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Energy conservation measures in buildings heated by district heating – A local energy system perspective

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Abstract

The extensive energy use in the European building sector creates opportunities for implementing energy conservation measures (ECMs) in residential buildings. If ECM are implemented in buildings that are connected to a district heating (DH) system, the operation of DH plants may be affected, which in turn may change both revenue and electricity production in cogeneration plants. In this study a local energy system, containing a DH supplier and its customer, has been analysed when implementing three ECMs: heat load control, attic insulation and electricity savings. This study is unique since it analyses economic and CO₂ impacts of the ECMs in both a user and a supplier perspective in combination with a deregulated European electricity market. Results show that for the local energy system electricity savings should be prioritised over a reduction in DH use, both from an economic and a global CO₂ perspective. For the DH supplier attic insulation demonstrates unprofitable results, even though this measure affects the expensive peak load boilers most. Heat load control is however financially beneficial for both the DH supplier and the residences. Furthermore, the relation between the fixed and variable DH costs is highlighted as a key factor for the profitability of the ECMs.

Keywords: Energy conservation measures, district heating, combined heat and power, optimisation, residential buildings.

1. Introduction

A large portion of the primary energy use in Europe is utilised in the building sector. In Sweden about one fifth of the total energy demand is used for space heating and domestic hot water in the residential and service sector [1]. Based on rising energy prices as well as environmental aspects, a reduction of the energy use in this sector is vital for a sustainable society. The European Commission has noticed this issue and established a directive promoting energy efficiency in buildings [2]. The aim of this directive is to improve the energy performance of new buildings as well as existing buildings when they undergo refurbishment. This directive was implemented in the Member States in 2006 and hence when major refurbishment of buildings larger than 1000 m² is carried out they should also include energy efficiency measures (within a reasonable expense level).

When implementing energy conservation measures (ECMs) in buildings, for example adding insulation, changing heating system or replacing windows, the potential for decreasing energy use can be substantial. In a Danish study the savings potential for

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space heating is forecasted at 80% up to the year 2050 [3]. Earlier studies in Sweden have also shown considerable potential for energy savings in the building sector [4, 5] and this potential is to a large extent still remaining as few improvements have taken place since the 1990s [6]. Even if all of this saving potential may be hard to realise financially, there is considerable room for ECMs in the building sector. ECMs and energy use within the building sector have been addressed in several papers. For example, in [7-9] the choices of heating system in detached houses were analysed in combination with different ECMs and parameters such as cost-effectiveness, primary energy use and CO₂ emissions. The potential for energy conservation in apartment buildings has been studied in [10, 11]. A number of papers have also concentrated on developing simulation and optimisation models for residential heating systems, often in combination with ECMs [12-17]. Tools for forecasting heat demand in order to optimise plant operation have been discussed in, for example [18, 19].

An outcome of implementing ECMs is that the heating system of the building will be affected to a great extent, either by a change in the heating system; from for example oil boilers or resistance heaters to district heating (DH) or heat pumps, or by reducing the heat demand. In Sweden, where DH is well established as the supply for space heating, a change in heating demand can have great effect on the local DH supplier. In 2007, 82% of the total heated area in multi-dwelling buildings was heated by DH [20]. Since the total demand for space heating and domestic hot water for multi-dwelling buildings in Sweden is 26 TWh [1], ECMs in multi-dwelling buildings have the potential to affect the economic situation as well as the DH demand of the Swedish DH systems. Hence, the consequence for the DH supplier, as addressed in this paper, is vital to study since it will show economic impacts in a supply perspective due to demand side measures. The Swedish DH sector stands before major changes like third party access (TPA), reduced heat demand due to milder climate and the competition of other heating systems. Consequently, it is of utmost importance to study the effect of ECMs for the DH system since the DH supplier has the possibility to promote certain measures by offering services such as energy efficiency audits where, for example, different insulation measures and heat load control can be recommended. In addition, introducing ECMs in the residential sector will also affect the residents financially in the form of investment costs and changed energy costs. Moreover, if the DH user is not satisfied with the DH service or prices the user can change heating system, or in the future when TPA has been introduced, change DH supplier or implement ECMs. It is also interesting from the societal perspective to study the combined effect of the ECMs for the DH users and supplier in case regulatory frameworks should be introduced to support beneficial ECMs.

1.1. Objective

The aim of this study is to analyse how the implementation of ECMs in multi-dwelling buildings, connected to the local DH system in the Linköping area in Sweden, will affect the energy costs and demand for the residences as well as the revenue and DH production for the DH system. Three ECMs - heat load control, attic insulation and electricity savings - have been implemented in this study. To evaluate the effect of the ECMs, the DH system has been modelled in an optimisation model along with one of the ECMs at a time. This study focuses on increasing the understanding of how demand side measures in a DH system affect the local energy system in terms of economic and CO₂ impacts as well as the marginal operation of the

DH plants. The local energy system is studied with a deregulated European electricity market in consideration.

2. Case Study

In this paper the local energy system of the Linköping region is studied. Linköping, with about 140,000 inhabitants, is located about 200 km southwest of the capital of Sweden, Stockholm. The local energy system includes the local DH system as well as the residential sector in form of the multi-dwelling buildings.

2.1. District heating system

The DH system in Linköping is managed by the municipally owned Tekniska Verken Linköping AB (TVAB). Besides the supply of DH, district cooling (DC) is distributed to the residential sector as well as heat and process steam to a number of industries. In 2008 the annual production of DH and steam was about 1,700 GWh and the maximum heat demand approximately 500 MW. For the DC the cooling demand was approximately 30 GWh in 2008 with a maximum cooling demand of 30 MW. The DC demand is 60% supplied by heat-driven absorption cooling which utilises heat from the DH production. During the winter the DC demand is supplied by free cooling from a river nearby, and for peak days during summer compression cooling is available.

