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Highlights:

- Real-life heat load data with demand side management actions analysed
- Demand side management benefits customers with lower heat consumption and costs
- Demand side management implementations increased short-term variation of heat load
- Co-operation between producer and customers is necessary for smart control strategy

Journal Pre-proof

From partial optimization to overall system management – Real-life smart heat load control in district heating systems

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Keywords: demand side management; demand response; customer involvement; real-life consumption data; energy transition

Abstract: District heating (DH) customers are becoming increasingly interested in finding ways to decrease their heat consumption and costs. A general assumption is that demand side management (DSM) actions in heating stabilize consumption profiles, reducing consumption and peak demand. While several simulation studies have shown these assumptions to be true, much less is known about how real-life DSM actions affect the heat consumption profiles of buildings. This study analysed real-life consumption data from 109 DH customers over a period of four years. Thirty-one of those customers implemented DSM actions including permanent energy conservation and demand response actions with temporal effects with autonomous control (called Smart control, SC). The remaining 78 customers did not implement DSM and are used as a reference group. This study compared changes in the SC customers' heat consumption profiles against the reference group and analysed how SC measurements reflect to DH system. The results show that these DSM actions decreased the heat consumption and costs for the customers but simultaneously increased short-term variations of heat load. This study highlights the need for greater co-operation between DH companies and their customers to develop more effective DSM control strategies that can provide better solutions for the whole system.

Abbreviations

DH – District heating

DR – Demand response

DSM – Demand side management

EU – European Union

SC – Smart control

$C_{E,i}$ – the monthly varying energy cost factor

C_p – the factor for heat peak cost

C_{yearly} – annual DH price for customer

G_{ST} – annual relative short-term variation

P_a – the annual average heat load (kW)

P_d – the daily average heat load (kW)

P_h – the hourly heat load (kW)

P_{ST} – the average heat load (kW)

P_{3h} – the heat load maximum for running three hours average during past 36 months

Q_{DHW} – annual heat consumption for the domestic hot water

Q_{Heat} – realized annual heat consumption without heat needed for the domestic hot water

$Q_{A,Tot}$ – annual total heat consumption

Q_{Tot} – the realized heat consumption in monthly level

S_N – heat degree day for comparison locality

S_R – realized heat degree day for the city analysed

W – the annual relative seasonal variation

x – the factor for peak cost in district heating pricing

1 Introduction

Intensifying competition in the energy markets and high targets for reduced emissions, such as those set by European Union (EU), have prompted district heating (DH) companies to increase energy efficiency and to decrease their emissions of production. At the same time, DH customers are increasingly interested in exploring ways to decrease their own energy demand and to reduce their monthly energy costs as a result.

This underlines the need for more smart energy systems which, by definition, highlights the integration of multiple different energy sectors with intelligent control and energy storage, as well as for customers to take a more active and central role [1,2].

One way for DH customers to reduce their heat energy demand is to implement demand side management (DSM) actions, which refers to various measures that affect their traditional heat consumption profile. In general, DSM is an umbrella term for different short term and long term actions with temporal or permanent effects. Long-term DSM measures concentrate on the strategic energy conservation measures (also retrofitting measures within buildings, but these are excluded from this study) or the strategic growth of heat consumption. Short term DSM actions may include shifting heat load from peak clipping to valley filling and these are often called as demand response (DR) actions. The permanence of the DSM actions varies and usually long term DSM actions have permanent effects while short term DR actions have temporal effects. DSM can also be implemented in different ways depending on the target, and who controls the actions. In direct DR actions the energy company controls the DR and the decision comes from the system level. In indirect DR actions, the customer has a full control of the energy loads. Indirect DR can be further subcategorized based on the DR control as well as the level of communication between the customer and the operator for autonomous control, price-based control and transactional control. In autonomous control the decision of DR actions is independently by building controller without communication with system operator. In price-based control a monetary incentive is given to a customer and in transactional control a bid-based market is generated where buildings can offer flexibility or demand side resources to market. The definitions of DSM and DR are typically concentrating on electricity systems from which DH systems differs especially in regard to pricing mechanisms: dynamic hourly-based pricing (as it is in electricity systems in Nordpool) is not available in typical DH systems to motivate customers for DSM and DR actions. Typical real-life DH price mechanism comprises of two components, energy cost and peak cost. [3–8]

