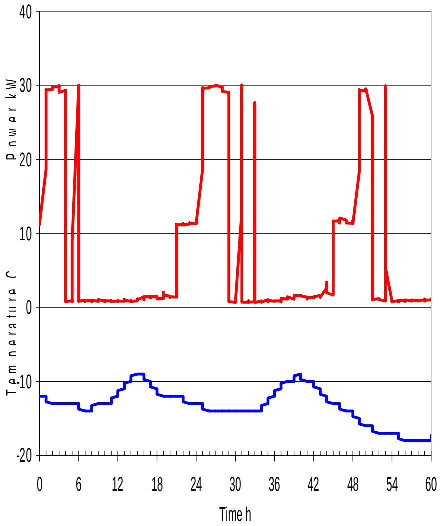

Full storage electrical heating

Method	kWh	Energy cost €	kWh increase	€ saving	% (kWh)	% (€)
No control	**1421,1**	**157,92**	**-2,81**	**-49,25**	**-0,20 %**	**-45,3 %**
ToU control	**1423,9**	**108,67**	**0,00**	**0,00**	**0,00 %**	**0,0 %**
Price control	**1423,8**	**105,18**	**-0,08**	**3,49**	**-0,01 %**	**3,2 %**
Optimised	**1423,7**	**105,12**	**-0,20**	**3,56**	**-0,01 %**	**3,3 %**

Partial storage electrical heating

Method	kWh	Energy cost €	kWh increase	€ saving	% (kWh)	% (€)
No control	**735,5**	**82,99**	**-13,14**	**-6,69**	**-1,8 %**	**-8,8 %**
ToU Control	**748,7**	**76,30**	**0,00**	**0,00**	**0,0 %**	**0,0 %**
Price control	**744,3**	**74,15**	**-4,38**	**2,15**	**-0,6 %**	**2,8 %**
Heuristics	**768,4**	**65,47**	**19,68**	**10,83**	**2,6 %**	**14,2 %**
Optimised	**749,3**	**63,47**	**0,60**	**12,83**	**0,1 %**	**16,8 %**

Comparison of price control methods for electrical heating, simulation study

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Summary

Day ahead spot market price based control of electrical space heating loads was studied by simulations The cost and energy performance of several different control methods was compared. As input data for the simulations the market prices and outdoor temperatures of week 3/2006 were used. This week was chosen due to high price peaks and rather smooth outdoor temperature behaviour. A full storage heating detached house and a partial storage heating row house apartment were simulated. Simple models of the heat dynamics of the houses based on measured temperatures and electricity consumptions and information on the most relevant properties of the buildings and their heating systems were used

Due to the small number of houses and weeks simulated the results are only indicative. The accuracy and representativeness of the results can be improved with more simulations.

The following observations can be made from the simulation results. 1) The full demand response potential of full storage heating systems is relatively easy to tap, but partial storage heating has more unused benefit potential. The main reason for this is that the full storage heating house studied has abundant heat storage, the temperature of which can be controlled independently from the temperatures of the rooms heated. The heat dynamics of the storing mass of partial heating are much more tightly connected to the room temperatures, which makes it a more challenging problem to control the storage optimally. 2) The existing static Time of Use control is clearly better than no load control at all. 3) There is benefit potential in replacing the static Time-of-Use control with dynamic market price based control methods.

Confidentiality	Public

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Preface

This simulation study was made as part of the ENETE project in 2009 to support the field tests on market price control being prepared by the Helen Sähköverkko Oy (Helsinki Electricity Networks).

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Authors

Contents

1 Introduction

In order to support the development and piloting of dynamic price control in the ENETE project several control methods for price control of electrical heating were compared with simulations. The ENETE piloting was focused on full storage heating control based on the day-ahead spot prices.

The following results of earlier studies by Helsinki Energy provided basis to the project. New dynamic load control methods do not increase the risk of network overload. [Uola 2001]. This is because, two rate Time-of Use tariff and control are already widely applied in the electricity distribution network in the Helsinki region since 1964 [Leksis 2009] describes a simple method for choosing the heating periods of the heat storage based on the spot price. This method was included in the comparison.

From one of the target houses there were interval consumption measurements for three years readily available and outdoor temperature measurements for one of those years from earlier research projects. Thus a simple dynamic model for this house was developed based on these measurements and data on the properties of the building and its heating system.

In addition to full storage heating houses also partially heated houses were simulated in order to learn how the benefits achieved with different methods depend on the type of the heat storage in the building. Modelling and partly the simulations of partial storage heating were done earlier in the MAHIS project [Koponen 2006, Koponen 2007], but now simulations of one more method were added.

