RESEARCH REPORT

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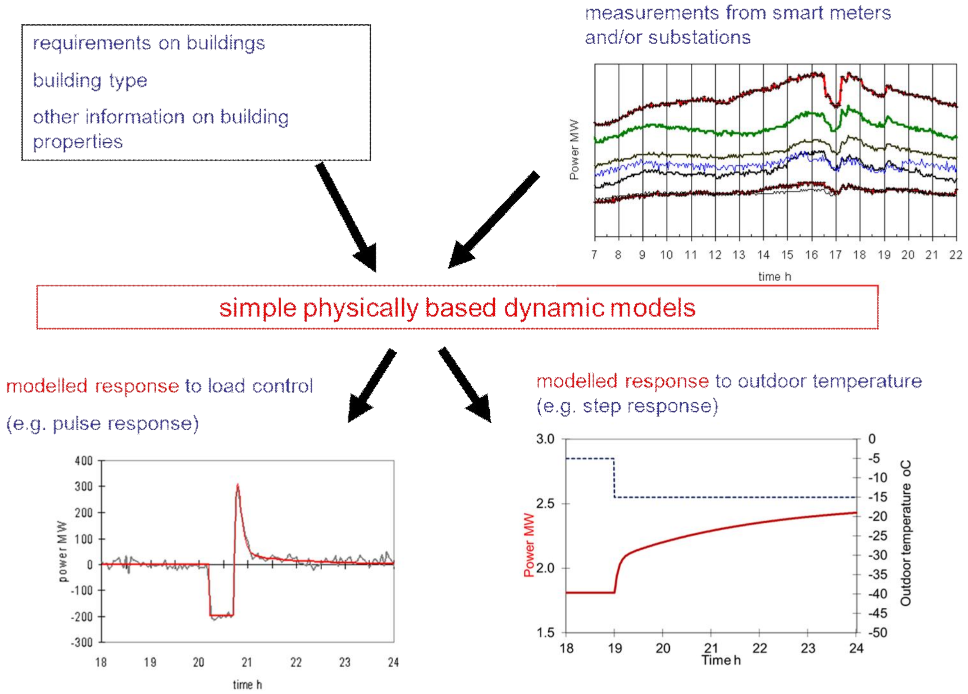

Measurements and models of electricity demand responses

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Summary

The expected increase in renewable and distributed generation and certain new loads will cause a need to invest substantially in the power grid and reserve and peak power generation, if the flexibility of the demand is not radically increased. Otherwise adequate quality of voltage and reliability of power supply will be compromised. Thus in the smart grids demand response will be applied extensively. It becomes necessary to predict the responses of load control actions. This report reviews research on measurements and models of load control responses. Simple physically based models of the responses are especially considered, because they have shown a potential for meeting this challenge.

Confidentiality	Public

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Project SGEM

Preface

This work was carried out in the Smart Grids and Energy Markets (SGEM) research program coordinated by CLEEN Ltd. with funding from the Finnish Funding Agency for Technology and Innovation, Tekes. I also wish to thank the SGEM partners who contributed to the report by reviewing it.

This report reviews load response model development and field tests carried out and reported by authors of earlier projects and field test. I wish to thank all of them.

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Author

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1 Introduction

The widely applied traditional load curve approaches, see Seppälä (1996), are not adequate for modelling the loads in the future smart grids were dynamic load control must be applied in large scale for demand response for the markets and for managing the distribution networks. The main problem with the traditional load curve approach is that it is not suitable for forecasting the responses to load control signals. It is also poor in forecasting how the loads depend on variations in the outdoor temperature. Updating the models may also be too slow, when traditional loads are replaced fast by new technologies, such as heat pumps and later charging of batteries of electrical vehicles. Thus new load prediction approaches will be increasingly needed. Research and development of physically based load response models started in 2011 in the project Smart Grids and Energy Markets (SGEM).

Paatero and Lund (2005) present and demonstrate a simplified bottom-up model, where the load is constructed from elementary end use load components such as individual household appliances. They also mention literature on demand models applied to load forecasting.

In Finland the electricity consumption of households is higher during weekends and depends on the outdoor temperature, daylight hours, etc. and roughly follows a sinusoidal pattern in part due to a low penetration of cooling loads (Haapakoski and Ruska, 1998). The loads of individual households vary much. When the number of households increases the stochastic variations of the aggregated load curve smoothen out rather rapidly.

The focus of this report is on the control of electrical loads, mainly space and water heating loads. It summarises several selected past and recent results on load control response measurement and modelling in Finland and in the Nordic countries. The selection is based on the judgement of the author who has reviewed and compared also some other measurements and models in his earlier reports, Koponen (1997) and (2006). Also projects not mentioned in this report might have made control response measurements that could be worth considering in this context.

The project SGEM also organised an expert workshop on load and response modelling. In its summary report, edited by Koponen and Saarenpää (2011), the presentations of Alvarez, Ruiz and Koponen addressed physically based load response models.

Physically based load response models for demand management have been studied by Chong and Debs (1979), Calloway and Brice (1982), Alvarez et. al. (1992, 2004), Molina et.al.(2003), El-Férik et. al. (2004) and Gomes et. al. 2009. Also Rikos et. al. (2008) applied simple physically based models in both defining the intervals and duration of load interruptions by a Virtual Power Plant and in validating simulations. Haase (1971) and Martikainen et. al. (1987) have reported in Finnish about the development and application of physically based models for simulating load responses to direct load control actions.

The purpose of this report is to collect existing background information from Finland and the Nordic countries for load response model development in the project Smart Grids and Energy Markets (SGEM). This report shows that physically based load response models have a potential for improving the forecasting of load responses to control actions and outdoor temperature variations.

2 Objective, scope and approach

2.1 Objective

The objective of this report is to collect and analyse readily existing models of load control responses. This information is used as a starting point in the related research and development in the project Smart Grids and Energy Markets (SGEM).

2.2 Scope and its limitations

The focus of this report is limited to

- automated responses of electrically heated houses and households on demand response signals,
- loads and appliances that have significant potential for providing new demand response capacity relatively fast such as different types of use of electricity for heating of space and hot domestic water,
- simple physically based response models as they are initially considered the most promising approach for solving this challenge and
- research in the Nordic countries, because of the similarities in climate and loads.

2.3 Methods

Both own previous work and some literature on modelling the load responses were analysed and reviewed.

3 Responses of electrical heating

3.1 Direct load control response in Northern Finland 1996-1997

In winter 1996-1997 direct load control field tests were carried out with nearly 7000 small houses and resort apartments and over 20 MW controllable power. The loads were measured from 11 distribution substations. There were no local measurements, except for measurements of indoor temperatures in only 5 houses. The field test area spanned from the coastal area around the city of Oulu via Pudasjärvi to Kuusamo at the Russian border. The customers had already earlier voluntarily joined the load control programme based on a small reduction in the tariff.

