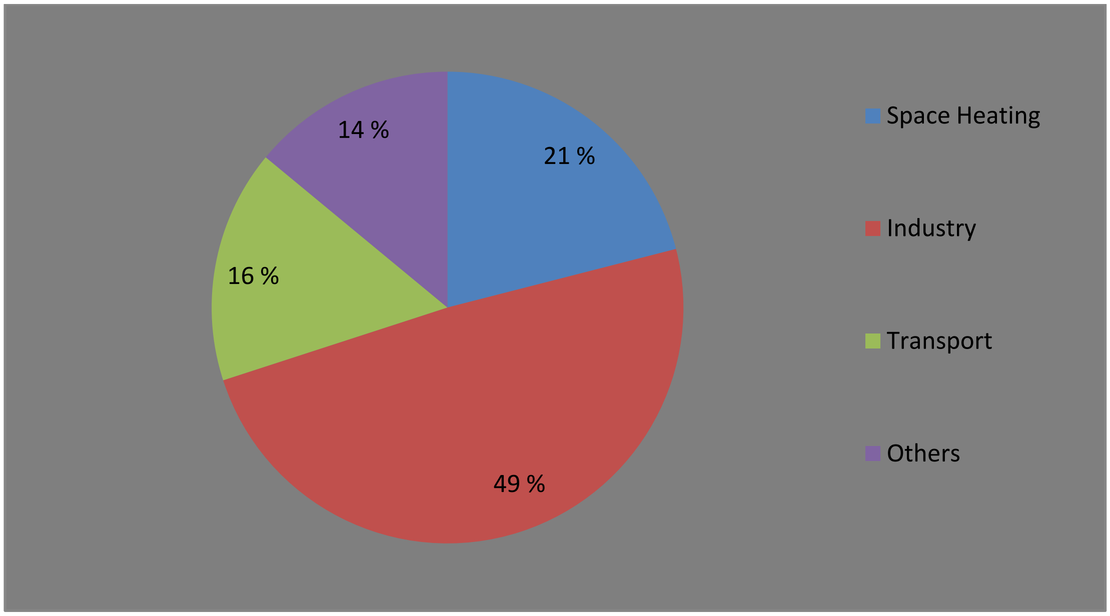

Fig 2.1.The Share of Space Heating in Total Consumption [10]

The contribution of space heating load to peak load is illustrated below

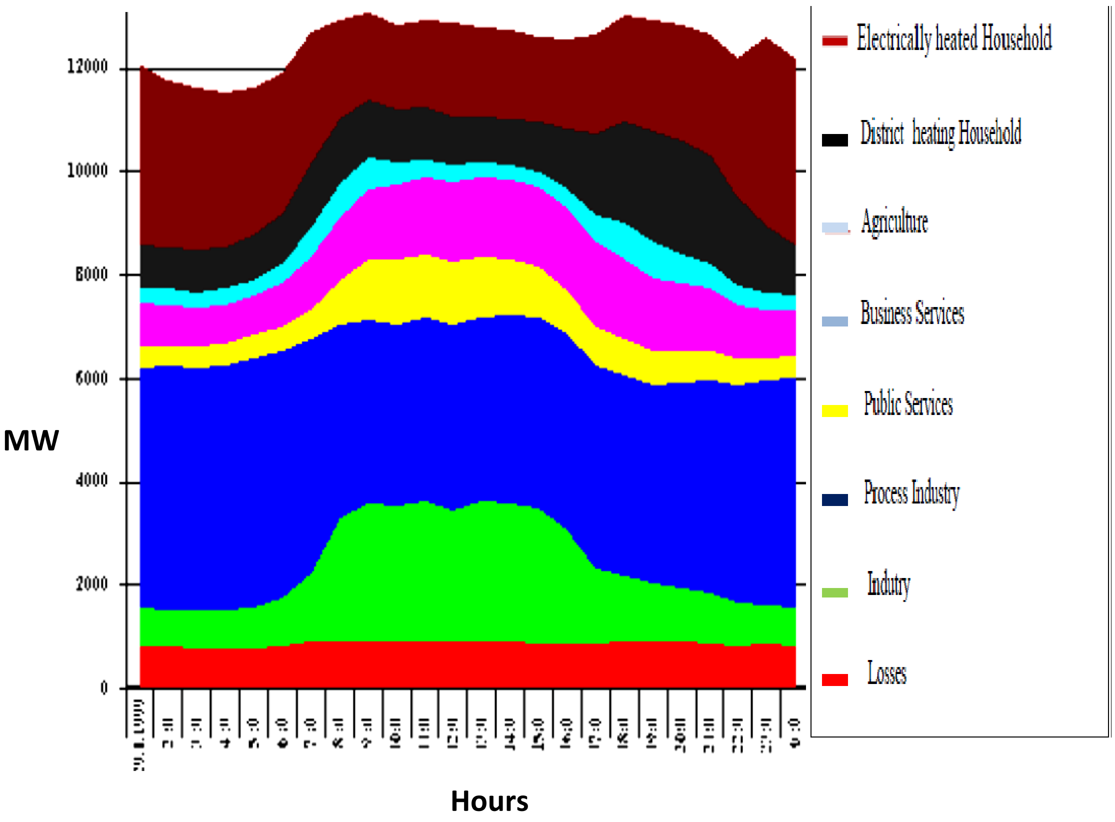

Fig2.2 Segmentation of Finland Peak Load curve [11]

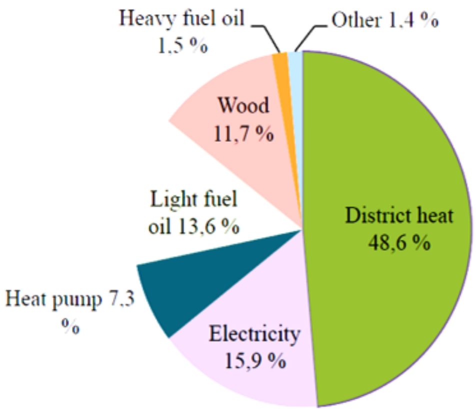

Fig 2.3: Market Share of Heating [12]

2.1.1 Electric Heating Technology in Finnish Houses

The forms of electric space heating that is common in Finnish houses are as follows:

- Direct electric heating:
- Resistor electric heating equipped with thermostat to change the set point.
- Storage electric heating
- Partial storage electric heating
- Heat pump

The full storage heating house has bounty of heat storage, the temperature of which can be controlled independently from the inside temperatures. The difference between the direct electric heating and storage electric heating is not in operation but in storage capability. Heat can be stored in a controlled manner. They can be charged at certain time and then allowed to coast for some period. In Finland, water circulating storage tank are often used. While massive bricks of thermal inertia are also used to store heat and radiate afterwards.

The following techniques are currently employed for controlling [13].

- Manual adjustment of thermostat
- Charging time setting
- Room temperature setting and set point change option during the day
- Optimize control.

In partial storage electric heating, the heat dynamics of the storing mass of partial heating are much more tightly connected to the room temperature, which poses a tough challenge to control the storage optimally. For instance: floor under heating etc.

The heat pump technology is still in its infancy (7% share of electric heating). The partial storage electric heating and heat pumps has currently lower share in the space heating. Thus they are not considered in the analysis. In Finland, nearly 79000 detached houses are equipped with storage electric heating while 300,000 houses with direct electric heating.

2.2 Calculating the Heat Loss of a Typical House

For calculating the heat loss, a typical house of Finland is considered whose dimensions and characteristic are listed in Table 1 and 2 respectively. The calculated losses may not be as accurate and deeper analysis and heat dynamic study is required to assess losses with higher accuracy. However such task is out of scope. So the analysis rests on basic calculation and data.

Table 2.1: House Dimension: (2 Bed rooms, living room, Kitchen, toilet)

Ground area (m^2)	60
Total floor area (m^2)	120
Floor plan (m^2)	60
External wall area (m^2)	38
Window area (m^2)	11
Total volume (m^3)	300

Total heat Loss (Q_{loss}) = Fabric Heat Loss (Q_f) + Ventilation Loss (Q_v)

- Fabric heat Loss is contributed by convection, radiation and conduction.
- Ventilation losses are due to non air tightness of house plus air changes per hour.

Fabric loss is given as:

$Q_f = U*A*(Tout-Tin)$

Where, U values are thermal transmittance coefficient

Table 2.2: Typical U-Values (W/ (m^2*K)) of Finnish Home *[14]*

Wall	0.25
Roof	**0.16**
Floor	**0.25**
Windows	**1.1**

2.2.1 Fabric Heat Loss

Section	U values (W/m2/°C)	Area	U*A Values (W/°C)
External wall	0.25	38	9.5
Roof	0.16	60	9.6
Floor	0.25	120	30
Windows	1.1	10	11
		Sum of UA values	60.1

2.2.2 Ventilation Heat Loss

It is given as:

$$\boldsymbol{Qv = \frac{C * N * V * \Delta T}{3600}}$$

Where,

- Q_v is the ventilation heat loss (Watts)
- C is the specific heat capacity of air (1210 J/m^{3}K)
- N is the number of air changes per hour
- V is the volume of the house
- ΔT is the difference in temperature

The total heat loss is the sum of fabric and ventilation losses,

Substituting Q_f and Q_v will lead to

Q (Loss) = 60 ΔT + 30ΔT $(with\ N = 0.3)$ = 0.09 ΔT KWh

So clearly heat loss is a function of differential temperature. Now moving on with this, temperature profile of average day of winter is selected to calculate the average heat loss of this typical house for that day.

Table 2.3: Average Heat Loss of Modeled House on a Typical Winter Day

Time	Avg. Outdoor Temp	Q(loss) KWh
00:00:00	-10.3	2.54
01:00:00	-10.2	2.53
02:00:00	-10.2	2.53
03:00:00	-10.2	2.53
04:00:00	-10.4	2.55
05:00:00	-10.7	2.58
06:00:00	-10.9	2.60
07:00:00	-11.7	2.67
08:00:00	-11.5	2.65
09:00:00	-12.5	2.74
10:00:00	-12.4	2.73
11:00:00	-12.3	2.72
12:00:00	-12.6	2.75
13:00:00	-13	2.7
14:00:00	-13.3	2.81
15:00:00	-13.8	2.86
16:00:00	-14.3	2.90
17:00:00	-14.8	2.95
18:00:00	-15.3	2.99
19:00:00	-16.2	3.07
20:00:00	-16.9	3.14
21:00:00	-17.2	3.16
22:00:00	-18.1	3.24
23:00:00	-18.6	3.29
	Total Heat Loss (KWh)	67.44

The total Heat Loss is a rough and exaggerated value as it doesn't take into account the natural thermal storage of a house (thermal mass or inertia). However type load model data of detached houses is used to performed case studies in the following chapters.

2.3 Calculating the Thermal Inertia of Modeled House

Before shifting gears to DR strategies, let’s find out the thermal time constant of the described typical house. The thermal inertia of the house will play a key role in DR, as it will allow shifting energy consumption without compromising the comfort of inhabitant. How long the heating can be shifted is totally dependent on the thermal time constant of typical house

The thermal time constant is given by the stored energy divided by the specific heat loss.

$$\boldsymbol{\tau = \frac{Stored\ Heat}{Specific\ Heat\ loss}}$$

The energy stored by the building, for a temperature rise Δθ above ambient, is E=MCΔθ

Where,

- E= Energy stored
- M = thermal mass of the building
- C = specific heat
- Δθ= Temperature rise

Mostly the stored heat will reside in walls cavity [15] and specific heat loss of considered home is 105 W/K and Assuming specific heat to be 880J/kg-k.

$$\tau = \frac{10000Kg * 880\frac{J}{Kg*K}}{105\frac{W}{K}}$$

Therefore thermal time constant comes out to be 83809 seconds or 23 Hours approximately.

2.4 Thermal Model of a House

The thermal model houses have been simulated in Simulink. The model has been adopted from Matlab but significant changes (U values and Thermal time constant) have been done according to Finnish housing model and control technique.

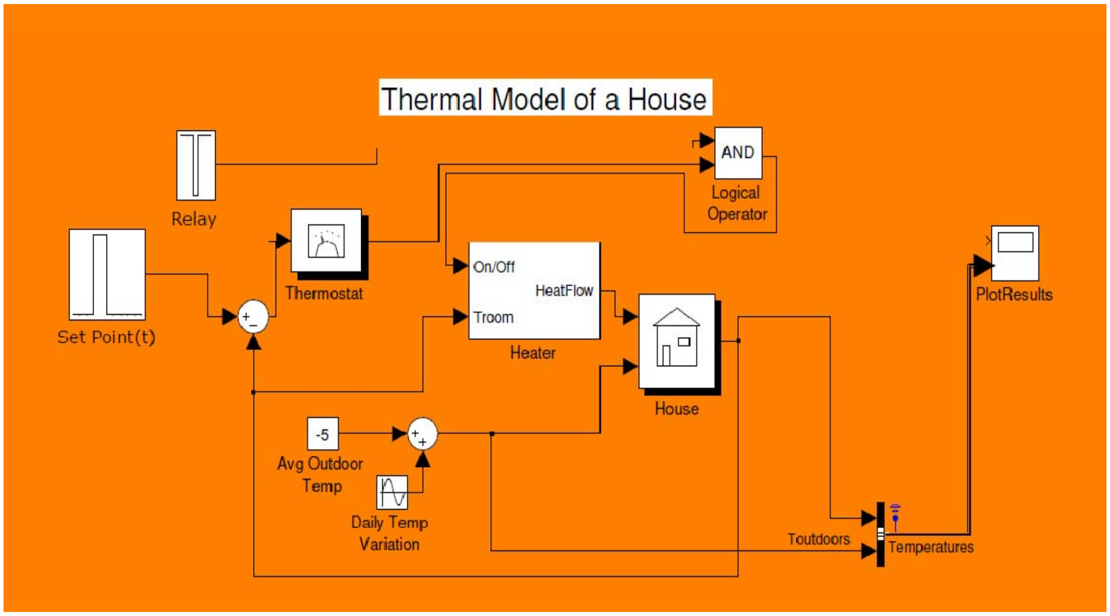

Fig 2.4: Thermal Model of House

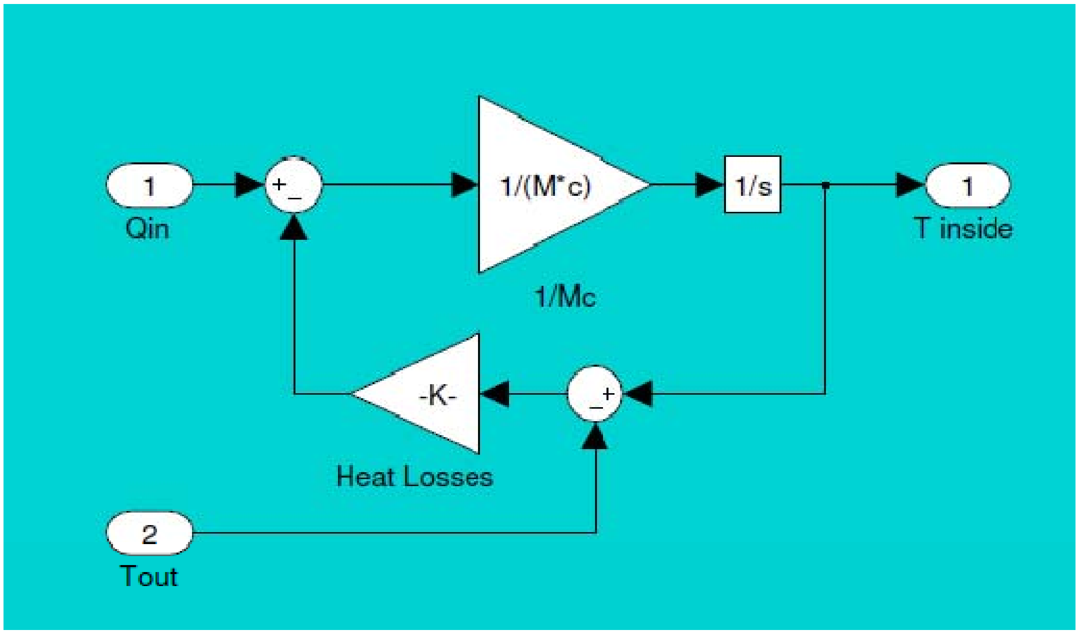

Fig 2.5: House Subsystem; Modeling losses as R equivalent

Typical thermal response of a house equipped with Direct Electrical heating

$$T(inside) = \Delta T e^{-\frac{t}{\zeta}} + T(ambient) \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots..1$$

Where,

- ΔT is Target Temperature Differential of building
- ζ is Thermal Time constant of House

Rate of heat loss from the house is given by the following equation.

$$\frac{\boldsymbol{dQ}}{\boldsymbol{dt}} = \frac{\boldsymbol{T(inside) - T(out)}}{\boldsymbol{R(equivalent)}}$$

Assuming an outdoor temperature of -8 degrees over the day, the inside temperature corresponding to an average outdoor temp of -8 degrees is plotted below. The model complies with following thermostat setting

From	TO	Set Point (^{0}C)
6:00 a.m	8:00 a.m.	21
8:00 a.m.	6:00 p.m.	16.5
6:00 p.m.	10:00 p.m.	21
10:00 p.m.	6:00 a.m.	16.5

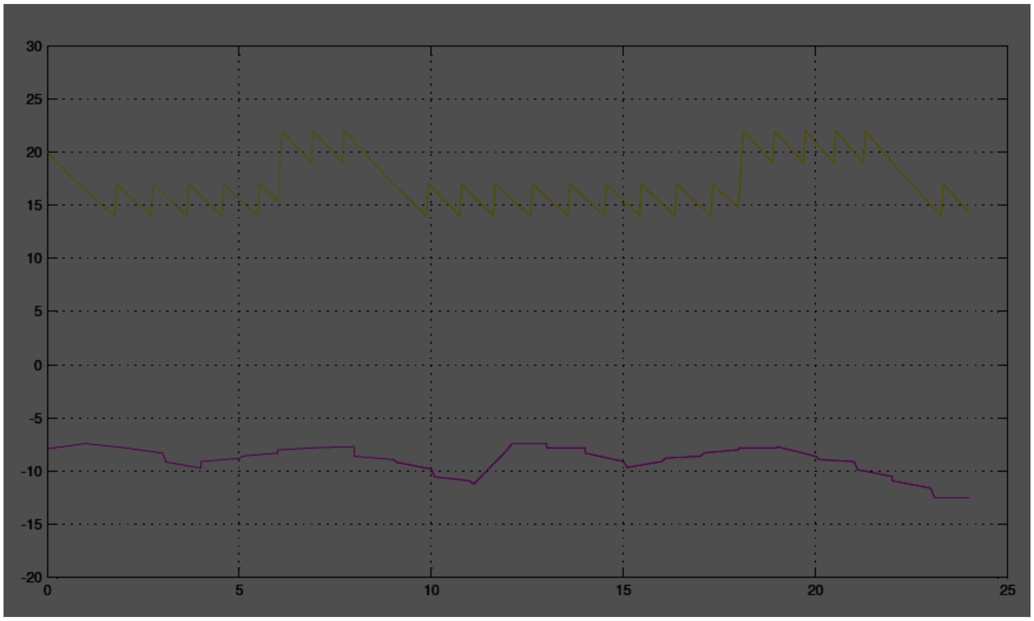

Fig 2.6: Heating pattern of a typical Finnish house

In case of House cooling phenomenon see Fig 7, which happens when the heater is switched off.

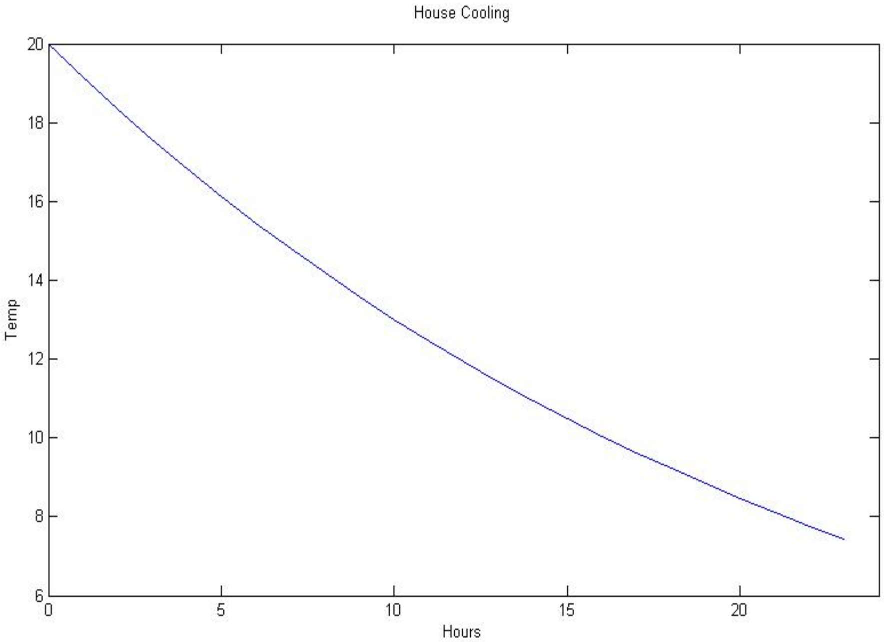

Fig 2.7: Cooling phenomenon of the Modeled House

3. Nordic Electricity Market

3.1 Operation of Nordic Electricity Market

Nordpool is the only Power market in Nordic Region and around 70% of Electricity trade is carried out through that platform while rest through bilateral agreement. The Nordic power system comprises of all type of major generation namely hydro, thermal (Coal, Oil, Gas) and quite a share of RES. The intraday variation and temporal variation of price is prominent in Nordic market. High consumption, extreme cold weather, transmission side problem are the basis of high prices. The unresponsiveness of demand side is also a factor for high price. Day-ahead market indicates that there is a significant potential of Demand response in peak price scenario [16] [17] [18].