The DH production is presently supplied by a number of different plants, both combined heat and power plants (CHP) as well as heat-only boilers (HOB), see Table 1. Furthermore, a number of different fuels are used in the system. The base production of DH is waste incineration, approximately 1,000 GWh annually. The incineration plant consists of two plants: one modern CHP plant with flue gas heat recovery and an older hybrid CHP plant where steam from waste incineration can be superheated with the flue gases from an oil-fired gas turbine and then expanded through a steam turbine. For this hybrid plant there can be no electricity generation without operating the oil-fired gas turbine since the steam from the waste incineration does not have sufficient steam qualities to operate alone in the steam turbine. However, oil prices have increased since the installation of the oil-fired gas turbine and currently this gas turbine is hardly ever operated. For both waste CHP plants a direct condenser can be used for heat-only production.

Besides the waste incineration CHP plants there are other CHP plants fuelled by biomass, coal and oil. In addition to the CHP plants there are a number of HOBs fuelled by biomass, oil and electricity, giving the energy system a high degree of fuel flexibility.

When the DH demand is low, the electricity generation in the CHP plants can be increased by cooling the DH network supply line in the nearby river and in the cooling tower. The total cooling capacity is 45 MW and this function is particularly used during the summer months. The overall electricity generation in the CHP plants is about 325 GWh annually.

2.2. Residential sector

In the Linköping area the residential sector accounts for about 50% of TVAB's total DH sales, most of which is distributed to multi-dwelling buildings (75%). Of the

70,000 apartments listed in 2008, about 80% are connected to the DH network. Since the majority of DH sales to the residential sector are to the multi-dwelling buildings, the effect of the ECMs has only been studied on multi-dwelling buildings.

3. Energy conservation measures (ECM)

Three ECMs are included in this study: 1) heat load control; 2) attic insulation; and 3) electricity savings due to reducing the electricity use of the residences by changing to new appliances, for example changing to new refrigerators and freezers and to low-energy lamps. Hence, these measures will affect the heating demand differently, for example the attic insulation will reduce heat demand during the coldest winter months while the electricity savings will reduce the excess heat and thus increase the heat demand. Specific heat load profiles have been obtained for the different measures, which are shown in Figures 1-3. In order to compare these ECMs the magnitude of the measures are the same, 10 GWh, to illustrate the marginal effect of implementing ECMs. However, since the total DH demand for the region is substantial compared to the 10 GWh the magnitude of the different ECMs have been increased in Figures 1-3 in support of better readability. The use of the figures is to show what effect the ECM has on the heat load profile.

3.1. Heat load control

The heat load control equipment used in this study is a recently developed software program that can be installed on the computer in the consumers' DH central. This software program is decentralized and agent based, and the idea is to utilise the building's heat inertia to reduce the peak load demand of DH, i.e. the house would act like heat storage. This software program is under evaluation and is currently being tested by a number of DH consumers in different parts of Sweden, for example in Linköping. For all participating buildings, an evaluation of the building's time constant is performed in order to grade the heat capacity of the buildings. From that information, in combination with the outdoor temperature and the current DH supplied to the building, the duration of the DH reduction to the building can be calculated. For the participating buildings the program calculates whether the DH demand can be reduced, and if so which building is most suitable for the DH reduction. See for example [21] for more information of the field test of the heat load control system. The preliminary result from the evaluation of the program shows that DH demand can be reduced by 7% annually [22]. Based on the DH supply to the multi-dwelling buildings, 10 GWh is equivalent to when about 24% of the multi-dwelling buildings connected to the DH network in Linköping implement the heat load control measure (based on total heat demand for multi-dwelling building).

In Fig. 1 the potential effect the heat load control has on the annual DH demand is illustrated. In the figure the local DH production is included as well as the energy conservation potential from heat load control. As shown in Fig. 1, heat load control has most effect for medium heat loads while for low and high heat loads the effect is almost unnoticeable. The reason for this is that the domestic hot water is unaffected by the heat load control and during the summer months almost no space heating demand is required, only domestic hot water, hence less heat load control can occur. During the winter months when the outdoor temperature is low the heat demand peaks, which results in fewer periods when the building can be without space heating and consequently a minimum of heat load control can be applied.

3.2. Attic insulation

For the attic insulation measure the multi-dwelling buildings have been divided into different categories depending on the construction date of the building (see Table 2). An optimum of 0.50 m of total attic insulation and a U-value of 0.1 W/m²K is the recommendation of the Swedish Energy Agency and therefore an extra insulation refurbishment of 0.30-0.40 m is used depending on the category, see Table 2. The new U-value is calculated using the equation

$$U_{new} = U_{ext} \frac{k}{k + U_{ext}t}$$

where $k = 0.0475$ is the thermal conductivity for mineral wool and t is the extra insulation thickness in meters [23]. The new calculated U-values are listed in Table 2 along with the difference in UA-values, which indicates the potential DH reduction for the different categories when implementing the ECM. An effective indoor air-temperature of 17 °C is used since the remaining heat up to 20-21 °C is assumed to come from household appliances, people and solar radiation [24]. The difference between the existing and the new UA-value, the temperature difference between indoor and outdoor (ΔT) along with the number of hours when this temperature difference occurs provide the potential reduction of DH use. Outdoor temperatures for the Linköping region have been obtained from the Swedish Meteorological and Hydrological Institute [25]. A reduction of 10 GWh DH corresponds to about 65% of the multi-dwelling buildings connected to the DH network in Linköping implementing attic insulation (based on total heat demand for multi-dwelling building).

The DH load duration curve for the DH production is illustrated in Fig. 2 along with the energy conservation potential from the insulation measure. As can be seen in the figure the attic insulation measure affects the DH load duration curve mainly during the peak heat loads, which represents the winter months, since the temperature difference between indoor and outdoor (ΔT) peaks during the winter period.