Temperature and spot price data for the winter 2005 -2006 were used in the simulations for two reasons: there were rather high price peaks, and temperature and price data was readily prepared for the simulations. The simulations were completed in autumn 2009.

The results give rough quantitative information on the performance of the methods compared with different types of storage heating. The accuracy of the results could be improved by making simulations for more houses and over more weeks.

2 Goals

The objectives of this work were

- to initially assess and compare the performance of load control methods when spot price based tariff is applied.; the purpose was to compare the energy costs to the customer but also roughly the relative impact on the energy consumption,
- to test and demonstrate the use of simulations in the comparison of the load control methods,
- to support preparation of dynamic load control field tests.

3 Control methods compared

The following control methods were compared with simulations:

- no control that is based on price or time (but on temperatures only)
- simple static ToU (Time of Use) control (the traditional purely clock based ToU control method used in large scale in Finland; it has been available in Helsinki from 1964)
- price based ToU control where storing loads are controlled on for those 8 hours of the day (24 hours) that have the lowest spot price
- price based ToU control where storing loads are controlled on for those 16 hours of the day (24 hours) that have the lowest spot price
- price control = the two methods above, when their both gave identical results
- two slightly different versions of a heuristic method developed and tuned with the help of optimisation based method described next; these were applied only for the partial storage, because they are not designed for full storage heating
- optimisation method with two slightly different values for the quadratic term in the optimisation criterion. With this method and model this quadratic term is used to tune the mutual weighting between comfort and energy costs.

The optimisation method is based on gradient optimisation, where the gradient is determined using the principle of Pontryagin. It solves this kind of nonlinear constrained dynamic optimisation problems efficiently. The method and its applications in control problems are explained in detail in [Hassdorf 1976]. A self made implementation of the method on Matlab completed prior to this project was used.

4 The simulated situation

Now simulations were done over one interesting week (week 3/2006) that included rather high price peaks and rather low outdoor temperatures as shown in Figure 1. For some of the methods with partial storage heating houses simulation analysis was done to cover 16 consequent winter weeks in the earlier project [Koponen 2006, Koponen 2007]. For consistency the ToU network tariffs and taxes for the same year (2006) were applied in addition to the hourly variable spot price based energy tariff in the simulations. The sum of these is shown in the Figure 1. In this analysis and simulations it is assumed that the control response does not affect the spot prices. If the methods were applied in large scale, this assumption would not be valid.

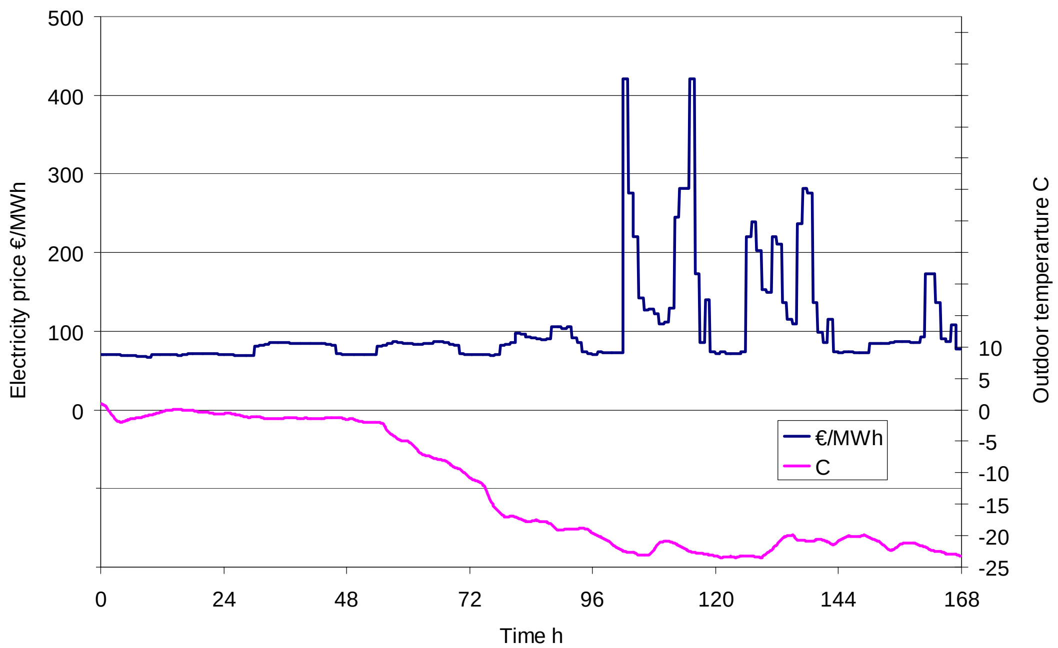

Figure 1. The outdoor temperature and the electricity price on week 3/2006.