In DH systems, DSM and DR target usually refer to smoother heat load profiles and lower heat consumption levels, which can impact both customers and the DH companies. Customers benefit from these efforts

through lower energy bills. The benefits for DH companies come from optimized energy production, with lower production costs and emissions, e.g. higher utilization rate of base production plants, decreased usage hours of peak production units and lower pumping costs [9]. For a DH company, increasing deployment of DSM measures may even allow them to delay new production investments or even shut down part of the peak production units due to less heat demand [10]. These result for greater energy efficiency on the system level but are only achieved if deep collaboration between customers and DH company is fulfilled. Intelligent control, as well as overall system management and optimization, is needed to realize the benefits of short term DSM for all parties [11]. The same applies to energy conservation measurements (other than retrofitting measures within buildings), which do not necessarily have a positive impact on the energy system level. One example of this is the use of night setback controls [12] by DH customers to lower their energy demand. When the whole energy system is considered, however, implementing the night setbacks has been found to increase the variation in heat demand in the short-term [13,14] and thus decreasing the total effectiveness of the system [15].

DSM-related studies have concentrated mostly on electricity systems or electric heating systems but especially in recent years, DSM in DH systems has gained increasing interest in academia and in practice. Several researchers have studied the effect of DSM in a DH system using different methods, including pilot tests, building-level simulations with development of different control strategies, as well as the effects of DSM on DH production. In most cases, pilot tests are performed on a small number of buildings, and, in some studies, the results are aggregated to the DH system level to analyse the energy savings and heat cut potential after DSM measures were implemented. Kärkkäinen et al. [16] tested DSM in two buildings (an office building and an apartment building for senior citizens) in Finland by decreasing the indoor temperature for two to three hour periods. The results suggested that if 160 similar buildings applied DSM, a 20% heat cut would be achieved, along with a potential 10%-20% energy savings at the DH system level. Another DSM pilot test done in Finland by Wahlroos et al. [17] measured indoor temperature and user satisfaction in office/education building during DSM implementations, where the heat cuts lasted 1-70 hours. The study showed a 4.6% energy savings during the test. Kensby et al. [18,19] studied the heat

storing capacity of five apartment buildings in Sweden by optimizing their inside temperatures. The study concluded that, if 500 of the largest customers employed DSM measures, the result would be a 50% reduction in daily load variation on the DH system level. The largest DSM pilot tests were done in Sweden and included 58 substations (residential buildings) [20]. The results of those tests showed that a 15%-20% peak load cut was achieved with 7.5% energy savings.

The use of DSM in DH systems has also been studied by simulating the behaviour of buildings during the DSM implementations or by studying the effect of DSM on the DH system level. Building level simulations have concentrated on residential buildings [21–23] or office buildings [24]. These studies provided theoretical insights to the limits of DSM from a technical viewpoint, and the results depended on the starting parameters. Many studies have concentrated on DSM control strategies of heating but most of these are studied in buildings with electric heating [7,25,26]. The effect of DSM on the energy system level by simulations have been studied by Difs et al. [27] where DSM implementations included 7% energy saving according to [28], and the greatest effect on the energy system was achieved in medium heat loads. Guelpa et al. [29,30] analysed the opportunities of peak load shaving during the morning peaks in heat load by simulating DH system in Italy and resulted with approximately 5% peak load reductions. Romanchenko et al. [31] studied the thermal inertia of buildings at the DH system level and found a 1% decrease in operating costs. Building-level simulations and energy system-level optimizations were combined in a study by Dominković et al. [21] and the results indicated that implementing DSM measures produced a 0.7%-4.6% savings in operational costs for the district heating system. Hedegaard et al. [32] presented the bottom-up modelling method of the DH consumption of residential buildings to analyse the aggregated demand response (DR) potential with model predictive control (higher DH prices during peak hours) with target to lower daily morning peak loads in heating. The results demonstrated two heat peak loads which were cut 5.2% and 4.3% with DR actions [32]. Kontu et al. [11] studied the effects of city-scale DSM on three different-sized DH systems by simulating different DSM control methods implemented to different types of customers (residential, industry, office, retail, education) to DH system level optimizations. The results showed that the value of DSM for DH companies remains less than a 2% cost savings for DH companies,