The houses in the field test were classified into controlled groups based on their heat storage and heat loss properties derived from the building year, building requirements and type of main construction material as reported by the consumers. Both residential houses and vacation houses in two skiing resorts were included. About 5 customers complained. (Less than 1/1000) The complaints came from customers that lived in houses that had higher heat losses than assumed thus being placed in a wrong control group. Most customers did not notice the control actions. Normally the groups were controlled in such a way that a smaller group was used to cancel the after-peak of the previously controlled group under the same substation. In the tests the time separation between group control actions was increased in order to be able to better separate the responses of the groups from each other.

Control signals were sent on four days (16th and 24th December 1996, and 8th and 24th January 1997.) The respective outdoor temperatures were about -19°C, -26°C, from - 23 to -29°C depending on the location, and -7°C. Figure 1 shows the responses measured on the substations on one of these days. The power measurements were recorder over the whole winter. Outdoor temperatures used in the analysis were recorder by Finnish Meteorological Institute at several locations in the test area.

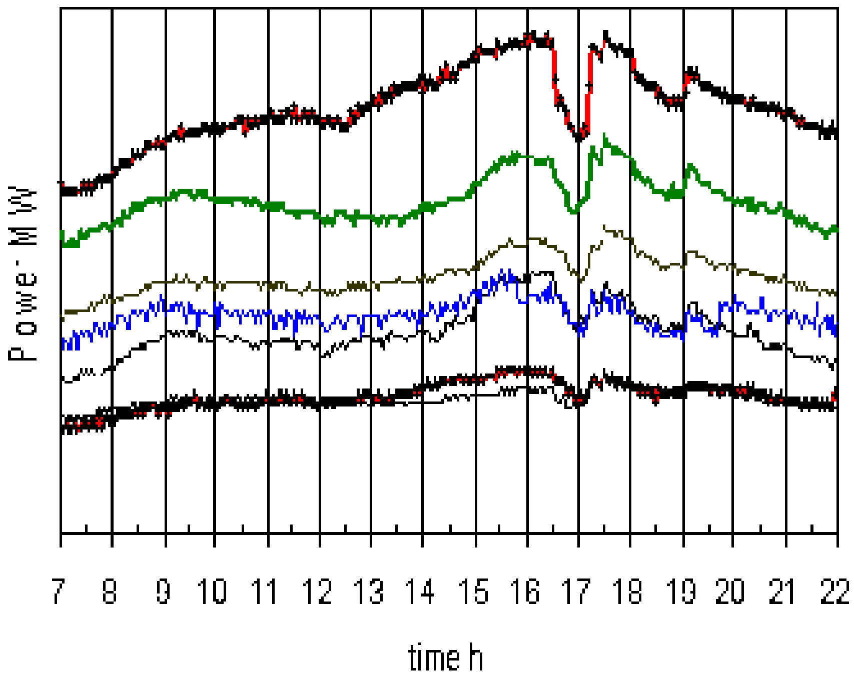

Figure 1. Measurements from the controlled substations in direct load control field test on 24 December 1996, when outdoor temperature was -26°C.

In the tests 24 December 1996 and 8 January 1997 control signals were sent to customers below seven substations. Measurements from some other substations suffered from poor resolution or occasional communication failures. The remaining three substations were used as non-controlled reference groups. Nevertheless it turned out that use and development of load and response models was necessary in order to be able to separate the control responses from the variations of all the other loads under these substations. Measurement data over one winter was not enough for developing adequate black box models for the purpose. This became evident when applying Time Series Analysis. Thus simple physically based models were developed. These models and the results achieved are discussed later in the chapter "Load response models".

3.2 Measurements of responses of full storage heating houses in Helsinki in 1997 and 2010-2011

During non-intrusive load monitoring research Pihala (1998), the electricity consumption of a full storage heating house was measured with good time resolution for long time periods over three years. Figure 2 shows an example of the results. In this case Time of Use control is applied so that first one third of the heating power is switched on and some hours later the full heating power is applied to the heat storage until the heat storage temperature reaches its upper temperature set point. After that the thermostat turns on the full heating power, when the storage temperature drops during the night tariff time.

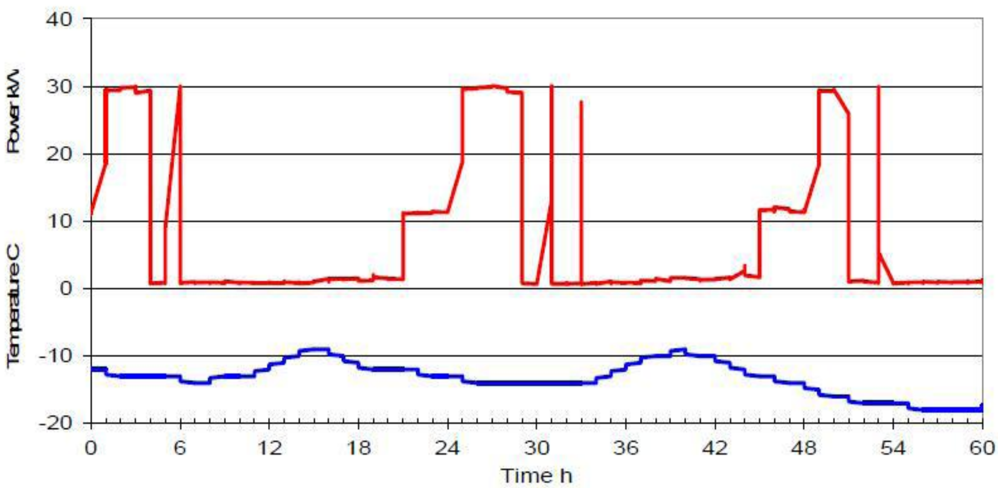

Figure 2. Measurements of a full storage heating house in Time of Use control in 1997. [a sample of measurement data provided by Hannu Pihala]

In winter 2010-2011 the same house and 5 other full storage houses were subject to field tests of dynamic load control based on smart metering. These tests continue with more houses. The heat demand is determined as a linear function of the average temperature for the previous 24 hours and the cheapest spot market hours during the night tariff time were selected as the heating periods. Figure 3 shows an example of measured responses. See Koponen and Seppälä (2011) and Seppälä and Koponen (2011) for more detailed information.

The control responses of full storage heating houses can be rather well predicted based on the chosen heating periods and the heat demand estimated from outdoor temperature. The most important uncertainty is related to the fact that the heat storage temperature reaches its upper set point before the end of the last heating period of the night, because the heating period must include some reserve for managing higher than normal consumption because of variations in consumer behaviour etc. For some other response prediction purposes it is also good to be on the safe side and predict similarly the maximum load. The good predictability stems from the fact that a large storage tank and the related temperature control of the house decouple the heat dynamics of the house from the response. In this respect modelling and predicting the responses of direct and partially storing heating are more challenging.