Table 3.1: Nordic Generation Capacity (MW) *[19]*

	Denmark	Finland	Norway	Sweden
Installed capacity	13530	16918	31393	35713
Nuclear Power	-	2696		9151
Thermal Power	19438	21802	1045	16374
Hydro Power	9	3124	29913	16200
Wind Power	3802	197	435	2163

Table 3.2: Generation Capacity by Producers, 2010 *[19]*

	Capacity(MW)	Share
Denmark		
Dong Energy	6265	6,4%
Vattenfall	1774	1,8%
Finland		
Fortum	4888	5,0%
PVO	3706	3,8%
Helsingin Energia	1342	1,4%
Norway		
Statkraft	12953	13,3%
Sweden		
Vattenfall	13552	13,9%
E.ON Sweden	6552	6,7%
Fortum	5819	6,0%
Other	40701	41,7%
Total Nordic region	97552	100 %

3.2 Price Scenario 2010.

The beginning of 2010 witnessed several price peaks in most of the Nordic price areas. Low temperatures, low Swedish nuclear power generation and low available transmission capacities contributed to these prices [20].

Table 3.3: Average Elspot prices in [EUR/MWh] (data from *[21]*)

YEAR	SYS	SE	FI	DK1	DK2	EE	Oslo	Kr.sand	Bergen	Molde	Tr.heim	Tromsø
2011	**47,05**	**-**	**49,30**	**47,96**	**49,41**	**43,35**	**46,41**	**46,09**	**45,85**	**47,49**	**47,49**	**47,48**
2010	**53,06**	**56,82**	**56,64**	**46,49**	**56,94**		**54,25**	**50,82**	**51,79**	**58,04**	**58,04**	**57,33**
2009	**35,02**	**37,01**	**36,98**	**36,05**	**39,88**		**33,74**	**33,74**	**33,74**	**35,55**	**35,55**	**35,53**

During the year 2010, all time extreme prices occurred on 22nd Feb 2010 when area prices increased over 1400 euro/MWh.

Table 3.4: Top 10 Spot prices (FI) in year 2010 (data from *[21]*)

Finnish Time	Euro/MWh
22.02.2010 10:00	**1 400.11**
22.02.2010 11:00	**1 400.11**
22.02.2010 12:00	**1 400.10**
22.02.2010 19:00	**1 000.09**
22.02.2010 09:00	**1 000.08**
22.02.2010 13:00	**1 000.07**
22.02.2010 20:00	**1 000.06**
08.01.2010 09:00	**1 000.01**
08.01.2010 10:00	**1 000.01**
08.01.2010 11:00	**1 000.01**

Studies have nevertheless shown a significant demand side response in high price periods, which suggest that there is certain demand side price elasticity when the conditions are right. However price equalization would only happen if the DR is included in the bids to the day ahead (DA) market (Elspot) [22]**.** The existing DR is due to industries at present.

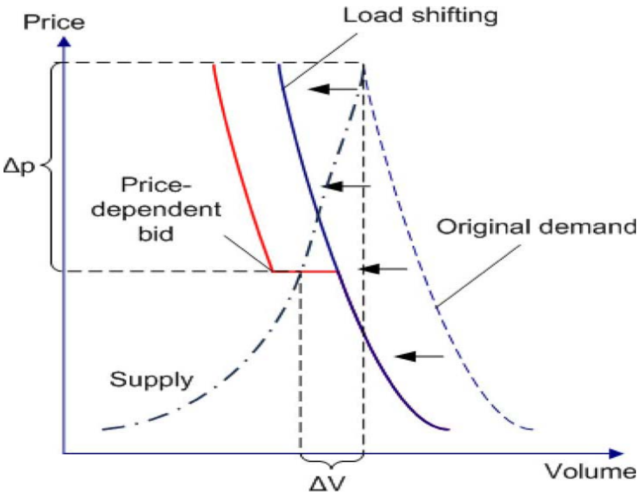

Fig 3.1: DR bid in DA market [22]

Demand reduction of few 100s of MW has a significant impact on spot prices (keeping available transmission capacity and other factors intact). The reason is the cost of generation increases manifold at higher level or sometimes the deficit of generation calls for stringent action to keep the system secure.

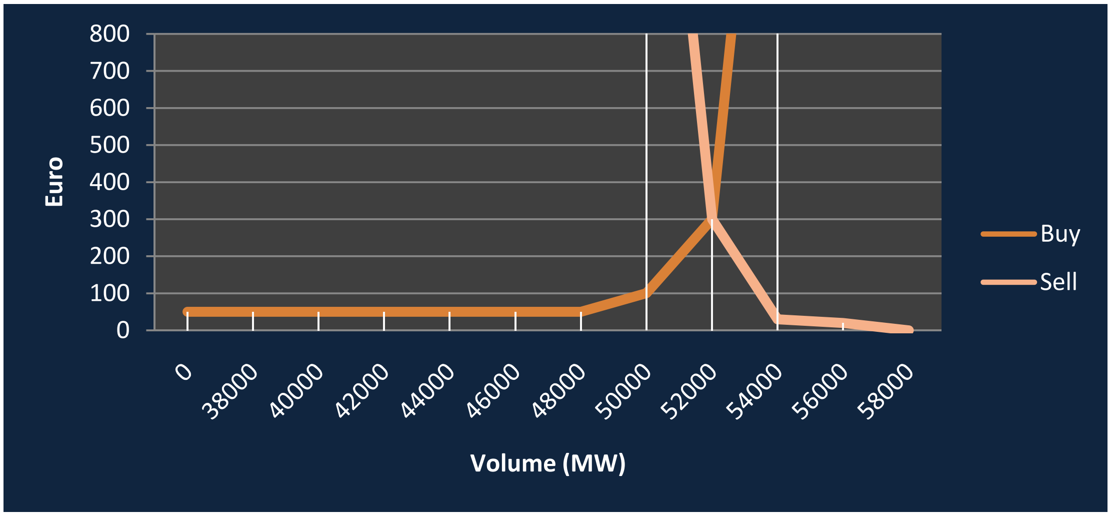

Fig 3.2: Impact of 1000MW reduction on Spot price [20]

3.3 Spot Prices (FI) Variation during winter 2011-‘12

The analysis of deviation in power exchange price is performed using the actual data from the Nordpool spot market. The result is that there is certain predictability is reflected in hourly spot prices. The study of almost 5 months (winter) period reveals the following statistics.

The average spot price (FI) was 44 Euro/MWh.

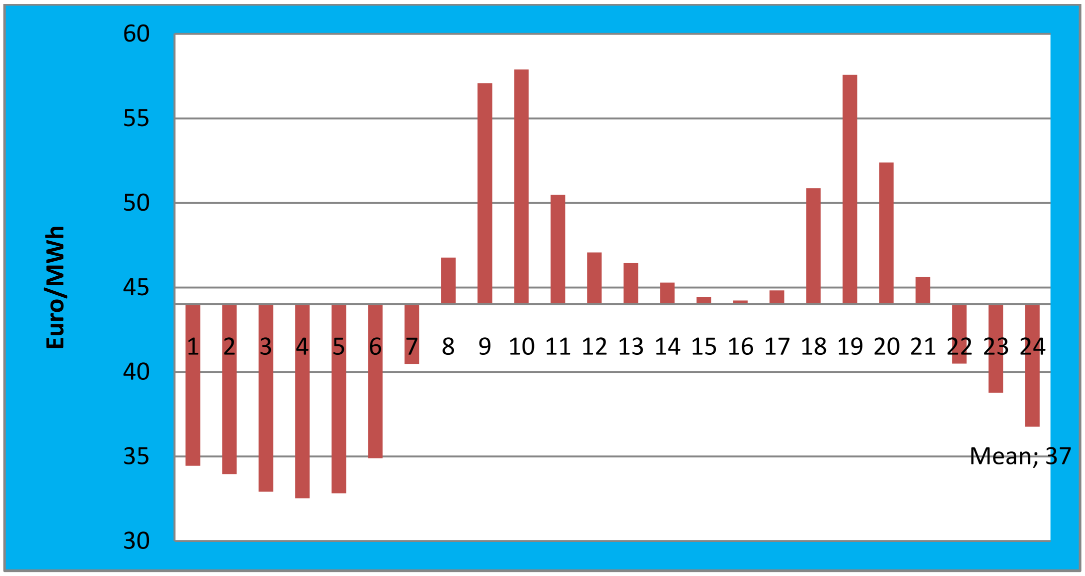

Fig3.3: Mean Hourly Elspot Prices during the Winter Period 2011-12

It shows clearly that there is fluctuation in prices during 24 hours. Exploiting the off peak periods would be beneficial. The Fig 3.4 represents the minimum and maximum occurs during this period. The standard deviation of prices is low during hours from 01-05 (off peak periods) and 14-16 (semi peak period) hours. It shows that off peak periods are consistent and highly predictable, whereas standard deviation of prices is higher during peak periods.

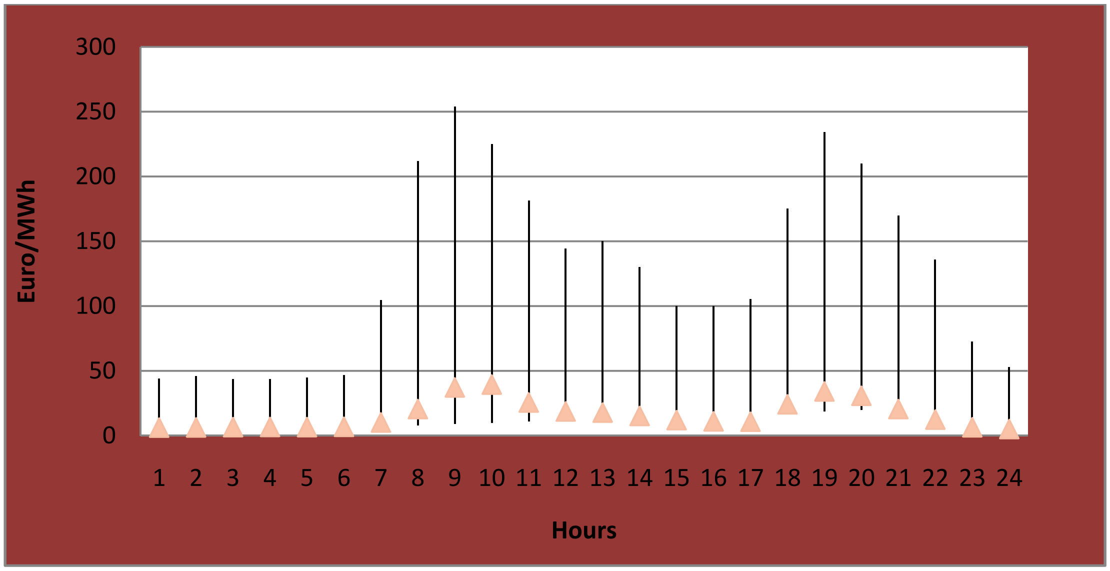

Fig 3.4: Minimum, Maximum and Deviation of Spot Prices

The range of fluctuation of spot price is represented by histogram showing frequency of occurrence of specific price interval in Fig 3.5. Around 50% of the time the price was below the average spot price during this period.

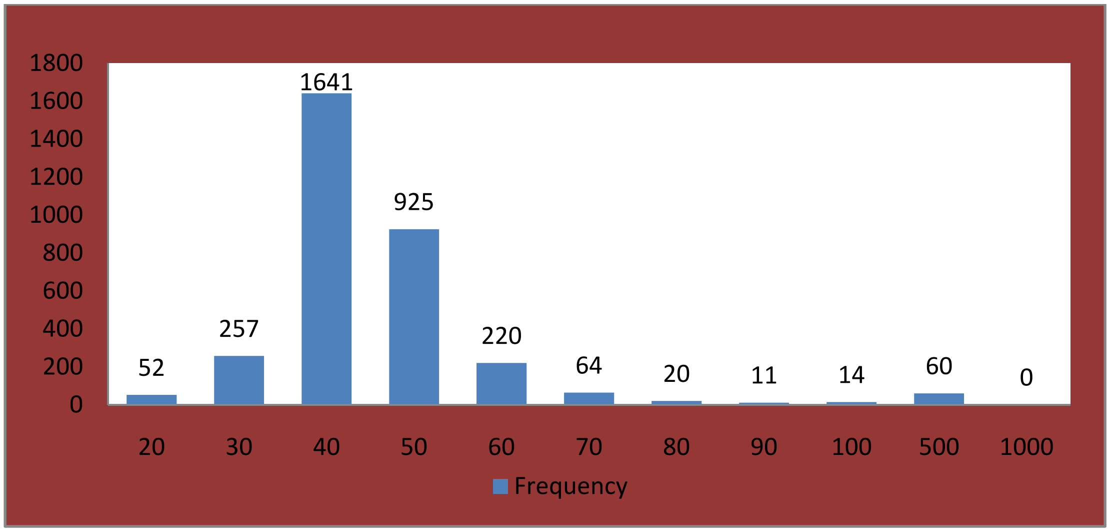

Fig 3.5: The Frequency (Y-axis) of occurrence of Spot prices (X-axis) in 2011

The Table 3.5 shows the top 10 highest peak prices occurred during the winter period (Nov 2011-Mar 2012)

Table 3.5: Top 10 Elspot (FIN) prices during the Period (data from *[21]*)

Date	Time	Elspot Price(Euro/MWh)
2.2.	08-09	253.92
3.2.	07-08	211.92
8.2.	19-20	210
1.2.	09-10	203.08
7.3.	09-10	199.91
10.2.	08-09	183.4
9.2.	09-10	169.9
6.2.	19-20	142.9
7.2.	09-10	120

Below is the histogram (see Fig 3.6) showing the hours when maximum spot prices occured. It also illustrates the repeating trend of peak load, semi peak and off peak periods. So the hour numbers 18 and 19 are the ones with maximum occurrence. It counts the number of days with maximum prices.

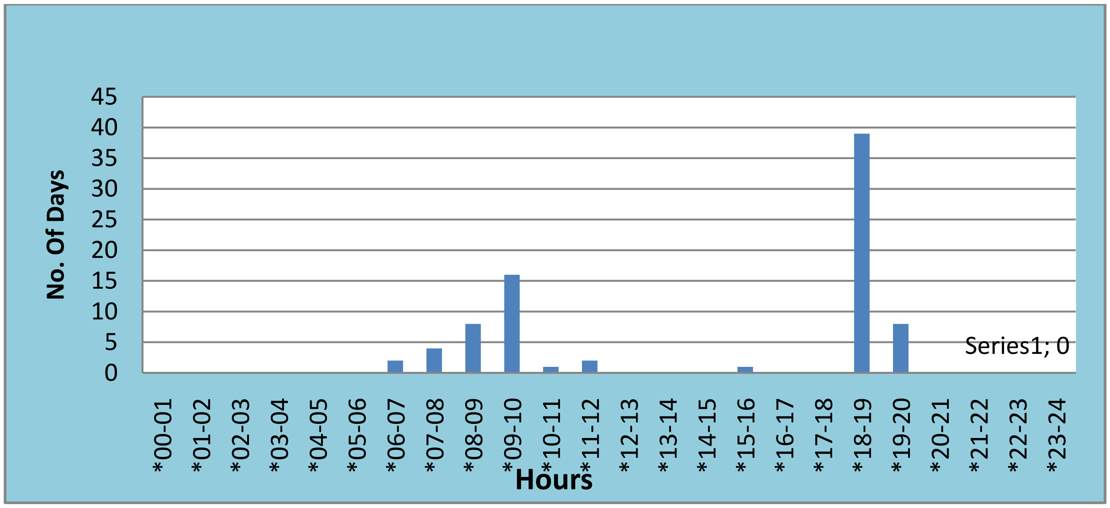

Fig3.6: Hour 0900 and 1800 hitting the Maximum Spot prices frequently

3.3.1 Main Causes of Spot Price Fluctuation

Elspot Prices can be categorize into the following

PRICE	CAUSES
• Extreme Prices	Transmission capacity, extreme cold weather, scarcity of supply, market abuse
• High Prices	Transmission Capacity, Cold Weather, Scarcity of Supply
• Average Prices	Low Demand
• Low Prices	Low Demand

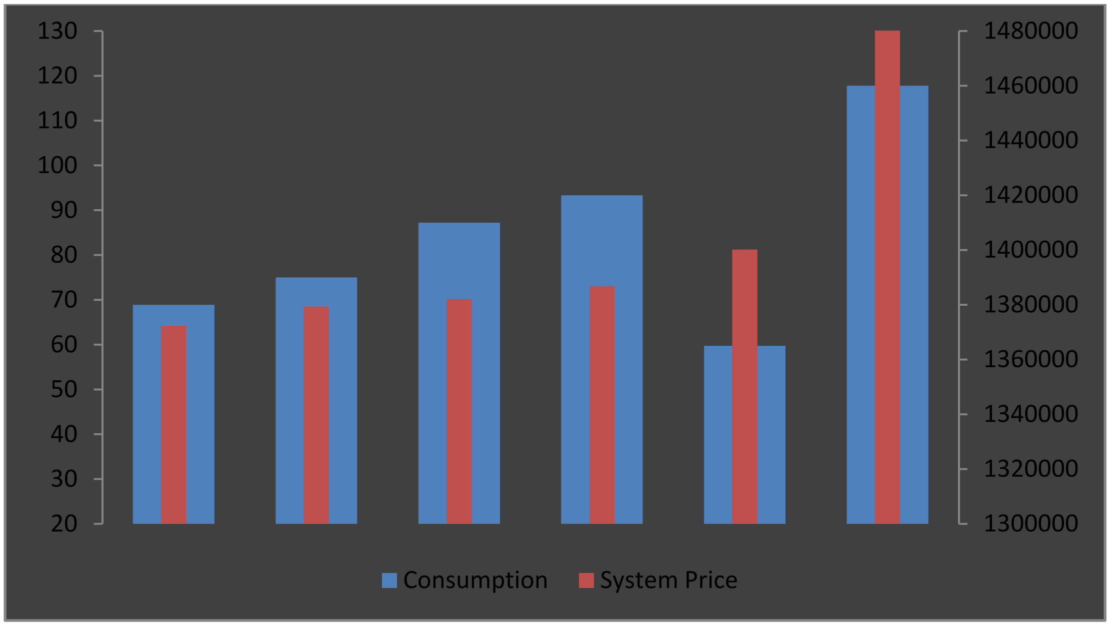

Fig 3.7: Nordic Consumption (MWh) and Elspot Prices (Euro) In 2010

The correlation between electricity consumption in Finland and Elspot prices comes out to be 0.3. It demonstrates a weak correlation but it is positive correlation also correlation doesn't tell about the cause. So it is safe to conclude the lesser the demand the lesser the price. So higher price hours certainly correspond to peak period and vice versa.

3.4 German vs. Nordic Market_ A comparison

Germany Electricty Market (EEX) is dominated by thermal and renewables energy while Nordic rest mainly on hydro. The total installed generation capacity of Germany was 152GW in 2010.

