City Scale Demand Side Management in Three Different-Sized District Heating Systems

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Abstract: Demand side management can add flexibility to a district heating (DH) system by balancing the customer's hourly fluctuating heat demand. The aim of this study is to analyze how different demand side management control strategies, implemented into different customer segments, impact DH production. A city scale heat demand model is constructed from the hourly heat consumption data of different customer segments. This model is used to build several demand side management scenarios to examine the effect of them on both, the heat producer, and the customers. The simulations are run for three different-sized DH systems, representing typical DH systems in Finland, in order to understand how the demand side management implementations affect the production. The findings imply that the demand side management strategy must be built individually for each specific DH system; the changing consumption profiles of different customer segments should be taken into consideration. The results show that the value of demand side management for a DH companies remains low (less than 2% in cost savings), having an effect mostly upon the medium loads without any significant decrease in annual peak heat loads. Also, the findings reflect that the DH pricing models should be developed to make demand side management more attractive to DH customers.

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1. Introduction

Smart energy systems are considered as a backbone of a "smart city" [1]. Lund et al. [2] define smart energy systems as the integration of multiple different energy sectors (electricity, heating, cooling, industry, buildings, and transportation) with intelligent control and energy storage, and with the customers playing a central role. In smart energy systems, consumers will not only be considered solely as points of consumption but also as customers who act as an integrated part of the system itself. District heating and cooling (DHC) systems have an important role to play in integrating energy systems into a smart city; it is argued that they are "important tools" for reaching energy targets such as those set by the European Union (EU) [3]. DHC systems can engage consumers in several ways: Customers can act as prosumers, supplying waste heat to the system [4,5], or as flexible consumers with heat storage opportunities.

The DHC network's flexible heat and cold energy storing capability will have an increasingly important role in the future where fluctuating energy sources will become more dominant. The heat storing capacity is also needed for the fluctuation of heat demand. The annual district heating (DH) consumption strongly fluctuates following the weather changes throughout different seasons. In the short term, heat consumption has weekly and daily rhythms, which is mainly due to the use of domestic hot water [6]. Also, different energy saving measures set by the customers (such as night-setback settings in offices) affect the rhythm of consumption. Studies made by Basciotti and Schmidt [7] and

Noussan et al. in [8] conclude that night-setback settings are causing problems in regard to energy system levels by causing higher daily morning peaks. The daily variations in heat demand cause challenges—for example, the extra start-ups of heat-only boilers (HOBs), which increase emissions from, and the cost of, heat production in DH systems. Especially in large DH systems, heat storage is used to balance the variations in heat consumption [9]. Studies and practical examples of buildings acting as heat storage have been made, as the following literature review exemplifies.

In general, the term "demand side management" (DSM) refers to the various approaches affecting the customer's traditional consumption profile. DSM can be applied in different ways depending on the target, the time frame of the DSM actions (short term/long term), or who controls the DSM actions. The target of DSM depends on the perspective—i.e., is it enacted to optimize energy production or to lower the energy costs of a customer. In the short term, DSM can be applied to carry out heat load shifting, which includes actions such as peak clipping, valley filling, and load shifting. In the optimal case, these short-term DSM measures are beneficial for both the energy company and the consumer. The energy company benefits when heat consumption variation is balanced and when the heat production is shifted from high- to low-cost production facilities: The energy consumers benefit from lower energy costs if heat pricing depends on the peak load demand. Long-term DSM measures concentrate on the conservation or the strategic growth in energy consumption. Conservation refers to energy saving that is enacted through retrofitting measures within buildings. Strategic growth is beneficial in cases where low energy consumption results in using less energy-efficient production plants. In this study, the term "DSM" is used as a general term for heat load shifting measures within the short term.

DSM-related research has concentrated mostly on electricity systems. Still, especially in recent years, along with the growth of interest in smart energy systems, DSM in DH has gained increasing interest both in academia and in practice. Pilot tests of actual DSM implementation in buildings within DH systems are reported in [10–13]. Few studies have utilized building simulation tools to investigate the dynamic behavior of buildings and the effects of the heat load cuts inside the buildings [14,15]. The same approach with building level simulations is used in several studies written in Finland [16–19]. Most of the studies concentrate on DSM in one type of customer segment such as residential [6,12–15] or office buildings [11]. Some studies have included different types of buildings. For example, in [17], the effects of DSM are studied in three different building types typically owned by municipalities in Finland—office, school, and residential. The above-mentioned studies have reported that the possibilities for heat load cuts vary from 15% to as much as 50%. It is important to point out that one has to be critical when studying the heat cuts implemented within the previously mentioned studies since they have different starting points that depend on factors such as the building's structure, the location of the building, the outdoor conditions, and the regulation of operative temperatures. For example, in [14], the determining factor for implementing a heat cut was that the inside temperature could not fall below 18 °C—which was in accordance with the Danish standard. Then again, in [6], the heat cut in building-level simulations was implemented according to Finnish standards, where the optimal inside temperature (affected by air humidity, gender, and age) was 21 °C and the inside temperature could not fluctuate over 1 °C inside the apartment [20].

Few studies have analyzed the effect of DSM on the energy system level. Difs et al. [21] have investigated the effects of DSM measures in multi-dwelling buildings on the energy system level by simulating the energy system of Linköping, Sweden. The DSM implementations, which included 7% energy savings, had the greatest effect on medium heat loads. Dominković et al. [14] combined the building-level simulations of residential buildings and the energy system-level optimization in Sønderborg, Denmark. The results in [14] show that the economic savings in the operational costs of the DH system were within the range of 0.7–4.6%. Romanchenko et al. in [22] made a techno-economic comparison between utilizing heat storage using a hot water tank and the thermal inertia of buildings in the DH system of Göteborg, Sweden. The study concludes that the annual operating costs of the system decreased by 1% when the thermal inertia of the buildings was added to the DH system.

Cai et al. [23] have studied DSM within the DH network of Copenhagen (21 customer nodes), including pumping costs to the analysis and results show up to 11% in the reduction of energy costs.

As presented earlier, several researchers have studied DSM actions in a DH system from different viewpoints, including pilot tests, building-level simulations, as well as the effects of DSM on DH systems. However, two main deficiencies can be identified in the past research. Firstly, most of the studies have concentrated only on a single type of customer segment and they have not analyzed the implementation of DSM in a large set of different DH customer segments. Different customer segments have varying heat load profiles as well as divergent possibilities and differing targets in regard to energy saving and DSM. This suggests that different customer segments should be included in DSM research more comprehensively. Secondly, the previous studies seem to have missed how different DSM control methods influence the operation of different-sized DH systems and production plants in existing DH networks. There are studies that have evaluated the value of DSM in DH systems, but too little attention has been paid to which DSM control method exploits different types of DH systems more effectively.