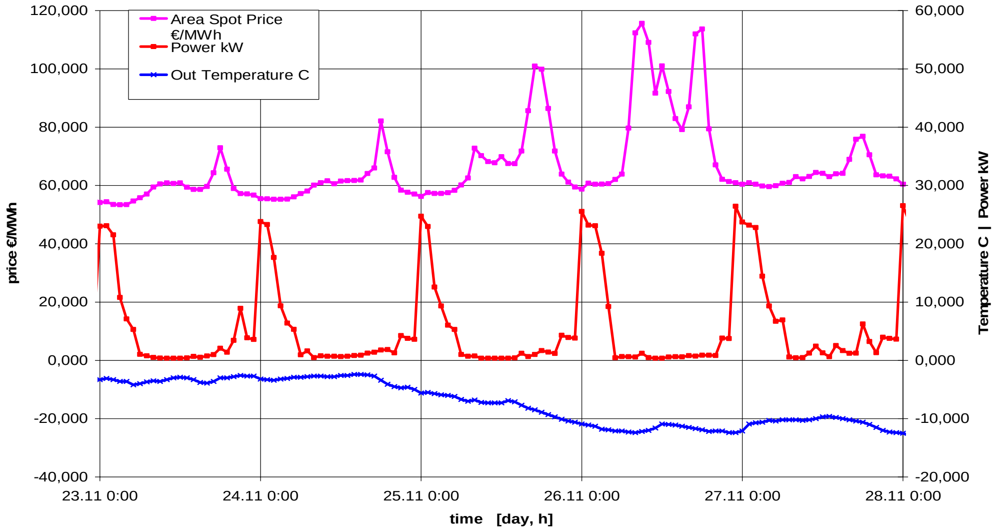

Figure 3. Measurements of a full storage heating house in November 2010.

3.3 Responses measured in Denmark in 2004

Responses measured in Denmark are reported in the pilot results report of EFFLOCOM-project, EFFLOCOM (2004). In Denmark a small pilot with 25 domestic customers with electric heating was carried out in 2004. The 25 households received an extra installation for load control, detailed metering of the heating consumption and remote reading. For example, Figure 4 shows the peak load day with control and without control (without control consumption is simulated since there were no other days with daily average temperature down at –7.8 C). Obviously some kind of a model has been used in the simulation. It can be observed based on the energy saving reported the model does not take into account the slow thermal dynamics of the building. Such slow dynamics are necessary for correctly estimating the energy savings, but not needed for response modelling.

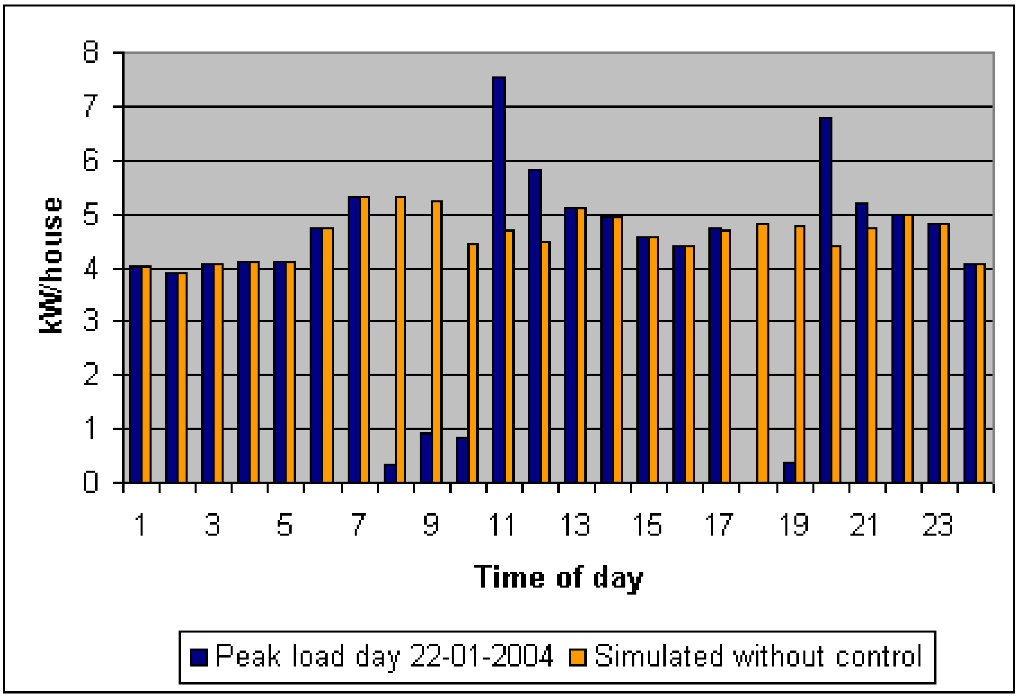

Figure 4. Control responses of a Danish electrically heated house during the peak load day 22 January 2004.

3.4 Direct load control responses measured in Sweden in 2004

Direct load control of electrical heating was tested in Jönköping in Sweden in 2004 and reported by Lindskoug (2006). Direct electrical space heating and domestic hot water heating were controlled in 50 households. The households were given a compensation of 300 SEK (about 33€) per annum. Electrical heating load was reduced to 67% of the heating requirement for 2 hours. Water heaters were switched off for up to five consecutive hours. The response was measured from the grid with 6 minute time resolution. Figure 5 shows the responses of a control experiment on 22 January 2004. Outside temperature was -14.6°C. The controlled space heating load observed was approximately 280 kW. The load control equipment has been installed over ten years earlier but it still worked. An average controllable load of 4-5 kW per family home at -10 … -15°C outdoor temperature was demonstrated. There were no complaints from the customers. The water heater control tests indicated a controlled load of roughly 0.8 kW per household which is in line with earlier trials in Sweden.