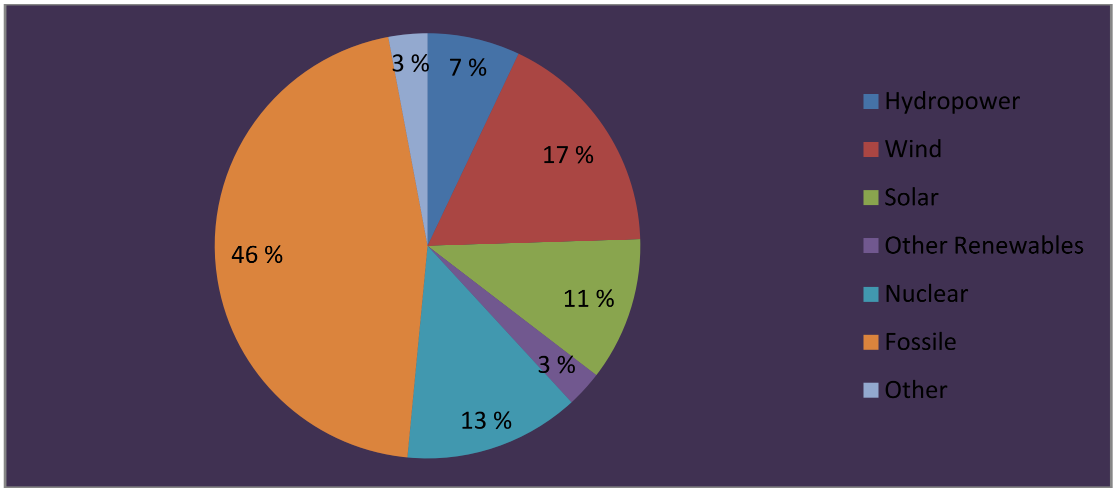

Fig 3.8: Share of Different Generation capacity of Germany in 2010 [23]

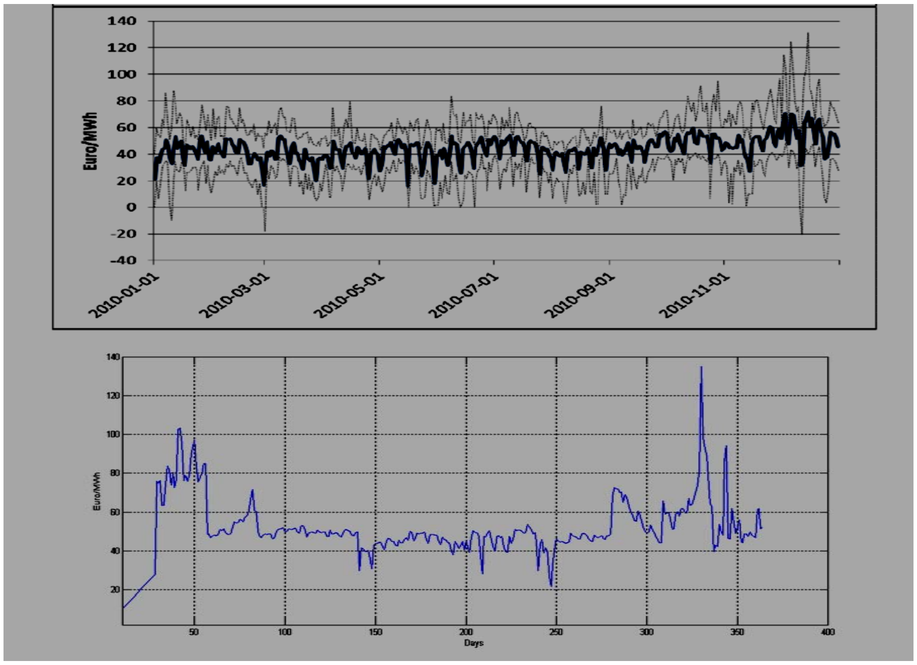

Fig 3.9: Comparison of Spot prices (2010) of two Physical Markets (EEX on top; Nordic on bottom)

The figure 3.9 illustrates there are considerable differences between a hydro dominated system and a system dominated by thermal power and renewables in terms of spot price. The fast response of hydro dominated system is much more reliable and better than thermal dominated generation system thanks to the storage capacity. Therefore variation of spot prices will be more fluctuating in countries like Germany. The variation in wind power owing to its unpredictability also contributes to volatile prices in Germany. However, peak prices in the Nordic region in winter 2010 shows that prices can be volatile in this region too [21]. Also the likelihood of merger of these two physical markets would make prices more mercurial [16].

3.5 Impact of Intermittent Renewables on Electricity Market

The barrier of implementing the integration of renewable energy sources is just not limited to technical difficulties like balancing, additional reserve etc. In fact, the market side is considered to be the biggest hindrance as well [24], [25], [26]. The day-ahead market is just not suitable for integration of intermittent renewables unless the prediction of the generation from these sources gets accurate with higher degree. The intermittent RES have introduced the negative prices in German electricity market and it’s not far when Nordpool would be experiencing this strange phenomenon which seems against all the principles of selling a commodity. The occurrence of negative prices in electricity market is not a surprise nowadays. The combination of high generation, thanks to the intermittent renewables, with low loads or vice versa is the major cause of negative prices. The excess of power causes over frequency and thus it’s incumbent to take some grave step. Findings have proved that it is economically profitable to receive losses (low or negative spot prices) during a short time as long as they are lower than dispatch adaptation [16]. It’s not only the RES feed-in that causes such negative prices in market but the predictability of these sources. The prediction accuracy of day ahead is very minimal, even the error is significant for few hours’ ahead prediction of physical delivery of power. So the unpredictable characteristic of RES put the market to take some acute turn in order to keep system secure and reliable.

The German power exchange EEX was the first electricity market in Europe to allow negative price bids in their auctions. Ever since September 2008, the negative prices are hitting the market on regular basis and it’s highly likely that more negative prices will occur in near future as installation of intermittent renewables is on hype. The electricity generated from renewable energy sources having reached over 90 TWh in

2008 in Germany (corresponding to 15.1 % of the gross annual electricity demand) can lead to new extreme situation in Power Market [27].

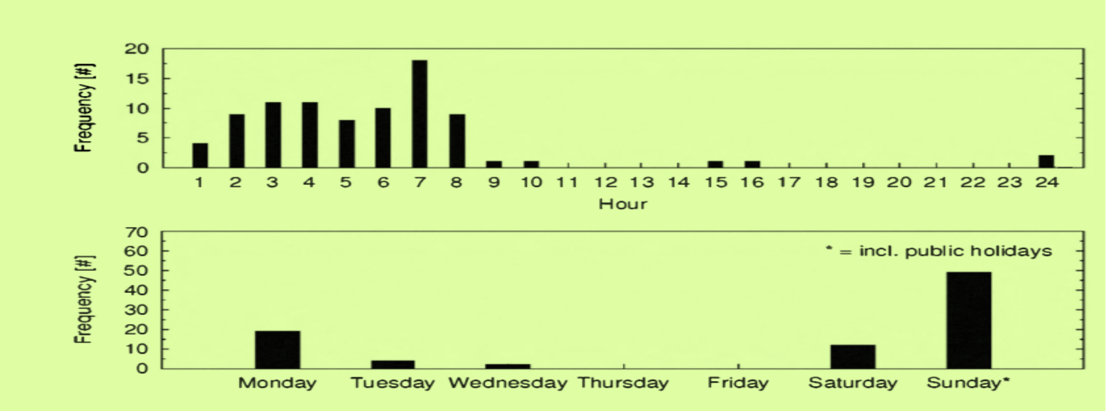

Fig 3.10: Negative Prices Occurrence in EEX Market [27]

Table 3.6: Substantially Negative Prices in EEX Market *[28]*.

Date	Hour	Price(Euro/MWh)
04.10.2009	3	-500
04.05.2009	2	-151
24.11.2009	4	-149
08.03.2009	7	-109.97
04.10.2009	2	-106
22.12.2008	3	-101.5
22.12.2008	4	-101.5
22.12.2008	5	-101.5
04.10.2009	4	-100
04.05.2009	5	-99

4. Space Heating DR Potential and Strategy

To realize the DR potential of space heating, it is incumbent to visualize the heating load profile of household. The information of consumer behavior and pattern is essential to determine the flexibility of heating load. That behavior would help to assess the available capacity to respond. In this chapter the focus is on determining the flexibility of load shifting (how much and how longer time is the flexibility for load shifting and shaving). The temporal and seasonal influence on the flexibility is studied in this chapter. The diurnal and seasonal variation of heating load would help us to understand the potential and response capability of any load.

4.1 Case Study of Storage Electric Heating

Nearly 79000 consumers in Finland are equipped with storage electrical heating. Normally these types of consumers are charged by ToU pricing. Night time prices are often as 50% lower than day time pricing [8], hence giving incentive to customer to store heat during night time and allowing it to coast for the rest of the day. The stored heat depends on the storage size. Usually the storage used in Finland detach houses is enough to coast the morning to evening period, however owing to losses in storage, it can be charged in the day time according to the need.

In this study hourly type load data for storage electric heating customer which is typical for Finnish detach houses is used. The heating load is generated from the hourly data by statistical means (i.e. after removing effects of day structure (i.e. Weekend, weekday and holidays)). State average consumption of 2010 is used as well to see the contribution of storage type electrical heating in the Finland peak demand. The data of average consumption is sorted accordingly and filtered (i.e. Weekend and holidays). To give some meaning to the data, average consumption with respect to season is considered rather than taking monthly average consumption.

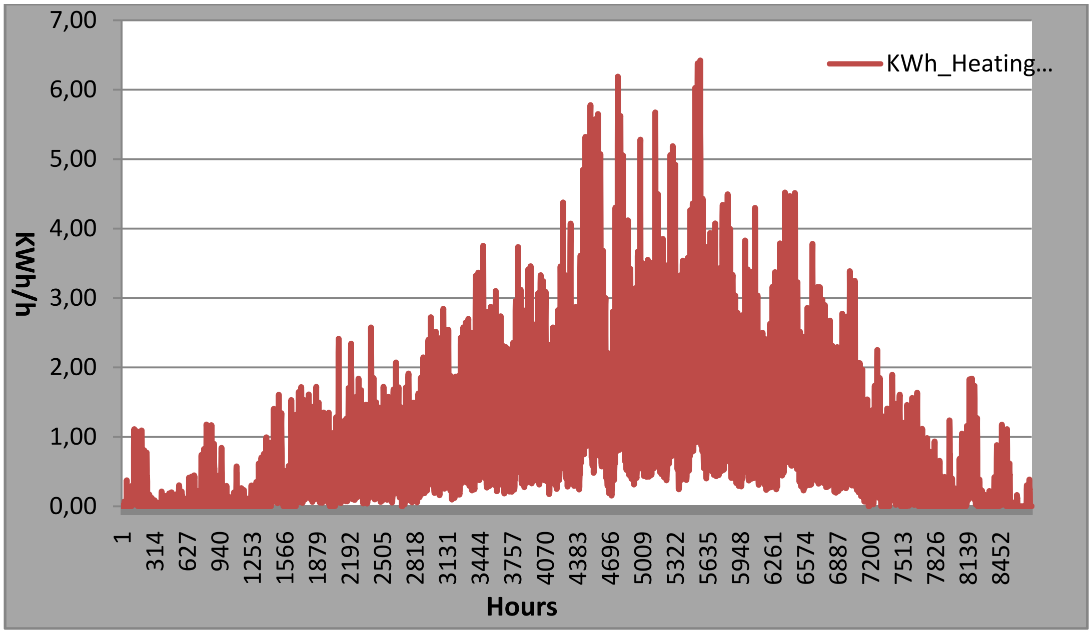

Fig 4.1: Type heating load data for Storage Electric Heating customers (X axis from Aug to July)

The state average consumption profile of winter is plotted in Fig 4.2. The peak periods are during 0800-0900 and 1700-2000 hours. By looking at the demand curve, it seems very flat and lacks valleys which could potentially be filled if load shifting is desired.

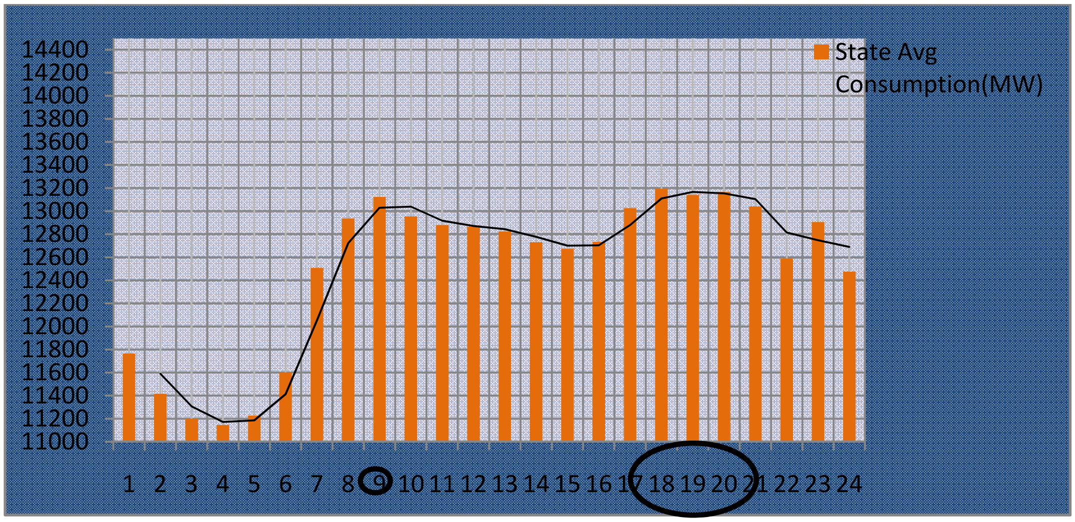

Fig 4.2: Finland Demand Profile in winter

Nevertheless, it’s an average value curve. On typical peakier day, the curve has pronounced valleys that can be filled and can be a decisive factor in State reliability.

To get the clear picture of storage electric heating load behavior and its contribution to the peak load, both, state average consumption in different season and storage electric heating load is illustrated on one graph on primary and secondary axis respectively.

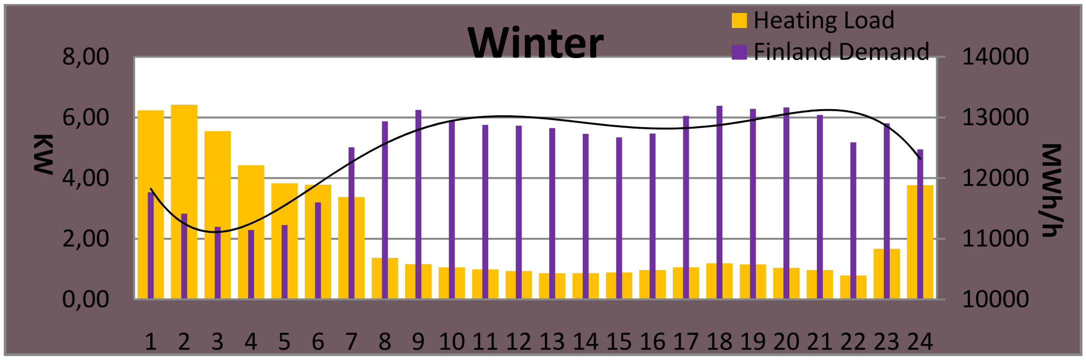

Fig 4.3: Electric Space heating Profile (Avg.) during winter

4.1.1 Results

The peak consumption of Finland occurs in winter season. Quite clear from the graphical picture that storage heating load are not contributing to peak load as much as they could. In other words the Finland demand profile is weakly coincident with of storage electric heating load shape. Hence the flexibility is minimal. They are not bringing any new demand response to the system. They are following the ToU pricing, and their usage is in low peak period, and since low peak period coincide with low price hour, thus their consumption is efficient in that aspect. They are already helping to fill out the valley and flattening the peak.

The demand response could be negligible if use for peak reduction or shaving unless robust techniques are implemented. The storage electric heating merely contributes to peak load. Its usage is mostly in off-peak or semi peak period. In winter 2010, state peak consumption is about 14GW and period between 0800-0900 and 1700-2000 hours are categorized as a peaky period. So the estimated DR from storage type customer can be approximately 1KWh/h during morning and evening peak. (Evening peak occurrence is more frequently than morning).The aggregated response of 50% of consumer taking participation in peak shaving program will be roughly 40 MWh/h (0.3% peak load) during morning/evening peak.

The aggregated demand response quantified is very optimistic. Even though, if we take optimistic values, the Demand response is low. The reason is twofold.

a) Nearly all Storage type Customers have load profile which helps in smoothing the peak.
b) The Number of consumers with adequate storage heating capacity is low in number.

Similarly for the other seasons

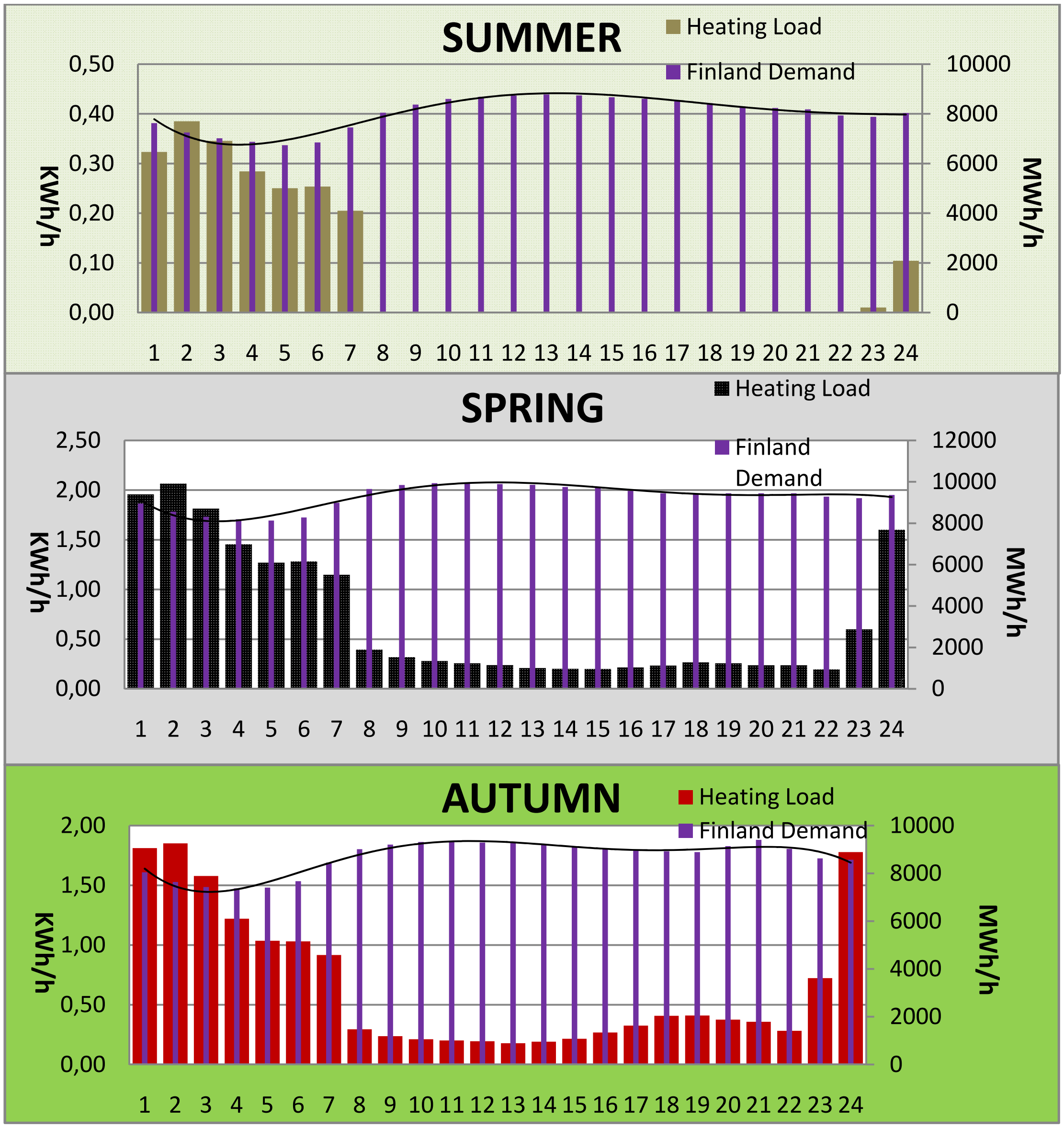

Fig 4.4: Seasonal Variation of Storage Electric Heating Load

4.2 Case study of Direct Electric Heating load

Given that the DEH has no additional storage, so the idea here is to develop a strategy that leads to the load reduction during critical period. The objective is not simply curtailment instead the technique rests on pre heating the house before the peak hours and then cutting it off until the quality (comfort) requirements are not violated. The decisive factor is indoor temperature which must stay in certain limit. So by changing the dead band for instance +-1, +-2, +-3 one by one and to see how much it is allowable to shift without compromising on customer quality of service.

The average room temperature for Finnish household is 21 degree centigrade [13]. Usually the thermostat setting in cold weather is fixed dead band, however for energy efficiency certain guidelines are recommended.

From	TO	Set Point (C)
6:00 a.m	8:00 a.m.	21
8:00 a.m.	6:00 p.m.	16.5
6:00 p.m.	10:00 p.m.	21
10:00 p.m.	6:00 a.m	16.5

Since the energy efficiency measure is not the objective thus it will not be considered here. Instead a novel strategy is formulated. The objective is to present space heating strategies leading to a load reduction during critical periods on the grid but also taking into account the occupant thermal comfort.

4.2.1 DR Strategies for Direct Electric Heating

The study performed here takes into account a Finnish typical (good insulated) house model. Also it doesn't involve any type of thermal storage or use of different fuel (wood etc).

Heating strategies are presented which lead to load reduction during critical period on Grid also taking into account occupant thermal comfort.

3 strategies are formulated

Strategy A	**Dead band variation of 1 degree**
Strategy B	**Dead band variation of 2 degree**
Strategy C	**Dead band variation of 3 degree**

In all of the above strategies, Reference temperature is 21 degrees Celsius while dead band varies (1, 2 or 3 degrees). The strategies are gauged then by only parameter called load reduction (L-R) That is to say how much load is reduced to the reference load. It has been observed that the higher the dead-band the greater the curtailment but least comfort as the variation of +-3 is noticeable. Also overcharging beyond certain limit is not optimal as the heat loss is dependent on temperature. Plus it alters the comfort ability level too.

In this study hourly type load data for direct electric heating customer which is typical for Finnish detach houses is used. The heating load is generated from the hourly data by statistical means (i.e. after removing effects of day structure (i.e. weekend, weekday and holidays)).