highlighting the need to develop an individual DSM strategy for each customer type and specific DH system. Similar results were found by Salo et al. [33], who studied optimal DR control strategies from the DH operator perspective by simulating the effects of DR strategies for DH system level. The DR strategies were implemented for all the other buildings except the residential and health care buildings. The results show only small decrease for heat production cost (0.7% in best case). Cai et al. [34] included the DH network (pumping costs) in their DSM analysis and found that this produced up to an 11% reduction in energy costs.

DSM actions in DH systems are generally assumed to stabilize heat consumption profiles, reducing peak demand and thus production of emissions. Several simulation studies have shown these assumptions to be true. However, these studies present optimal cases of DSM implementations in collaboration between DH company and customers resulting greater energy efficiency on energy system level. In real-life, at least in Finland where the customers own their DH appliances, the customers implement DSM actions (which are put into practice by separate DSM service provider) and DH company is not involved or even informed the details of DSM actions of customers. This study presents a real-life case of DH customers using smart heat load control to optimize their energy costs with specific group of DSM actions. These actions include both, long-term permanent energy conservation actions (i.e. checking the heating level to avoid over-heating) resulting lower energy consumption level, as well as DR actions with temporal effects. In this case study, customers are implementing these specific DSM actions with autonomous control and only typical DH pricing is used as a control strategy for DSM actions. This means that no special pricing methods are used (such as hourly changing dynamic heat price) and customer can achieve lower heat costs with two ways: lowering heat energy consumption and avoiding peak loads. The term “Smart control” (SC) is used to describe these specific DSM actions from now on. The study analyses how these real-life SC actions affects the overall DH system. This study aims to analyse changes in SC customers’ heat consumption profiles and heat consumption levels after implementing SC actions by examining real-life consumption data from 109 DH customers (hourly data from 2014–2017) which all are residential block buildings. From these 109 DH customers 31 implemented SC solutions in their building-level heating systems starting at year 2016 with the aim of saving energy and cutting heating costs. The remaining 78 customers did not implement any SC

solutions in their heating systems and they are used in this study as a comparison group to the SC customers. This study provides new and unique insights into the performance of real-world DSM implementations by comparing the results of two sets of DH customers, those who implemented customer centric SC and those who did not.

The remaining part of the paper proceeds as follows: Section 2 describes the data used in this study, as well as the parameters that were analysed. Section 3 presents the results of the study in four parts with following order: heat consumption, heat peak load, costs of district heating for customers, and annual relative variations. Section 4 contains a discussion of the results and section 5 presents the conclusions.

2 Methods

This study examines whether the generally known benefits of DSM are realized in buildings implementing SC actions and how these actions affect the DH system. The study analyses real-life hourly heat load data from buildings where customers are implementing SC actions. The heat load profiles of these buildings are compared to those without any DSM actions. The benefits of DSM are then analysed using four different parameters which describes the heat consumption level, the peak heat load and heat load variations, both in the short-term and long-term. This section presents the data used in the study with references, as well as the parameters that are analysed.

2.1 Data

This study analysed heat load data for 109 separate residential block buildings (DH customers, which each of them have multiple residents) constructed between 1960's and 2010's. The customers are located in the Finnish cities of Espoo and Vantaa, which both have their own separate DH systems. Espoo has the second largest and Vantaa the fourth largest population in Finland. Together with Helsinki, they form the capital region in Finland. A majority of the inhabitants of both cities is connected to the local DH network, with 84% and 89% for Espoo and Vantaa, respectively [35]. Fortum, which operates Espoo's DH system, sold a

total of 2035 GWh of heat energy in 2017 (58% to residential customers) [35]. In Vantaa, the DH system operated by Vantaa Energy sold 1681 GWh (52% to residential customers) during the same period [35].