3.3. Electricity savings

Use of electricity can be reduced by replacing household appliances and the measures included in this study are: 1) switching from incandescent lamps to low-energy lamps and 2) investments in a new refrigerator and freezer. For all changes in appliances it is assumed that the reduced electricity use implies a reduction of excess heat of the same magnitude (except during the summer months), even though not all excess heat is useful. The reduction of excess heat is assumed to affect the total DH demand for the apartment even though the appliances, for example the refrigerator, are placed locally.

The preliminary result from a study made by the Swedish Energy Agency (SEA) of the electricity use of Swedish households concludes that of the total annual electricity demand of 3000 kWh/apartment about 23% is used for lighting [26]. When switching from incandescent lamps to low-energy lamps the electricity use for lighting can be reduced by 50% and hence reduce the electricity use by about 350 kWh/apartment [26, 27]. However, the use of lighting is not constant during the year, but rather dependent on the season. The use of lighting is similar to the DH demand for the year, i.e. more lighting is required when it is winter and dark outside and less lighting is

required when it is summer and light outside. Therefore, more DH is required during the cold winter months to replace the loss in excess heat when changing the lighting bulbs.

Furthermore, the SEA study also identifies that about the same amount of electricity is used for cold appliances (refrigerator and freezer) as for lighting, about 720 kWh/apartment. Hence, by investing in new cold appliances with an energy efficiency class of A+ the electricity use can be reduced by about 440 kWh/apartment. When including both switching lamps and investments in new cold appliances, a total electricity reduction of about 790 kWh/apartment is possible. By switching to more energy efficient household appliances the electricity use can be reduced, thus decreasing the excess heat from these appliances which will affect the DH demand. The cold appliances are assumed to operate the same independent of the season and produce the same amount of excess heat for all months. The increased DH demand due to less excess heat from the cold appliances is assumed to be constant during the year, except for June to August where it is assumed that no external heat is needed for space heating.

An aggregated required DH load for replacing the loss in excess heat when changing lighting and refrigerator/freezer is shown in Fig. 3, together with the production of DH. An increase in DH demand by 10 GWh corresponds to a reduction of the electricity demand by 12.5 GWh due to no excess heat from the household appliances is utilised during the summer months. An increase in the DH demand by 10 GWh corresponds to about 25% of the apartments in the multi-dwelling buildings connected to the DH network in Linköping replace their household appliances. This figure is when both the cold appliances and the lamps are changed in the same household.

4. Method and input data

The ECMs included in this study have been evaluated by using three perspectives: 1) the DH system; 2) the residences; and 3) a combination of the DH system and the residences (referred to as the local energy system). The ECMs have been chosen since they represent realistic and cost-effective investment options and since they have specific and very different heat load profiles. To evaluate the effect these ECMs have on the local energy system, the DH system has been modelled in an optimisation model (MODEST) along with one of the ECMs at a time. One reference system without ECMs has also been modelled to represent business as usual. From the optimisation model the system cost for respectively ECM and the reference system has been obtained. The difference in system cost between the reference system and the system including the ECM has been used to calculate the economic effect of the ECM for the DH supplier. Another output from MODEST is the marginal DH costs, i.e. the cost to produce the last unit increase in DH (or the saved cost for the last unit decrease in DH). The marginal DH costs for the reference system have been used as variable DH tariffs for the users. Along with a power fee the marginal DH costs represent the total DH cost for the users (as well as the income for the DH supplier). Moreover, when implementing the ECMs in multi-dwelling buildings the energy use is altered. Hence, the economic effect for the residences when implementing ECMs is calculated as altered energy costs in combination with the annual capital costs for the ECM. Finally, studies of the ECMs' effect on the local and global CO₂ emissions have also been performed. For a schematic overview of the methodology, see Fig. 4.

4.1. Optimisation model

For optimising the DH system of the Linköping region an optimisation model called MODEST, an acronym for Model for Optimisation of Dynamic Energy System with Time-dependent components and boundary conditions, is used. The model is based on linear programming and has been developed to optimise DH and electricity production in regional and national energy systems. The objective function of the model is to minimise the system cost of the DH system. Included in the system cost is the total cost of meeting the demand for heat and steam, which includes plant investment costs, fuel and maintenance costs, fuel taxes and fees as well as income from electricity generated in the CHP plants and sold. Other input data that need to be defined are the time-division, efficiency, power-to-heat ratio (for CHP plants), heat and steam demand as well as technical and economic lifetime of the plants. Outcomes from the model are the system cost, plant operations and marginal DH costs. The marginal costs have in this study been used as DH prices for the residences. For more details of the model, see [28-30].

To illustrate how DH demand varies according to the seasonal changes, one year is divided into 88 sub-periods. During the winter months (November to March) when the DH demand peaks, the time divisions are divided into the smallest increments and in the morning hours even modelled hour by hour. During the remaining part of the year (April to October), longer time divisions can be used since the variations in heat demand are smaller.

The MODEST model has been used to optimise different kinds of energy systems, from local energy systems to national energy systems. For example, over 40 local energy systems have been optimised as well as the Swedish power supply [29, 31]. To validate the results from this study, the outcome from the model has been verified against real data for the local energy system.

4.1.1. Input data for the DH system

In this study the energy system has been optimised over a 20-year time period, divided into four five-year periods. The optimisation starts in the year 2013 and continues to the end of the year 2032. The fuel and electricity prices, illustrated in Table 3 and Table 4, are forecasted prices for the year 2013 and are developed from the collaboration of different working groups within the TVAB organisation. The fuel prices are subject to an annual increase of 0-2.5%, depending on the fuel, while the annual electricity price increase is 1.5%. The electricity prices are the selling prices for the electricity generated in the CHP plants. To illustrate the variation in electricity price over the year the price is divided in several time steps. Include in the time steps is one peak day per month during the winter, see Table 4. An exchange rate of 1 Euro = 9.40 SEK is used for all costs and prices.