This study has two main objectives. Firstly, it aims to find out how different DSM control strategies impact DH production in different sizes and types of DH systems. Secondly, it aims to evaluate which DSM strategy creates the largest economic value for the DH company and for the DH customers. In this study, the examination of the hourly heat loads of different DH customer segments—representing the DH consumption of the city—is combined with the DH system-level simulations for three different-sized DH systems. The studied DH systems represent typical systems in Finland. This study emphasizes the importance of different customer segments; it attempts to understand their divergent targets for DSM implementation by including five customer segments in the DSM analysis.

This paper is divided into four sections. The first section gives an introduction to the topic. The second section is concerned with the data used in this study, as well as describing the methodology used in order to build the DSM profiles and control strategies. This section also presents the input values used in the DH system-level simulations as well as information on how the simulation tools were used in the study. Section 3 presents the results of the study and the last section contains discussions on the results and conclusions.

2. Methods

In this section, methods and data used to answer the research questions, are presented in Figure 1. Firstly, the hourly consumption data from different customer segments are used to construct the consumption profile for the whole DH system. Then this base consumption profile is modified to build different DSM scenarios. DSM scenarios are used as input data for the hourly heat load simulation of three different-sized DH systems in order to ultimately identify how DSM implementation changes the merit order and fuel use of different power plants. The used energy system-level simulation tools are also presented in this section.
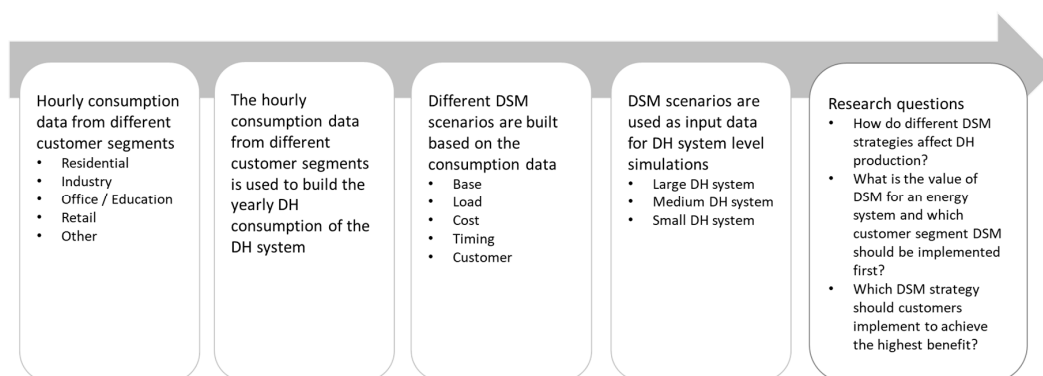

Figure 1. Methods, research questions and the course of the study.

2.1. Consumption Data and Customer Segments

Vantaa Energy [24] provided hourly peak heat load data for the year of 2016 for different building types. The data received was for eight office, eight hotel, six retail, seven industrial, and six residential buildings. The data also included the building area, volume, and construction year of every building. The hourly consumption (W/sqm) profiles of each building were weighted with the building-specific area and the construction year. The end result consisted of the average hourly consumption (W/sqm) per construction year for all of the above five customer segments. Figure A1 in the Appendix A shows the average weekly heat peak load patterns for these segments. It is noticeable that the heat load patterns differ significantly among customer segments, which indicates different daily heat consumption rhythms. The dashed grey line represents the average weekly heat load for a DH system where different customer segments have been compiled as a system (or as a share of the maximum heat load). Apartment buildings typically have two peaks in consumption per day while retail buildings and offices use the night-setback setting during nights and weekends to save energy. Similar heat load patterns have been presented by Gadd and Werner for DH substations [25] and for DH systems [26] in Sweden.

Since the data received and the accompanying average hourly profiles per customer segment are based on the specific construction decades, namely 2010, 2000, 1990, 2010, and 1990 for residential, industrial, retail, office, and hotel buildings, the profiles have to be scaled to cover the changes in the average heat consumption through different construction periods. The scaling is based on extensive data that cover actual heat consumption (per cubic meter) per construction decade (ranging from 1960 to 2010) for existing buildings [27]. The end result is the hourly heat consumption per sqm, per property type, per construction decade.

Data from [28] cover the number of buildings and building area per property type per construction decade in the city of Vantaa. Multiplying the above profiles with this data allowed us to create the aggregate hourly consumption for different customer segments for the city of Vantaa. Calculating together the consumption of these customer segments resulted in a total annual heat consumption of 1681 GWh, which is within one percentage point of the real consumption of 1696 GWh provided by the official data [29]. Vantaa Energy [24] also provided the actual hourly consumption rates (for the year of 2016) for the whole energy system in order to match the approximated consumption profile with the actual consumption profile. This has to be done because the DSM actions are compared to the real heat production of the system; i.e., the consumption and production have to match with each other for every hour of the year.

This bottom-up approach was taken in order to define the actual consumption profiles for individual buildings—i.e., the end-users. This allowed us to calculate the benefits of DSM for the system, different property sectors, and finally for individual buildings. The consumption profiles presented in Figure A1 highlight the importance of different DSM actions per each different customer segment. Additionally, data received from the city of Vantaa [30] include the following data entries for every building: property identifier, date of construction, frame construction material, floor space, number of floors, heating type, type of use, address, and postal code. This dataset of over 30,000 buildings allows us to pinpoint the actions of DSM on each individual building.

2.2. Demand Side Management Scenarios

Now that the hourly consumption profile for a DH system has been created (called the Base scenario), the methodology for creating the DSM scenarios can be presented. With different DSM control methods, four DSM scenarios are built (Load, Cost, Timing, and Customer scenarios) with the following methodology. Within the methodology, every day (24 h) of the year is adjusted individually. Firstly, the individual hours of the day must be rearranged into a descending order based on either the hourly heat load or the hourly heat production cost (HPC), depending on the control method used in each DSM scenario. The hourly HPC data is drawn from a simulation of a DH system in conjunction

with the Base scenario consumption profile (described in detail in Sections 2.3 and 2.4). Then, the following parameters must be chosen for each day:

1. Is DSM implementation based on hourly peak heat demand or HPC?
2. The number of DSM hours—i.e., how many hours are adjusted for DSM? This is explained in more detail within Table 1.
3. The depth of DSM—i.e., how large is the heat load cut for the given hours (x*initial heat load)?
4. The number of hours to return the heat load cut—i.e., how many hours are used for extra heating in order to recover the DSM implementation? It is expected that the DSM does not reduce energy demand, rather it just shifts the timing of the heat demand. The hours participating in returning the heat are selected so that adding the extra heat does not increase the hour's total heat demand over the lowest hour, which is reduced downwards. This is done so that the DSM actually lowers the peak demand during the day. Additionally, the selected hours are firstly selected as hours before the DSM implementation (i.e., pre-heating recovers the peak reductions), and, if this is not possible, then they are selected afterwards. Finally, if for a certain day DSM implementation cannot be done without returning the energy, then the depth and the participating hours are reduced.
5. The energy saving percentage per hour—i.e., whether or not it is assumed that DSM reduces the energy demand. In this study, it is assumed that DSM implementation does not save energy, as explained above; the main results in Section 3 explain this. However, the impact of potential energy savings is also analyzed through a sensitivity analysis (the results are discussed in Section 4) since some literature shows an energy saving potential of 5–10% [10,11,21,31].
6. The number of the day's hours where DSM is implemented first—i.e., is DSM started by the highest peak load or by the highest HPC hour of the day, the second highest cost, and so on? This control method is used in the Timing scenario and explained in detail later.
7. Whether or not the HOB running hours are prioritized (on/off).

Four different DSM scenarios are then constructed, and they are titled: Load, Cost, Customer, and Timing. Table 1 sums up the determining factors for different DSM scenarios. The base scenario presents the Base-case with the initial heat demand profile where no DSM control has been implemented, and the other scenarios are then modified from this scenario. Other DSM scenarios differ from each other in multiple factors (as explained in Table 1).

In the Load scenario, the customer controls their heat load based on the daily peak heat load. Since the daily heat pattern differs for different customer segments, the DSM actions are implemented for customer segments separately. The DSM is implemented for a given number of hours starting with the hour with the highest heat load. Since the daily energy demand is not reduced (see point 5 in the listing above), the heat load is returned (as explained in point 4 of the listing above).

In the Cost scenario, the DH company controls the DSM actions. There are two determining factors for DSM implementation. Firstly, the hours where HOBs are producing heat and, secondly, the hours with the highest hourly HPC. If the HOBs are off for the whole day, DSM is implemented based on the HPC alone. DH systems with different production mixes have unique hourly HPCs, which are affected by multiple factors such as production plants, given input values, and the hourly varying electricity prices. DSM is implemented simultaneously for all of the customer segments.

In the Timing scenario, the determining factor for DSM is the HPC, as in the Load scenario. The difference is that in the Timing scenario, the DH company controls the DSM timing for different customer segments in order to extend the effect of the DSM. In the Customer scenario, the DSM actions vary between different customer segments: Apartments and retail buildings are adjusted based on the peak heat demand, industrial buildings are adjusted based on the HPC, and the offices and educational buildings aim to reduce the night-setback setting.

Table 1 presents the limiting values for the DSM scenarios. During the coldest winter days, when the daily average outdoor temperature decreases to under −10 °C, the depth of the DSM was 0.9

compared to the initial heat load and the number of DSM hours was 3 h. During summer, DSM is not implemented at all, since in summer, heating only covers the need for domestic hot water. During spring and autumn, the downward adjustment was 4 h, the depth of DSM was 0.8, and the number of DSM upward adjustments was 5. On winter days, the depth of DSM was 0.85 and number of downward adjustment was 4 h and upward adjustment 5 h. In the Timing scenario, where customer segments were performing DSM based on HPCs but with different timings, DSM was implemented so that the apartments adjusted the heat demand during the four highest HPCs (during 24 h), industrial buildings during the 3rd, 4th, 5th, and 6th highest HPCs, and offices and educational buildings during the 5th, 6th, 7th, and 8th highest HPCs, and so on. The above-mentioned limiting values were chosen to present the used values of the DSM implementation from the literature (see Section 1 for the literature review). General values for DSM implementation do not exist since they differ depending on several issues—such as the buildings' structures, the purpose of their usage, the location of the buildings, as well as the regulations regarding the operative temperature.

Table 1. DSM scenarios for simulations and factors determining DSM.

-	Base	Load	Cost	Timing	Customer
DSM controller	No DSM, initial heat load	Customer	DH company	DH company	DH company
Determining factor for DSM	No DSM, initial heat load pattern	Customer segments perform DSM separately based on daily peak heat load	DSM implemented firtsly based on hours with HOB production, and after this based on daily peak in HPC	Customer segments perform DSM based on HPC but with different timing of DSM	DSM impelemeted separately for customer segments with different control methods
Other description	-	-	-	Same as in Cost-scenario but different customer segments have DSM with different timing	Apartments and retail buildings based on peak heat load; Offices and educational buildings: aim to reduce night-setback; Industry: based on peak HPC; Other: based on peak heat load
DSM	Depth of the DSM (x*initial heat load in)/number of DSM hours/number of hours returning heat				
Spring/autumn	-	0.8/4/5	0.8/4/5	0.8/4/5	see [1]
Winter	-	0.85/4/5	0.85/4/5	0.85/4/5	see [1]
Cold winter days	-	0.9/3/4	0.9/3/5	0.9/3/5	0.9/3/4
Summer	-	-	-	-	-

[1] Apartments, Retail buildings and Others, as in the Load scenario; Industry, as in the Cost scenario; and Offices and educational buildings in spring, autumn, and winter—0.7/6/7 (the difference in energy consumption in the Base and Customer scenarios within 24 h could not exceed 5%, otherwise the DSM depth was decreased).

2.3. Simulated District Heating Systems

Three DH systems are simulated to determine how the implementation of different DSM scenarios affect the merit order of different production plants, their fuel usage, and the DH producer's economics. Simulated DH systems vary in size and in the production mix. The simulated DH systems represent existing DH systems in Finland [29]. Table A1 in the Appendix A shows the heat production plants of the different-sized DH systems used in the simulations.

A large DH system consists of several production units. There are two power plants with five combined heat and power (CHP) units that produce the base load of the heat demand and there are also several HOB plants for peak production that are fueled by gas and oil. HOBs are simulated as two separate HOB plants (one fueled with gas and one fueled with oil) since the DH network and thus the spatial heat demand is not analyzed in this study. One power plant has two CHP plants with a coal boiler and a biofuel boiler. Both boilers are connected to steam turbines. There is also a gas turbine that is connected to a heat-recovery steam generator. The other power plant has two waste-to-energy boilers that are connected to a single steam turbine. This power plant also has a gas turbine with a

heat-recovery steam generator. The large DH system includes two heat storage units that are used to even out the short-term heat demand variations.