The data used in this study includes [36–40]: hourly peak heat load (kW), hourly outdoor temperature (°C), location, construction year, construction material and purpose of use. Each customer (one block building is one customer) has a heat meter which consists of a flow sensor, temperature sensors, and a heat consumption meter. The flow sensor measures the volume of circulating water flow. The temperature sensors are installed in two locations to measure the temperature of supply and return water. The heat consumption meter calculates the consumed heat energy using the water flow, temperature difference and the specific heat capacity for water. The hourly peak heat load is measured once on the hour. The heat load data sets were automatically collected via meter readings and they were provided by the energy companies. The DH companies also provided values of hourly energy consumption and compared to hourly peak heat load (measured on the hour) these values were close to each other. In some cases, the use of domestic hot water changes the return water temperature inside an hour which made the difference and gives the peak load for an hour. Data sets included hourly peak heat load (kW) data for the time periods of 1.1.2014 – 31.12.2017. Each data set is data from one block building and it accounts both, space heating and heating for domestic hot water. In cases where there were gaps in the data, the data sets were corrected using one of two methods. Missing data for gaps of three or fewer hours was replaced by interpolating between measurements from the previous and following hours. If more than three hours of data was missing, the gap was filled by adding the heat load data for the corresponding hours of the following day. Fortunately, these data gaps were very rare. The hourly outdoor temperature was obtained from the Finnish Meteorological Institute [36]. Building information was received from each city's surveying department [39,40].

Of the 109 buildings included in this study, 31 started implementing SC actions in 2016 (called *SC buildings*). These SC implementations were controlled from the customer's side, by a company delivering DSM service to DH customers, and DH company did not have any information of the DSM strategy and it included energy efficiency measures and/or demand response actions. It is possible that there may have been more

than one DSM service provider and examining the providers is not in the scope of this study. The remaining 78 residential buildings, which did not employ SC (called as *reference buildings*), were used as comparative data sets. The reference buildings were selected so that they were located close to the SC buildings (based on the postal code) and that they had similar building characteristics, such as construction material and construction decade.

2.2 Parameters

The impact of SC implementations on both customers and the energy companies was analysed by calculating the following four parameters:

- 1) Normative annual heat consumption
- 2) Annual peak heat load (in hourly and three-hour running averages)
- 3) Annual relative short-term variations of heat load (in both 4-hour and 24-hour time frames)
- 4) Annual relative seasonal variation of heat load

Normative heat consumption describes the heat consumption of DH customers within different years, after eliminating the effect of outdoor temperatures. This parameter was analysed to determine if DH customers had saved energy after implementing SC measures. Examining normative annual heat consumption enabled comparison between heat consumption during different years. The normative annual heat consumption was defined as [41]:

$$Q_{Norm} = \frac{S_N}{S_R} \cdot Q_{Heat} + Q_{DHW}$$

where S_N is heat degree day for comparison locality calculated for inside temperature of 17°C, S_R is realized heat degree day for the city analysed, and Q_{Heat} is realized annual heat consumption, not including the heat needed for the domestic hot water, i.e. Q_{DHW} is subtracted ($Q_{A,Tot} = Q_{Heat} + Q_{DHW}$). Heat energy consumed for DHW was not separately measured but an approximation is done and Q_{DHW} is calculated as an average heat consumption of summer months (June, July, August) for each customer. Heat degree day (S_N and S_R) was calculated as the sum of the daily difference between inside temperature

(using 17°C for heat degree day calculation) [42] and the daily average outdoor temperature. The values are listed in ref. [43]. Different heat degree days were considered for the two different cities analysed in this study.

Annual peak heat load was analysed as hourly values, as well as by a 3-hour running average. The maximum annual heat load on an hourly level was calculated to examine whether SC impacted the heat production of the whole DH system with potential to diminish the heat production capacity. The 3-hour running average was chosen because of the DH pricing mechanisms.