4.2. Evaluation of economic performance

4.2.1. District heating system

The economic performance of the DH system is obtained from the optimisation model where the system cost is determined. To analyse the effect the ECM has on the DH system the difference in system cost between the case including the ECM and the case where no measures are included (reference case) has been calculated. This figure is

referred to as the DH production cost (Euro/MWh DH) and a negative value indicates that a reduced production cost is obtained when the ECM is implemented and vice versa with a positive value. Also included in the evaluation of economic performance for the DH system is the change in income from sold DH due to increased or decreased DH consumer use. Since the local DH supplier TVAB is in the process of adjusting its DH tariffs according to the actual seasonal production cost, the marginal DH costs, obtained from the optimisation model (see section 4.1), are used as DH prices. Since the model is divided in 88 sub-periods, there are 88 marginal DH cost per year. On average, the marginal DH cost during the winter (November to March) is 40 EUR/MWh DH and for the rest of the year 1 Euro/MWh DH. For more information about marginal DH costs used as DH tariffs, see for example [32, 33]. Besides the marginal DH costs the DH supplier also has a fixed fee (power fee), which is 67 Euro/kW DH.

4.2.2. Residential sector

The financial effect of the ECMs for the residences, i.e. the annual capital cost, has been calculated by using the annuity method. The annual capital cost is compared to the altered annual energy costs due to the changed energy usage. From that figure the cost per saved or increased MWh of DH is calculated. Included in the economic performance of the residences are the annual capital costs for the ECMs as well as the altered energy costs due to changed energy usage. The annual capital costs depend on the technical lifetime of the measure and the real discount rate. As described in 4.2.1 the marginal DH costs obtained from the optimisation model are used as the DH prices along with the power fee.

4.2.2.1 Heat load control

For the heat load control measure one software license is required per DH central and one central can supply a whole apartment building complex with DH. The investment cost is an annual license cost of 270 Euro/central and a communication cost of 200 Euro/central; hence the investment cost is dependent on the size of the building. In Fig. 5 the investment cost in Euro per MWh saved DH is illustrated for different building sizes (1000-11000 m²). A building size of 6800 m² is used in this study since this is the average building size of the eight buildings included in the test study of the software program in the Linköping region (see section 3.1).

4.2.2.2 Attic insulation

For attic insulation different building categories have been developed which require varied insulation thickness. Hence the insulation cost differs for the categories but also the amount of saved DH use (see Table 5), which results in an annual capital cost that varies between 51-196 Euro/MWh saved DH. A technical lifetime of 40 years and a discount rate of 6% are assumed.

4.2.2.3 Electricity savings

The investment costs regarding the electricity savings due to changing household appliances are difficult to estimate. No investment cost for switching from incandescent lamps to low-energy lamps is included since the incandescent lamps will be phased out in a step-wise process by 2013 according to an EU directive [34] and hence the incandescent lamps must be replaced in any event. The investment cost for replacing an old refrigerator and freezer is also hard to estimate since this measure is not directly linked to the electricity and DH use but may have other reasons such as

operation failure. However, if a refrigerator is replaced five years ahead of its expected lifetime, due to poor energy classification of the refrigerator, the investment has to take place five years sooner and this extra cost has to be accounted for in the electricity reduction calculations. In Table 6 different investment costs for changing to new household appliances are displayed as well as the extra cost and the annual capital cost when investing in a new refrigerator five years ahead of schedule. The annual capital cost varies from 0-77 Euro per MWh electricity saved for the five years when a discount rate of 6% is used in the calculations. The electricity price used for the households is 124 Euro/MWh and this value is calculated using the electricity prices in Table 4 along with the extra costs for taxes, VAT and grid fee. However, a decreased electricity use of 1 MWh results in an increased DH demand of only 0.8 MWh due to no excess heat from the household appliances is utilised during the summer months.

4.2.3. Local energy system

In the evaluation of economic performance for the local energy system both the DH system and the residential sector are included. From the changed costs for the DH system and the residences a total sum for the local energy system is calculated for the different ECMs.

4.3. Evaluation of the effect on global CO₂ emissions

Considered in the global CO₂ emissions are the changes in local emissions due to increased or decreased DH production and the changes in global CO₂ emissions that derive from the altered electricity production and use. All changes in DH and electricity production and use are in relation to the reference case without ECMs. Due to the deregulated European electricity market the change in electricity production and use in the Linköping region is assumed to affect the European marginal electricity production. In this study two marginal electricity facilities are considered: coal condensing power and gas combined cycle condensing power. Coal condensing power with low electricity efficiency reflects the present situation while the gas combined cycle reflects a potential future situation.

The effect on the total global CO₂ emissions is calculated as:

$$\Delta Total\ global\ CO_2 = \underbrace{\Delta DH_{prod} F_{DH}}_{local\ CO_2\ emissions} - \underbrace{(\Delta Electr_{CHP} - \Delta Electr_{residence}) F_{electr}}_{global\ CO_2\ emissions}$$

where ΔDH_{prod} is the change in DH production and F_{DH} the fossil CO₂ fuel emissions for DH production (see Table 7), $\Delta Electr_{CHP}$ is the change in electricity production in the CHP plants while the $\Delta Electr_{residence}$ is the change in electricity use in the residences and ΔF_{electr} the fossil CO₂ emission factors for European electricity production, listed in Table 7.

5. Results

The economic effect when the ECMs are implemented is evaluated from three perspectives: the DH system, the residences and the local energy system. For all perspectives a negative value of the economic calculations indicates reduced costs but

also reduced income from sold DH while a positive value represents increased costs and increased income from sold DH.