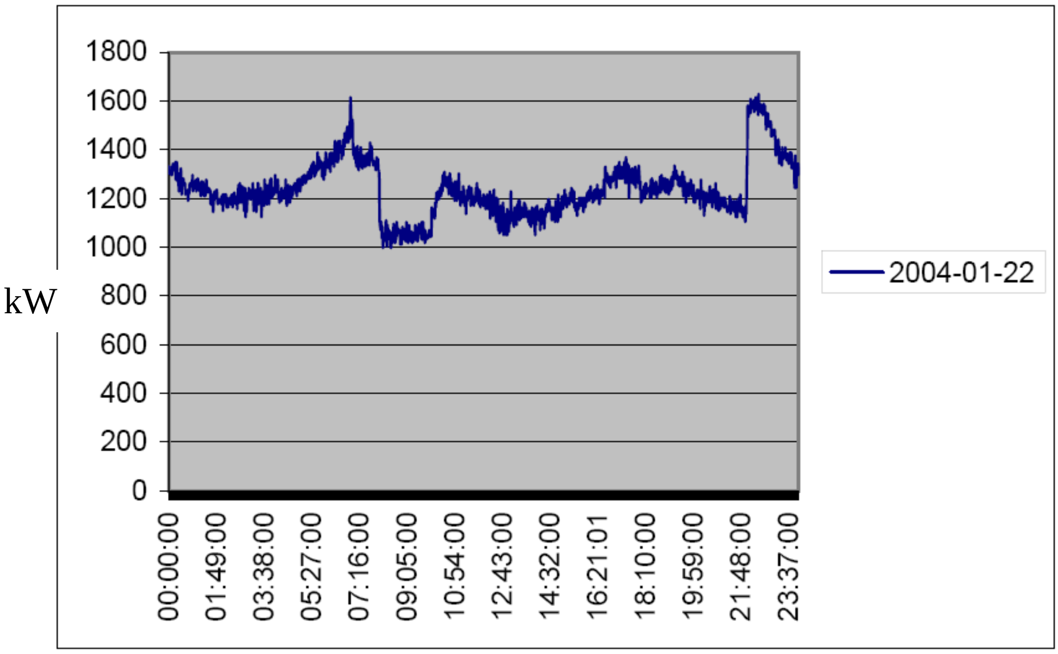

Figure 5. Direct load control experiment in Sweden 22 January 2004. Load reduction is about 280 kW. [Lindskoug 2006]

3.5 Price control responses in Sweden in 2005

Electricity retailer applied a higher price (3 - 10 SEK per kWh. 1 € was about 9.2 SEK) for the customer for a maximum of 40 hours. For the rest of the year a compensating deduction is made from the customer's fee. The customers had already hourly metering. Customers were notified the day before high price by text message or e-mail. 93 households participated in the experiment.

Main findings of the experiment were

- Price sensitivity exists towards temporary price levels in the 3-10 SEK per kWh interval
- Results were achieved without installing new technology to the customers
- Load was reduced momentarily by 50 % at point of higher electricity price. The actual load reduction has been greater because some participant had an option to switch to oil and had switched to oil the previous night.
- Customers have gradually dared to reduce the load further as they have not seen any disadvantage.
- In the trial period there were no really cold days. Thus the response on very cold days is not known (more heating would be on, but also indoor temperature would drop faster due to control actions.)

The responses measured are shown in Figure 6.

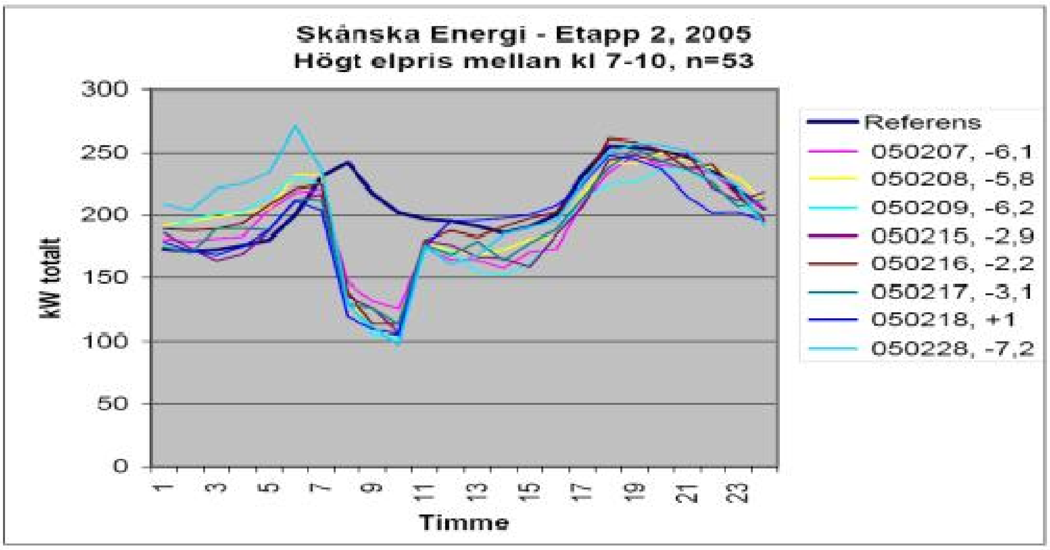

Figure 6. Price control experiment in Sweden in February 2005. Load reduction is about 280 kW. . [Lindskoug 2006]

3.6 Demand response field tests in Norway

The Norwegian project Market Based Demand Response included the following five pilots:

- Remotely controlled load shifting (Moving of demand from peak load hours).
- Fixed price with return option energy contract
- Automatic demand response to the electricity spot price
- Smart house functions in a housing cooperative
- Low prioritized loads controlled by building energy management system of medium size customers (institution and shop).

See Grande et al. (2008). The slides of Möller (2009) provide an overview of the pilots. Here the two first pilots are the most interesting regarding responses.

3.6.1 Moving demand from peak load hours

Saele and Grande (2011) and Grande et. al. (2007) explain demand response field tests in the Norwegian project Market Based Demand Response. In those tests a Time of Day network tariff was applied to reflect the higher costs for using the distribution network in peak load periods. The responsive customers would also benefit from avoiding higher spot prices that normally appear at the same time with the network tariff price peaks. Hourly metering and remote load control via smart metering system were offered to 40 customers. In addition they were advised to have an energy contract with the spot price on an hourly basis, and 37 customers chose it.

Each household in the pilot study was equipped with three small tokens placed on dishwashers, washing machines, etc., to remind the households to avoid usage of these energy consuming appliances in the predefined peak load periods on work days during (08:00–10:00) and (17:00–19:00). Also remote load control was performed on the same hours. Registered average load reduction during morning peak load was approximately 1 kWh/h for customers with standard electrical water heaters and approximately 2.5 kWh/h for customers with hot water space heating systems with electrical boilers. In a previous research project the potential of demand response from electrical water heaters was 0.6 kWh/h. The main difference was the token that reminded of the manual load reduction during peak hours. Figure 7 shows the load shifting to off-peak periods.