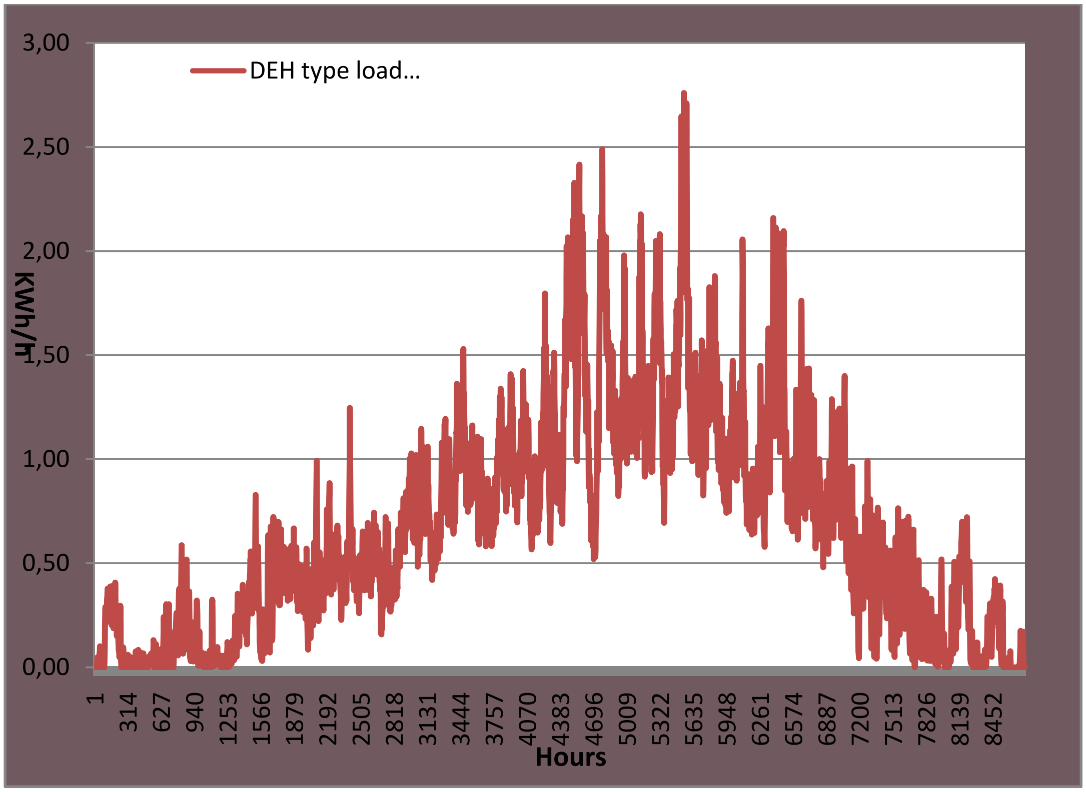

Fig 4.5: Type Load for DEH customer (X axis from Aug to July)

The analysis is restricted to winter season only as direct electric heating load is significant in winter. State average consumption of winter 2010 is chosen and load behavior is observed in view of that.

In view of the above the dead band of thermostat of household is varied to observe how much the load can be temporarily reduced without altering the quality of service. The dead band variation is done by changing the thermostat setting in the thermal model house and then performing simulation by considering a typical winter day averaging temperature -11 degrees. The effect of dead band variation on internal temperature and load profile is shown with aid of simulations. Scenarios of both daytime and evening time are simulated to observe the effect of curtailment on peak load.