5.1. District heating system

The operations of the DH plants are affected when the ECMs are implemented. In Fig. 6 the altered fuels consumption for the local DH plants is illustrated. For the waste plants there are no change in operation since they are base load plants and hence not affected by marginal changes in DH demand. As can be seen in the figure operation of the coal CHP plant is reduced by the same amount for the heat load control and the attic insulation measures. The attic insulation measure has on the other hand the potential to reduce the operation of oil plants more than the heat load control. The electricity savings measure, which increase the DH demand, increase the fuel consumption for the fuels listed, where the oil consumption has increased the most.

Regarding the economic impact for the DH system the implementation of electricity savings is the most beneficial measure followed by heat load control, see Table 8. The heat load control has no effect on the maximum heat load and consequently no impact on the power fee. On the other hand the electricity savings do increase the maximum heat load and therefore also the power fee.

Attic insulation is the most expensive measure for the DH system even though this measure has the largest effect on the DH production cost. Since this measure has the largest impact on DH use during the winter period, the maximum heat load will be affected and therefore also the power fee. The relation between the variable DH costs (marginal DH costs) and the fixed cost (power fee) is critical for the profitability of the measures affecting the peak heat load demand.

5.2. Residential sector

The economic performance of the residences includes the annual capital costs for the ECMs as well as the altered energy costs due to changed energy usage. The investment costs for the different ECMs are difficult to estimate since the investment costs vary depending on, for example, the building category (attic insulation), building size (heat load control) and other circumstances (electricity savings). In Table 9 the economic performance for the different ECMs is listed, where all measures show positive economic results for the residences. The electricity savings is the most beneficial measure followed by heat load control. Hence, by changing heating source from electricity to DH by a reduction of the surplus heat from household appliances the energy costs can be reduced for the multi-dwelling buildings.

However, since the dispersion of the annual capital costs is substantial (see Fig. 7), the economic profits for the residences depend on the situation. For example, the annual capital cost for the attic insulation in the table is a weighted value based on the costs for the building categories mh-40 and mh 41-60 since they are oldest and least energy efficient and therefore most likely to be refurbished. The economic performance of the heat load control also depends on the size of the building where a minimum building size of 1300 m² is required for the heat load control to be favourable for the residences. On the other hand, the electricity savings measure is economically beneficial for the residences even if the household appliance is considered to be

replaced five years ahead of its expected lifetime, given an investment cost lower than 1000 Euro.

5.3. Total economic effect for the local energy system (DH system and residences)

When considering the economic effect for the local energy system, where both the DH system and the residences are included, the results show that the heat load control and electricity savings measures are economically beneficial (see Table 10). Implementing these measures shows profitable results for both the DH system and the residences. Attic insulation on the other hand is only profitable for the residences and since the increased cost for the DH system exceeds the reduced costs for the residences the outcome for the local energy system is unprofitable. However, as mentioned in the previous section, the results for the local energy system are highly dependent on the investment costs of the ECMs.

5.4. Global CO₂ emissions

Included in the total effect on the global CO₂ emissions, when implementing ECMs, are the changes in local CO₂ emissions due to altered DH use as well as the changes in global CO₂ emissions because of the altered electricity production and use. When implementing ECMs the DH production is affected and hence the electricity production in the CHP plants. Depending on the heat load profile of the measure different DH plants and hence fuels are affected, which results in different changes in CO₂ emissions for the measures (see Table 11). The attic insulation decreases the local CO₂ emissions the most since the production in DH plants during peak hours when oil and coal boilers are operating can be reduced (see Fig. 6). Both attic insulation and heat load control reduce the electricity production in the local CHP plants and hence these measures benefit from a CO₂ perspective when the marginal electricity production has low CO₂ emissions, like the gas combined cycle. However, when only the DH production is affected the influence on the CO₂ emissions is barely noticeable, especially when coal condensing power is used as marginal electricity technology. Regardless of the marginal electricity technology the electricity savings measure has the overall most positive effect on the global CO₂ emissions.

6. Discussion and conclusions

Due to the extensive energy use in the European building sector the implementation of measures leading to efficient energy use are important both for climate change mitigation but also for reducing energy costs. Here, the effects of implementing ECMs in the residential sector have been analysed from both a DH user and supplier perspective regarding economic and global CO₂ impacts.

Three ECMs were included in this study and they were chosen primarily for their different heat load profiles. Included in the study are measures affecting the maximum and medium heat loads as well as measures increasing the heat load. For example, attic insulation has the largest effect on the DH demand during the coldest period and hence affects the peak load boilers most. In this case the use of oil can be reduced which will decrease the local emissions. Heat load control has a different heat load profile and consequently affects the DH demand typically during the spring and fall when base load plants are used to produce DH. Hence, this measure has less effect on the peak load boilers. Additional ECMs could have been included but the idea was to

study how measures with different heat load profiles affect the operation of the DH plants and hence the operation costs. Consequently, the outcomes of the measures studied can be generalised for other measures with similar heat load characteristics. For instance, attic insulation has a specific heat load profile similar to other insulation measures; hence the effect of attic insulation for the DH supplier can be considered the same as for other insulation measures. The specific heat load profiles can also be scaled for better conformity of the DH systems studied.

The results from this study indicate that electricity savings is the most economically beneficial measure for the residences, the DH system and consequently also the local energy system. Also, from a global CO₂ perspective the electricity savings measure has the largest effect regardless of the marginal electricity production considered. Thus, reduced electricity use should be prioritised over a reduction in DH use. Heat load control also shows profitable results for both the DH users and supplier, even though it is only minor profits for the DH system. Furthermore, the heat load control measure is a robust solution with reduced energy cost for buildings larger than 1300 m². Attic insulation can be economically beneficial for the residences but this depends on the building category. However, for the DH supplier and the local energy system this measure shows unprofitable results. Finally, heat load control and attic insulation show smaller CO₂ reductions except the heat load control where an increase in emissions is observed when coal condensing power is the marginal electricity technology.