In winter 2009-2010 there were much higher day-ahead spot price peaks than during week3/2006. See Figure 2. A possible further study is to do similar simulation analysis with them and some price and outdoor temperature data was stored for the purpose.

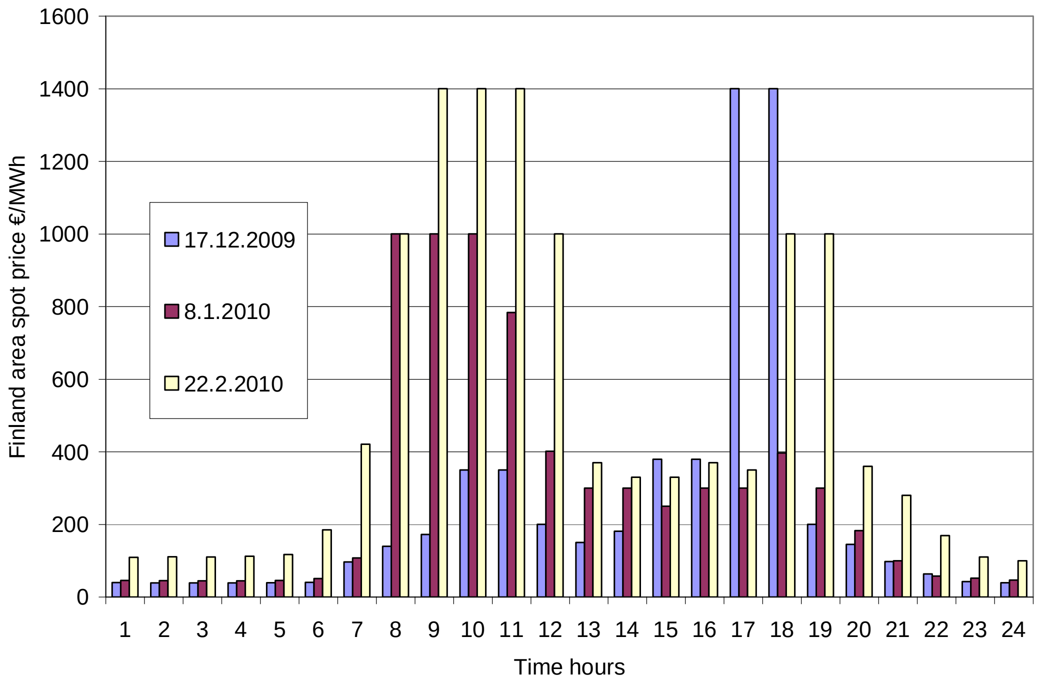

Figure 2. Finland area spot price during three days with the highest price peaks in winter 2009-2010.

5 Dynamic temperature balance models

The dynamic heat balance models of the buildings are highly simplified. 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 or in case of the full storage heating the temperature of the heat storage water tank.

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.

Some more information on the model is in [Koponen 2007]. The structure of the model is explained in more detail in [Koponen 2006].

6 Input data for the modelling

The most important properties of the full storage heating detached house modelled and simulated were:

- indoor volume of the house 640 m3
- volume of the heat storing water tank 3.7 m3
- max heating power for the heat storing tank 30 kW
- power of the electrically heated sauna 7.5 kW
- power of the electric cooker with oven 12 kW

The same heat storing tank provided also hot domestic water.

A sample of the measured data for the house is in Figure 3.