The base load in the medium-sized DH system is produced by a biofuel-fueled CHP plant and the peak load with a gas-fueled HOB. A small heat storage unit is included in the simulations of the medium-sized DH system; however, it presents only the heat accumulator capacity of the DH network and not of the separate heat storage unit. The small DH system includes a biofuel-fueled HOB, which produces the base load for the heat demand, and an oil-fueled HOB, which produces the peak load.

The input values for the DH simulations are the values from the year 2016 and they are shown in Table A2 alongside their references. The heat production profile data (the heat load including the heat losses of the DH network) without any DSM actions and the outdoor temperature data [32] are presented in Figure A2. The heat load profile is built from the consumption data of different customer segments (as described in Section 2.1) and it represents the Base scenario (as explained in Section 2.2). The heat losses of the DH network are added to the heat demand. The factors affecting the heat loss are multiples such as the outdoor temperature, the DH water temperature level, and the DH pipe size. The yearly average heat loss for the DH network is 17%, which is within the range of the average heat loss in Finland [33]. The electricity price series is realized spot-price in Finland in 2016 from Nordpool [34].

2.4. Simulation Tools

To calculate the merit order of the production plants based on the given heat demand in the energy system, two different simulation tools were used. Small and medium-sized DH systems were simulated with the energyPRO simulation tool and the large DH system was simulated with energyOptima. Simulations of the large DH system have been made with the Energy Opticons Energy Optima 3 program. The program is used by two of the largest DH companies in Finland for their production planning [35]. Energy Optima 3 performs a total optimization that includes electricity production and the DH production. The program minimizes the production cost and maximizes the system revenue [36].

EnergyPRO [37–39] is an input–output modeling software package used for modeling energy systems. It is used to optimize the operation of power plants and heat plants using technical, financial, and external parameters. As a result, energyPRO calculates the merit order of different production plants, minimizing the cost of producing the heat demand. The EnergyPRO simulation tool has been used in various cases presented in the literature, for example, in DH systems with an excess heat from nearly zero-energy buildings [40], to different storage-to-energy systems [9,41], and to simulations of the utilization of waste heat for DH [42]. The annual production is calculated in steps of one hour, which takes the hourly varying electricity prices into account.

3. Results

This section presents the main results. Firstly, hourly heat demand changes in different DSM scenarios are compared to the Base scenario. The figures are used to illustrate how the DSM implementation and control strategies affect the heat load demand and HOB production. The medium-sized DH system is used in the figures. Secondly, the economic value of DSM is calculated for different DH systems and the reasons for value formation are identified. From a DH producer's perspective, customer segments that have the highest potential for DSM are also analyzed. Finally, the DSM implementation is examined from the customer's perspective. The results present which DSM strategy has the highest value for customers. It is noted that the results concentrate on DSM strategies without energy saving, as explained in Section 2.2.
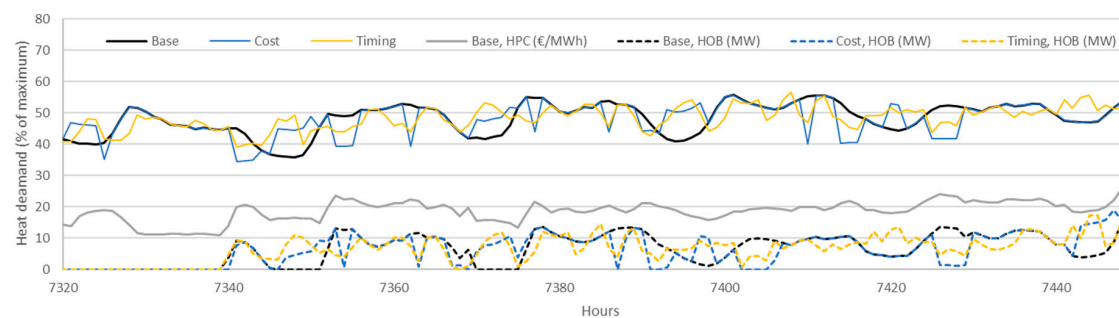
3.1. The Effect of Demand Side Management Control Strategies on District Heating Production

Figure 2 shows an example of the Load (upper figure), Cost, and Timing (middle figure), and Customer (lower figure) scenarios for medium-sized DH systems across the five selected days.

Load scenario with Base scenario
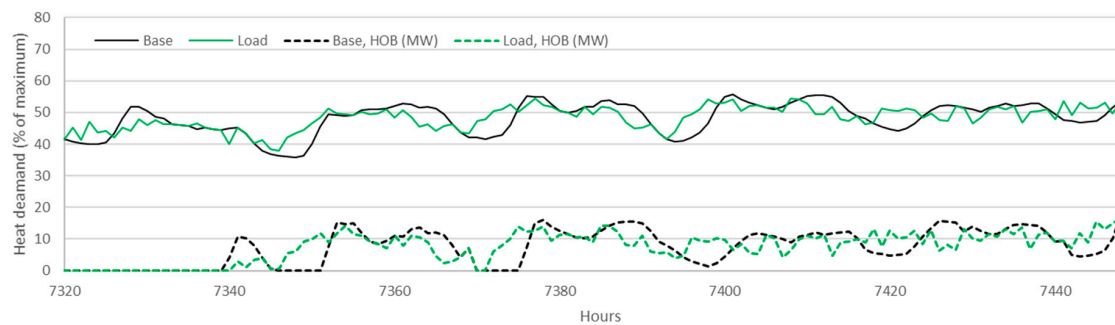
Cost and Timing scenarios with Base scenario
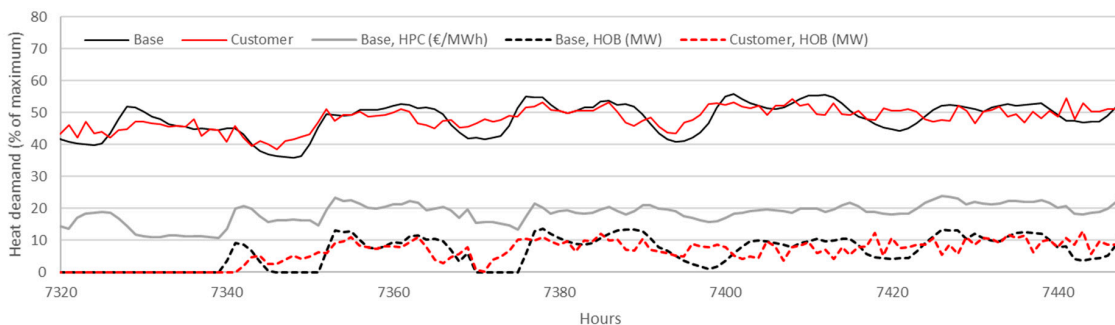

Customer scenario with Base scenario

Figure 2. The effect on heat production with heat-only boilers (HOBs) in medium-sized district heating (DH) systems with different demand side management (DSM) scenarios (Load, Cost, and Timing, and Customer). The black line represents the heat load in the Base scenario. The dashed lines represent how the HOB production changes in different scenarios, respectively. The grey line represents the heat production cost of the Base scenario (secondary axis), which is used as a control strategy for the Cost and Timing scenarios.