Furthermore, in this study the marginal DH costs from the optimisation model have been used as variable DH prices. Using marginal DH costs reflect a situation where variable DH prices are optimally constructed, which in reality can be hard to achieve. However, TVAB's intentions are that the factual costs of producing DH should be used as DH prices in the near future. Besides, the power fee used in this study (obtained from TVAB) has a large impact on the cost of implementing ECMs. Since the power fee and the variable DH prices are of the same magnitude (on a yearly basis), a reduction of the maximum heat load has a large impact on the annual DH costs, as can be seen for the attic insulation. By adjusting the relation between the variable and fixed DH costs the DH supplier can promote different measures. As illustrated in the results of this study the current relation between the variable and fixed DH costs makes it unprofitable for the DH supplier to implement measures such as attic insulation. This can seem remarkable since attic insulation reduces the expensive peak load boilers the most and consequently the DH production costs. However, with a changed pricing system for DH and when consider that attic insulation has the possibility to postpone future investments in peak load DH plants and back-up DH plants this measure can be profitable. On the other hand, when the economic effect of attic insulation is studied for the local energy system, where the DH prices are included both for the DH supplier and for the residences and hence are cancelled, this measure is still not profitable. From a societal perspective the electricity savings should instead be promoted.

To summarise, in countries with high density of DH the EU Directive promoting energy efficiency in buildings can have a major effect on DH demand. This makes it important for the DH supplier to review the DH pricing system and find new fields for the application of DH to retain profits as well as promote electricity savings measures. For the residences there is potential for reduced energy costs but this has to be

evaluated on a case by case basis. From an environmental point of view implementing ECMs will decrease the energy demand as well as the emissions of CO₂, especially when the electricity use can be reduced.

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References

- [1] SEA. Energy in Sweden 2008, report no. ET 2008:16. Stockholm: Swedish Energy Agency (SEA): 2008. See also:
<http://webbshop.cm.se/System/TemplateView.aspx?p=Energimyndigheten&view=all&cat=/Broschyrer&id=76dc15c9a8344575bbb75704487723ef>.
- [2] EC. Directive 2002/91/EC of the European Parliament and of the Council of 16 December 2002 on the energy performance of buildings. 2002. See also:
<http://eurlex.europa.eu/LexUriServ/LexUriServ.do?uri=CELEX:32002L0091:EN:NOT>.
- [3] Tommerup, H. and Svendsen, S. Energy savings in Danish residential building stock. *Energy and Buildings* 2006; 38(6): 617-626.
- [4] Gustavsson, L. District heating systems and energy conservation - Part I. *Energy* 1994; 19(1): 81-91.
- [5] Gustavsson, L. District heating systems and energy conservation - Part II. *Energy* 1994; 19(1): 93-102.
- [6] Nässén, J. and Holmberg, J. Energy efficiency - a forgotten goal in the Swedish building sector? *Energy Policy* 2005; 33(8): 1037-1051.
- [7] Gustavsson, L. and Joelsson, A. Energy conservation and conversion of electrical heating systems in detached houses. *Energy and Buildings* 2007; 39(6): 717-726.
- [8] Joelsson, A. and Gustavsson, L. Perspectives on implementing energy efficiency in existing Swedish detached houses. *Energy Policy* 2008; 36(1): 84-96.
- [9] Joelsson, A. and Gustavsson, L. District heating and energy efficiency in detached houses of differing size and construction. *Applied Energy* 2009; 86(2): 126-134.
- [10] Balaras, C.A., Drousa, K., Dascalaki, E., and Kontoyiannidis, S. Heating energy consumption and resulting environmental impact of European apartment buildings. *Energy and Buildings* 2005; 37(5): 429-442.
- [11] Balaras, C.A., Drousa, K., Argiriou, A.A., and Asimakopoulos, D.N. Potential for energy conservation in apartment buildings. *Energy and Buildings* 2000; 31(2): 143-154.
- [12] Liu, X., Hewings, G.J.D., and Wang, S. Evaluation on the impacts of the implementation of civil building energy efficiency standards on Chinese economic system and environment. *Energy and Buildings* 2009; 41(10): 1084-1090.
- [13] Gustafsson, S.-I. and Bojic, M. Optimal heating-system retrofits in residential buildings. *Energy* 1997; 22(9): 867-874.
- [14] Rolfsman, B. Optimal supply and demand investments in municipal energy systems. *Energy Conversion and Management* 2004; 45(4): 595-611.