4.2.1.1 Dead-band variation of 1 degree

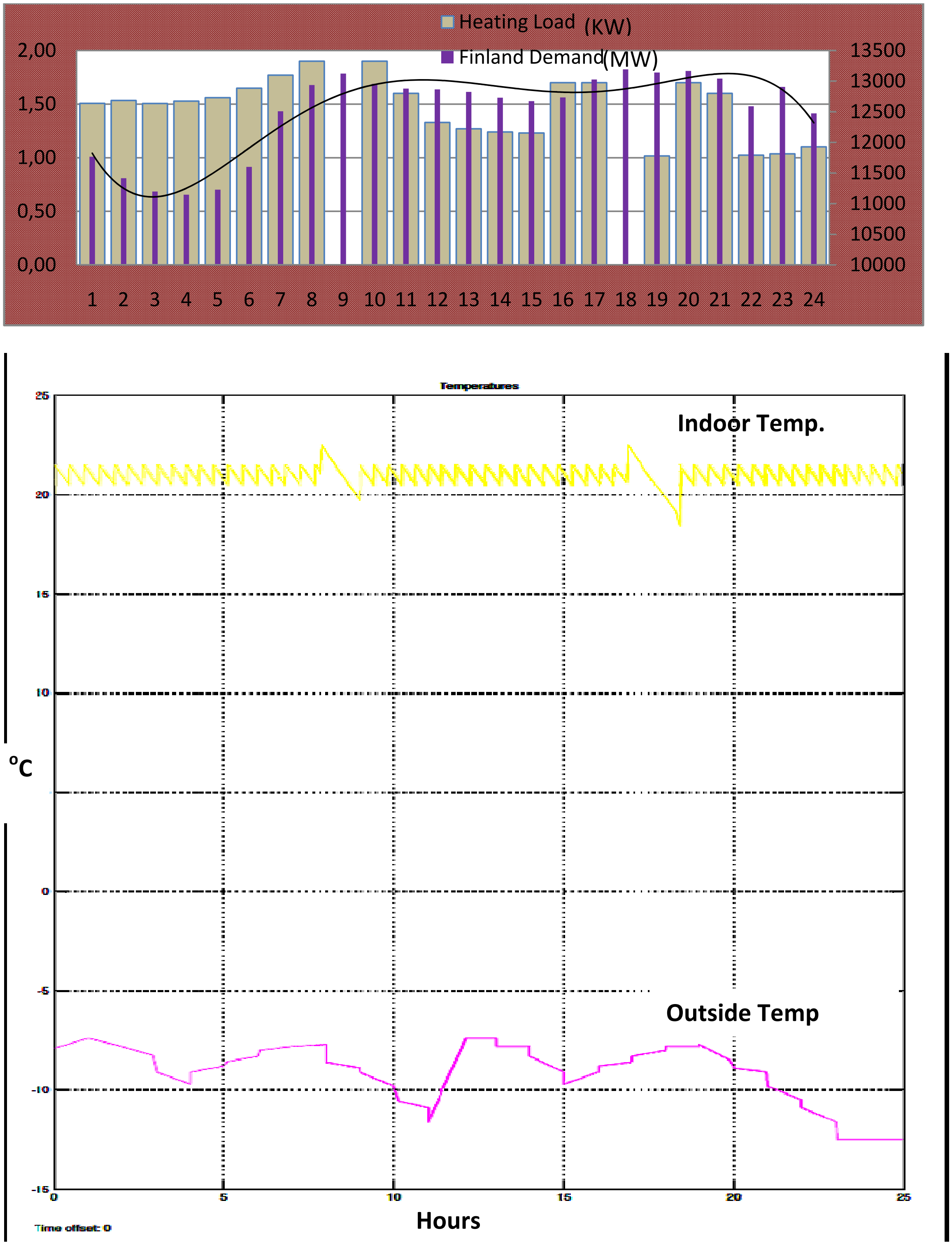

Fig 4.6: Strategy A

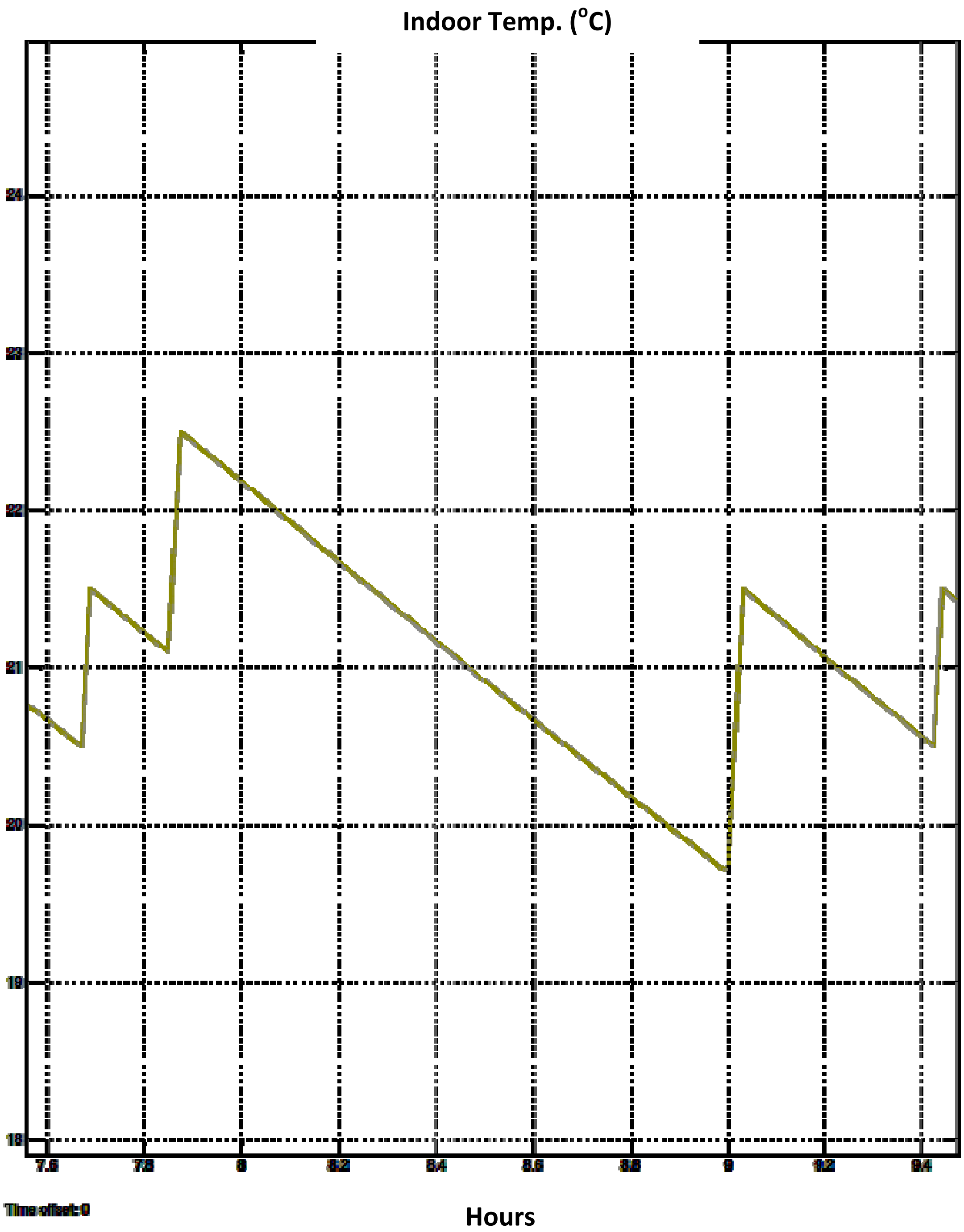

Fig 4.7: Strategy A_ Morning Peak Scenario

4.2.1.2 Dead-band variation of 2 degrees

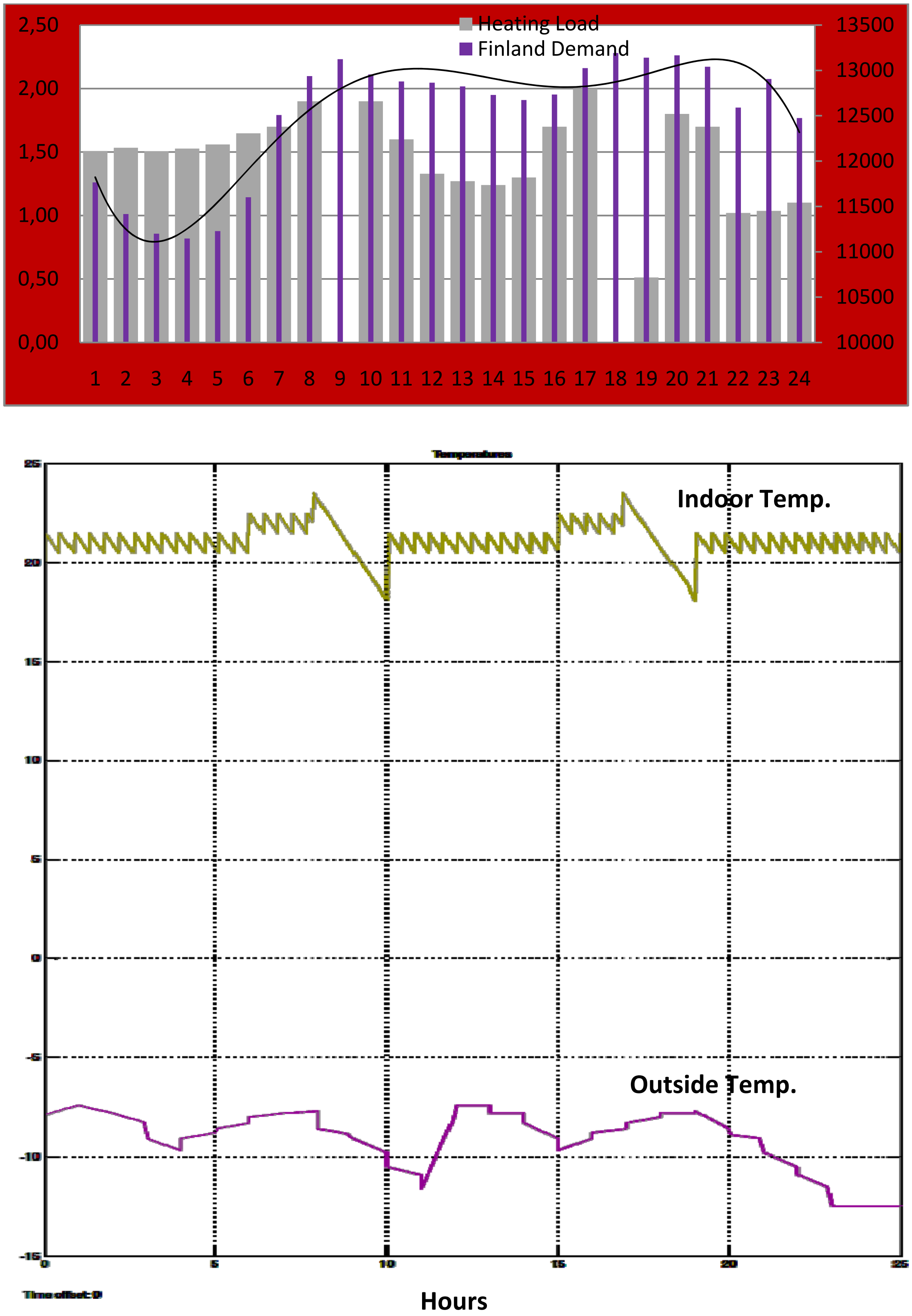

Fig 4.8: Strategy B

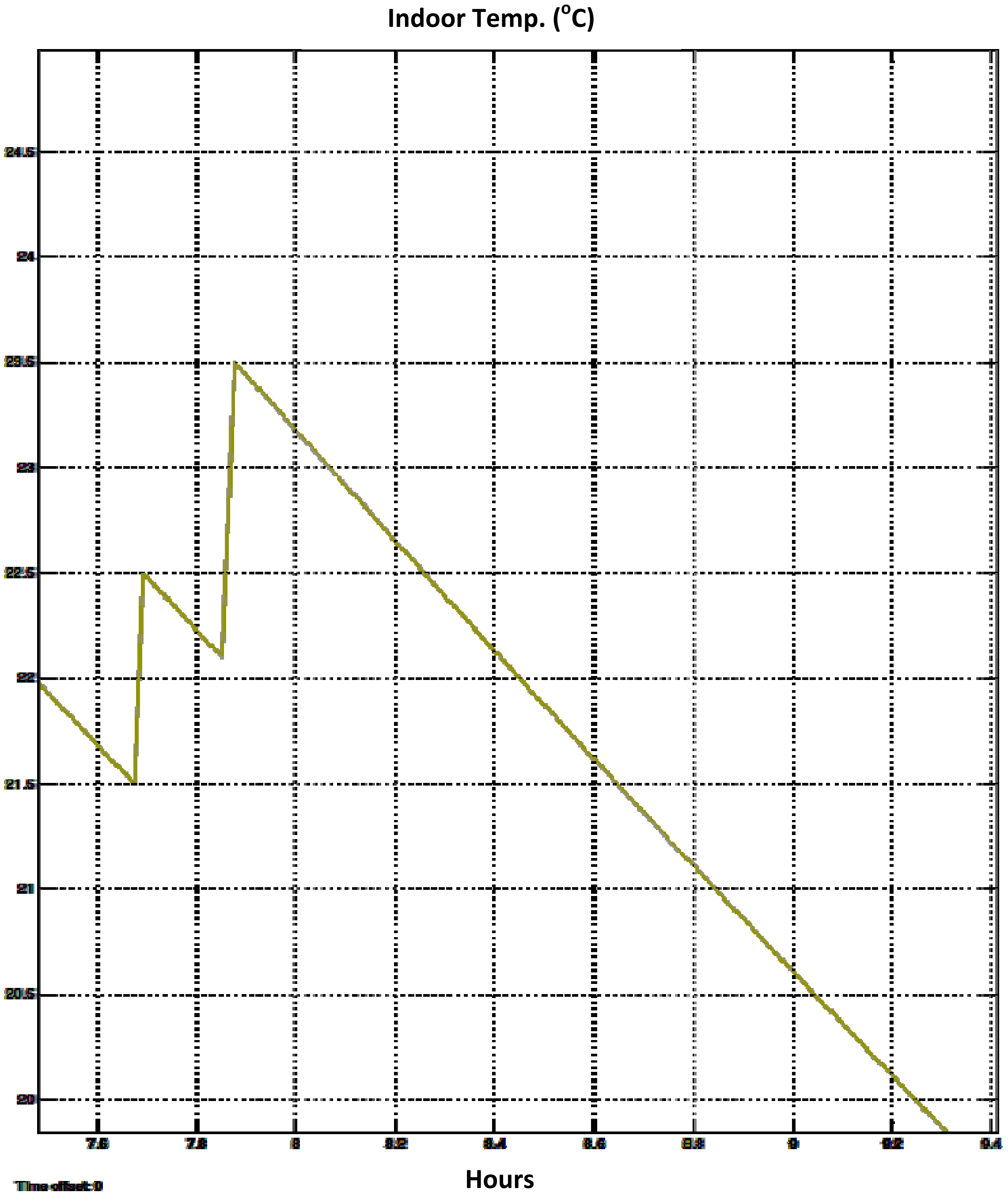

Fig 4.9: Strategy B_ Morning Peak Scenario

4.2.1.3 Dead-band variation of 3 degrees

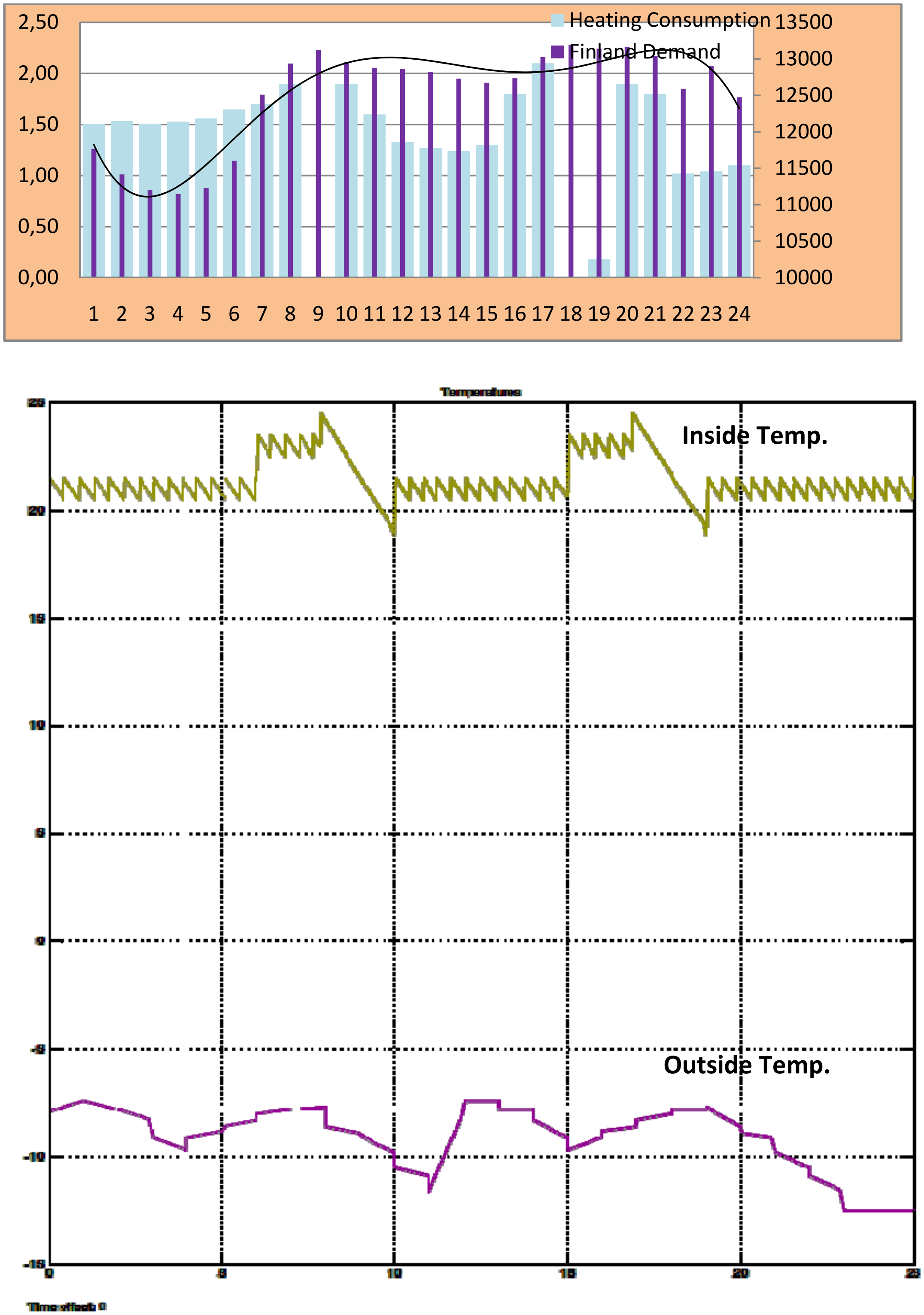

Fig 4.10: Strategy C

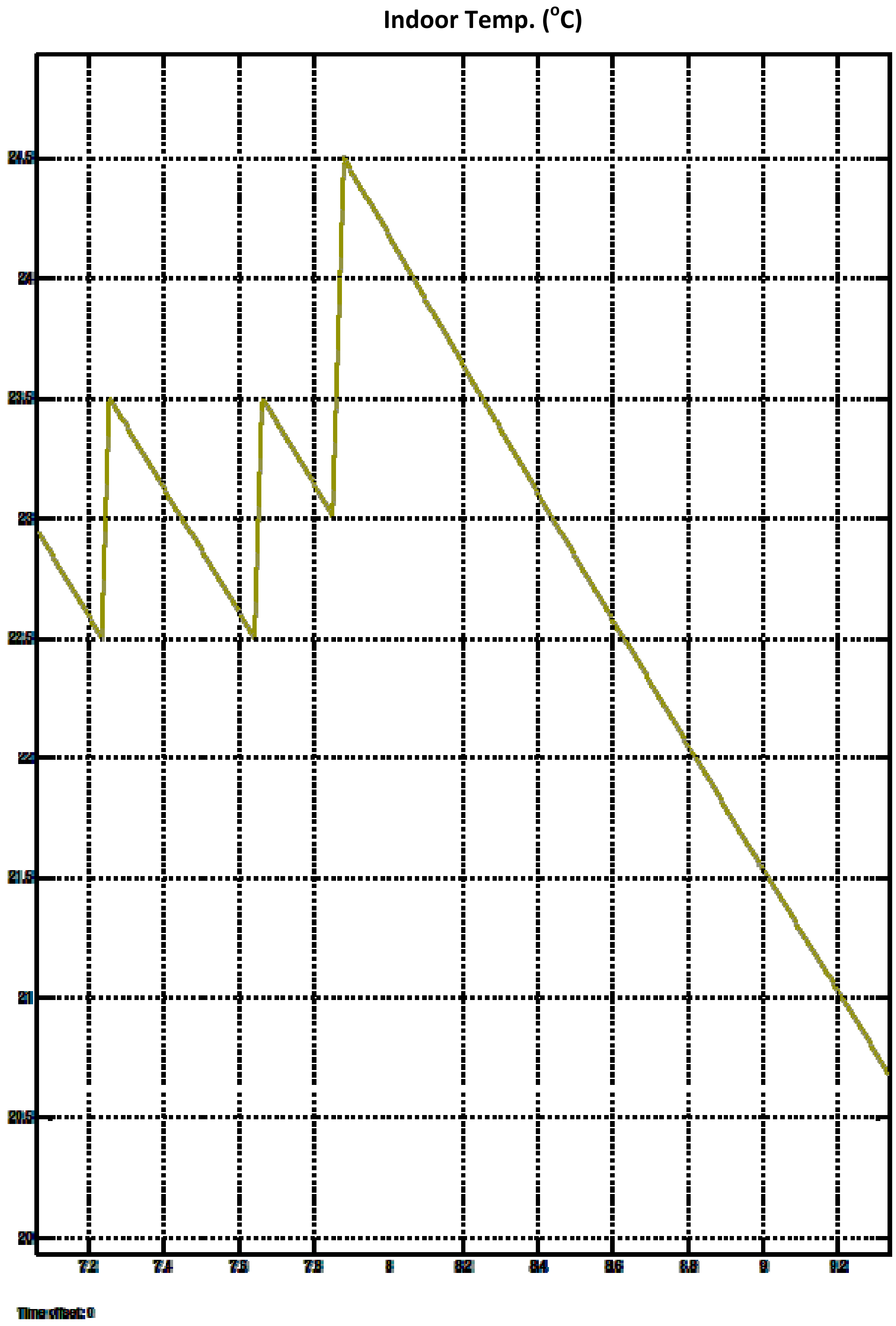

Fig 4.11: Strategy C_ Morning Peak Scenario

4.2.2 Results

Summarizing the result in the following Table:

S.No	Strategy	Morning Peak 0900	Evening Peak 1800	Evening Peak 1900	Evening Peak 2000
		Load Reduction	**Load Reduction**	**Load Reduction**	**Load Reduction**
1	**± 1 degree**	**100 %**	**100 %**	**23.50 %**	**0**
2	**± 2 degree**	**100 %**	**100 %**	**61.50 %**	**0**
3	**± 3 degree**	**100 %**	**100 %**	**86 %**	**0**

By increasing the Reference point and then allowing it to coast will certainly reduce the load and will allow curtailing for 1 hour at least without loss of comfort. Almost 100 percent load can be reduced during morning peak with even 1 degree dead band. While Evening peak duration is usually 2-3 hours hence a higher dead band (+-3 degree) can shift for 2 hours maximum while temperature then stay at the lowest as far as comfort is concerned.

Suppose 300,000 houses opt for DR program, then reduction of 550 MWh/h is possible (accounts for 4 % of registered Peak load demand).

Cold Load Pickup current will not be problem owing to two reasons.

Since Cold Load Pickup current depends on:

- Curtailment or shifting time
- Thermal Insulation level
- Outdoor Temp.
- DR strategy

The strategies adopted were PRE heating then settling or coasting. It is not setback only. The coasting time is shorter than 2 hour so the background temperature of air never falls below 18 degrees. Hence picking up current won't be higher.

Nevertheless, there is nothing on earth for free (i.e. it's shifting not curtailing), the preheating can be tricky. Given the flat demand curve, preheating can produce secondary peak. However it has been found that preheating doesn't load as much and its worth doing it. Also, if more intelligent ways are added (Taking into account the occupancy / consumer behavior), load reduction will be more pronounce.

5. Space Heating Load as a Frequency Responsive Load

The conventional way of controlling frequency in large power systems is usually by adjusting the production of generating units in response to changes in the load. This sort of stuff is usually performed by high capacity generating units. Load side is excluded from providing such facility and demand side get activated in emergency situation only. However, given the high levels of penetration of wind resources, the intermittency problem might become too rigorous to manage. The Increase in the share of wind power production makes the power system lighter and larger frequency deviations are likely to occur when wind die out or rise or wind lull or gust situation [29].

Wind and solar are intermittent and are characterized by their variability and uncertainty. The inherent aspect of these renewables introduces an additional burden on conventional resources and power system as well from security point of view. As the amount of intermittent renewables generation increases and the proportion of flexible conventional generating units decreases, a contribution from the demand side to primary frequency control becomes technically and economically desirable thanks to the communication technologies these days. With the significant penetration of intermittent renewables in power system, extra ancillary services are required to achieve the performance criteria [30]. The major obstacle so far was the perceived difficulties in dealing with many small loads rather than a limited number of generating units and specially their reliability. However with the progress in communication infrastructure and their penetration in power system indicate positive signals to mitigate this issue. Responsive loads are barely used for power system security and reliability services and are thus minimally utilized. Loads like electric space heating could provide infrequent long response for critical emergencies and would be comfortable providing the typical fifteen minutes response perhaps during contingency. The behavior of large aggregation of controllable loads is analogous to the reserve [31].

The space heating load has the potential to be used as a spinning reserve and storage electric heating could be act a power sink in case of excess of power generation. Renewable energy sources especially wind is intermittent and variable in its production and requires expensive storage for its firm operation. The storage electric heating load has the ability to absorb the excess power and thus making the integration of renewables easy on large scale. Here, it has been argued that direct electric heating is more suitable for spinning reserve rather than peak load reduction owing to its no or very limited storage. Direct load control for 15 minute time frame can provide fast response and consumer will barely notice as our typical house model already proved that because of long thermal time constant. On the other hand, storage electric heating is equipped with a latent storage whose potential to act as a resource is huge. However the DR potential and performance need to be bridged.

5.1 Wind Power Variability in Nordic Region

To get a little idea about the variable nature of RES, wind power production case is discussed. Wind power penetration is higher than solar in Finland and solar has a typical diurnal and seasonal variation. So here, study is restricted to intermittent nature of wind.

For wind power case, variation of minute and hour scale is important. With good spatial distribution of turbines, variations are much smoother. Also it is obvious that within hour variation is lesser than hourly variation. The hourly variation of large scale wind power production in Denmark are between +- 5% for 90% of the time and 99% of the time its +-10% of capacity. For the 15 minute variation in Denmark, production can vary 8% of capacity 6 times per month and maximum is 11 % [32]. These figures can give estimate about reserve and storage capacity for smoother and reliable operation of power system. The production in winter months is 110-140 % of yearly average, while summer has lower production. Nevertheless during the year 2001 there was more production in autumn than winter [33].

5.1.1 Seasonal and Diurnal Variation of Wind Power Production in Nordic

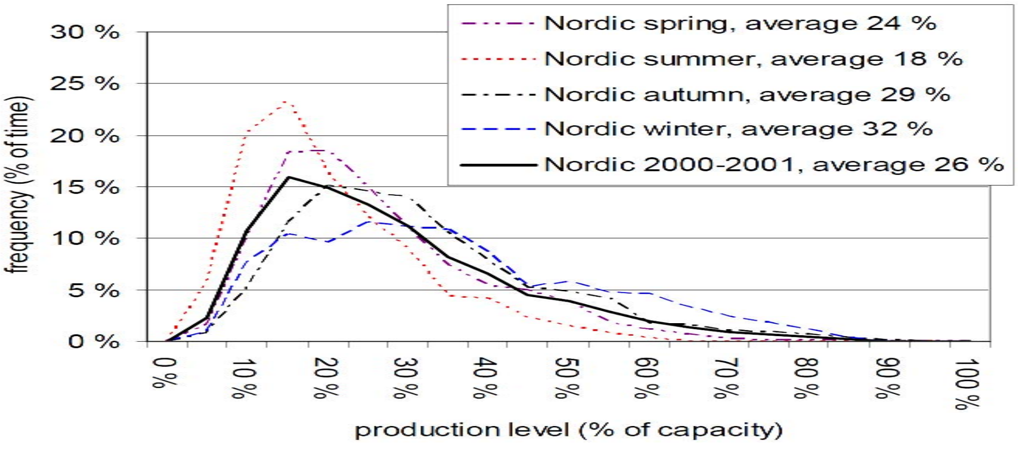

Fig5.1a: Seasonal Variation of Wind Power Production (2001) [33]

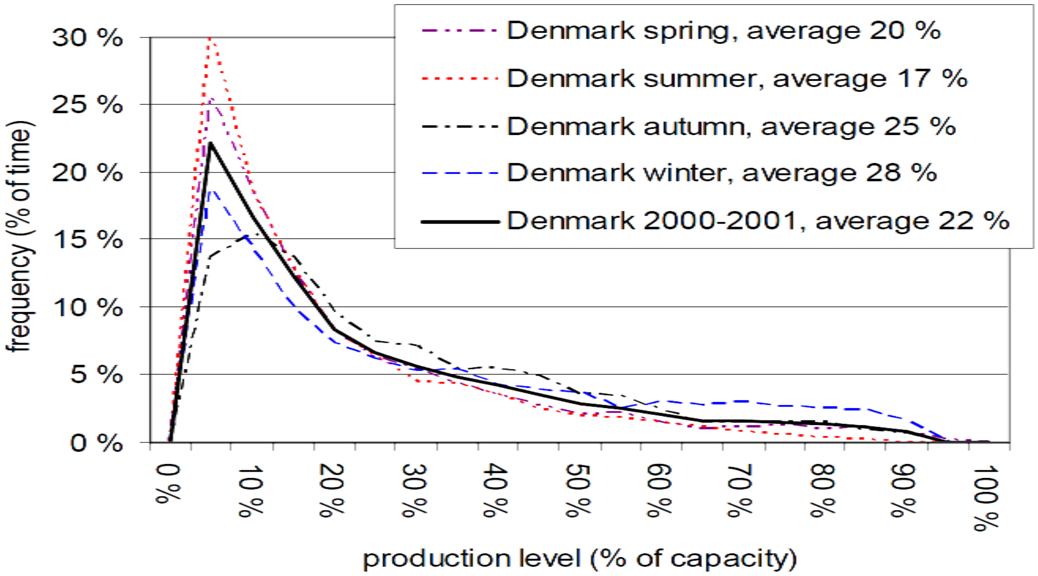

Fig 5.1b: Seasonal Variation of Wind Power Production (2001) [33]

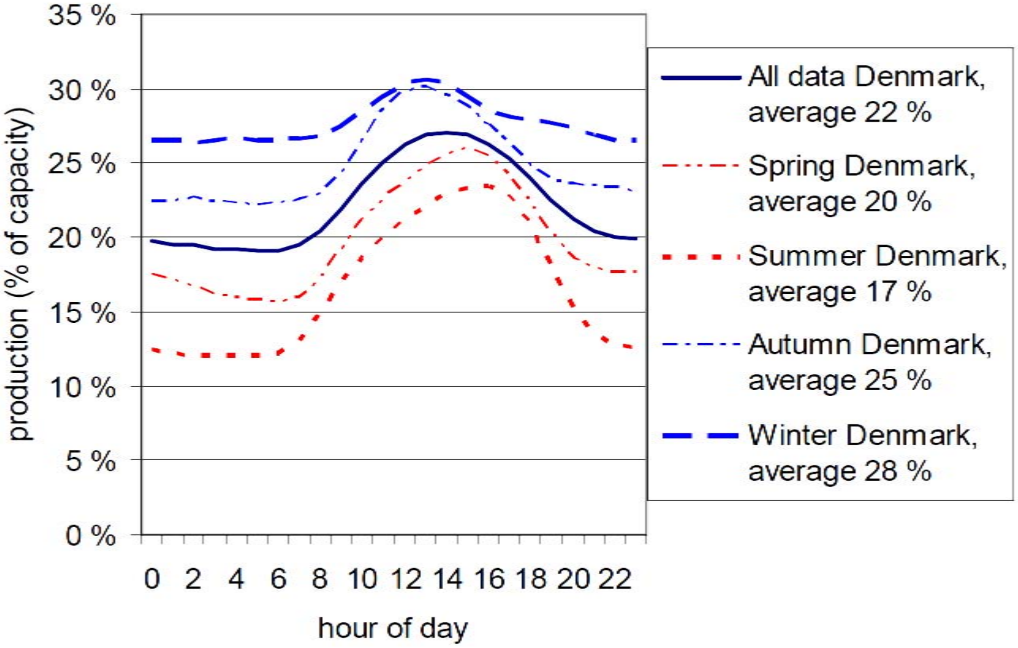

Fig 5.2: Diurnal variation of Wind Power Production [33]

Wind Power variation is more related to the turbine output level. So when less wind also less variability. But in that respect, as winter has the strongest winds it also has the strongest variability.

5.1.2 Instant Penetration of Wind Power

In [34], variability of wind power production in Nordic region is analysed in detail using real data (2009-10) measurement and with some scaling data and the result of the study can be used to estimate the effect of instant wind penetration on the daily load ramp pattern. It is worth to report the findings

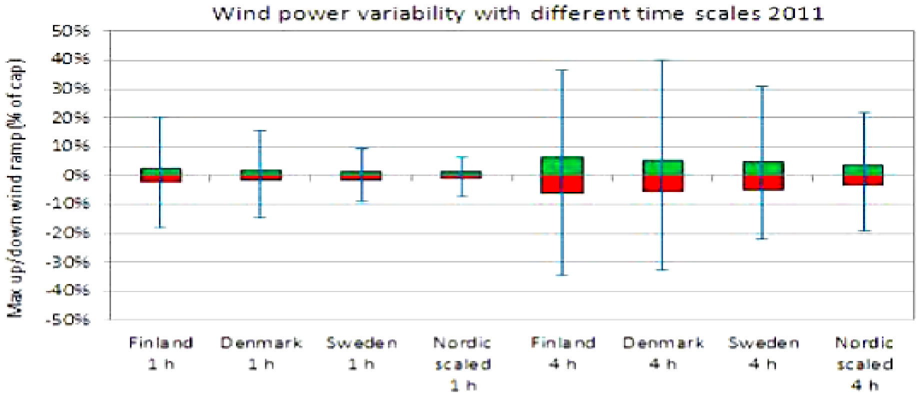

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Fig 5.3: Average 1hour and 4 hour wind power up ramps (green) and down-ramps (red) during. Variation is indicated by blue bar [34]

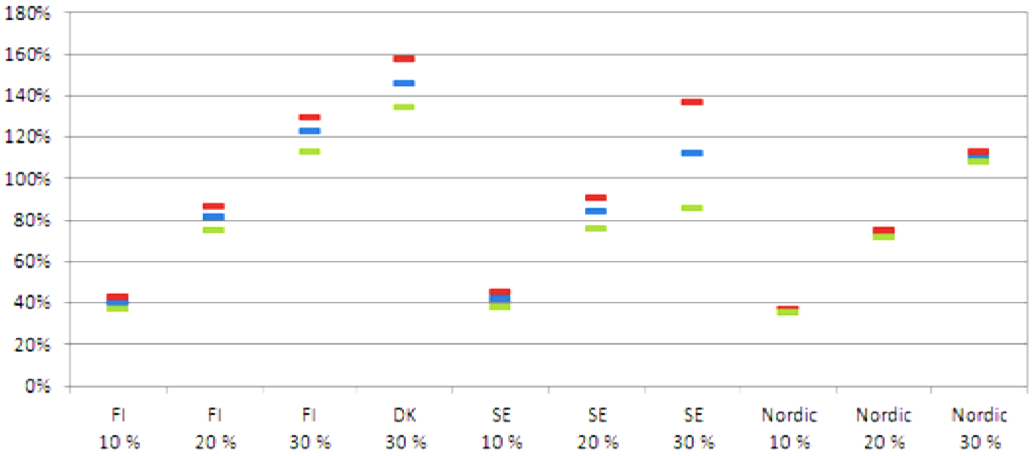

Fig 5.4: Maximum Instant Wind Penetration (During 1 hour) [34]

Table 5.1: Hourly variation in load (% of Peak load) and wind power production (% of installed capacity) *[34]*

	FI	DK	SE	Nordic
Load 1 hr Variability Max Up/Down	7.7% -4.6%	15% -12%	9.2% -6.4%	8.1% -5%
Wind 1 hr Variability Max Up/Down	18.1% -22.5%	18.4% -9.4%	11.5% -9.4%	7.8% -7.3%

The variation in wind power is highly dependent on production capacity. The variations are higher when the production is around 50% of installed capacity [34] .