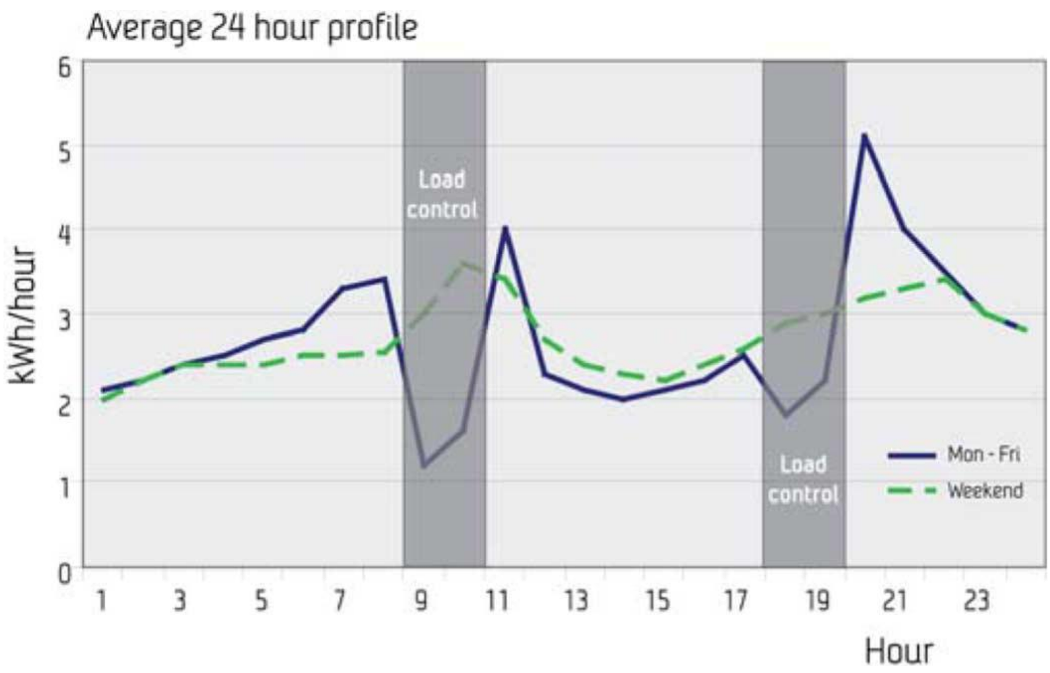

Figure 7. Responses to a time of day network tariff in Norway in 2007, (Saele and Grande 2011)

3.6.2 Fixed price with right to return

Trondheim Energi, now Statkraft, has developed an electricity tariff that is based on electricity spot price applied on top of a fixed price fixed volume component. About 2500 customers have had this tariff. The impact on consumption has been studied. Statkraft has changed the name of the product and it has been developed further to include automatic price based load control, to fit to a large scale smart metering rollout and wide scale application. See Möller (2009).

3.7 Direct load control responses in Kainuu in 2010

In February 2010 E.ON Kainuu and the system operator Fingrid made direct load control experiments with about 3600 electrically heated customers, see Jäppinen et al. (2011). In outdoor temperature -26°C about 7.5 MW load reduction was measured, see Figure 8. In -8°C load reduction was 4.4 MW. The responses were measured from substations with time resolution of 3 minutes and summed over the whole network area. Also hourly metered data was measured by the kWh-meters.

These measurements would be very valuable for updating the response models, if also measurement data of hourly power consumption for the test group and the control group were recorded. E.ON Kainuu is planning new improved field tests for 2012 and 2013 and related collaboration with project SGEM.

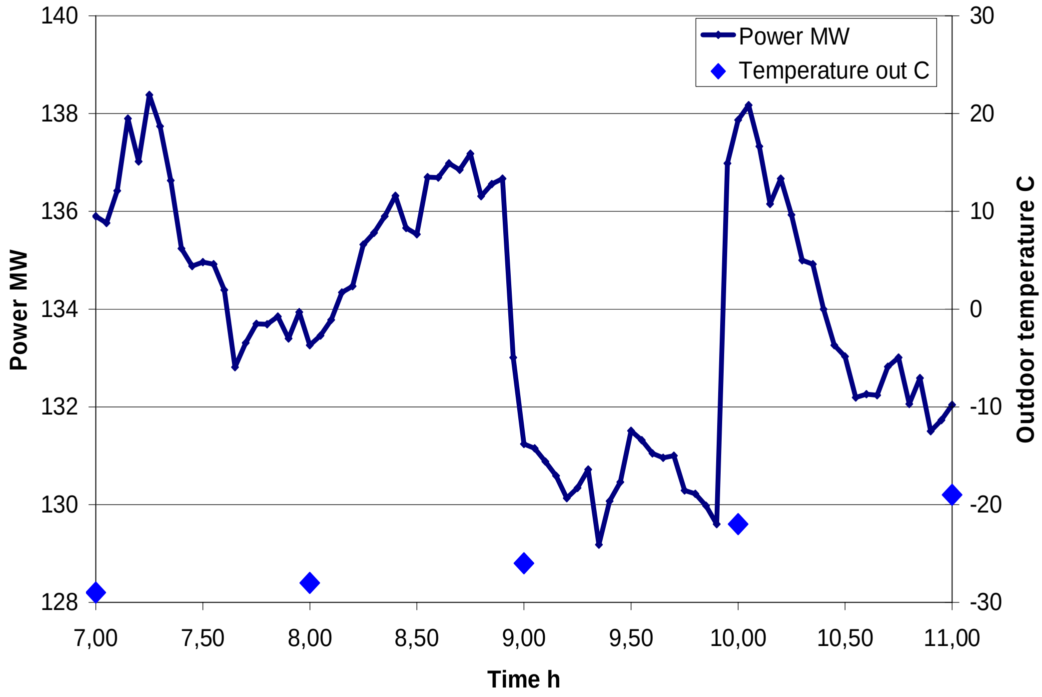

Figure 8. Response measured at direct load control field test at E.ON Kainuu.

3.8 Responses of cool storages and other heat pump applications

Cool storages and heat pumps operate in cycles. Thus the availability of their flexibility depends on the indoor temperature that varies with time. The typical length of the cycle varies depending on the thermal dynamics of the storage or building and on the cooling or heating equipment. In Figure 9 an example is shown. It is one of the three cool storages measured in the MAHIS project on market price based control in Finland, see Koponen et al. (2006) (2007). In this case the load flexibilities are based on: 1) controlling the temperature limits for switching cooling on and off, and 2) interrupting cooling in the middle of the cycle. In these cool storages the on-off cycle is normally about 10 hours long. The flexibility can be increased significantly with the help of a simple physical model based control algorithm, if the load reduction needs are known in advance. The model describes the most predominant features of thermal dynamics of the cool storage.

Often the duty cycles for cooling or heating are much shorter than in these cool storages. For example, Gomes et. al. (2009) show roughly 19 minute long measured duty cycles for cooling indoor temperature. Molina et. al. (2003) show duty cycles of around 10 minutes.

Such models are not directly applicable in predicting the aggregated loads and control responses in the network, because each storage has its own operating rhythm, but are useful in simulations for developing and verifying such models.