The pricing of DH in Finland typically depends on two components: the realized heat energy consumed multiplied by a monthly varying cost factor, and peak heat load during a given time period (determining time period varies in different DH companies and can be annual, three years maximum or some other time period). Annual heat consumption and annual peak heat load were used to calculate the annual energy costs to customers. The formula for calculating DH energy cost for individual buildings is presented in the Appendix A. It is used to analyse whether and why energy costs have decreased due to SC implementation. A similar pricing formula was used by Fortum in 2018 [44] with the distinction that the peak cost component in this study was calculated according to each year's maximum value of the 3-hour running average for heat load, while in Fortum, a 3-hour running average was examined over a 3 year period.

The last two parameters, *annual relative variations in short term* (in four and 24 hours) and *annual relative seasonal variation*, as defined by Gadd and Werner [12,15,45], illustrate how DSM affected the DH system. The annual relative short-term variation describes how much the hourly heat load varies during a given time period (in four and 24 hours) as compared to an average value in the same time period. Annual relative short-term variation occurs mainly due to social factors, such as the use of domestic hot water, which typically causes heat load peaks to occur in mornings and evenings. For a DH producer (energy company) variations even in shorter time frame, 4 hours, are meaningful because large short-term variations cause challenges in production, as companies aim to stabilize heat production in short-term. The annual relative seasonal variation describes the large variation in heat demand across different seasons.

The main factors affecting this are the changes in outdoor temperature between winter and summer, while the indoor temperature is kept constant.

In this study, we calculated the annual relative short-term variation for both 4 and 24-hour time periods. These short-term variations were calculated for all customers for four years (2014 – 2017) to examine whether DSM implementations had affected the level of variation. The annual relative short-term variation was defined as [12]:

$$G_{ST} = \frac{\frac{1}{2} \sum_{i=1, j=1}^{8760, 365} |P_{h,i} - P_{ST,j}|}{P_a \cdot 8760} \cdot 100[\%]$$

where P_h is the hourly heat load (kW), P_{ST} is the average heat load (kW) with two different time frames and P_a is the annual average heat load (kW). The two different time frames for P_{ST} averages are 24 hours and 4 hours (from 00-04am, 04-08am, and so forth). The annual relative seasonal variation is the accumulated positive difference between daily average heat load and annual average heat load:

$$W = \frac{24 \cdot \frac{1}{2} \sum_{j=1}^{365} |P_{d,j} - P_a|}{P_a \cdot 8760} \cdot 100[\%]$$

where P_d is the daily average heat load (kW) and P_a is the annual average heat load (kW).

3 Results

The results are divided in four sections according to the analysed parameters that were previously noted: heat consumption, heat peak load, costs of district heating for customers and annual relative variations of heat load.

3.1 Heat consumption

Figure 1 shows the annual normative heat consumption for each building compared to the heat consumption levels in 2014, which is presented by the red line at the centre of each chart. The average normative heat consumption per building volume in 2014 was 28.6 kWh/m³ for the SC buildings and 29.0 kWh/m³ for the reference buildings. These are typical levels in Finland [35]. What stands out in the figure is

that the annual consumption level decreased in SC buildings after DSM measures were implemented in 2016, as compared to reference buildings which did not implement any DSM measures. The average heat consumption for the SC buildings (compared to year 2014) were 92.9% in 2016, and 86.2% in 2017. The same numbers for the reference buildings were 101.7% and 97.4%, respectively.

Figure 1. Annual normative heat consumption for reference buildings (above) and for SC buildings (below) for 2015, 2016 and 2017, compared to the consumption levels in 2014 for reference and SC buildings respectively (represented by red line). Each dot represents the annual normative heat consumption for each building.

3.2 Heat peak load

Figure 2 presents the actual maximum hourly heat load per building volume for the years 2014 to 2017. The effect of outdoor temperature on heat peak load can be clearly seen. For example, in 2016, when the minimum outdoor temperature was -26.1°C [36], the heat loads were higher in both the SC and reference buildings. Comparing the difference in maximum heat loads between different years does not, in itself, provide answers. Since the time period of received data was four years and only one whole year after the SC actions started, it is difficult to conclude how SC actions affect the annual maximum heat load. Still, it can be seen from the figure that before SC measures were implemented, the annual maximum heat loads were at the same level for all buildings in the study. It is important to notice the higher heat loads in SC adjustment period in 2016 since they affect the price level of DH for customers: load demand component

comprising approximately one fourth of DH price for residential customers is in some DH companies defined according to actual maximum peak load and the time frame can be as long as three years.