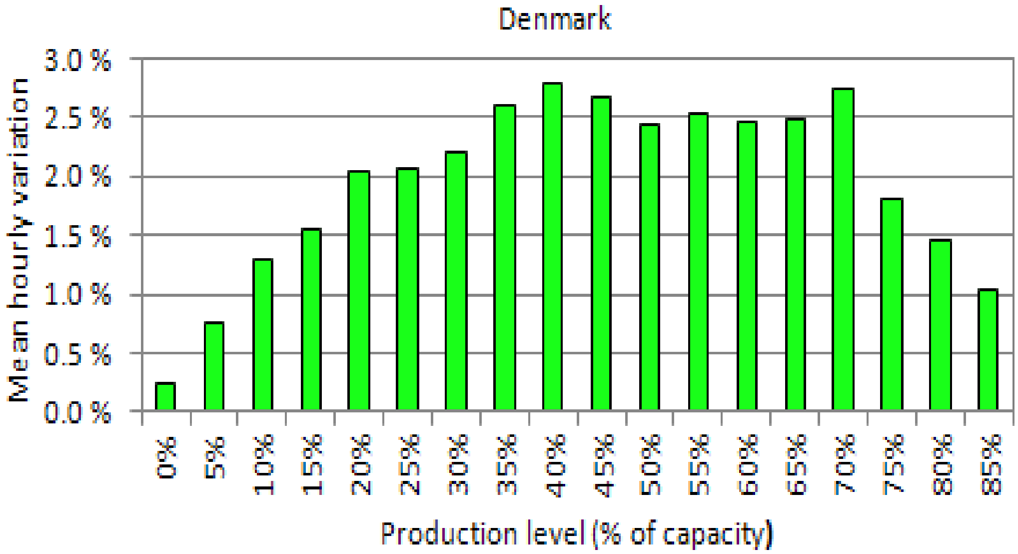

Fig 5.5: Average absolute variation during different production levels in Denmark (2010) [34]

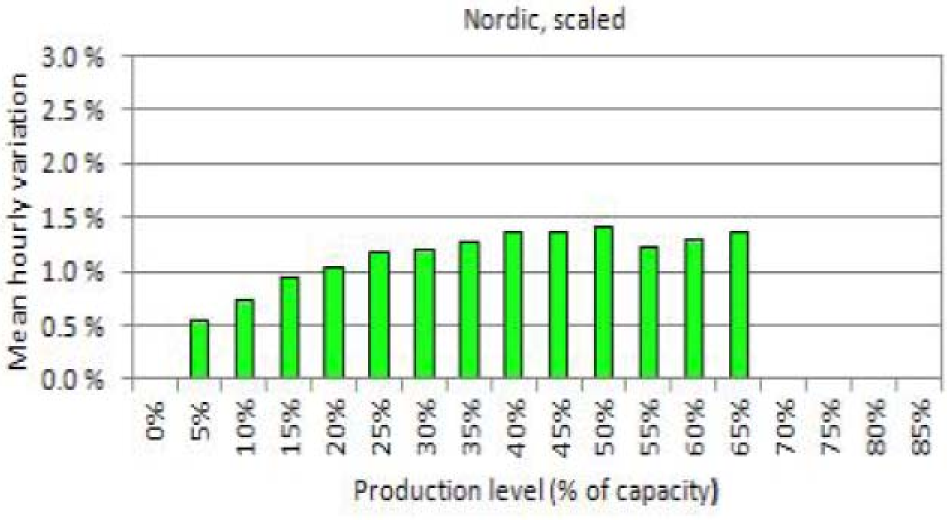

Fig 5.6: Average absolute variation during different production levels in Nordic, year 2010. [34]

5.2 Electric Space Heating Load as a Spinning Reserve

Spinning reserve is allocated to meet imbalances between predicted and actual demand. The unbundling of the electricity supply industry and the birth of competitive markets for electrical energy have required the definition of ancillary services. The function of these ancillary services is to help maintain the security and the quality of the supply of electricity. The frequency control of the network requires that fraction of active power to be kept in reserve to be able to re-establish the balance between load and generation at all times. In practice, different types of reserve services are required to respond to different types of events over different time frames. As for spinning reserve, the generators are liable to respond in contingency and participation of demand side was barred. However, it is no more going to work like that. Active load should be able to respond just like generators for 15 minutes time interval to keep the frequency in the desire limits. So in view of that spinning reserve can now be defined as

> ***"The spinning reserve is the unused capacity which can be activated on decision of the system operator and which is provided by devices which are synchronized to the network and able to affect the active power"*** [35]**.**

The reserve demand on the Power system varies from grid to grid. Depending on the type of generation and strength of network and various other factor leads to assign the reserve. In Nordic, the share is divided among the Nordpool participants. Every country of Nordpool AS has different share of spinning reserve to respond during contingency. At present the Finland share is around 300 MW. However with the upcoming of new nuclear power plant, the capacity should be raised and since there is no extra station capacity available to meet that, the demand side should participate to provide spinning reserve services. Although Industrial sector can provide such services with only few load could make up the share. However it's an uneasy situation. As these service comes at the cost of either curtailing or postponing the processes and it's a barrier. The very end side, that is household sector, has got the potential to provide spinning reserve. Aggregation of many small loads will certainly come up with a big capacity and reliable as well. The question now arises whether quality of service will be deteriorated or not. If the service is not altered despite the curtailment then it can be seen as the most feasible solution towards Spinning reserve capacity. Next step would be then how to bridge the gap between potential and performance.Research of Nordic grid shows that system with wind power penetration up to 10%, secondary reserves increase up to 8%of wind turbine capacity installed. The demand for secondary reserves increases with 3-7% of peak load or capacity in the Nordic countries with the wind power penetrations up to 20% [36] .

5.2.1 Case Study

The case study is performed to analyze whether DEH is suitable for providing fast response for 15 minutes. Direct electric heating load has seasonal and daily variation. But that is not a big problem because spinning reserves are badly needed in peak time. Finland state consumption is highest in extreme winter (Jan, Feb). Also in summer or spring or in night time there are lots of generators that are partly loaded so no need for direct electric heating to act as a spinning reserve on those seasons.

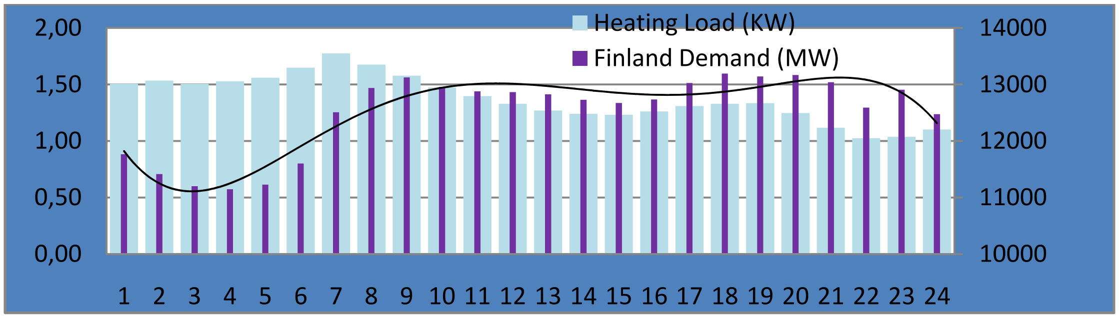

Fig 5.7: DEH load profile on typical winter day

The target is to find the flexibility in terms of capacity and how much load would be available for fast response typically 15 minutes. The results are pretty much in favor of this type of heating to act as a spinning reserve and thus play an effective role in Power system reliability apart from the environmental and economical benefits. However they are beyond the scope of this work.

5.2.2 Results

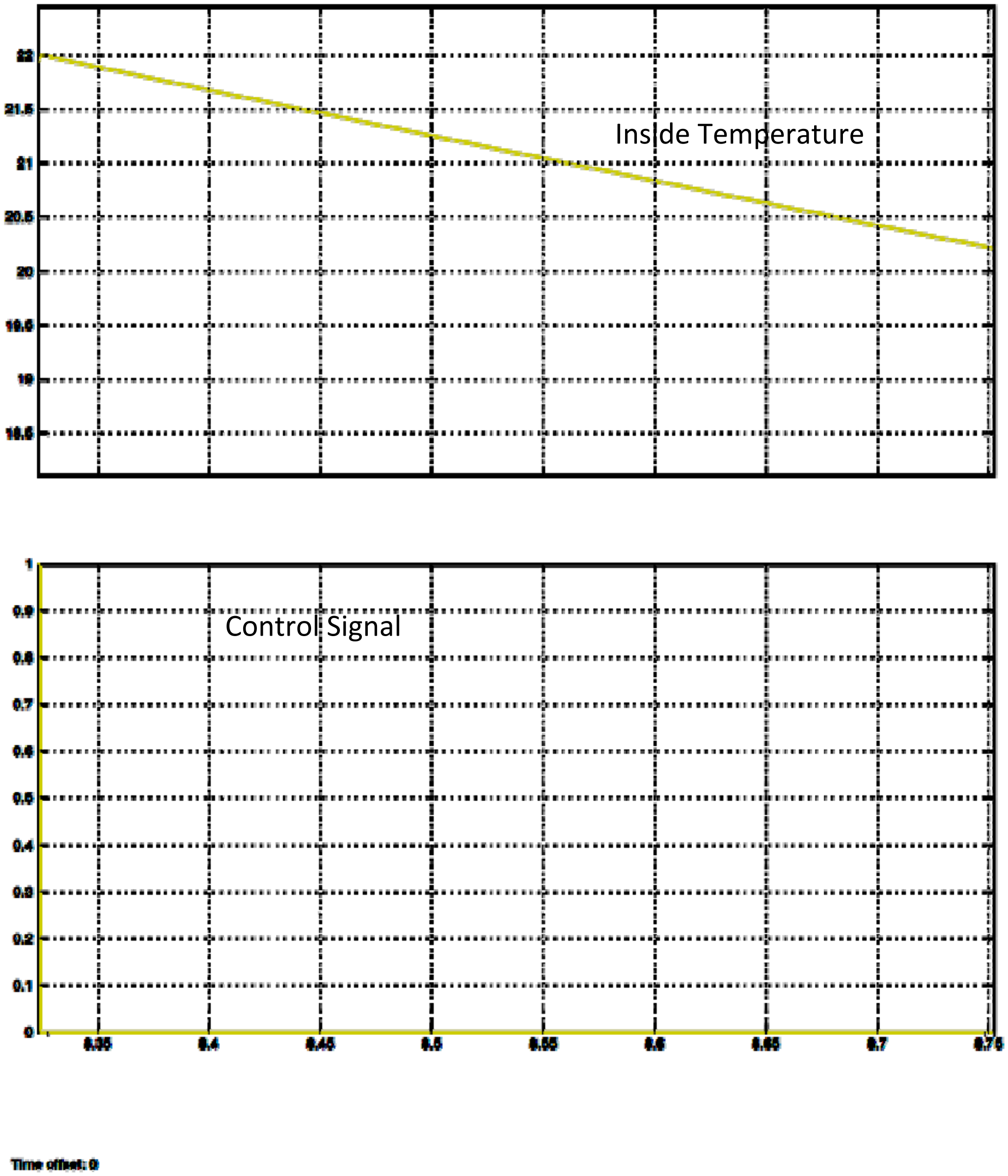

Fig 5.8: Effect of Curtailment (appx 20 mins) in Daytime on Temperature (inside); outside temperature averaging -8 degrees

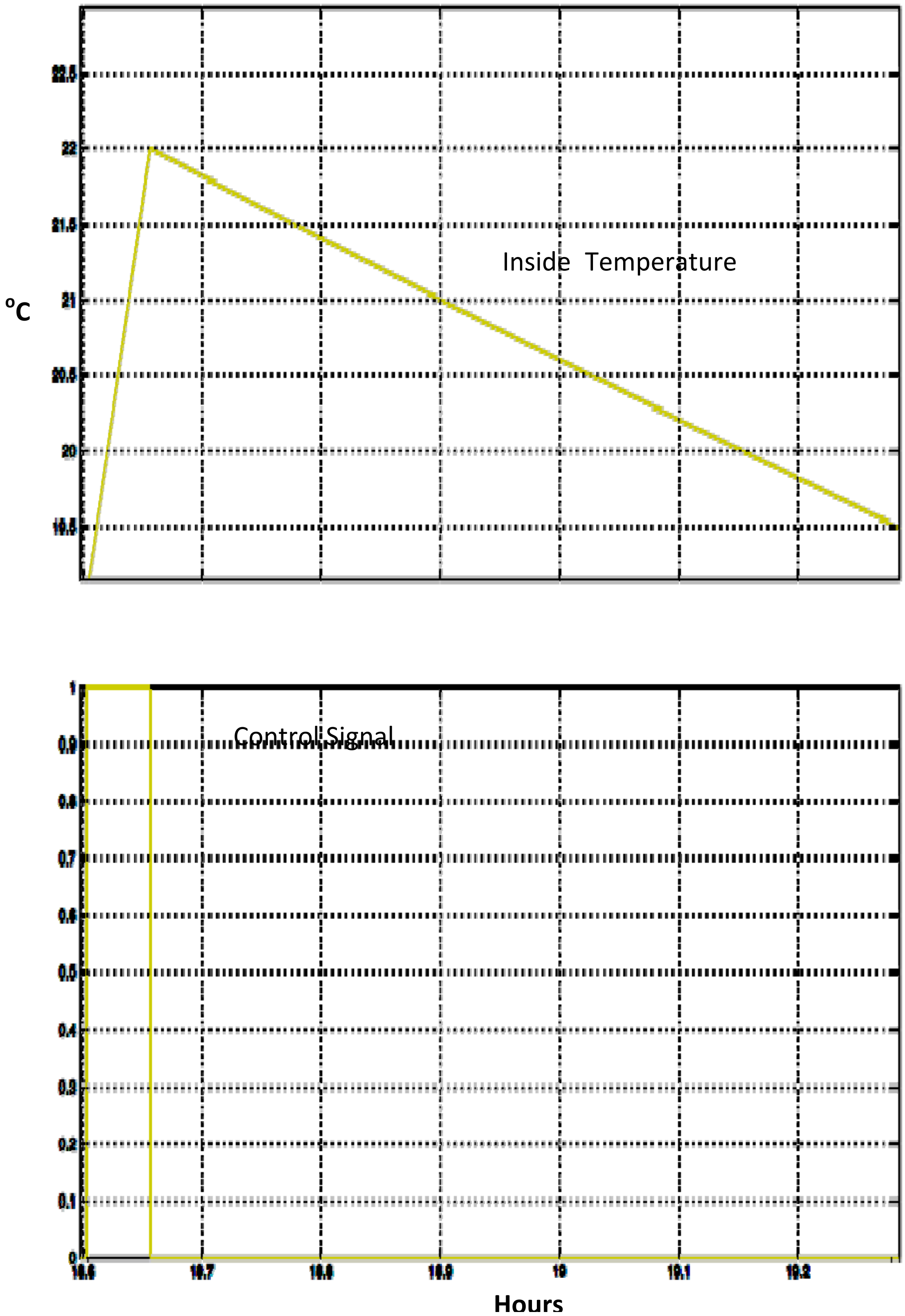

Fig 5.9: Effect of Curtailment (appx. 20 mins) in evening on Temperature (inside); outside temperature averaging -8 degrees

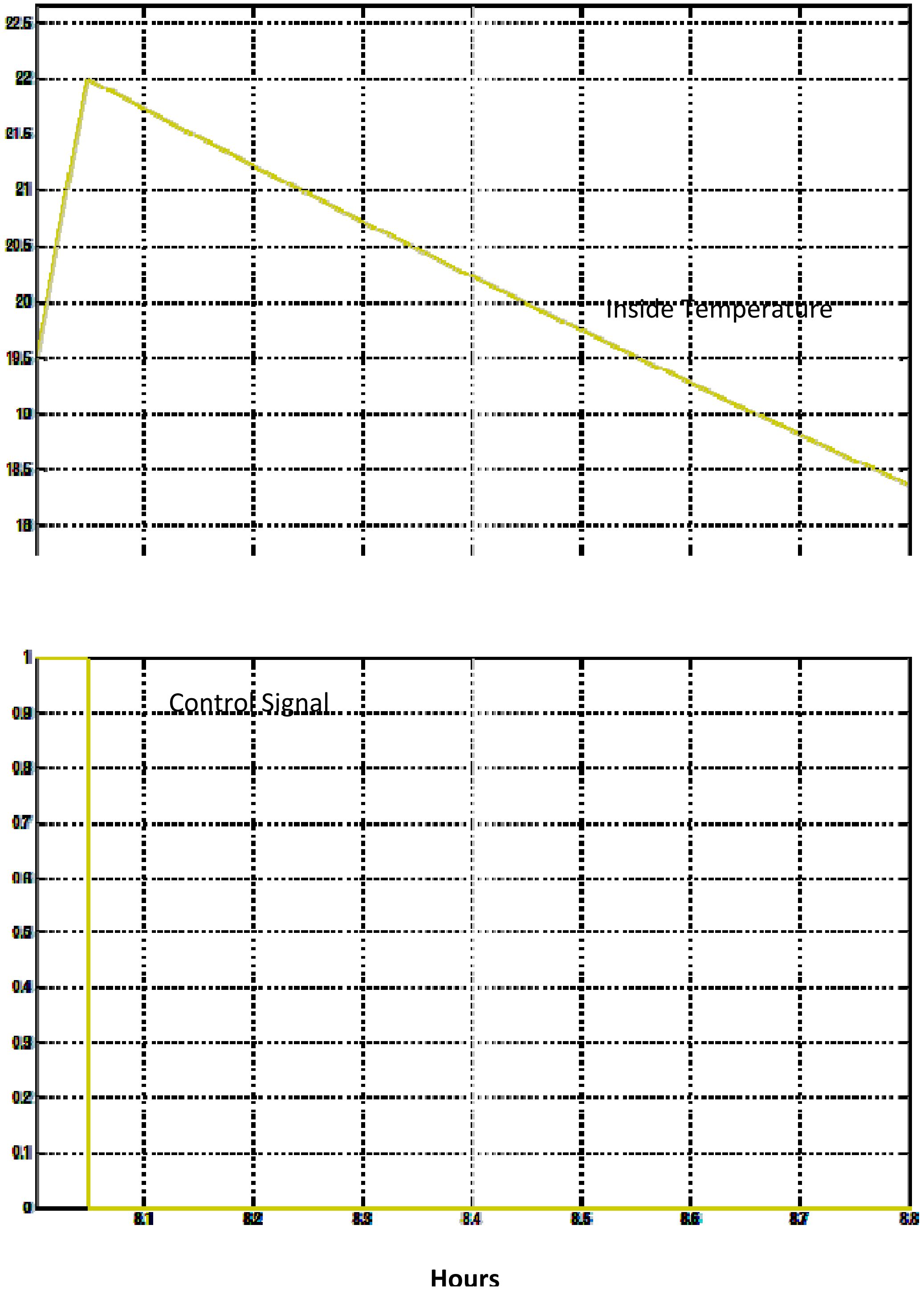

Fig 5.10: Effect of Curtailment (appx. 20 mins) in daytime on Temperature (inside); outside temperature averaging -16 degrees

In extreme weather and even little milder weather heating load is present. Not considering hourly based optimization and using it solely for spinning reserve in case of contingency. Suppose that 50 % of consumers are willing to bid it as a spinning reserve (15 min time interval) then potential of this kind of reserve in peak period are 1.5 KW*300,000*50% is around 225 MW and between 200-250 MW all the time.

Also, the responsive loads are much more reliable than generator. The response from aggregations of small loads (which individually may be less reliable) is actually better than the reliability of response from large generators owing to their inherent ability [30].

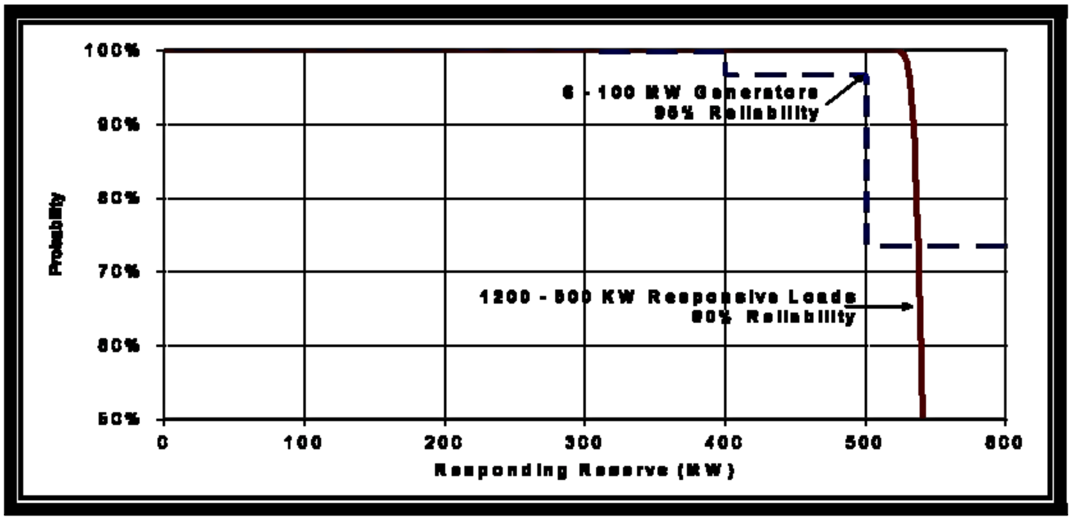

Fig 5.11: Reliability response of aggregation of small load vs. aggregation of large load [30]

The primary reason that the Direct Electric space heating loads are better suited for supplying spinning reserve rather than peak reduction is because load response duration is limited. Nevertheless, spinning reserve usage is rare. Intelligent techniques can be developed to take dual advantage, benefit of hourly based optimization for peak clipping as well as some percent of load can be shifted and present all the time. For instance if p percent of consumer opt for peak clipping then 1-p percent of the load can be used as spinning reserve

5.3 Space heating Load as a Resource

There are situations when there is excess of production owing to the intermittency of renewables. It’s not only the variability but the predictability that has resulted in over frequency issues. That means in such peculiar situation which is caused by the maximum feeding by renewable energies, either energy has to be filled or exported or tuned down to cope with the problem. The surplus electricity produced by intermittent RES frequently goes unutilized owing to insufficient power demand [37].

So in situations of excess production of wind power that typically depends on the operational strategy of power system fraction of that wind energy is curtailed and goes wasted. As the system has no capability of absorbing while maintaining the reserve. This is particularly true for the power systems that have limited pumped hydro storage facility. Certainly there are storage options but they are expensive to be utilized and cost to benefit ratio seems higher. When wind power production is about 20 % of yearly consumption, the amount of discarded energy will become substantial and about 10 % of the total wind power produced will be lost [38]. Tuning down the renewables in excess generation case is against the essence of their integration and perhaps an unfeasible solution with the increasing share of intermittent renewables. This means that even in times of maximum feed-in by renewable energies, storages has to be filled or energy has to be exported. Grid storage is seeing a rush in interest among utilities, but justifying the investment is challenging because many storage technologies are very expensive and most utility regulations are designed for investments in power plants, not storage.