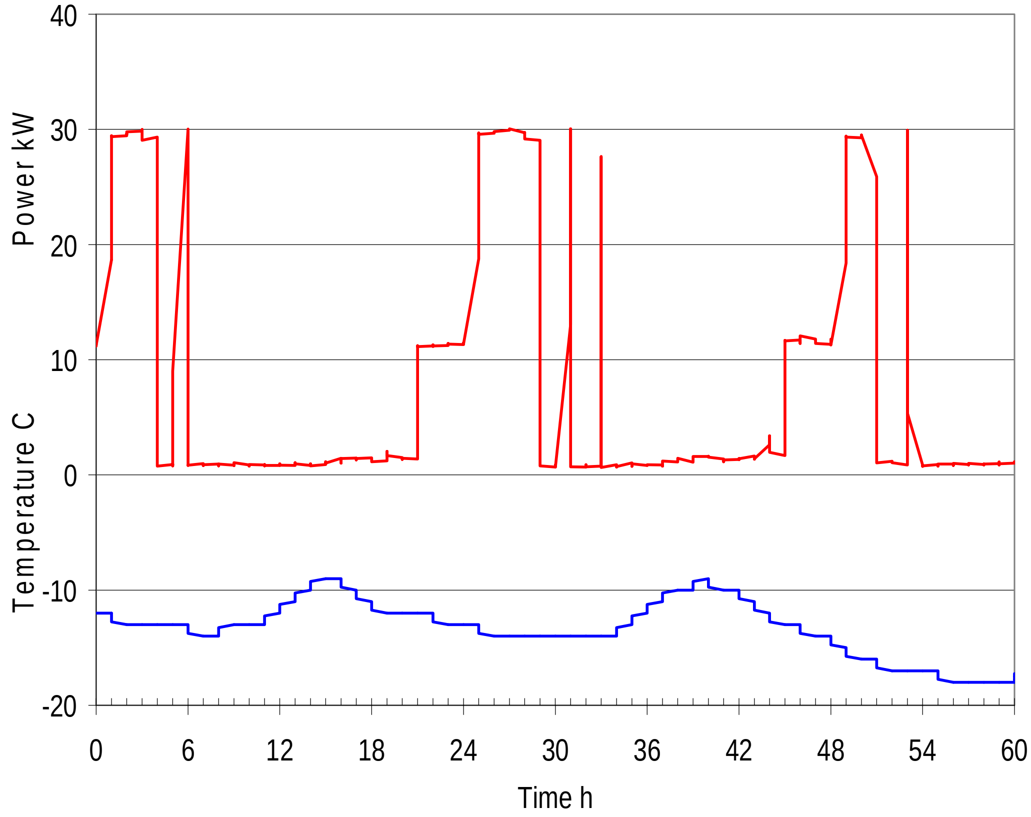

Figure 3. A sample of the power and outdoor temperature measurements from1997 used in the modelling of the full storage heating house.

In the evenings one third of the heating power is switched on slightly after 21:00 and then full heating power turns on about 4 hours later. In the simulations described later this intermediate setting was not applied. The late night power peaks occur because the heating turns back on when the temperature of the tank has dropped below the thermostat setting and hysteresis.

The properties of the 120 m^2 row house apartment simulated are described in [Koponen 2006] and [Koponen 2007].

7 Simulations of the full storage heating detached house

The simulations of a full storage heating detached house were done only over the week 3/2006 with its historic outdoor temperatures and electricity prices. Table 1 summarises the simulation results.

Table 1 Comparison of price control methods for a full storage heating detached house, simulation results of a week 3/2006 with high price peaks.

Method	kWh	Energy cost €	kWh increase	€ saving	% (kWh)	% (€)
No control	**1421,1**	**157,92**	**-2,81**	**-49,25**	**-0,20 %**	**-45,3 %**
ToU control	**1423,9**	**108,67**	**0,00**	**0,00**	**0,00 %**	**0,0 %**
Price control	**1423,8**	**105,18**	**-0,08**	**3,49**	**-0,01 %**	**3,2 %**
Optimised	**1423,7**	**105,12**	**-0,20**	**3,56**	**-0,01 %**	**3,3 %**

The methods in the Table 1 are explained in the following.

- "No Control" means that electricity price and time do not affect the heating in any way. The control of heating is based on temperatures only.
- "ToU control" means static Time of Use control based on 2-time tariff clock , (used here as the base case to which other methods are compared)
- "Price control" means heating during the hours with the lowest spot price,
- "Optimised" means the best solution found with the optimisation method.("Optimised 2" in the Table 2)

The differences in the energy consumption are insignificant in the Table 1. The actual differences would be even smaller, because the models applied tend to overestimate the energy losses, because the longest time constants of heat dynamics are modelled as losses and not as storage.

The existing ToU control is much better than no control at all. The benefit of price control compared to the ToU control is rather small in Table 1, but closer analysis revealed that in this case the ToU control had just reached the heat storage upper temperature set-point, before the high price hour in the early morning. With a lower outdoor temperature and also with certain higher outdoor temperatures the difference in performance would have been somewhat bigger, because the ToU control would have heated also during high price. The behaviour that can cause this is seen also in the Figure 3.