The annual peak heat loads for single buildings were higher compared to the total sum of all customers. This has important implications for understanding when DSM results for a single building are used to extrapolate results at the DH system level. When comparing the sum of the results for all buildings in year 2017, the difference in maximum heat load per building volume was 0.78 W/m³, indicating that approximately 350 kW less maximum heat capacity was needed, due to the DSM implementation realized in 31 buildings included in this study.

Figure 2. Maximum heat load per building volume (W/m³) for the sum of SC and reference buildings, average values of maximum heat load, and yearly minimum outdoor temperatures [36]

3.3 Costs of district heating for customers

As described earlier, DH pricing is constructed from the energy cost component and the peak cost component. In the DH pricing used in this study, the peak cost component was calculated using a 3-hour running average for an annual level (instead of using the average for three years, which is how Fortum prices its heating, as we only had data for a four-year period). The 3-hour running average is naturally slightly smaller compared to one-hour peak heat loads. Surprisingly, the values for the 3-hour running average were approximately 15% smaller than the one-hour values for reference buildings, and for SC buildings they were only 10% smaller. This reflects a higher variation of heat load for SC buildings with DSM

actions. For DH pricing, the smaller heat cuts resulted in lower peak heat costs. Still the largest part of the DH bill for the customers comes from the energy cost component.

Figure 3 presents the change in total costs for DH for the SC and reference buildings, over the 4-year period from 2014 to 2017, as well as how those costs were affected by changes to the different cost components (energy and peak cost components). Approximately 75% of the DH cost comes from the energy component and the remaining 25% from the peak component. This means that customers should concentrate more on the energy component when minimizing costs. Due to higher peak heat load in SC buildings in 2016, the share of peak cost varied during different years. The results show that the energy bill for SC buildings in 2017 was, on average, 5% smaller compared to 2014 levels, while for reference buildings, the energy bill increased 1% respectively. The figure shows that decreases in the energy bill were mostly due to lower heat consumption levels.

Figure 3. Total costs, divided by energy and peak cost components, for SC buildings and reference buildings based on pricing presented in the Appendix A.

3.4 Annual relative variations

The results shown in Figure 4 present the annual relative seasonal and short-term variations of heat load in 4-hours for the SC (blue dots) and reference (orange dots) buildings. The annual relative seasonal variations of heat load, as indicated on the horizontal axis, varied from 12% to 24% (with an average of 20%) for the reference buildings. These findings align with those found by Gadd and Werner [12] and it is characterized that residential buildings have a consistent heat load all year. Compared to other buildings used for other

purposes (e.g. industrial, commercial, public, and health and social buildings), the relative seasonal variations for residential buildings are in a low level, which means that the heat load has low variations between different seasons compared to other building types [12].

Figure 4. The annual relative 4-hour variation of heat load and annual relative seasonal variation of heat load.

In Figure 4, the annual relative 4-hour variation ranges from 1% to 12% (4.5% on average) for the reference buildings. The high variation in values comes from a few outliers as most of the values are closely grouped in the diagram. In 2014 and 2015 the figures show no specific variations between SC and reference buildings. However, in 2016 and 2017, the SC buildings have higher values, which can be seen by the blue points in Figure 4. The annual relative daily variation varies from 2% to 19% (7.2% on average) for the reference buildings.

A similar phenomenon is seen in the results for annual relative daily (24 hour) variation. In 2014 and 2015, *before* the SC measures were implemented, there are no specific variations between SC and reference buildings. However, in 2016 and 2017, the SC buildings have slightly higher values. The values of relative daily variations are similar to the study by Gadd and Werner [12] and the heat load profile of residential

buildings are characterized as rather consistent, having heat load all year and all day with social components determining variations in the short-term. Compared to other building types, residential buildings have rather low variations in the short-term and different energy saving measurements, such as nightly set-back patterns, were not used in the buildings in this study which increases heat load variations.