In the Load scenario, the daily peak heat loads are slightly decreased in the medium-sized system when compared to the Base scenario. However, the use of gas HOBs is not significantly decreased. Most of the HOB production periods are longer than the daily number of DSM hours used in this study, for example, four hours in the autumn season—i.e., the need for HOB production is not entirely gone, instead only the timing is shifted.

The Cost scenario reveals several problems when DSM is controlled based on the HPCs simultaneously for all the customers. Firstly, changes in HPCs on the daily level are quite small in the simulated DH systems. Bigger leaps in the level of HPC occur when peak production plants are added to the production and after that the level of HPC depends on the share of heat production with different heat production units. The second problem (which results from the first problem) is that the highest daily levels of the HPC values do not necessarily follow each other, which results in the DSM

hours being temporally far from each other (within a day). This leads to sharp valleys (or peaks) for the demand curve that complicate the production and might even shut down the gas HOB plants for a short period of time. This is partly due to a problem with the simulation program, since, in practice, production plants are not turned off that often, even for short periods of time; instead, the heat is stored in the DH network.

When comparing the Cost and the Timing scenarios, the demand curve appears smoother in the Timing scenario and has less valleys, thus resulting in fewer HOB shut downs. When analyzing the production for a whole year in the medium and small DH systems, the total heat production costs were lower in the Timing scenario than in the Cost scenario, even though the difference was small. This demonstrates that a DSM strategy should not be implemented similarly and simultaneously for all of the customers; rather, intelligent DSM implementation is needed across all customer types. Interestingly, this is not the case in the large system where the yearly heat production cost was slightly smaller (less than 1%) in the Cost scenario compared to the Timing scenario.

The example of the Customer scenario shows that decreasing the level of night-setback control decreased the daily heat demand fluctuation, making the demand curve smoother. Even though DSM control is used, heat production with gas HOBs in a medium-sized DH system at the annual level remains almost at the same level as in the Base scenario. This surprising result can also be seen in the large DH system: The heat produced with the peak production plants (gas HOB) is increased but production with the intermediate production plants (gas- and coal-fueled CHP) is decreased in the Customer scenario, compared to the Base scenario. The difference in cost is small, less than 1%. The reason for this is that the peak heat loads are not cut as much as the intermediate loads are. This decreases the amount of production with fossil fuels, but the reduction impacts the CHP production more causing less revenue from electricity production. In the small DH system, the Customer scenario manages to cut a share of heat production from peak production plants. This, together with a smoother heat demand curve, and therefore less oil HOB start-ups, results in the lowest total production cost of all the scenarios when compared to the Base scenario.

3.2. The Value Formation of Demand Side Management for District Heating Companies

Next, the annual energy production is analyzed more closely to explain how DSM actions benefit the different-sized DH systems. As mentioned earlier, one of the main targets for implementing DSM for a DH company is to reduce the use of fossil fueled HOBs, which cover the peak heat demand. Without any energy-saving measures, this should result in a higher utilization rate for the base production plants by changing the timings of the heat demands.

Table 2 presents the summary figures of the DSM scenarios for different-sized DH systems. Annually, heat energy was saved by less than 0.9% in the different DSM scenarios when compared to the Base scenario (heat energy demand). The results also show that DSM scenarios hardly affect the annual peak heat loads. In the Base scenario, the shares of heat produced with peak production plants were 16%, 12%, and 1% in the small, medium, and large DH systems, respectively. In practice, the share of peak production is usually higher because the used simulation tools are not DH network simulation tools—i.e., they do not consider the spatial heat demand and possible bottlenecks in the heat network. Also, longer revisions or sudden shut downs of the base production plants increase the need for HOB production.

Overall, the results in Table 2 indicate that DSM actions impact different-sized DH systems in different ways. This means that it is not possible to give a general one-size-fits-all DSM control method for different DH systems as the DSM strategy has to be built individually for a specific DH system. In general, the results seem to point out that with the given input values, the benefits of DSM for a DH company remain low.

In the small-sized DH system, heat produced with oil HOB plants decreased in all of the DSM scenarios when compared to the Base scenario. The Timing scenario gave the lowest production share with an oil-based HOB plant. Still, the savings in total production costs were very small, less than 1%.

One reason for this was that the DSM scenarios increased the start-ups of HOB plants, especially in the Cost scenario, and surprisingly, this gave slightly higher total production costs (€/year). In the medium-sized DH system, the lowest total production costs were established through the Timing scenario, resulting in 1.5% lower costs. In a large DH system with a more versatile production mix, the use of the cheapest fuel, waste, and biofuel, remained practically the same in all scenarios. Larger differences were seen in the use of coal, which surprisingly increased slightly in the Load and Customer scenarios. However, the largest change was achieved in the Cost scenario, where annual production costs decreased by 1.8%.

Table 2. Results of the DSM scenarios for different-sized DH systems.

	Heat Energy Demand [1]	Max Heat Load	Production with Peak Units	Production with Base Units [2]	Gas Consumption [3]	Coal Consumption [3]	Total Production Cost
	GWh	MW	%	%	%	%	%
				Comparison with Base-scenario			
Large system							
Base	1871	679					
Load	1868	672	93.8		93.2	101.4	100.3
Cost	1861	679	111.1		97.7	98.2	98.3
Timing	1861	672	105.3		95.4	100.1	99.6
Customer	1865	672	104.1		98.7	98.9	98.7
Medium system							
Base	262.0	95.0					
Load	261.5	94.1	99.3	99.9			99.8
Cost	259.7	95.0	97.3	99.4			98.7
Timing	260.0	94.1	96.0	99.7			98.5
Customer	261.3	94.0	98.8	99.9			99.6
Small system							
Base	137.9	50.0					
Load	137.7	49.5	97.4	100.3			99.2
Cost	136.9	48.9	98.6	99.4			100.2
Timing	136.7	48.9	96.5	99.7			99.6
Customer	137.7	49.6	96.9	100.4			99.1

[1] Including heat losses; [2] Medium and small systems; [3] Medium and small systems.