Based on the result it seems likely that the simple price control method is so close to the optimum that the application of the optimisation method with all its complexities is not justified even when the convergence problems discussed in the following chapter are solved.

8 Optimisation convergence problems with full storage heating house

With the full storage heating model the optimisation method suffered from convergence problems at the constraints. The reason for this seems to be that in full storage houses charging and discharging the heat storage are so loosely connected that the indoor temperature related quadratic terms in the criterion have very little impact on the solution. Thus the problem is actually very close to linear and solutions are at control constraints and the transitions from one constraint to the opposite one are instantaneous and not smooth. [Hassdorf 1976] describes how alternative problem formulation of the optimisation problem can be used to avoid this problem: control signal switching times could be used instead of control signal magnitudes as decision parameters. Such a reformulation was not implemented, because it was not necessary to do it for the purposes of this analysis and there were more urgent things to do in the ENETE project and other projects.

The optimisation method was run starting from several starting points including the solutions given by the other methods. The main results are shown in Table 2. The starting points are in bold font and the corresponding solutions reached by the optimisation method with two different criterion weights are shown next below.

Table 2. Comparison of price control methods for a full storage heating detached house, simulation results of a week 3/2006 with high price peaks ("Price control" means heating during the hours with the lowest spot price, "ToU control" means control based on 2-time tariff clock , "No Control" means that electricity price and time no not affect the heating in any way, "Optimised 1" and "Optimised 2" mean that the optimising control method is applied using the solution of the other method mentioned next above as the starting guess.

Method	kWh	Energy cost €	kWh increase	€ saving	% (kWh)	% (€)
Price control	**1423,819**	**105,180**	**-0,08**	**3,49**	**-0,01 %**	**3,21 %**
Optimised 1	1423,875	105,219	-0,02	3,45	0,00 %	3,18 %
Optimised 2	1423,694	105,116	-0,20	3,56	-0,01 %	3,27 %
ToU control	**1423,895**	**108,673**	**0,00**	**0,00**	**0,00 %**	**0,00 %**
Optimised 1	1424,206	108,519	0,31	0,15	0,02 %	0,14 %
Optimised 2	1423,973	105,472	0,08	3,20	0,01 %	2,95 %
No control	**1421,084**	**157,923**	**-2,81**	**-49,25**	**-0,20 %**	**-45,32 %**
Optimised 1	1422,286	107,796	-1,61	0,88	-0,11 %	0,81 %
Optimised 2	1422,007	120,263	-1,89	-11,59	-0,13 %	-10,66 %

The optimisation method has clearly failed to convergence to the optimum in many cases. From all the starting points the optimisation methods was able to improve the solution at least slightly and in some cases much. The traditional ToU control is taken as the base case in the Table 1. When optimisation 2 started from ToU control, it converged very close to the price control case. From some other starting points the optimisation method converged close to the same price control solution and there were all of the best solutions that the optimisation method found.

9 Simulations of a partially storing row house apartment

An overview of the results of the simulations of a partial storage electrical heating row house is in the Table 3. It is comparable to the Table 1 as the week (3/2006) is the same week as well as the methods. In addition a heuristic method is included.

Table 3. Overview comparison of price control methods for a partially storing row house apartment, simulation results of a week 3/2006 with high price peaks.

Method	kWh	Energy cost €	kWh increase	€ saving	% (kWh)	% (€)
No control	**735,5**	**82,99**	**-13,14**	**-6,69**	**-1,8 %**	**-8,8 %**
ToU Control	**748,7**	**76,30**	**0,00**	**0,00**	**0,0 %**	**0,0 %**
Price control	**744,3**	**74,15**	**-4,38**	**2,15**	**-0,6 %**	**2,8 %**
Heuristics	**768,4**	**65,47**	**19,68**	**10,83**	**2,6 %**	**14,2 %**
Optimised	**749,3**	**63,47**	**0,60**	**12,83**	**0,1 %**	**16,8 %**

The Table 3 is based on Table 4 that shows simulation results with two slightly different tunings of each method. It demonstrates that with different tunings the results of the methods vary in some respects.

Table 4. Comparison of price control methods for a partially storing row house apartment, simulation results of a week 3/2006 with high price peaks.