The thermal storage capability of residential sector can be unleashed to support high wind power hours or under-forecasting of demand. The idea of negative spinning reserve is that in case of excess of generation from renewables, there must be some sort of power sink to avoid regulating or tuning the wind power production. Storage electric space heating load has the tendency to act as negative spinning reserve. Purely resistive in nature, termed as frequency responsive load, they have the ability to dump the excess energy without having any impact on consumer. Storage electric space heating load equipped with bounty of storage. That stored energy can be used later and ultimately helps in flattening the load curve. Nevertheless, before quantifying the capacity, instant penetration of wind power must be given consideration.

5.3.1 Up/Down Controlling of Electrical Space heating load with different degree of Storage

Storage Electric space heating profiles follow a certain trend owing to ToU pricing. However the trend is kind of constant, that is, charging on night time typically from 11pm to 6am and then allowed to coast the whole day, regardless what the variation of power price and power system critical conditions. Hence the approach followed is very rigid and it is just meant for space heater with high degree of storage only.

Here, the goal is to optimize the DR control of Storage Electric space heating load so that it can offer a lot more flexibility in control. The idea is to charge the storage in a manner to fulfill some set objective. The price is used as a signal. The price of power exchange is use to optimize the control of load. In this way providing the incentive to aggregator/retailer that is minimizing the overall cost and increasing the profit by playing with demand elasticity. Nevertheless the price signal can be set by aggregator to dictate his terms and to obtain certain objectives and goals as long as comfort requirement is not violated. The signal can be a function of wind power variation and in that case it is suitable to use the load to match the wind power variability. This approach would be a general approach for different degree of thermal storage and it is not at all restricted to Full storage. Having said that the next step is to make a mathematical model of up/down control of storage electric heating and find optimization point. Optimal design of price based Demand response program will take into account the quality of service. The model would first describe the storage behavior and its limitation with the help of mathematical expressions/equations and then followed by the DR optimization control technique.

Modeling the Thermal Storage:

It is safe to assume that the amount of heat energy that can be stored is always limited by the energy demand of 1 day.

Considering an Ideal storage this can be expressed as:

$S \leq Ed$

While, $E_d \alpha f(T)$ { f(T) : function of Outside temperature

S : Realizable Storage Potential

E_d : Energy (heat) Demand of a day

Realizable storage would change as a function of energy demand of the day

$S=x * Ed$

Where,

$0 \leq x \leq 1$ { x: Degree of Storage ; 0 for No storage, 1 for Full, 0-1 for Partial storage

While, {$S \leq Ed$ & $E_d \alpha f(t)$, for t>0

If the charging speed is Pi expressed in KWh/h

Then,

$0 \leq P_i \leq P_{i \text{ Max}}$

And, Energy stored at any instant given as:

$S_{i+1} = S_i + \alpha P_i(t) - W_{out}$

Where, α is duty cycle and W_{out} is Energy Consumed for that period

So, Charging Mode: $S_{i+1} > S_i$; Discharging Mode: $P_i=0$ and $S_{i+1} < S_i$

And each day there will be certain no. of hours for charging and discharging, considering ideal storage

$T_{charging} = \frac{X}{Pi-Pout}$; $T_{discharging} = \frac{X}{Pout}$ { T is TimePeriod

$S \leq E_d$ and $0 \leq P_i \leq P_{i \text{ Max}}$

Optimal Space Heating load control with Dynamic Pricing:

Up/Down Control of Electric Space heating load is solved using Linear Programming. (***linprog*** optimization tool in MATLAB).

Objective Function

Minimize: $K_1X_1 + K_2X_2 + K_3X_3 +$ ………….$K_{119}X_{119} + K_{120}X_{120}$

{Optimizing for 5 days

Where,

- K is the Power price signal (Known), (it can be any signal depending on the objective)
- X is KWh/h (Unknown)

Constraints:

- $X_1 + X_2 + X_3 +$……………………$X_{120} > E_d$

  {E_d is Energy Demand for 5 consecutive days.

- $0 < X < P_{max}$
- $X_1 > q_1 - q_0$
- $X_1 + X_2 > q_1 + q_2 - q_0$
- $X_1 + X_2 + X_3 > q_1 + q_2 + q_3 - q_0$

  ……………..
  ……………..
  ……………..
  ……………..
  ……………..

- $X_1 + X_2 + X_3 +$………………………..$X_{119} > q_1 + q_2 + q_3$………$q_{119} - q_0$

- $X_1 + X_2 < S + q_1 + q_2 - q_0$

- $X_1 + X_2 + X_3 < S + q_1 + q_2 + q_3 - q_0$

  ……………….

  ………………..

  …………………

- $X_1 + X_2 + X_3 + \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots X_{119} < S + q_1 + q_2 + q_3\ldots\ldots\ldots q_{119} - q_0$

Where,

- q_n represent the Average Demand of that hour.
- q_0 is the initial level of storage at t=0

5.3.2 Case Study

Having developed the model for optimizing control of heating with dynamic price as a signal, the next step is to consider a real scenario. Here, again, type load model data for Electric space heating customer is used. Heating profile is generated by statistical means (Multivariate regression analysis). By knowing the average demand of every hour, next step is to optimize the load control in a fashion that minimizes the overall cost. This in turn reduces Peak to average ratio of Finland consumption as it has already been proved that high prices correspond to high demand. Also the flexibility offered by storage can be potentially exploited. The latent storage which is present in thousands of houses in Finland can be very resourceful. DEH houses are greater in number than full storage heating so by adding certain degree of storage more flexibility can be achieve in terms of load controlling. The storage would be helpful in providing some ancillary services with certain reliability. Since the aggregated level of storage of consumer cluster would be known with accuracy then it can be used as a fast frequency reserve. That is using it as fast spinning reserve and negative reserve as well, which is the dire need owing to growing proportion of variable and uncertain renewables power production.

Here we consider the last week (excl. weekend) of Feb 2010 situation, where Power exchange prices shows anomalous behavior. The peak prices rose well over 1000 Euro/MWh and average were around 200 Euro/MWh for that period. This was a crunch situation from power system reliability and economy point of view. So the thermal storage present at most houses would have played huge role in curbing these sorts of scenarios. Finally we optimize DR control for that period by using Linear programming tool in Matlab to satisfy our objective without compromising on quality of service (User Comfort). The price signal was chosen as power exchange price for that period for simplicity in order to demonstrate the effectiveness of our optimal control. The price could take any form if not power exchange. Use of Price as a signal would act as a biggest incentive for customer to respond. The desire response can be achieved by setting the price signal accordingly to fulfill the objective. The results are discussed in the following section.

5.3.3 Simulation Results

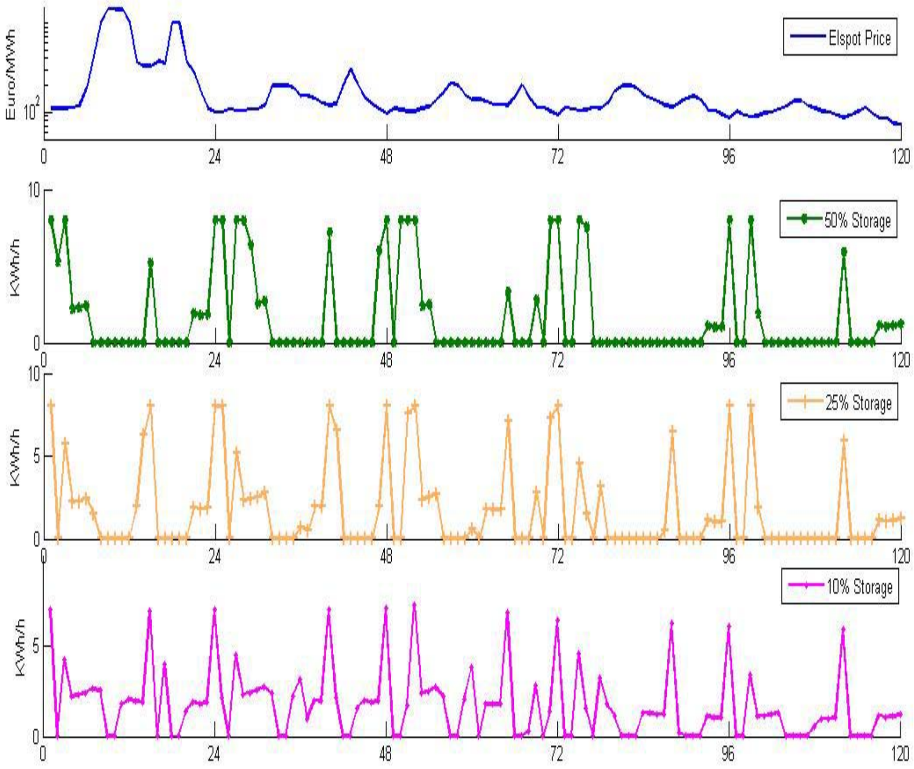

Fig 5.11: Effect of Thermal Storage on Heating Load Profile

Storage is expressed as percentage of average energy demand of a typical winter day. Clear from Fig 5.11 that bigger the storage the greater the flexibility in load shifting and greater the savings under dynamic pricing atmosphere.. The DR potential of sufficient storage level is tremendous nonetheless minimum storage could be useful than having no storage at all.

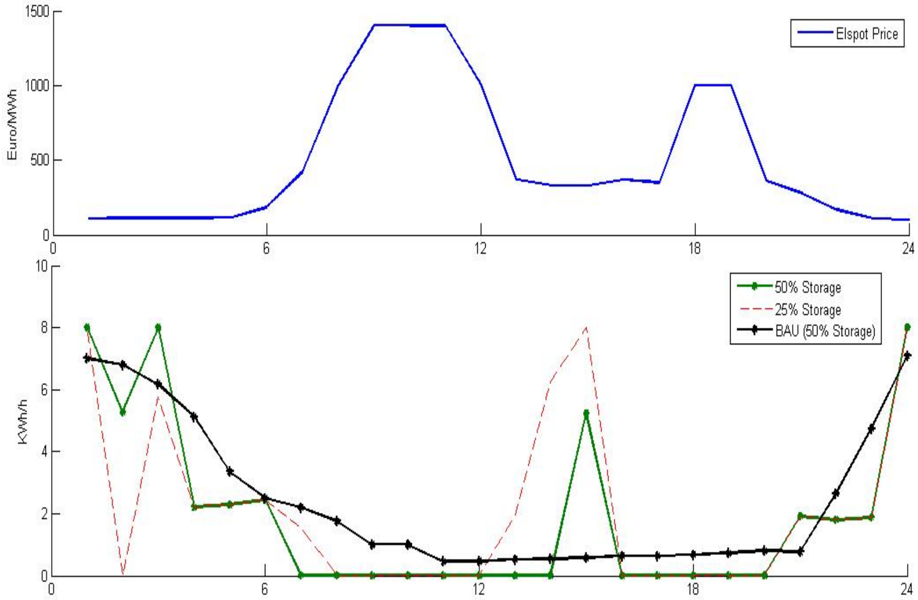

Fig 5.12: Scenario_ Abnormal Peak Price day and Optimizing Control

The bigger the storage the greater the load shifting and have more flexibility to response to the price to attain maximum benefit. While low level storage tends to optimize fully as much as they can. The last subplot of Fig 5.13 reveals the flexibility scenario of Full storage capacity. Since the storage is limited by the energy demand of the day so having big storage will not be productive that much. Because demand sets the limit how much you can store. For instance in summer season the storage may be less filled but one cannot filled it more unless there is a certain demand of that energy in coming hours or so. That restriction would put a limit to storage capacity point and beyond that point there is no as such advantage. The coefficient of variation of different degree of storage in the case study increases as the storage level decrease. The dispersion of storage level is around its mean is maximum with low level of storage and storage level often reside on maximum and lower level. Contrast is the case with high degree of storage (>100%).

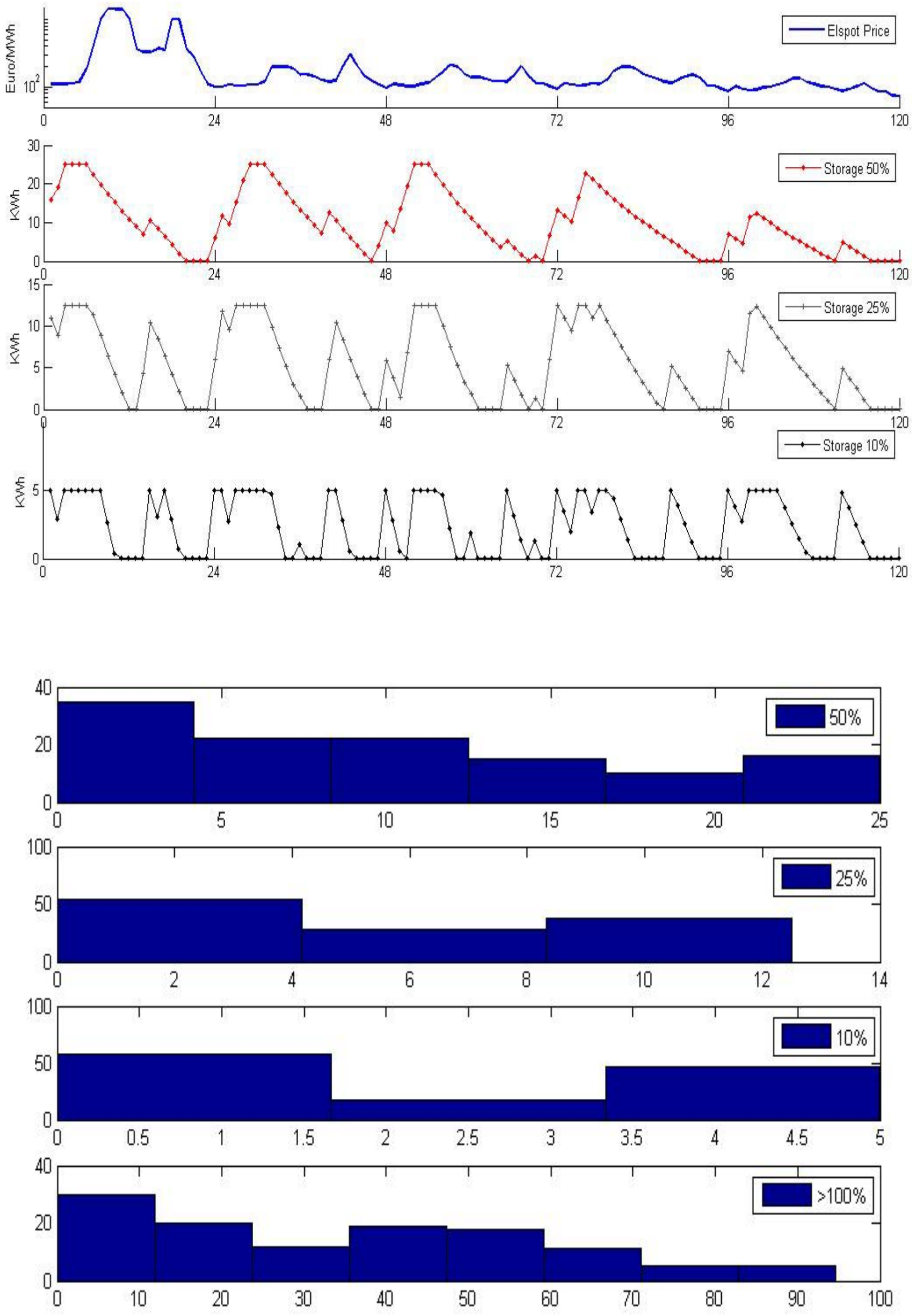

Fig 5.13: Behavior of different degree of Storage under the Dynamic Price Signal

A comparison of the optimal control technique with BAU is depicted in Fig 5.14

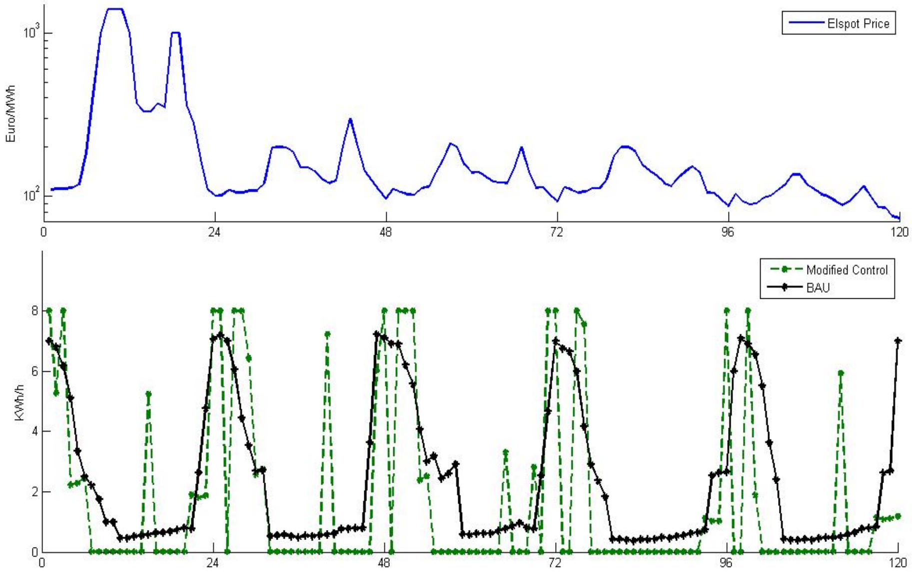

Fig 5.14: Comparison of Optimal control with BAU

6. Conclusion

The thesis focuses on the Demand response potential of Electric Space heating. The price-based optimal demand response control model is proposed and the extent of aggregate demand response participation of several household is analyzed. The DR potential evaluation exclusively rest on type load data and simulated thermal model of house. The need of load shaping under the smart grid scenario is highlighted by stressing on the risk posed by integration of intermittent renewables.

Research findings are listed below:

- The thermal inertia of modeled house offers the flexibility of load shifting without altering the quality of service. Preheating and then coasting the house in winter can shift the 100% of space heating load from Peak hours. The greater the dead band alteration the greater the shifting potential.

- The DEH loads are particularly suitable for providing fast reserve in case of contingency. The finding proves that quality of service in winter is not deteriorated for 15 minutes time interval; however the latent potential is overwhelming. For a cluster of 300,000 houses equipped with DEH, aggregate potential demand reduction by 50% participation is found to be around 225 MW for 15 minutes demand response event.

- The aggregated BAU DR potential of cluster of 79000 storage electric heating customers is minimal and load is less coincidence with the Finland peak demand. Nevertheless some robust means of load shaping can make this type of load very responsive in view of the strong penetration of Intermittent RES and changes in operation of Electricity market in future.

- Optimal DR control of Electric storage heating is suggested. It is shown that optimal control makes such load more flexible in terms of load shifting. Also controlling of up down of Electric space heating load with some degree of storage would be of tremendous help in abating the load balancing problem caused by intermittent renewables. The effectiveness of proposed DR control algorithm is highlighted by simulation results

Contribution:

The work presents mathematical descriptions; optimization and modeling that will serve as a basic tool of systematically analyzing demand response potential of electric space heating load. Aggregator/retailer companies can be benefited by the findings of the research which are pertinent to expected constraints and benefits of heating load control. Methodologies such as demand scheduling and pre-heating, introduced in this research will serve as a design criterion to operation with demand response and future electric power system planning in view of smart grid scenario and high penetration of renewables. The work can be extended to consider other household loads especially electric vehicles and optimal DR control method can help to shape the load accordingly and schedule the load in such a way that Grids and distribution system are maximally utilized.