The results indicate that the benefits of DSM for a DH company, and the most suitable DSM control strategy for a DH system, depend on how the DH system's production mix is originally planned. The larger the share of heat energy produced with base production plants, the less profitable the DSM actions are to the DH company. This is illustrated in Figure 3, which presents the heat load duration curves of different DSM scenarios and the production mix and shares in a medium-sized DH system. The changes in heat load curves are small and thus difficult to present in the figure, but text boxes highlight the most important changes. The timing of the heat load production should be transferred from peak production to base production. For example, DSM actions in the Cost scenario cut the share of base production, which reduces the profits from electricity production and the possible subsidies from green production. In the case of the large DH system, the benefit of DSM is even less, since an even higher share of heat energy is covered with cheap base and intermediate production.

The effect of DSM implementation on different customer segments was analyzed in the medium-sized DH system with the Cost scenario. The target of the analysis was to study which customer segments have the highest benefits for the DH company. The medium-sized DH system was simulated so that one customer segment at a time would implement DSM based on the Cost scenario, and all the other segments would follow the Base scenario. Table 3 presents the results of how DSM implementation in one segment impacts the different heat production plants and production costs. Overall, the results show that the benefit from a single customer segment is very low. In total, the Residential segment has the highest potential to decrease the costs. However, the number (n) of

residential customers is very large, thus the highest potential per individual customer is the industrial segment. The customer segment, "Other," includes customers such as hospitals and hotels where DSM implementation might be more difficult.
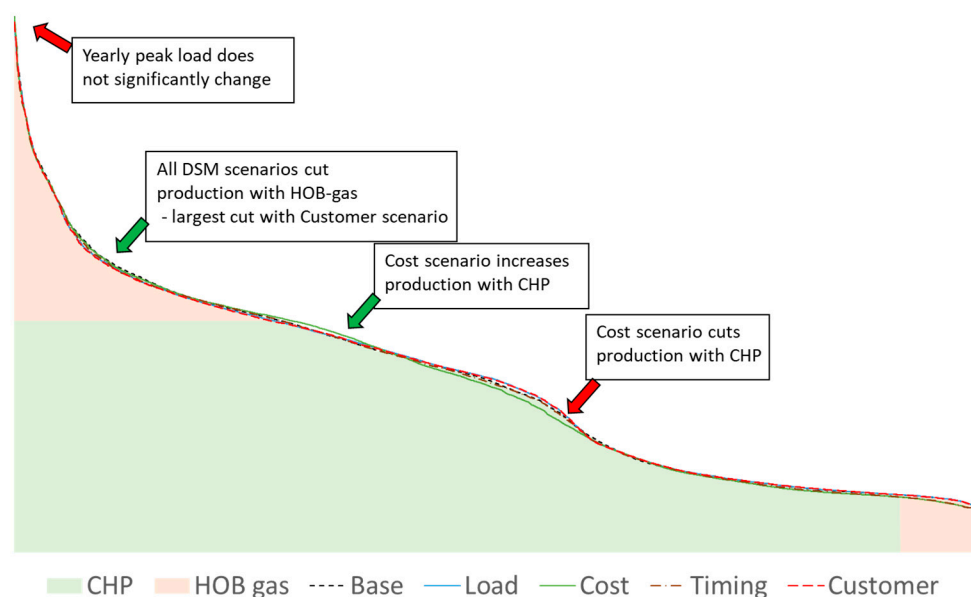

Figure 3. The changes in the heat load curve in the medium-sized DH system. Since changes in the annual demand curve across the different DSM scenarios are small and thus hard to see in the figure, the highlights are written in boxes.

Table 3. The effect of the Cost scenario DSM implementation on separate customer segments in the medium-sized DH system. The first row in the table (Cost—All segments) represents the situation when all the customers are implementing DSM within the Cost scenario. The following rows represent the situation when only one customer segment implements DSM within the Cost scenario, and others follow the Base scenario. The results are compared to the Base scenario.

	Number	Area	Production with Gas-HOB	Production with CHP	Heat Production Cost	Heat Production Cost per n
	n	m^2	%	%	€/year	€/year/n
				Comparison with Base-scenario		
Cost-All segments			97.3	99.4	−78,000	
- **Residential**	990	888,670	98.1	99.6	−55,000	56
- **Industrial**	82	439,086	99.7	100.0	−7000	86
- **Officies and education**	34	61,619	100.1	100.0		−30
- **Retail**	24	118,125	100.0	100.0	−1000	37
- **Other**	34	179,740	99.2	99.9	−18,000	527

3.3. The Most Profitable Demand Side Management Strategy for District Heating Customers

The consumption profiles differ between customer segments. Furthermore, different segments (such as residential apartment owners or professional commercial property investors) have different targets and decision-making processes when considering energy saving and/or cost savings in heating.

From the customer's perspective, the target of DSM is often focused on cost savings. The present DH pricing methods used in Finland in many DH companies [43] comprise of the cost of heat from two factors—energy cost and peak cost. Thus, the customer can save energy costs by saving heat energy and/or by cutting the heat load peaks. In this study, the DSM was implemented by shifting the timings of the heat load and it was assumed that energy was not saved. For the customer, the best DSM strategy is the one with the highest heat load cut; i.e., the Load scenario, as identified in Figure 4. The monthly