	€	Energy cost €	kWh increase	€ saving	% (kWh)	% (€)
no control	735,54	82,99	-13,14	-6,69	-1,8 %	-8,8 %
simple TOU	748,67	76,30	0,00	0,00	0,0 %	0,0 %
price based TOU (8h/24h)	744,26	75,51	-4,42	0,79	-0,6 %	1,0 %
price based TOU (16h/24h)	744,29	74,15	-4,38	2,15	-0,6 %	2,8 %
heuristics	768,36	65,47	19,68	10,83	2,6 %	14,2 %
heuristics	769,75	65,55	21,08	10,75	2,8 %	14,1 %
optimised	749,27	63,47	0,60	12,83	0,1 %	16,8 %
optimised	749,51	63,54	0,84	12,76	0,1 %	16,7 %

In the Tables 3 and 4 the traditional ToU control is used as the base case to which the other methods are compared. The models applied tend to overestimate the energy losses, because the longest storage time constants are modelled as losses.

In the partial storage case the optimal control method is in general superior to other methods. The heuristic method is almost as good as the optimal control in saving energy costs but wastes some energy when compared to any other method. The relatively simple price control methods waste slightly less energy than the traditional ToU and the optimal control. It also gives relatively small cost savings compared to the traditional ToU method.

10 Good optimisation convergence with the partial storage heating house

With the partially storing case the optimisation method and problem formulation the convergence was much better than with the full storage case. This is due to the fact that the optimal solution is not on-off type. In the full storage case the well controllable heat storage decouples the heat dynamics of the house while in the partial storage case the temperatures of the building and the heat storing material are tightly connected via the heat transfer dynamics. Thus the optimal control must take into account these dynamics and the resulting solution does not include as fast jumps from one control constraint to the opposite one. An example of the solution is shown in Figure 4.

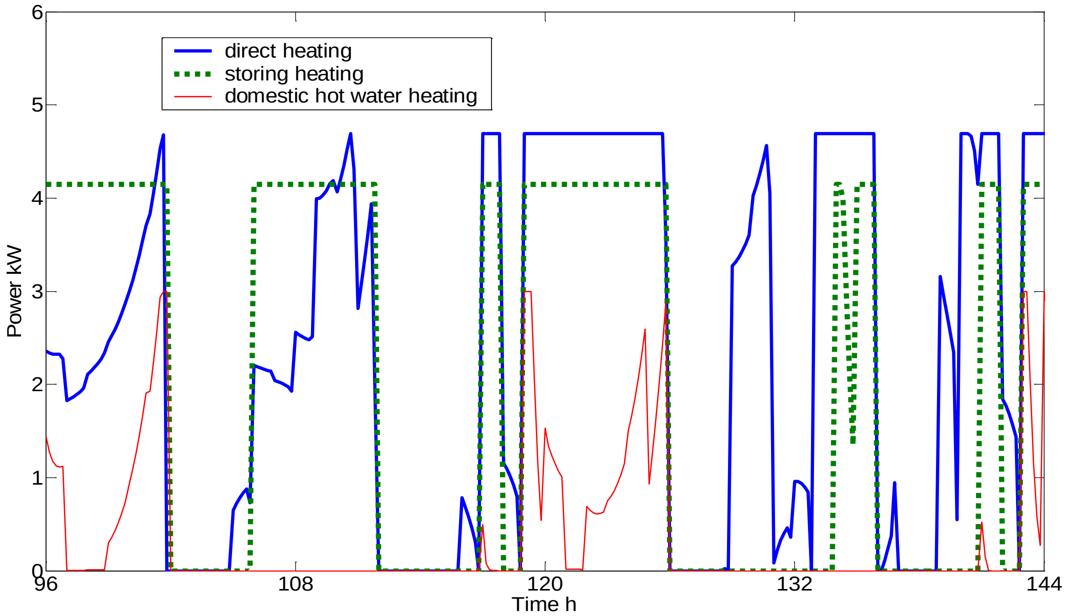

Figure 4. Optimised heating of a partially storing row house apartment during 19 and 20 January, the price peak days of the Figure 1. Simulation.

11 Limitations of the simulation study

Simulating only one week and only one house cannot give results that accurately represent the long term performance For possible further simulations the whole winter 2005-2006 and also the winter 2009-2010 are very interesting for these comparisons due to high spot price peaks. Simulations of the autumn and spring conditions can also be expected to give interesting and somewhat different results regarding the relative performance of methods and house types. The regular price and outdoor temperature variations are different compared to the winter time and the limits of storage capacity have less impact

The models applied in these simulations are strong simplification of the real buildings. For example, the models applied overestimate the energy losses, because the longest time constants of heat dynamics are modelled as losses and not as storage. In addition they are only rather arbitrary instances of groups that are not very homogenous. Reservations should be taken regarding the accuracy of the results and how well they represent their segment. The purpose of this comparison was to find out how the different methods behave relative to each other. For that purpose the accuracy is adequate.