- [15] Gustafsson, S.-I. and Rönnqvist, M. Optimal heating of large block of flats. *Energy and Buildings* 2008; 40(9): 1699-1708.
- [16] Popescu, D., Ungureanu, F., and Hernández-Guerrero, A. Simulation models for the analysis of space heat consumption of buildings. *Energy* 2009; 34(10): 1447-1453.
- [17] Shimoda, Y., Asahi, T., Taniguchi, A., and Mizuno, M. Evaluation of city-scale impact of residential energy conservation measures using the detailed end-use simulation model. *Energy* 2007; 32(9): 1617-1633.
- [18] Dotzauer, E. Simple model for prediction of loads in district-heating systems. *Applied Energy*; 73(3-4): 277-284.
- [19] Marik, K., Schindler, Z., and Stluka, P. Decision support tools for advanced energy management. *Energy* 2008; 33(6): 858-873.
- [20] SEA. Energy statistics for multi-dwelling buildings in 2007, report no. ES 2009:02. Stockholm: Swedish Energy Agency (SEA): 2009. See also: <http://www.energimyndigheten.se/Global/Energifakta/Energistatistik%20%C3%B6r%20flerbostadshus%202007.pdf>.
- [21] Wernstedt, F. and Johansson, C. Intelligent distributed load control. In: *Proceedings of The 11th International Symposium on District Heating and Cooling*, Aug 31 - Sep 2, 2008, Reykjavik, Iceland.
- [22] Wernstedt, F., Johansson, C., and Wollerstrand, J. Sänkning av returtemperaturer genom laststyrning (Decreased return-temperatures through heat load control), report no. 2008:2. Stockholm: Swedish District Heating Association, 2008. See also: http://www.svenskfjarrvarme.se/download_biblo/1404/S%C3%A4nkning%20av%20returtemp.klar.pdf.
- [23] Gustafsson, S.-I. Optimisation of insulation measures on existing buildings. *Energy and Buildings* 2000; 33(1): 49-55.
- [24] Werner, S.E. The heat load in district heating systems, Dissertation No. 496. Chalmers University of Technology (Sweden): Department of Energy Conversion, 1984.
- [25] SMHI. The Swedish Meteorological and Hydrological Institute. Normal outdoor temperatures for the Linköping region 1961-1990. See also: http://data.smhi.se/met/climate/time_series/month_year/normal_1961_1990/SMHI_month_year_normal_61_90_temperature_celsius.txt.
- [26] Bennich, P. (Personal communication), Swedish Energy Agency, Stockholm, 2009.
- [27] Bladh, M. and Krantz, H. Towards a bright future? Household use of electric light: A microlevel study. *Energy Policy* 2008; 36(9): 3521-3530.
- [28] Henning, D. Cost minimization for local utility through CHP, heat storage and load management. *International Journal of Energy Research* 1998; 22(8): 691-713.
- [29] Henning, D. Optimisation of Local and National Energy Systems: Development and Use of the MODEST Model, Dissertation No. 559. Linköping University (Sweden): Department of Mechanical Engineering, 1999.
- [30] Gebremedhin, A. Regional and industrial co-operation in district heating systems, Dissertation No. 849. Linköping University (Sweden): Department of Mechanical Engineering, 2003.

- [31] Sundberg, G. and Sjödin, J. Project financing consequences on cogeneration: industrial plant and municipal utility co-operation in Sweden. *Energy Policy* 2003; 31(6): 491-503.
- [32] Difs, K. and Trygg, L. Pricing district heating by marginal cost. *Energy Policy* 2009; 37: 606-616.
- [33] Andersson, M. Shadow prices for heat generation in time-dependent and dynamic energy systems. *Energy* 1994; 19(12): 1205-1211.
- [34] EC. Directive 2005/32/EC of the European Parliament and of the Council with regard to ecodesign requirements for non-directional household lamps, No 244/2009 of 18 March 2009. 2009. See.
- [35] Rolfsman, B. Interaction between energy systems of buildings and utilities in an ever-changing environment, Dissertation No. 827. Linköping University (Sweden): Department of Mechanical Engineering, 2003.
- [36] Juneus, H. (Personal communication), Linköpings Träförädling AB, Linköping, Sweden, 2009.
- [37] Sjödin, J. Swedish district heating systems and a harmonised European energy market—means to reduce global carbon emissions. Dissertation No. 795, Linköping University (Sweden): Department of Mechanical Engineering. 2003.
- [38] Uppenberg, S., Almemark, M., Brandel, M., Lindfors, L. et al. Environmental handbook for fuels (Miljöfaktaboken för bränslen). IVL report B1334A-2, B1334B-2, Stockholm (Sweden): Swedish Environmental Research Institute. 2001. See also:
<http://www.ivl.se/nyheter/startsidenyheter/uppdateradmiljofaktabokforbranslen.5.360a0d56117c51a2d30800064005.html>.

Fig. 1. Annual DH demand including the DH plant operations and the effect the heat load control measure has on the DH demand (developed by the TVAB).

Fig. 2. Annual DH demand including the DH plant operations and the effect the attic insulation measure has on the DH demand (developed by the TVAB).

Fig. 3. Annual DH demand including the DH plant operations and the effect the electricity savings measure has on the DH demand (developed by the TVAB).

Fig. 4. Schematic overview of the methodology.

Fig. 5. Annual capital cost (Euro/MWh saved DH) for the heat load control for different building sizes.

Fig. 6. Altered fuels consumption in the local DH plants for the different ECMs.

Fig. 7. Dispersion in annual capital costs for the different ECMs where the grey bars illustrate the values used in the calculations and the error bars illustrate the range of the annual capital cost.

Tables

Table 1

Technical data for the DH production plants in Linköping energy system. FGHR = flue gas heat recovery, ST = steam turbine, GT = gas turbine. HOB = heat only boilers. All efficiencies are annual averages for LHV of fuel.

Technical utility	Size (input)	FGHR/Economiser	Efficiency (at max load)		
			Electricity	DH heat	Total
Waste CHP	70 MW	14 MW	0.22/0 ^a	0.85/1.1 ^a	1.1
Waste hybrid CHP	77 MW waste, 76 MW oil	10 MW	0.31/0 ^b	0.59/1.0 ^b	0.9/1.0 ^b
Coal CHP	63 MW	4 MW	0.19/0.27/0 ^c	0.73/0/0.92 ^c	0.92
Oil CHP	150 MW		0.20/0.28/0 ^c	0.71/0/0.91 ^c	0.91
Biomass CHP	60 MW	15 MW	0.18/0.26/0 ^c	0.91/0/1.1 ^c	1.1
Diesel engines	31 MW		0.39	0.41	0.8
Biomass HOBs	42 MW			0.85	0.85
Oil HOBs	280 MW			0.85	0.85
Electric boilers	25 MW			0.98	0.98
Recoolers	45 MW				

^a Efficiencies for production of CHP/heat only, respectively

^b Efficiencies when GT is used/not used, respectively

^c Efficiencies for production of CHP/condensing power/heat only, respectively

Table 2

Roof area, U-values and UA-values for different building categories in Linköping. Mh indicates multi-dwelling buildings [14, 35].