heat cuts through different customer segments varied from 1.2% to 20%. However, on an annual level, the variation was much smaller, varying from 1.2% to 7.9%. Heat load cuts in the Cost scenario—where heat is decreased for the hours when the HPC is the highest—do not match with daily peak heat hours, therefore it is not the most profitable DSM strategy for the DH customers. This finding is important to comprehend while a DSM strategy is being planned, especially if customer involvement in DSM is desired. With the currently-used DH pricing mechanism, different DSM strategies are profitable for different actors.
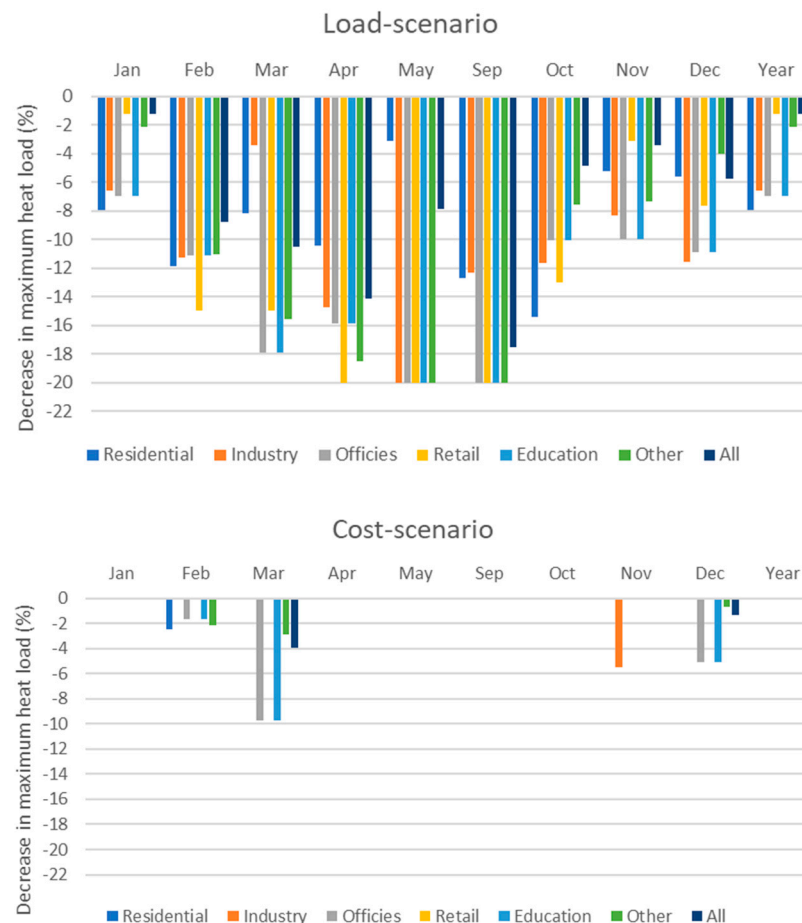

Figure 4. The monthly peak heat load for different customer segments in the Load and Cost scenarios.

4. Discussion with Conclusions

A general assumption is that DSM actions within DH systems, without significant energy-saving measures in heating, stabilize consumption profiles, reducing the peak demand and the cost of production. This was also assumed in this study, but it was quickly found that implementing and evaluating DSM actions in a DH system is a more complex process than was originally thought. The aim of this study was to find out how different DSM strategies implemented into different customer segments affect heat production in different size and types of DH systems. The economic value of DSM for both the system and the customers was calculated in different scenarios. Furthermore, an analysis was carried out to determine which customer segment had the highest economic potential for DSM implementation.

This study indicates that DSM control strategies should be distinctively built for different customer segments as well as the size and production mix of the underlying DH system should be accounted for. For the DH companies, it is not possible to give a general one-size-fits-all DSM control method for the different DH systems; rather, the DSM strategy must be built individually for a specific DH system.

Overall, the results indicate that DSM actions impact different-sized DH systems in different ways and that, with the given input values, the value of DSM for a DH company remains low—at less than 2% in cost savings compared to the Base scenario without any DSM implementation. Similar results were also reported by Romanchenko et al. in [22], where the cost savings achieved were approximately 1%.

Surprisingly, DSM implementation decreased the annual peak heat load very little when energy savings were not included. In the large DH system, the peak heat load was decreased by 7MW and in the small and medium DH systems, the decrease was only 1MW. The reason for this is that peak heat loads are needed for the coldest days of the year, and during the coldest period, the possibility for DSM measurements for buildings is lower. This illustrates that decreasing the level of reserve capacity is rarely possible. The situation would change if energy savings were included—such as is outlined in the literature review in [10,11,21,31], where an energy saving potential of 5–10% is noted. If a 5% energy saving potential is included in the simulations, the annual peak heat load would decrease by 39 MW, 6 MW, and 4 MW in the large, medium, and small DH systems, respectively. Especially in the large-sized DH system, this is already a significant decrease in reserve capacity, which indicates the decommissioning of at least one or two of the HOB plants [23]. However, the reasons for these kinds of energy savings are only approximations in the literature, and it remains unclear whether they can actually be implemented in practice, especially on a system-wide level.

This study identified that the benefits of DSM for a DH company and the most suitable DSM strategy for a DH system depend on how the DH system is originally planned. The results show that most of the changes in heat load are due to the DSM actions that occurred during medium heat loads. Similar findings were found in a study made by Difs et al. in [21]. When heat production is divided between two different types of heating plants (as in the small and medium-sized DH systems), the target is to transfer production from expensive peak production to lower cost base production plants. In a large DH system, this is a more complex problem, because heat is produced with a more versatile production mix—this also includes CHP plants and their subsidies. In a large DH system, the share of heat produced with peak plants was small (only 1%) and cutting these hours through DSM is very challenging.

Finally, the results indicate that DSM strategies benefit DH companies and DH customers in different ways. The customer's benefit was highest when DSM was implemented based on a daily peak heat load, since the current DH pricing methods often punish high peak loads. The problem is that this strategy gave the lowest economic benefit to the DH company. This is the reason why DH pricing should be reformed in a way that the customer's willingness for energy and cost savings is acknowledged, yet simultaneously, the overall system is also optimized. Reformation of DH pricing is an interesting area for further research because the customer's role is likely to become more significant in the near future. Besides this, more work is needed to determine the spatial value of DSM; i.e., including simulations of the DH networks—as they usually have several bottlenecks causing higher usage hours for the peak production plants.

Author Contributions: K.K. was the main author of the study, built the DSM scenarios and simulated the energy systems with different DSM scenarios. J.V. was responsible in building the DSM model. P.P. gathered the required consumption data for the study and co-simulated the energy systems with different DSM scenarios. S.J. acted as a support author reviewing the manuscript.

Appendix A

Table A1. Input values for heat production plants in simulations.

	Small	**Medium**	**Large**
System side			
- Max heat load in 2016 (MW)	50	95	680
- Yearly production in 2016 (GWh)	138	262	1870
Base production	HOB wood	CHP bio	CHP waste
- max fuel/heat/electricity (MW)	22/20/-	56/43/15.5	140/140/36 [1]
			CHP wood
			120/126/35
- max fuel/heat/electricity (MW)			CHP coal
			265/230/73
Intermediate production	-	-	CHP gas
- max fuel/heat/electricity (MW)			235/90/94
			CHP gas
- max fuel/heat/electricity (MW)			100/200 [2]/34.8 [1]
Peak production	HOB oil	HOB gas	HOB gas
- max fuel/heat (MW)			520/470
			HOB oil
- max fuel/heat (MW)			100/90
Other			
- heat storage (m^3)		3000	30 000

[1] Combined maximum electricity of the whole power plant is 78MW, [2] This heat recovery steam generator unit is connected to a steam turbine, thus maximum heat load is achieved in combination with the two waste boilers and flue gas condensers.

Table A2. Technical and economical input values used in simulations.