12 Development of smart metering systems to support dynamic load control.

The partners of this project developed a load control system model, which can utilise, for example, the fluctuations of electricity prices in the electricity market. See Figure 4. Moreover, we proved in practice that the system can be implemented with current remote reading systems, with the information produced with the current information systems.

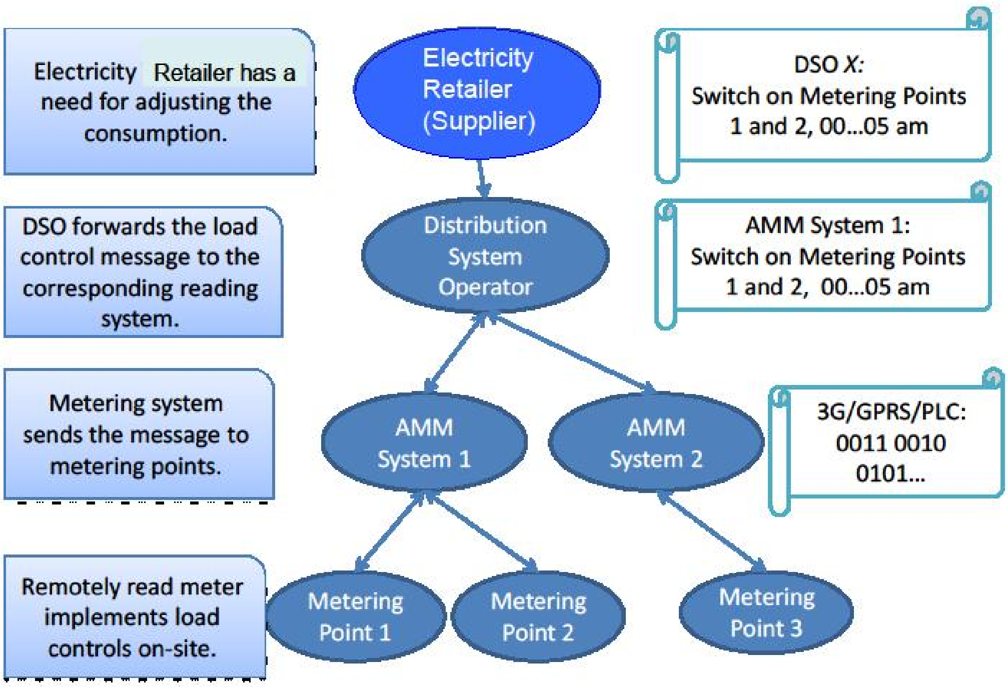

Figure 4. The hierarchical principle of the load control system model.

The system can be introduced by any electricity distribution network company using modern measurement data management and remote reading systems. In addition to controls carried out on the basis of the price, the system also enables power restriction or service controls in accordance with the needs of the network company or electricity retail supplier. The management of the algorithm can be granted, for example, to the electricity retail supplier, in which case the network company only acts as the implementer of load controls.

The benefits gained from load control are substantial compared with its investments. The benefits can be further improved by optimising the time frame of heating with respect to each metering site, for example, in accordance with the heating needs detected from the hourly energy series. Optimisation can be implemented at the upper level by the body forming the algorithm, and the load control model now created does not restrict this kind of optimisation.

The results of the development project can be utilised directly in a versatile way according to the network company's needs. Helen Sähköverkko will utilise the developed system in controlled night-time sites for the control of heating loads, and it will continue developing the system to enable its more extensive utilisation for the emerging needs of the electricity market.

The functionalities of this system model include:
• connecting the customer with this distribution product
• time-of-use control to be used as default in the absence of more dynamic controls
• control based on day ahead spot price
• fast service control
• reading the hourly consumption according to the normal procedure required by the Finnish electricity market legislation that came into effect in March 2009.

The data exchange between different systems is based on XML (eXtensible Markup Language) the WebServices interfaces.

The smart meter manufacturers Aidon and Landis&Gyr upgraded their products to meet these requirements. Laboratory test of the modifications to smart metering systems and the systems of the network company were completed in June 2010 and a continuation project that includes field trials and needed development of the systems of the electricity retailer are planned for the next winter. In these field trials the spot price control system model will be implemented and tested for eight full storage electrical heating houses.

13 Cost benefit analyses

According to an earlier study, transferring the storage heating of controlled night-time sites in the Helsinki region to the cheapest hours of the 24-hour period would bring a benefit of €100,000 per year compared with the current control when only the price of electric energy according to the spot price is examined [Leksis 2009]. The relative benefit in the costs of energy use, achieved on the basis of simulations, would be 3–15% depending on the heating system of the site.