Category ^a	Roof area (thousands m ²)	Extra insulation (m)	U-value (W/m ² K)		UA-value (MW/K)		DH reduction (MWh/year)
			Existing	New	Existing	New	
mh-40	130	0.40	0.42	0.092	0.056	0.012	3 900
mh 41-60	160	0.40	0.49	0.095	0.077	0.015	5 600
mh 61-80	330	0.30	0.25	0.11	0.083	0.035	4 300
mh 81-99	200	0.30	0.17	0.088	0.034	0.018	1 500

^aRepresents the construction date of the building, where the category mh-40 is used for buildings built before 1941.

Table 3

Forecasted fuel prices (excluding taxes and fees), developed by the TVAB organisation, for the DH plants for the year 2013.

Fuel prices (EUR/MWh)	
Oil	45
Waste	-13
Coal	13
Biomass	10-40 ^a

^aDepending on the biomass (recycled wood, pellet or wood powder)

Table 4

Forecasted electricity prices (excluding taxes, grid fees and VAT), developed by the TVAB organization, for sold electricity production for the year 2013.

Month	Day and time	Electricity price (EUR/MWh)
Nov-Mar	Mon-Fri 06-22	58
	Nights & weekends	50
	*Mon-Fri 06-07	58
	*Mon-Fri 07-08	180
	*Mon-Fri 08-06	95
April	Mon-Fri 06-22	58
	Nights & weekends	58
May	Mon-Fri 06-22	52
	Nights & weekends	42
June	Mon-Fri 06-22	44
	Nights & weekends	35
July-Oct	Mon-Fri 06-22	55
	Nights & weekends	47

*Peak day

Table 5

Annual capital costs (Euro/MWh saved DH) for attic insulation for different building categories.

Category	Extra insulation (m)	Roof area (thousands m²)	DH reduction (MWh/year)	Insulation cost (Euro/m²)^a	Annual capital cost (Euro/MWh DH)
mh-40	0.40	130	3 900	27	61
mh 41-60	0.40	160	5 600	27	51
mh 61-80	0.30	330	4 300	22	111
mh 81-99	0.30	200	1 500	22	196

^a[36]

Table 6

Annual capital costs (Euro per MWh saved electricity) for a household when changing to new household appliances.

Investment cost for household appliances (Euro)	Extra cost when investing 5 years ahead of schedule (Euro)	Annual capital cost when investing 5 years ahead of schedule (Euro/MWh electricity)
0	0	0
500	130	38
1000	250	77

Table 7

Fossil CO₂ emission factors for fuels and electricity [37, 38].

Fossil CO ₂ emission factors (tonne CO ₂ /GWh)	
Oil	300
Coal	340
Waste	90 ^a
Electricity (coal condensing power, electricity efficiency of 33%)	1000
Electricity (gas combined cycle condensing power, electricity efficiency of 58%)	370

^aCO₂ emissions from fossil fraction of waste

Table 8

Economic performance for the DH system when comparing the ECM cases to the reference case.

Energy conservation measures	DH production cost (Euro/MWh DH)	Income from sold DH^a (Euro/MWh DH)	Total cost (Euro/MWh DH)
Heat load control	-32	-28	-4
Attic insulation	-43	-67	+24
Electricity savings	+37	+60	-23

^a Average annual marginal DH costs (including power fee, see 4.2.1) according to the heat load profiles.

Table 9

Economic performance for the residences when implementing ECMs.

Energy conservation measures	Annual capital cost (Euro/MWh DH)	Changes in energy cost (Euro/MWh DH)	Total cost (Euro/MWh DH)
Heat load control	+6 ^a	-28	-22
Attic insulation	+55 ^b	-67	-12
Electricity savings	+48 ^c	-95 ^d	-47

^aOne DH central supplying a building of 6800 m² (average building size for the buildings included in the test study of the software program in Linköping).

^bWeighted value based on area for the building categories md-40 and md 41-60.

^cWhen investing in new appliances five years ahead of schedule and when taking into account that reduced electricity use of 1 MWh corresponds to an increased DH demand of 0.8 MWh (see section 4.2.2.3).

^dDifference between increased DH cost and reduced electricity price (see section 4.2.2.3).

Table 10

Economic performance for the local energy system when implementing the ECMs.

Energy conservation measures	DH system (Euro/MWh DH)	Residences (Euro/MWh DH)	Local energy system (Euro/MWh DH)
Heat load control	-4	-22	-26
Attic insulation	+24	-12	+12
Electricity savings	-23	-47	-70

Table 11

Total effect on the global CO₂ emissions for the local energy system when implementing ECMs and when two different technologies for marginal electricity production are used (see section 4.3).

Energy conservation measures	DH production (GWh)	Local CO₂ emissions (tonne)	Electricity production TVAB (GWh)	Electricity use (residence) (GWh)	Global CO₂ emissions (tonne)^a	Total effect on global CO₂ emissions (tonne)
<i>Coal condensing power as marginal electricity production technology</i>						
Heat load control	-10	-1800	-2.0	-	2000	200
Attic insulation	-10	-2600	-2.4	-	2400	-200
Electricity savings	10	2200	2.2	-12.5	-14,700	-12,500
<i>Gas combined cycle condensing power as marginal electricity production technology</i>						
Heat load control	-10	-1800	-2.0	-	740	-1,100
Attic insulation	-10	-2600	-2.4	-	890	-1,700
Electricity savings	10	2200	2.2	-12.5	-5400	-3,200

^a1 GWh electricity = 1000 tonne CO₂ (see Table 7)

^b1 GWh electricity = 370 tonne CO₂ (see Table 7)