Heating values [44]	unit	value
oil	MJ/kg	42
biofuel	MJ/kg	10
coal	MJ/kg	24.9
gas	MJ/kg	50
waste	MJ/kg	10
Fuel prices [45]		
oil for HOB	€/MWh$_{fuel}$	40
biofuel fuel for HOB and CHP	€/MWh$_{fuel}$	20
coal	€/MWh$_{fuel}$	8
gas	€/MWh$_{fuel}$	24.7
waste	€/t$_{fuel}$	0
Taxation and subsidies [46,47]		
oil tax	€/MWh$_{fuel}$	25
subsidy for CHP with biofuel fuel	€/MWh$_{elec}$	18.6
coal tax	€/MWh$_{fuel}$	14
gas tax	€/MWh$_{fuel}$	19.9
Other costs		
HOBs for peak production	€/MWh$_{heat}$	1.1
HOB wood for small DH system	€/MWh$_{heat}$	2
CHP biofuel for medium DH system	€/MWh$_{el}$	4
CHP waste for large DH system	€/MWh$_{fuel}$	4

Table A2. *Cont.*

|		
CHP wood for large DH system	€/MWh$_{fuel}$	2
CHP coal for large DH system	€/MWh$_{fuel}$	2
CHP gas for large DH system	€/MWh$_{fuel}$	3
Revision time		
HOB wood for small DH system	months	1
CHP biofuel for medium DH system	months	1
CHP waste for large DH system	days	18
CHP wood for large DH system	months	1
CHP coal for large DH system	months	3
CHP gas for large DH system	months	1
Outside temperature [32]		
average	°C	8.2
minimum	°C	−26.2
maximum	°C	37.4
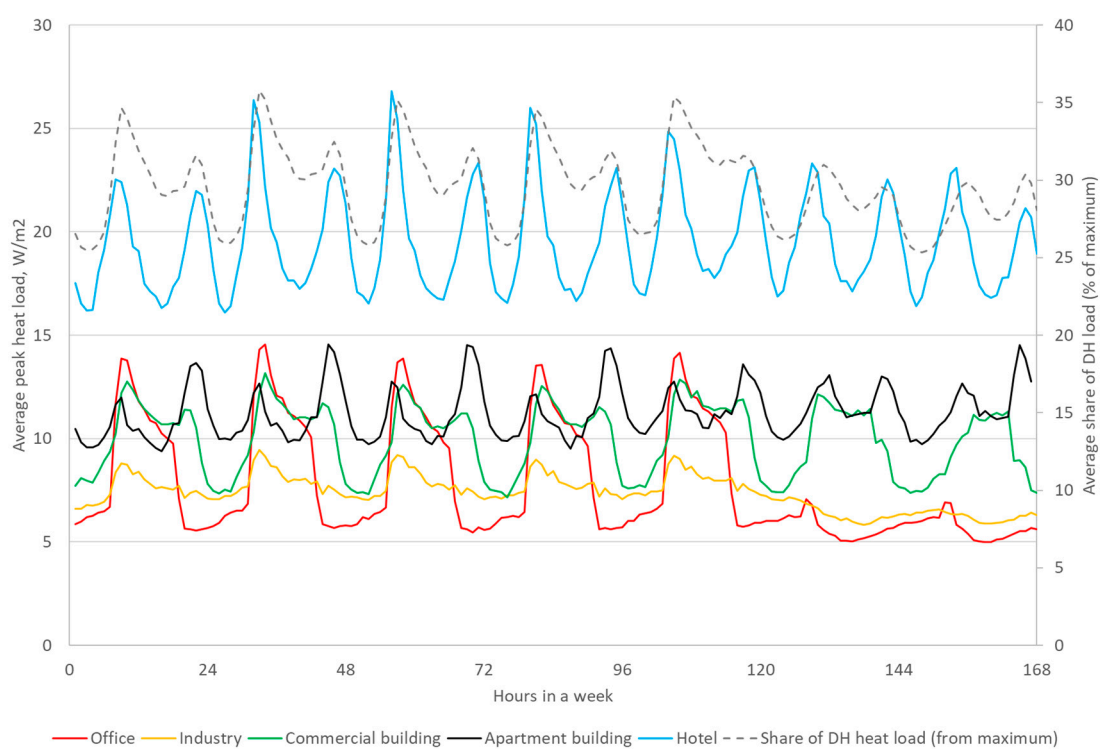
Figure A1. Average weekly heat peak load patterns for different customer segments for year 2016 (primary vertical axes) and average weekly share of DH load (secondary axes).
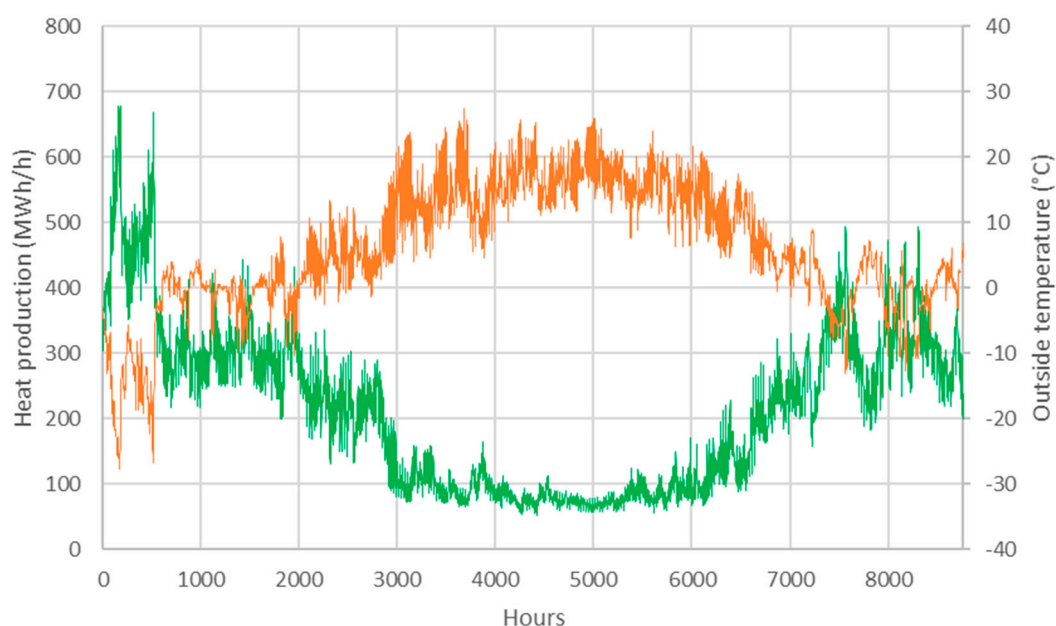
Figure A2. Hourly heat load and outdoor temperature as input values to the simulations.

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