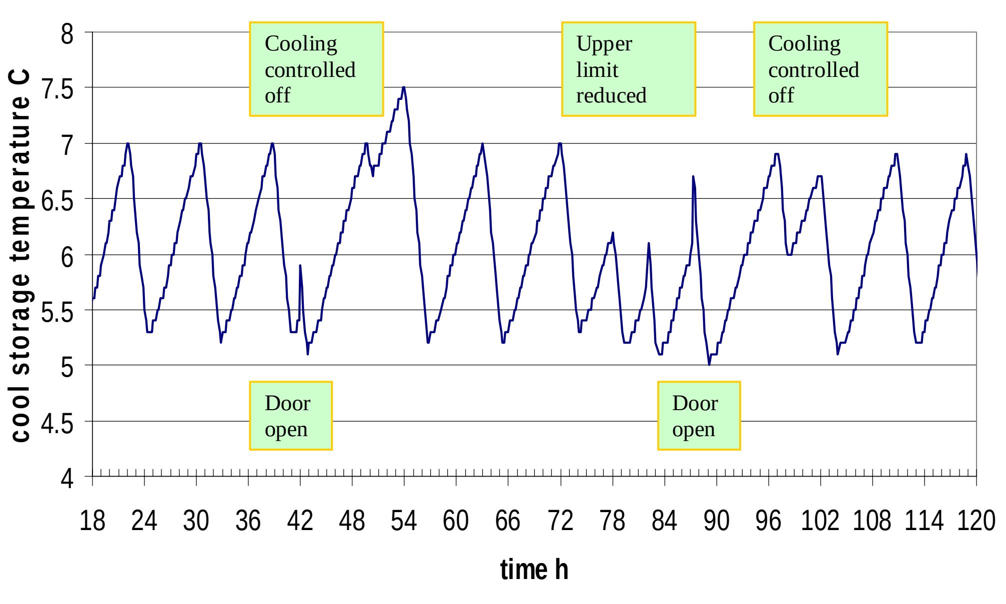

Figure 9. A measurement of cool storage temperature and its response to two load control actions.

4 Load response models

4.1 A simple physical model for load response analysis and prediction

With physically based dynamic heat balance models we mean models that have the following structure

$$dx(t)/dt = f(C,K, x(t), p(t), T_{out}(t)) \quad (1)$$

$$p(t) = f(x(t), x_{set}(t), u(t))$$

such as

$$C\, dx(t)/dt = K\, x + p(t) \quad (2)$$

$$p(t) = f(x(t), x_{set}(t), u(t))$$

where

$x(t)$	the state variable vector that comprises lumped temperatures
C	heat storage capacities
K	thermal conductivities between the variables
$T_{out}(t)$	outdoor temperature
$p(t)$	the power heating the house, which can be a vector
$x_{set}(t)$	set points for state variables

u control signals.

Rather simple models are easier to identify and maintain and offer better performance in prediction and optimisation. Thus emphasis here is on simple models.

In Finland dynamic models for the load control responses of electrically heated houses were presented already by Haase (1971). Also Martikainen et. al. (1987) applied such dynamic models. These are simulation models. In response prediction such detailed models have too many uncertain parameters and a much more simple model is necessary for optimum prediction performance. In addition, tuning many uncertain parameters of the detailed model requires much more measurement data for tuning than what was available. Power measurements with 3 minute time resolution were collected from 11 substations over one year and including load control tests in two days. Also measurements of the outdoor temperature at several points in the research area were measured and collected for the over the same period of one year.

Thus the following simple physical model (3, 4) was developed by Koponen (1997) in order to enable the identification of load control responses from the power measurements at the substations in the direct load control field tests in winter 1996-1997. For comparison, also black box time series analysis was applied to the same data, but the models identified by them turned out to be inaccurate (high variance between substations and not in line with the known physical facts) and thus useless; it seems that there was too much process and measurement noise compared to the amount of response data.

$$
\begin{aligned}
C_1 \frac{dx_1}{dt} &= -k_{12}(x_1 - x_2) + P \\
C_2 \frac{dx_2}{dt} &= k_{12}(x_1 - x_2) \\
&\quad + k_{23}(x_3 - x_2) \\
&\quad + k_{24}(x_4 - x_2) \\
&\quad + k_{2o}(T_{out} - x_2) \\
C_3 \frac{dx_3}{dt} &= k_{23}(x_2 - x_3) \\
&\quad + k_{3o}(T_{out} - x_3) \\
C_4 \frac{dx_4}{dt} &= k_{24}(x_2 - x_4)
\end{aligned}
\tag{3}
$$

The state variables were the following lumped temperatures:

$x_1(t)$ temperature of the heating element e.g. in case of floor heating
$x_2(t)$ temperature of the indoor air
$x_3(t)$ temperature of the outside walls
$x_4(t)$ temperature of the other heat storing masses of the building

The constant parameters were

C_1, C_2, C_3 and C_4	the heat storage capacities related to each state variable
k_{12}, k_{23}, k_{24}, k_{2o}, k_{3o}	the thermal conductivities between the model temperatures

The time variable input variables were

$T_{out}(t)$	outdoor temperature
P(t)	the electrical power heating the house

In the model P(t) was calculated as controlled by a PI-controller controlling the indoor temperature

$$
\begin{aligned}
P(t) &= f_{PI}\,(T_{set} - x_2(t))\, u(t) \\
0 \le P(t) &\le P_{\max}
\end{aligned}
\qquad (4)
$$

Where
u(t) is the controllable input that gets only binary values u(t)=0 or u(t)=1.
T_{set} is the temperature set point for the indoor air $x_2(t)$
P_{max} is the nominal maximum power of the electrical heating.

In the actual houses studied the temperature was controlled on and off with hysteresis defining the operating cycle. Statistical variations in the timing of the peaks make the load of a group of buildings much smoother than the load of an individual house. The need to simulate or predict a big number of houses individually was avoided by using in the model a control algorithm that gives smoother load behaviour than the actual control loops in the houses. That is why in modelling the common or average response of the group of houses, the PI-controller (4) was used with the model (3).

The controllable houses were first classified to some segments based on the building properties. Measurement data and a-priori information were used for this. Selected parameters of the simple dynamic model (3, 4) were identified by using constrained non-linear optimisation. Those model parameters were fitted so that the response agrees with measured control responses, load of non-controlled reference group and long term measurement data. The other parameters and feasible ranges of the model parameters identified were defined based on information on building properties.

A similar model was in 2005 and 2006 used as the optimisation model in the simulations of price based control, see chapter 4.4. That required small structural modifications and parameter identification based on temperature and load measurements from the target houses. In models of partial storage heating houses both direct and storage heating have their own heating powers in the model. Also air-conditioning and occupancy were included in the models.

4.2 Field test results in Northern Finland 1996-1997

Models for simulating and predicting load responses were developed and verified as part of the direct load control field tests of electrically heated houses in winter

1996-1997 in Northern Finland. The test, models and the results are explained in Koponen (1997).

Figure 10 shows the modelling approach. The model structure was as defined in equations (1) and (2) above. Its parameters and their possible ranges were first estimated based on building requirements based on the temperature zone, age and insulation and heat storage capacity of the controlled group of buildings. Then selected parameters were fitted with data measured from substations. Some substations were used as reference group were control actions were not applied. The model predicts the power consumption using outdoor temperature and control signal as inputs.