The costs of the program processing the initial data were approx. €2,000. The size of the 24-hour control data package sent to the meter is approx. 200 bytes depending on the communication method and medium between the meter and the reading system. The data transfer costs depend on the system operator's service contracts and data transfer medium. The annual costs of data transfer are in the region of €0–1 per metering point.

Over a period of ten years, the theoretic discounted yield on a system investment of €2,000 is €750,000 with a five per cent imputed interest. The beneficiary depends on the pricing structure of the electricity transmission and sales product. If the system can be introduced on a nationwide scale, it may also have an impact on prices at the system level because the controlled night-time product has approx. 70 MW of controlled load in the Helsinki region alone. Thus there is a possibility of obtaining a direct financial benefit with almost negligible investments and operating costs.

Business cases for demand response investments were considered for Finland and the other countries participating in the IEA DSM Task XIX. [Hull 2010] The analysis was done based on 1) historic prices and 2) comparing with alternative investments such as peak generation. In the Finland electrical heating case the results of both these approaches were not much different.

14 Concluding remarks on the comparison of control methods

The following conclusions can be drawn:
- ToU control brings clear benefits compared to not having any control based on time or price. Further benefits can be achieved by improving the control from the existing simple static ToU control.
- Such benefit potential seems to be somewhat bigger for partially storing buildings. Relative to the size of consumption this difference is even bigger.
- With rather simple price based control methods and without new building automation the full benefit potential of full storage heating houses can be achieved close enough. With this control method the existing in house systems for Time-of Use control can be used without any changes.
- Achieving the full benefit potential of partially storing houses requires on-line use of rather advanced optimisation methods. Data processing and storage capacity are now so cheap that their cost does not prevent the use of such methods, but there are still significant challenges regarding further development and maintenance of such methods. Good methods, for example Mixed Integer Programming (MIP) solvers suitable for the purpose, are also commercially available, but their licence fees tend to be prohibitively high for this kind of distributed application.
- The own optimisation method implementation works adequately with partial storage heating, but with it a different problem formulation is needed for most purposes with the full storage heating case. Even with the original formulation and with both heating types the own optimisation method gave a necessary reference solutions for the assessment of the other methods.
- The models applied in these simulations are strong simplifications of the real buildings. Reservations should be taken regarding the accuracy of the results. The

purpose of this comparison was to find out how the different methods behave relative to each other. For that purpose the accuracy is adequate.
- Simulations of only one house over only one week are only a sample that is not able to give accurate quantitative assessments of the performance and benefits of the methods. With different outdoor temperatures and price signals the results are somewhat different. More simulations are needed and winter 2009-2010 provided suitable input data for them.
- Full storage heating houses are a somewhat heterogeneous group. If the insulation level is lower or the heat storage smaller than in the simulated house, the benefits of price control can be expected to be bigger. But for such a house improving the insulation of the house is likely the recommended action.
- Possible directions for further studies include: 1) extending the comparisons to cover simulations over more houses and more weeks and including the winter 2009-2010, 2) selection, development and comparison of optimisation algorithms for the purpose, 3) further development of the physically based models for simulation, prediction and optimisation of the responses.

15 Summary

Day ahead spot market price based control of electrical space heating loads was studied by simulations The cost and energy performance of several different control methods was compared. As input data for the simulations the market prices and outdoor temperatures of week 3/2006 were used. This week was chosen due to high price peaks and rather smooth outdoor temperature behaviour. A full storage heating detached house and a partial storage heating row house apartment were simulated. The simulations used simple models of the heat dynamics of the houses developed based on measured temperatures and electricity consumptions and information on the most relevant properties of the buildings and their heating systems.

Due to the small number of houses and weeks simulated the results are only indicative. The accuracy and representativeness of the results can be improved with more simulations.

The following observations can be made from the simulation results. 1) The full demand response potential of full storage heating systems is relatively easy to tap, but partial storage heating has more unused benefit potential. The main reasons for this is that the full storage heating house studied has abundant heat storage, the temperature of which can be controlled independently from the temperatures of the rooms heated. The heat dynamics of the storing mass of partial heating are much more tightly connected to the room temperatures which makes it a more challenging problem to control the storage optimally. 2) The existing static Time of Use control is clearly better than no load control at all. 3) There is benefit potential in replacing the static Time-of-Use control with dynamic market price based control methods.

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