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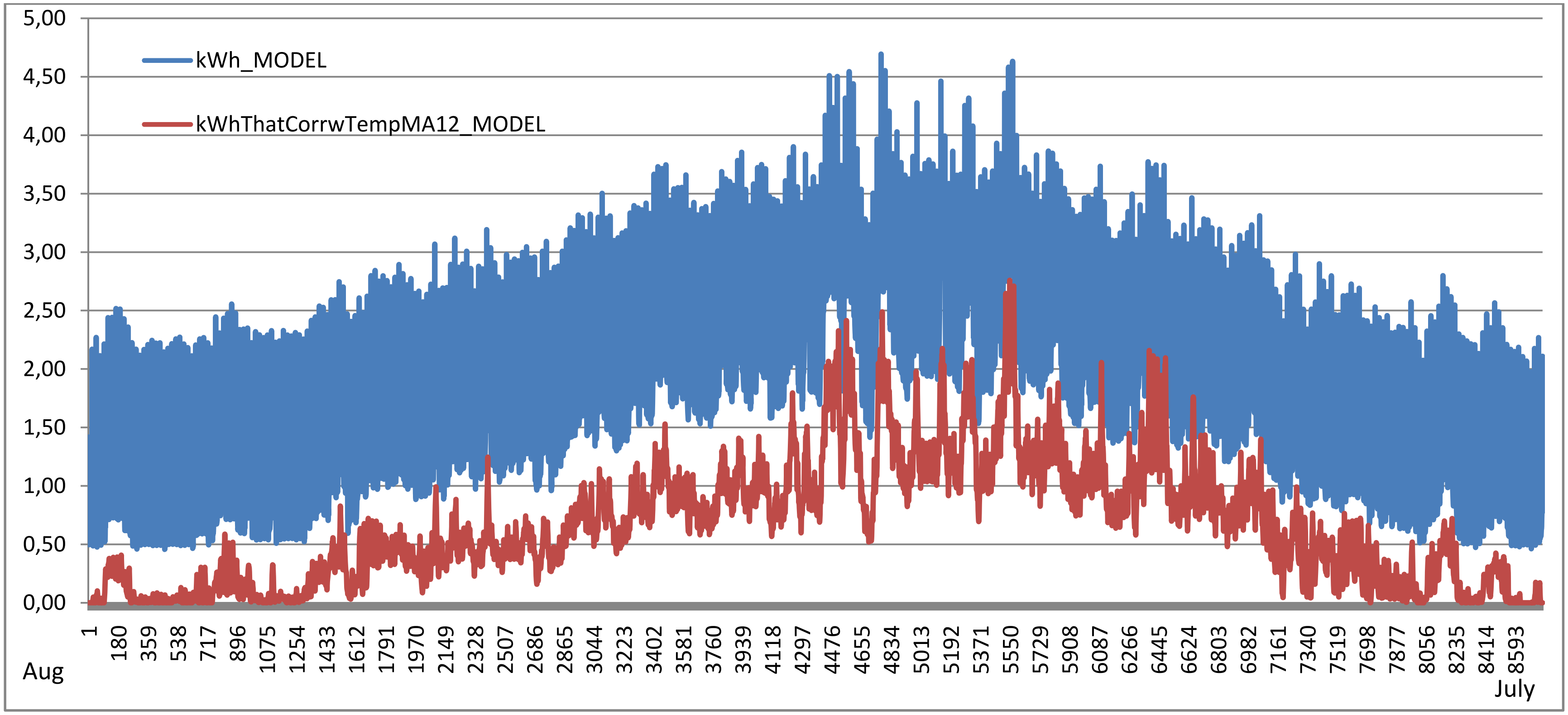
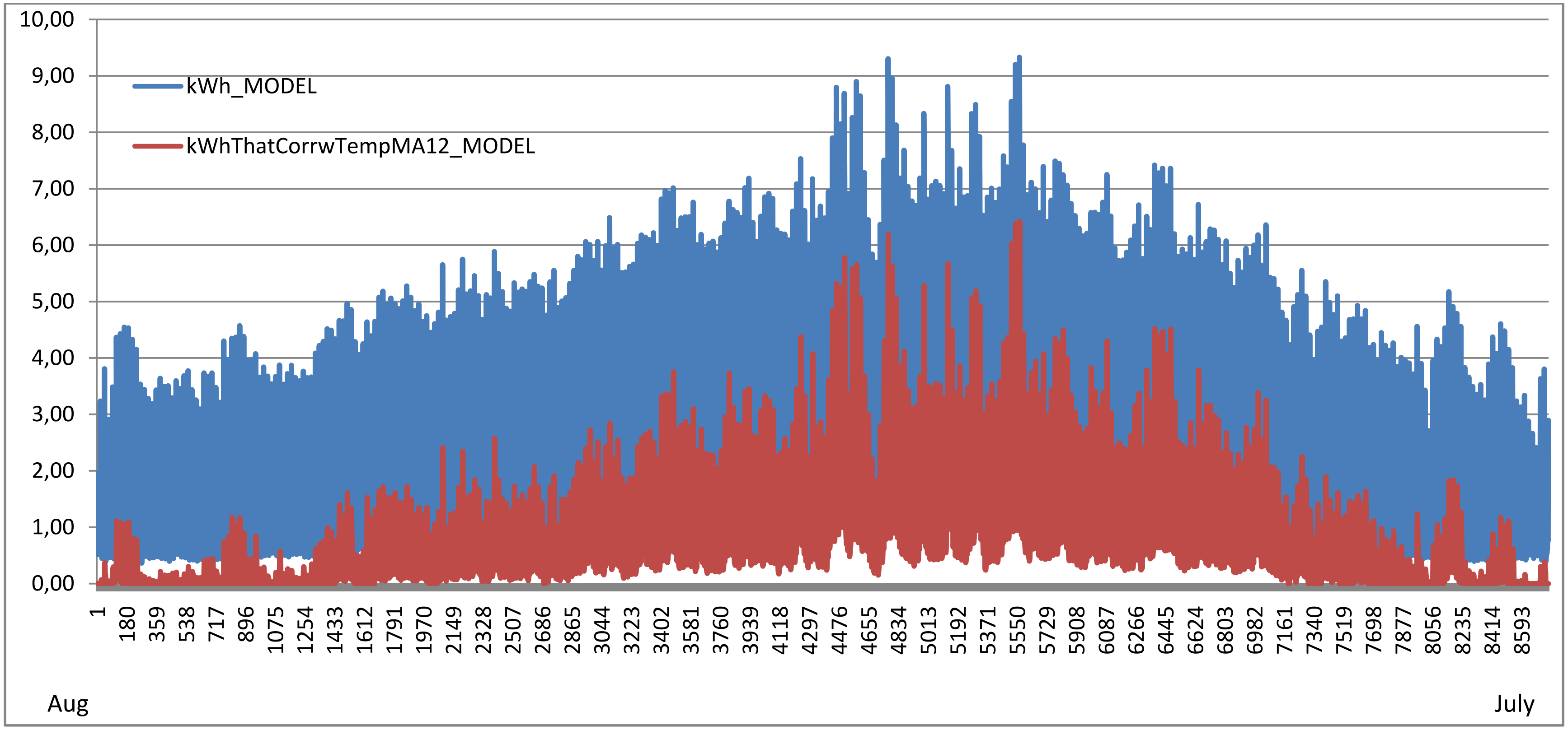
Appendix A: Data used in the Case Studies

Type Load Model Data for DEH Customers



Appendix A (Contd.)

Type Load Model Data for Storage Electric Space Heating Customers



Appendix A (Contd.)

Finland Average Demand(MW) 2010

Hours	Winter	Spring	Summer	Autumn
1	11765.52	8952.22	7628.091	8042.476
2	11416.24	8559.122	7247.273	7641.762
3	11199.19	8316.415	7018.682	7428.857
4	11146.05	8192.732	6871.5	7370.524
5	11227.62	8132.732	6736.091	7406.429
6	11601.19	8275.634	6852.636	7673.81
7	12507.86	8987.902	7455.273	8451.381
8	12936.67	9655.195	8042.909	9014.714
9	13123.48	9848.805	8371.818	9207.286
10	12955	9938.122	8599.909	9311.952
11	12878.95	9922.415	8688.045	9301.952
12	12864.81	9894	8738.273	9286.905
13	12824	9853.171	8777.864	9270.762
14	12729.29	9748.805	8743.136	9193.81
15	12673	9748.805	8671.136	9101.762
16	12734.14	9563.171	8609.364	9048.571
17	13025.9	9449.61	8505.091	8946.619
18	13192.62	9449.61	8425.182	8926.143
19	13140.81	9449.61	8290.409	8888.714
20	13166.62	9449.61	8239.818	9138.238
21	13040.76	9449.61	8181.182	9403.905
22	12589.95	9285.195	7935.909	9027.524
23	12905.52	9209.122	7878.409	8625.524
24	12474.52	9365.634	8032.591	8569.048

Appendix A (Contd.)

Elspot Prices (Euro/MWh) _ Nov ’11-Mar ’12

DATE	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
01.11.2011	37	38	37	35	32	34	37	42	45	45	46	45	46	45	44	43	43	46	49	47	46	42	41	39
02.11.2011	37	36	34	35	35	37	38	43	50	46	43	43	44	46	45	46	46	48	53	50	44	42	42	39
03.11.2011	38	36	35	35	35	36	38	43	45	45	45	44	45	45	45	45	45	48	53	47	45	42	39	39
04.11.2011	37	36	35	34	34	36	38	41	42	43	43	42	42	42	42	40	41	43	51	48	45	40	37	38
07.11.2011	39	38	37	35	35	37	39	49	58	52	48	48	50	57	52	51	55	67	69	49	43	41	41	40
08.11.2011	39	39	38	39	38	39	41	46	55	50	47	46	47	48	47	47	49	58	61	48	46	43	43	41
09.11.2011	40	40	39	39	39	40	42	46	50	51	49	49	49	49	48	48	50	55	65	48	45	43	43	43
10.11.2011	40	41	40	40	40	42	43	46	55	45	43	43	44	49	47	47	50	58	68	51	44	43	43	42
11.11.2011	41	41	40	40	40	40	41	45	51	45	45	44	45	45	44	44	44	49	52	46	43	43	43	42
14.11.2011	41	42	40	39	39	40	43	46	49	45	44	44	45	46	47	47	47	47	47	45	43	42	44	44
15.11.2011	42	42	42	42	42	42	44	49	55	44	44	44	44	50	51	49	52	59	62	51	46	45	45	44
16.11.2011	43	43	42	42	41	42	44	48	51	49	46	46	46	46	46	46	47	51	55	46	46	44	44	44
17.11.2011	43	43	42	42	42	43	44	49	47	47	46	46	46	47	47	47	55	59	70	61	55	46	46	45
18.11.2011	44	43	42	42	41	41	44	50	58	55	48	48	48	46	45	45	46	47	52	45	44	43	43	42
21.11.2011	42	40	40	40	40	40	42	45	44	43	43	43	44	45	44	43	49	65	70	49	43	42	42	42
22.11.2011	41	40	40	40	40	41	43	44	43	43	42	42	43	43	42	42	44	54	54	44	42	41	41	41
23.11.2011	40	40	39	39	39	40	42	42	42	42	41	41	41	41	41	41	42	43	43	41	41	40	39	39
24.11.2011	38	37	36	36	36	37	38	40	41	41	40	40	40	40	40	41	43	42	42	41	40	40	39	39
25.11.2011	37	35	34	34	34	35	36	38	39	39	39	39	39	39	39	39	39	40	40	39	39	37	37	37
28.11.2011	34	26	27	33	33	34	35	37	41	41	41	41	42	43	41	43	45	50	56	42	40	38	37	36
29.11.2011	35	35	34	33	34	34	35	38	40	40	38	39	39	39	39	39	41	41	41	39	38	37	36	35
30.11.2011	33	32	28	27	29	32	34	36	37	37	37	37	37	37	37	38	38	39	40	38	37	37	36	35
01.12.2011	34	33	29	29	30	31	34	36	37	37	37	37	37	37	37	37	38	39	39	38	37	37	37	36
02.12.2011	35	34	34	34	35	35	37	37	39	39	39	39	39	39	39	39	40	40	40	39	39	38	37	37
05.12.2011	35	36	34	29	30	31	36	38	40	40	39	39	40	39	39	40	44	41	41	40	39	38	38	37
07.12.2011	36	35	35	35	35	35	37	39	44	44	41	40	42	42	42	43	45	49	51	43	40	39	39	38
08.12.2011	37	35	35	34	33	34	37	39	46	47	43	42	44	45	45	44	43	44	43	40	38	37	37	36
09.12.2011	35	31	27	27	29	30	34	36	38	39	39	38	38	38	38	38	38	39	39	38	37	36	36	35
12.12.2011	35	34	34	34	31	32	35	42	51	39	39	39	39	39	39	40	55	51	45	39	38	37	36	35
13.12.2011	34	34	34	32	29	29	37	40	46	38	37	37	37	40	39	41	47	47	38	38	37	36	36	35
14.12.2011	33	31	27	27	24	28	34	35	37	37	37	37	37	37	37	38	39	39	39	38	37	36	35	34
15.12.2011	33	33	28	27	24	27	34	36	37	38	37	38	38	38	38	38	39	42	40	39	38	37	37	36
16.12.2011	35	34	33	34	34	35	35	38	40	40	39	39	39	40	39	39	39	40	39	39	38	37	36	35

Appendix A (Contd.)

Elspot Prices (Euro/MWh) _ Nov ’11-Mar ’12 contd.

DATE	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
19.12.2011	32	33	33	33	33	34	35	36	38	38	38	38	38	38	38	38	39	39	39	38	37	36	35	35
20.12.2011	33	33	33	33	33	33	34	37	39	40	39	39	39	39	38	39	41	41	40	39	38	37	36	35
21.12.2011	34	33	33	33	33	34	35	36	39	40	39	39	39	39	39	39	40	41	40	39	38	37	36	35
22.12.2011	34	34	33	33	33	34	35	37	38	39	38	38	38	38	38	38	38	38	38	37	37	35	34	33
23.12.2011	32	32	32	31	31	31	32	33	34	34	34	34	33	33	33	33	33	34	34	33	32	32	32	31
27.12.2011	13	17	13	11	12	16	21	26	29	30	31	31	31	32	32	32	34	34	34	34	33	32	32	31
28.12.2011	28	30	29	28	28	29	30	31	32	33	33	33	33	32	32	32	33	33	33	32	31	30	28	25
29.12.2011	22	22	16	13	12	12	18	23	28	30	30	31	31	30	30	30	31	32	32	32	31	30	30	29
30.12.2011	25	21	20	20	20	20	25	31	32	33	33	33	33	33	33	33	34	35	36	35	34	33	33	33
02.01.2012	25	29	29	28	28	29	30	38	40	39	38	39	39	37	35	36	41	40	38	36	35	34	33	32
03.01.2012	29	29	26	23	23	25	29	32	33	34	33	33	33	33	33	33	34	34	34	34	33	32	31	29
04.01.2012	24	23	23	22	22	24	26	29	37	33	33	33	33	33	33	33	37	35	34	35	35	33	32	31
05.01.2012	27	28	27	27	27	28	39	46	40	35	35	36	36	35	35	35	40	40	40	37	36	33	32	30
09.01.2012	34	35	33	33	32	33	36	43	59	65	59	57	56	56	55	52	51	52	57	61	53	40	36	34
10.01.2012	32	32	31	31	29	31	40	48	48	53	51	51	53	52	53	52	52	55	61	61	41	36	35	33
11.01.2012	32	32	31	30	29	30	39	40	48	42	40	38	39	40	40	40	43	46	47	41	38	35	34	33
12.01.2012	31	31	31	30	29	29	40	43	60	46	38	36	37	38	36	37	40	42	41	37	35	34	34	33
13.01.2012	31	28	25	25	26	28	33	37	38	38	36	35	35	35	34	37	40	40	39	35	34	33	33	32
16.01.2012	34	34	34	33	34	33	41	44	58	61	48	45	48	53	52	49	50	52	60	47	43	40	38	35
17.01.2012	34	34	34	33	34	34	40	47	57	59	53	49	50	52	51	50	50	54	62	58	46	44	38	36
18.01.2012	34	34	34	33	33	34	40	44	52	52	44	43	43	43	41	41	41	43	44	40	37	35	35	34
19.01.2012	33	32	31	31	31	32	36	38	40	42	40	39	40	41	41	39	39	42	45	41	38	37	36	34
20.01.2012	34	32	32	30	30	31	36	39	46	50	46	44	45	45	42	41	43	45	50	45	39	36	36	35
23.01.2012	33	32	31	31	30	32	42	45	52	55	51	51	52	50	48	47	45	47	55	60	52	43	41	37
24.01.2012	36	35	34	34	34	35	37	42	55	55	56	54	54	53	52	51	51	55	65	67	55	42	39	37
25.01.2012	36	36	36	35	36	37	39	43	58	58	55	52	50	48	46	45	45	47	61	63	54	41	38	36
26.01.2012	35	35	35	35	34	34	37	45	58	58	52	49	46	42	43	43	45	46	58	55	39	36	36	35
27.01.2012	34	33	33	33	33	34	45	61	52	56	59	55	55	57	51	48	45	60	59	65	50	38	38	37
30.01.2012	35	35	34	33	32	33	45	71	52	57	53	49	45	45	45	44	46	50	59	59	49	39	38	36
31.01.2012	35	37	36	36	37	37	45	67	95	85	61	53	52	53	49	46	50	86	95	71	57	50	44	40
01.02.2012	38	39	39	39	39	40	48	54	199	203	135	92	65	59	60	59	60	175	203	150	57	52	48	46
02.02.2012	42	42	40	40	40	42	44	68	254	225	135	144	150	130	73	84	79	164	234	125	100	66	56	50
03.02.2012	44	46	44	42	43	44	60	212	200	207	181	86	85	68	60	60	60	148	199	112	75	58	51	53

Appendix A (Contd.)

Elspot Prices (Euro/MWh) _ Nov '11-Mar '12 contd.

DATE	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**	**21**	**22**	**23**	**24**
06.02.2012	43	41	41	41	40	42	45	58	100	120	109	102	91	80	80	74	74	85	119	143	125	66	53	45
07.02.2012	43	43	43	43	43	45	47	67	120	120	115	99	96	96	84	70	68	73	100	82	66	62	54	45
08.02.2012	43	43	43	42	43	44	48	65	120	156	125	108	112	101	100	99	105	121	152	210	170	136	73	50
09.02.2012	44	44	43	43	42	43	51	60	104	95	86	74	79	68	74	68	60	69	103	170	121	55	51	46
10.02.2012	44	45	44	44	45	46	50	60	183	176	125	105	90	86	74	60	60	70	110	158	101	70	51	47
13.02.2012	41	41	40	40	40	41	43	55	85	100	60	53	49	46	46	45	45	47	56	46	44	43	42	41
14.02.2012	40	39	38	38	38	40	41	42	47	53	47	46	45	43	43	42	42	42	44	42	41	40	39	37
15.02.2012	34	34	31	30	31	36	43	46	46	44	41	40	39	39	40	40	40	44	47	44	42	40	39	38
16.02.2012	37	38	38	38	38	40	43	51	64	80	77	62	51	49	46	44	43	44	50	45	40	39	38	37
17.02.2012	36	35	35	35	35	36	43	46	43	46	42	40	40	40	40	40	40	40	53	43	40	39	38	37
20.02.2012	35	35	34	35	35	36	50	97	65	65	51	43	40	47	57	57	48	68	75	47	41	38	38	35
21.02.2012	33	31	31	31	31	39	54	65	64	65	50	41	41	46	57	51	51	58	70	49	43	38	37	36
22.02.2012	35	33	32	32	32	40	52	59	59	60	48	40	39	42	50	49	47	50	60	47	39	34	35	34
23.02.2012	29	26	25	25	25	26	35	40	40	39	35	36	34	33	33	33	33	33	40	41	39	34	33	32
24.02.2012	31	30	29	29	29	40	55	52	50	50	44	39	37	40	45	45	44	48	55	44	38	32	36	32
27.02.2012	34	34	34	34	34	41	49	56	58	60	55	46	45	45	49	46	45	45	52	57	42	36	34	33
28.02.2012	33	33	32	32	32	33	40	45	45	46	35	34	34	34	40	40	39	40	50	38	35	34	34	33
29.02.2012	32	31	30	30	32	33	40	40	41	40	35	35	34	34	39	36	35	37	43	37	34	34	34	33
01.03.2012	32	32	31	30	31	33	40	39	38	38	38	39	37	34	33	34	33	35	40	36	34	33	33	32
02.03.2012	31	30	30	29	30	32	41	40	38	38	39	38	38	33	32	34	34	34	40	34	33	33	33	32
05.03.2012	32	31	30	29	27	31	45	56	58	58	55	50	48	39	40	48	46	48	58	47	43	37	39	33
06.03.2012	32	32	31	31	33	45	54	53	58	58	55	53	56	45	45	47	46	47	58	47	45	39	39	36
07.03.2012	32	33	30	30	38	47	104	58	117	200	56	53	49	44	44	48	48	48	58	45	45	41	43	37
08.03.2012	32	35	32	29	31	35	47	46	46	46	43	40	40	39	33	33	33	35	40	45	45	39	40	38
09.03.2012	32	31	30	30	32	34	44	43	46	46	44	40	38	35	36	35	34	35	39	40	40	36	37	35
12.03.2012	29	26	26	26	29	41	55	55	55	55	51	50	47	38	34	43	40	40	47	40	39	33	36	31
13.03.2012	29	26	25	25	33	37	44	44	43	42	42	44	43	43	44	45	40	40	40	40	40	40	45	35
14.03.2012	29	27	27	27	28	41	45	45	49	52	52	46	46	43	43	49	44	45	48	48	44	40	42	37
15.03.2012	30	29	28	27	33	46	49	52	52	52	49	55	55	40	42	46	44	44	47	42	40	40	42	33

Appendix B: Matlab Code for Optimizing DR Control

- **% LINEAR PROGRAMMING**

```
AB; % 238 by 120 (defined in Work Space)
Aeq=[]; %Equalites
beq=[]; % vector (Equalities)
lb;
ub; %Lower bounds and Upper bounds (defined in Work Space)
Elspot_new; % Power Exchange Prices (defined in Work Space)
xy=10;      %Qzero (initial level of Storage)
buffer=25;  %Storage capacity
```

- **% Quality of Service Constraints**

```
g=zeros(119,1);
for j=2:119
   g(1)=D(1)+D(2)-xy;  %xy is q(zero)
   g(j)=g(j-1)+D(j+1);
end
```

- **% Realizable Storage Capacity Constraints**

```
g=g*-1;
h=buffer-g; % Storage capacity
gh=[g;h]; % Vector size (238 by 1)

%LINEAR PROGRAMMING Tool

[xnew10 fvalnew10] = linprog(Elspot_new,AB,gh,Aeq,beq,lb,ub);
```

- %STORAGE INFO

```
st=zeros(120,1);
  st(1)=xnew10(1)-D(1)+xy;
   for i=1:119;
      st(i+1)=st(i)+xnew10(i+1)-D(i+1);
   end
```