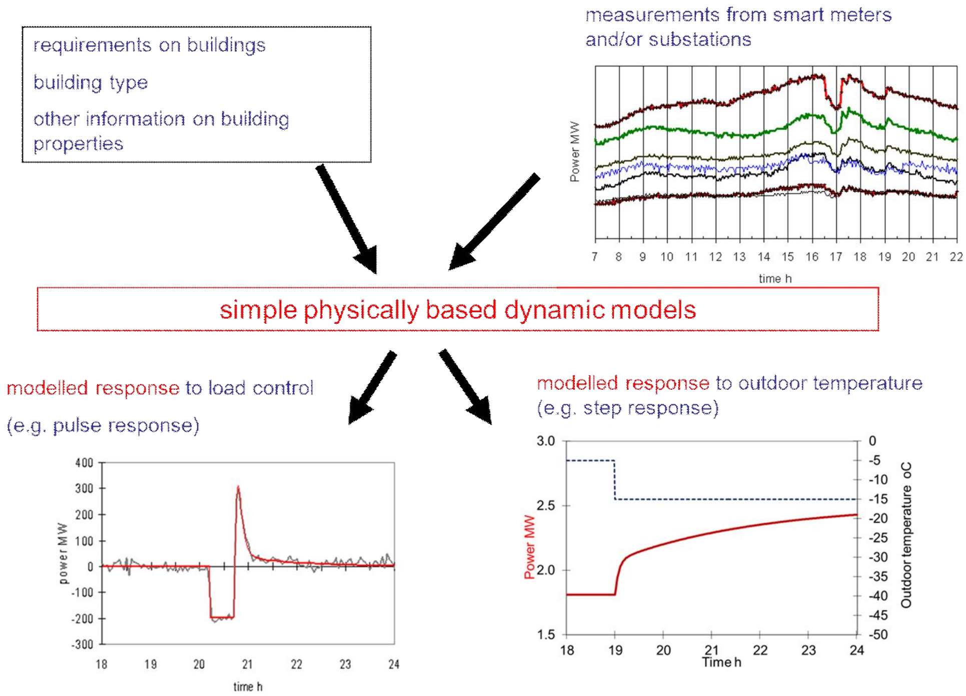

Figure 10. The responses to outdoor temperature and load control are modelled using simple physically based models based on information on building properties and measured data from different sources.

Figure 11 shows a comparison of the model (3, 4) response (simulation) with response estimated from measurements (measured) for load control of 463 vacation house metering points in two skiing resorts. Outdoor temperature was -19^{o}C. The experiment was done during low season of the resorts thus avoiding load variations due to the activities during high occupancy. Regularly repeating load variations and impact of temperature variations are filtered out: The responses and the models were identified from measurements at several substations. The normal load profile was eliminated using both simultaneous measurements at non controlled reference substations and the temperature dependency model identified from measurements over one year. Normally the 4 groups were operated in a way that roughly cancelled the payback peaks, but in this test the timing was different to make the payback peaks visible and better identifiable. Rather poor resolution of the pulse measurements (somewhat too big pulse size) caused some fast oscillations of the measurement values, so the actual consumption is most likely smoother than the measured.

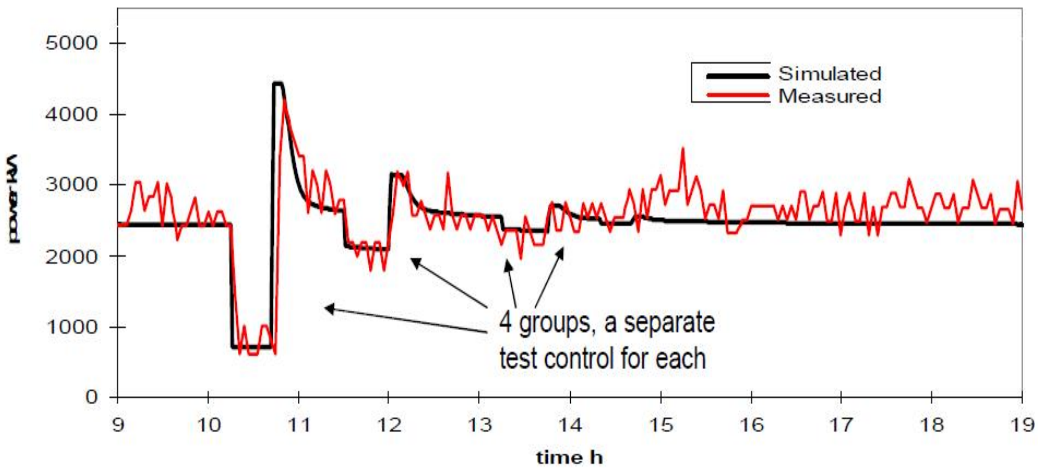

Figure 11. Load control responses measured from substations at two skiing resorts and the responses of the simple physically based model [Koponen 1997].

In the residential areas the modelling accuracy was not as good as on the ski resorts during low season. More stochastic variation in the other loads disturbed the measurement.

The results show that the model developed can enable the prediction of the control responses with a useful accuracy.

4.3 Field tests in 2006 to support model identification and verification

In the MAHIS project, Koponen et. al. (2006), the simple physical model described by Koponen (1997), see formulas (1) and (2) was slightly developed further and applied for modelling 5 detached houses or 5 row house apartments individually. All the small houses and apartments had partially heat storing electrical heating, electrically heated domestic hot water tank, a wood burning fireplace and electrically heated sauna. The test houses were the following:

- A detached house, its floor area is 200 m2.
- A group of four detached houses with heat storing electrical heating and buying electricity together, their floor areas are 168 - 252 m2.
- A row house comprising 5 apartments; they buy electricity separately and have floor area 120 - 155 m2.

Power consumption and temperatures both outside and inside the house were recorded with 10 minute or better time resolution to support the tuning and verification of the models.

4.3.1 Detached house

As an example, measurements from a detached house in the beginning of 2005 are shown in Figure 12 below.

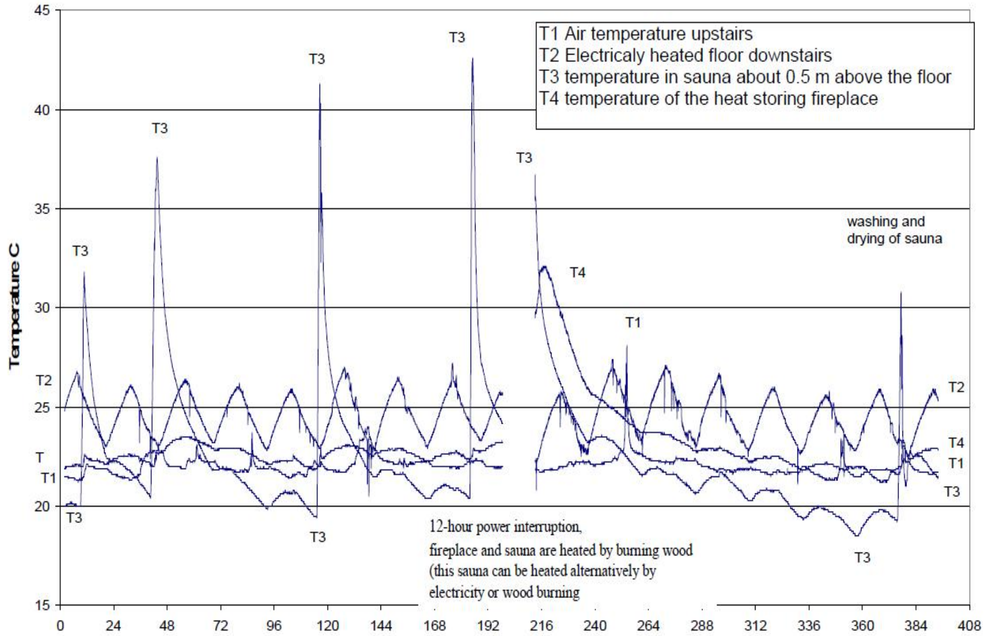

Figure 12. Temperature measurements from a detached house in Helsinki area. [Koponen 2006]