Table 1 summarizes the values of annual relative 4-hour, 24-hour and seasonal variations. These figures are presented as the sum and average for each building category – SC and reference. What stands out from the table is that the SC implementations increased short-term variations for both the 4 and 24-hour levels. The average values were in similar level for SC and reference buildings in 2014 and 2015 but, in years 2016 and 2017, these figures were higher for the SC buildings. Further analysis showed that, when the buildings were analysed as a sum (SC buildings and reference buildings separately), the short-term variations were smaller, which confirms previous results indicating that the heat load variation of the sum of buildings is smaller than in the individual buildings. Still, the sum of the SC buildings varied more when compared to the sum of reference buildings.

Table 1. Average values and sums of SC buildings and reference buildings of annual relative short-term variations and annual relative seasonal variation.

SUM	Annual relative 4 hours variation		Annual relative 24 hours variation		Annual relative seasonal variation	
	G(4hours)		G(daily)		W	
	SC	Reference	SC	Reference	SC	Reference
2014	1.88	1.84	4.66	4.52	21.03	20.54
2015	1.97	1.88	4.90	4.60	18.77	18.10
2016	2.19	1.69	4.84	4.12	22.20	21.43
2017	2.04	1.70	4.25	4.08	19.25	18.60
AVERAGE						
2014	4.18	4.53	6.87	7.09	21.01	20.49
2015	4.62	4.79	7.82	7.50	19.10	18.17
2016	5.22	4.43	7.94	6.89	22.32	21.92
2017	5.14	4.53	7.39	7.06	19.35	18.15

4 Discussion

The results show that the DSM targets for the customers were achieved. The normative heat consumption decreased after SC implementations started in 2016, i.e. the SC buildings had an average of 13.8% less heat consumption compared to their level in 2014, whereas the reference buildings only decreased their consumption by 2.6%. The results of this analysis of real-life data match those observed in earlier pilot studies, which found a potential energy savings of 5%–20%, depending on the study [16,17,20]. The results of this study also indicate that, after accounting for an adjustment period after SC was implemented in 2016, the annual maximum heat loads were lower for the SC buildings compared to the reference buildings. However, the findings do not support previous research that reported high, even 15%-20% peak load cuts (e.g. ref. [16,20]). In fact, the heat load cuts were rather small, as can be seen in Figure 2. The energy bills were smaller for customers implementing SC, averaging 5% smaller in 2017 compared to level of 2014, while for reference buildings the energy bill increased 1% for the same period. According to the data analysed in this study, average sized apartment buildings (building volume 20000m³ with 80 apartments [46]) would see a rather small annual savings of 6000€ (75€ per apartment) due to SC implementations as compared to reference building. The largest share of the cost savings is derived from lower heat consumption levels in SC buildings, since for residential buildings approximately 75% of the costs is based on consumed energy. The remainder is based on peak heat load. This raises an interesting question over where the energy saving arises from and is it only due to rationalization of the temperature curve of heating?

Contrary to previous studies, this study did not find significant benefits from DSM for the DH company. Short-term variations in heat load, in particular, increased for the SC buildings as compared to the reference buildings, which make heat production less efficient. This finding is contrary to previous case studies in ref. [11,12] which presented that DSM implementations had even 50% less daily load variation at the DH system level. Naturally, the DH company benefits from the smaller annual peak heat load of SC buildings but the benefit remains rather small with such a small amount of DH customers implementing DSM, at approximately 350kW of less maximum heat capacity needed in the system level. Obviously, if a

larger share of customers implemented DSM, the maximum peak heat reduction would be higher. This would benefit the DH company by reducing the requirement for peak and reserve production capacity. Still, it must be highlighted that extrapolating the results for single building to apply to sum of buildings most likely does not give an accurate answer. Due to the different timing of the daily peak heat loads for different customers, the single peak heat cuts cannot be extrapolated for the whole DH system level, because the annual peak heat loads for single buildings are higher compared to the sum of customers. Thus, it is argued that when the results of earlier studies regarding the system level peak heat cut are observed, they must be interpreted with caution. Beside this, it is relevant to ask where the cut in peak heat load results from: was it from the demand response actions (changing the timing of the heat load) or only from the energy savings?