Simple models for the dynamic heat balances of the buildings were developed based on preliminary information on the buildings and on measurements made during 2004 and early 2005. The structure of the models was roughly the same as in the simple physical models developed in 1996-1997, but included more controllable inputs and also some more state variables. The number of the controllable inputs comes from the problem formulation and it also makes it necessary to add related state variables. In addition more measurements were available for modelling which also enabled a slightly more detailed model structure. MATLAB System Identification Toolbox was used in the model development. The models developed were linear except for constraints and the effect of ventilation.

The state variables were the following lumped temperatures:

- temperature of the indoor air
- temperature of internal walls
- temperature of the outside walls
- temperature of the heat storing floors
- temperature of the heat storing fireplace
- temperature of the sauna
- temperature of the domestic hot water storage

The state variables describe the heat content or average temperature of each lumped mass and thus do not necessarily represent directly any of the temperatures measured.

Models with some other state variables were tried, but abandoned. For example, parameter identification turned out to be very difficult, if the floors of the buildings were modelled separately. The main reason for this is the nonlinear heat transfer between the floors.

The main uncontrollable input variables were outdoor air temperature and occupancy. The heating powers of direct heating, storing heating and domestic hot water heating were the controllable inputs.

4.3.2 Row house with ToU-tariff

Similar model as for the detached house was also developed for row house apartments. Figure 13 shows a comparison of the model response of a row house apartment to the power measurement of another similar apartment in the same row house when 2-time Time-of-Use (ToU) control is applied. These apartments have partial storage heating, which means that there is both direct electrical heating and heat storing floor heating. In partial storage heating the heat flow from the heat storing floor to the indoor air cannot be controlled, but in full storage heating the heat flow from the heat storage tank to the house is controlled by thermostats controlling the indoor air temperature. The time period shown is week 3/2006.

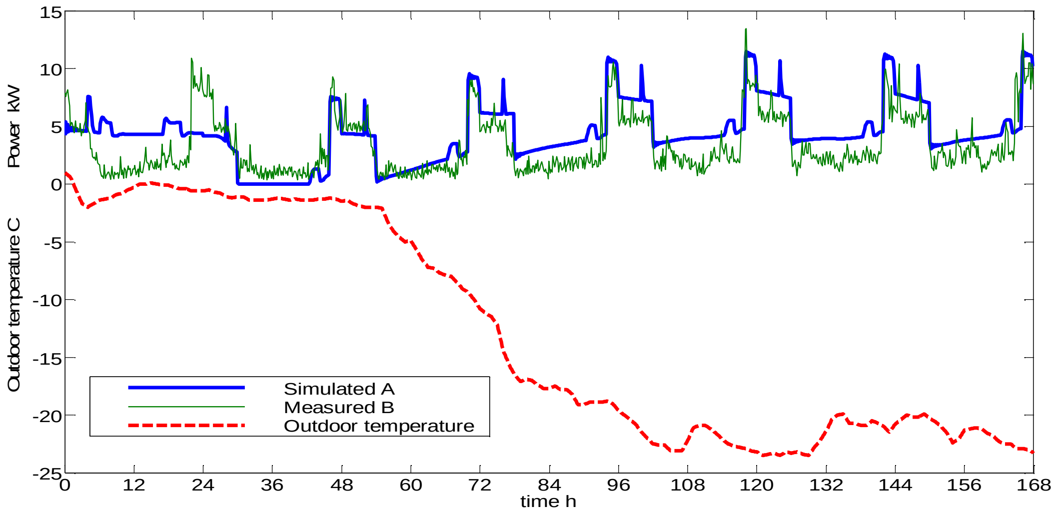

Figure 13. Measured and simulated loads of a row house apartment in Time-of-Use control in Helsinki area. [Koponen 2006]

The first day was a low tariff Sunday and the measurement shows wrong control action, because low price was applied during nights and Sundays. On the following days the control actions were similar both in the measured and simulated case. Some of the differences between the simulated and measured stem from the different control actions on Sunday. But comparison also shows that the longest time constants identified from earlier measurements were somewhat too small. Modelling the slow dynamics of the house requires either very much measurement data or good a-priori knowledge of the thermal properties of the building.

5 Measurements and models of appliance responses

Appliances interesting from the demand response point of view are those that have high penetration now or in the foreseeable future and have possibilities to control the timing of energy consumption. These include:

• refrigerators and deep freezers

• dishwashers
• washing machines,
• air conditioning units and heat pumps (increasing penetration)
• sauna (in Finland)
• car heating (in Finland)
• loading batteries of electrical vehicles (now low penetration, but substantial increase in the penetration is expected in the future)

Heating of space and domestic hot water as well as cool storages have the highest demand response potential, but that is also why their measurements and models were already covered in the previous chapters. Some other appliances have low penetration or very limited control possibilities or both. These include:

• ovens and cook tops (loss of comfort)
• dryers (low penetration)
• TV-sets, DVD players, music players, computers, (loss of comfort, etc.)
• modern energy saving lighting (increasing penetration but also low energy consumption.)

Here the focus is on the dynamic behaviour of these loads and the possibilities to control them. Penetrations and total energy consumptions are now outside the main scope, but some information on them is available from national statistics and research studies, such as the study by Adato (2008) in Finland, and from Sweden in the slides of Johansson and Bennich (2006) and in an old Nutek (1994) report.

Smart-A project [Stamminger 2008] carried out a European analysis of residential energy consumption. Results included start time probabilities for most important household appliances, such as washing machines, dish washers and dryers. It also found out that between 32% - 39% of such wet loads in Europe already contained a timer that allows the user to set the start time of the operation. ADDRESS project (www.addresssfp7.com) identified power profiles during the operating cycle of some such appliances.

In Finland Rissanen (1998) collected data on appliance power levels and working cycles and Pihala (1998, 2001) has applied Non-Intrusive Load Modelling to appliances. Paatero (2005) modelled the impact of simulated appliance load postponement and cut on the aggregated load curve of 10 000 households.

6 Conclusions and summary

Rather much measurement data already exists, but much of it is old and thus may be somewhat outdated. Models suitable for predicting load control responses have also been initially developed. Simple physically based models of the dynamic responses have already shown promising results. Further model development can start with the existing data but more up to date measurements preferably covering also new types of loads, such as heat pumps, are needed for tuning, completion and verification of the response prediction models.

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