The findings suggest that, if the number of customers implementing SC measures to reduce energy costs increases, the efficiency of the energy system could actually decrease due to higher short-term variations in heat load. This might lead to a situation where a DH company must increase the costs of heating or change their pricing methods, to cover the extra expenses of heat production. The results of this real-life study support the findings of the studies presented in Kontu et al. [11] as well as Hedegaard et al. [32] and highlight the importance of co-operation between customers and heat producers to jointly manage the DH load with DSM control strategies to find the best results.

This study was limited to analysing data from existing SC implementations by DH customers and by the concentration on identifying the benefits that were possible to analyse from that data. It should be noted that the DSM control strategies implemented by the customers in this study reflect only one way to perform DSM and different types of control strategies may give different results. Follow-up studies should concentrate on examining DSM control strategies that could benefit all parties. Another further research topic is to examine possible benefits of DSM that are less studied, such as the spatial value of DSM, including the possible elimination of hydronic bottlenecks for DH producers, the value of possible avoidance of production plant investments due to DSM and possibility of reserve capacity from DSM.

5 Conclusions

High targets for reduced emissions, wider availability of new digitalization techniques, and increased customer desire for energy savings and participation on smart energy transitions, encourage DH companies to push their operations in new directions. During the last few years, implementations of DSM in DH systems have become more common and, at least in Finland, they are mostly done by the customers. DSM service providers promote their product to the DH customers with energy saving possibilities, together with lower energy bills. In recent years, DSM in DH systems have also been increasingly researched.

Several studies have used different research methods to analyse the benefits of DSM actions in DH systems. However, much less is known about how real-life DSM actions, implemented by customers for their own benefit, change the heat consumption profiles of buildings and what subsequent implications are for the whole DH system. In this study we analysed real-life heat load data to find out whether the most often-mentioned benefits of DSM are realized. The benefits were studied from both the customers' and the DH producer's perspectives, concerning the heat consumption, and maximum heat load, as well as variation of heat load profiles in the short-term. This study analysed the real-life heat consumption data for 109 customers, from 2014-2017. Thirty-one of those customers had implemented SC measures in their heating system starting at 2016. The remaining 78 customers did not implement any DSM solutions and were used as a reference group. The results of this study provided unique insights into the real-world effect of implementing SC measures.

The results showed that the customers who had implemented SC decreased their energy bills by lowering their heat consumption levels. It is obvious that, with such promising results for customers, the implementation of SC by DH customers will likely become more common. Based on this data set and on the current DSM control strategy in use, this benefit did not extend to the DH company as it resulted in a higher short-term variation in heat load. These findings highlight that the control strategy of DSM must be developed in co-operation between different parties – customers and DH companies alike – to develop

DSM control strategy that can increase the overall efficiency of the energy system. DH companies need to make this development a priority in their strategy to better serve their customers.

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Appendix A

A1 – DH pricing used in the analysis [44]

DH yearly price for customer (C_{yearly}) consists of two factors, energy cost and peak heat cost, and it is defined as:

$$C_{yearly} = \sum_{i=1}^{12} (C_{E,i} \cdot Q_{Tot,i}) + (P_P \cdot P_{3h} - x)$$

where $C_{E,i}$ is the monthly varying energy cost factor presented in Table A2, Q_{Tot} is the realized heat consumption in monthly level, C_P is the factor for heat peak cost presented in Table A3, P_{3h} is the heat load maximum for running three hours average during past 36 months, and x is the factor presented Table A3.

Table A2. Monthly varying energy cost component based on the DH pricing in Fortum [44]

Month	1	2	3	4	5	6	7	8	9	10	11	12
Energy cost factor $P(E)$, €/MWh	57	57	51	45	35.2	22.5	22.5	22.5	35.2	45	51	57

Table A3. Peak heat cost component for different peak heat load variation for residential buildings based on the DH pricing in Fortum [44]

Peak heat load variation, kW		Heat peak cost, €/year	
min	max	P_p	x
0	120	47	-60
181	400	29	3180
400		14	9180

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