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Use of smart meters as feedback for district heating temperature control

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Abstract

Smart meters implemented at the end-user in the energy sector create the opportunity to develop data-intelligent methods for district heating systems by using a large amount of fine-granular heat consumption time series from end-users. The current state-of-the-art methods for temperature control in district heating systems rely on predefined critical points in the network and a set reference temperature curve that expresses the minimum forward temperature as a function of the outdoor temperature at the end-users. The critical points are used to ensure that the consumers' supply temperature requirements are met all times. To predefine the critical points at the network, the location of the lowest temperature in the grid needs to be identified at any point in time. Since the lowest temperature often varies over time, one must have a set of critical points in a district heating network. This paper proposes a method to estimate the temperature at an artificial critical point for the network using time-wise quantile estimation using smart meter data at end-users. This novel approach eliminates the need for physical critical points in the net or sensors in wells and creates the possibility of changing the critical point location if needed. The benefits for the provider of using smart meters as feedback, makes the measurement wells redundant and flexibility of the location. The location of low temperature areas in the network can change overtime hence the flexibility of being able to change where the feedback is located. The proposed method to replace the well measurements to provide feedback for temperature control at the production site groups a predefined set of smart meter readings together for each point in time. The grouping is done to have reliable measurements from each smart meter device, excluding some of the meters when a faulty reading occurs. The set of acceptable readings is used to estimate the street pipe's temperature using the estimated quantile of the forward temperature. The approach is tested on two demo cases. The first demo consists of smart meters to estimate the forward temperature of the main street pipe. The second demo uses three smart meters at large apartment buildings as feedback for the control. Initial results show that the estimated temperature of the network can replace the well-measurements which traditionally are used as feedback for temperature control and give a better and more flexible control.

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1. Introduction

The European Union requires houses connected to a district heating network to be equipped with smart meter devices where feasible [1]. This allows linking the consumption to billing from the district heating and enables the end-user to be more aware of their energy consumption. In Denmark, the digitalization of district heating has been occurring in the past decade by installing smart meters and weather stations in the cities. This digital transformation has given rise in studies relating to district heating and investigating how smart meters data can be used to give valuable insight into the network performance and building energy efficiency, i.e. leakage in the systems or insufficient cooling of the water from inlet to outlet in some buildings. Kristensen and Petersen [2] use smart meter data to derive three heating efficiency indicators of buildings and give an overview of the smart meters system at the district heating utility in Aalborg in Denmark. The same study estimated that 54% of the building area in Denmark is supplied with district heating. Bacher et al. [3] propose a method to separate the total heat load from a single-family residential building into domestic hot water heating and space heating using a non-parametric method to identify the domestic hot water heating. Hence, smart meter data has been studied to improve building performance. However, there have not been any studies on using smart meter data to operate the network and production more efficiently. Smart meter data opens up the possibility to use it as feedback of the network for temperature control at the production site. This is highly valuable for the district heating sector as it is changing from traditional fossil fuels to renewable sources in district heating and is more and more connected to other energy sectors. Therefore, the district heating utilities need to be operated efficiently, utilizing periods when intermittent renewable energy sources (e.g. wind and solar) are available to be used for producing heat, and CO2 reduction. Hence, smart meters can increase the possibility of making the district heating sector more sustainable and flexible.

Operating the district heating network adequately can be done by implementing a control strategy with the objective of reducing heat production and heat losses in the network by minimizing the supply temperature at the production site. Using data-driven temperature optimization in district heating could reach between 240 and 790 million DKK in yearly savings by lowering the supply temperature between 3 and 10 degrees [4]. Madsen et al. [5] propose a novel method to introduce a control strategy that minimizes the supply temperature by regulating the flow to match the consumers' heat demand without violating any requirements, i.e. minimum supply temperature to the end-user. The temperature control strategy needs feedback on how the network reacts to changes at the production site to vary the supply temperature adequately; therefore, measurement wells are installed in the network where the network operators believe are the critical points, i.e. where the lowest temperature of the network is. A network usually has only a few of these critical points as they are expensive and need to be maintained regularly. Nielsen and Madsen [6] demonstrate the energy savings at a district heating utility by using data-driven temperature control that is based on Madsen et al. [5]. We propose to use smart meters at end-users as feedback of the network's supply temperature for temperature control to get the response characteristics of the network back to production. This novel approach makes the measurement wells redundant and the critical points flexible. For example, as the networks get older or new areas are added to the network, the location of a critical point could change. Therefore, using smart meters to create temperature feedback allows them to change the critical point location when needed.

We used two case studies to demonstrate how smart meters can be used as feedback for temperature control. The first case study used data from a group of single-family houses' smart meters to estimate the network's temperature. This estimated network temperature would then be used as feedback for temperature control. We compared the estimated network temperature to the supply temperature measured at a measurement well that is located before the group of houses that were used to create the estimated temperature. The second case study demonstrates how to use three different smart meters from large apartment buildings as feedback of the network for temperature optimization. A temperature controller uses these three smart meters as input to optimize the supply temperature for the network. We then demonstrate the results of having temperature optimization that uses smart meters as feedback in an online operation. The novelty in this paper is to demonstrate that smart meters can be used as the feedback of the network characteristics either by using a group of meters to estimate the temperature or using them directly.

2. Methodology: Dynamics of smart meters in district heating

The proposed algorithm uses data from a group of smart meters at the end-user to estimate the supply temperature in the main distribution pipe in the street where the end-users are connected to. The mass flow, supply temperature, and timestamp of the readings are the only variables used from the data-set for the algorithm. The flow is used to estimate if the temperature at the smart meter is reliable or not. When there is almost no flow, the water in the pipe leading into the end-user's house becomes still, and the temperature starts to drop due to the heat loss to the surroundings. Therefore, readings with a low flow are removed from the data set and not used to estimate the supply temperature in the main pipe as they do not represent the temperature in the distribution pipe due to the heat loss in the service pipe leading into the end-users. If the data from the smart meters do not send data with fixed time intervals and do not send them at the same time, but rather at random times and different frequencies. The data needs therefore to be aggregated and filled such that they have the same time points and resolution. The readings from each smart meter are therefore aggregated with a fixed interval by aggregating the readings within the interval to timestamp. The median is computed from those readings to represent the temperature at the timestamp at the given smart meter. For example, for 30 min resolution, the rounding will be to 30 min and the time is rounded to the nearest hour or half-hour. Thus, timestamps between 45 and 15 are rounded to the hour, and between 15 and 45 are rounded to the half-hour. After rounding the readings for all smart meters, readings with the same timestamps from every smart meter are grouped, and an appropriate quantile of the grouped temperatures is computed. This approach creates an estimation of the distribution pipe temperature using the smart meters at the end-user. Note, it is not recommended to use too high quantile for the estimation. For example, the 90th quantile is more suitable instead of using the 100th quantile, i.e. the maximum temperature of the dwelling for the given timestamp. It is done to remove any measurement noise, or faulty readings thus creating more robust feedback of the street pipe temperature.

For the second case study, a trial was carried out during the heating season 2020/2021 to demonstrate how digitalization can improve the operation of existing district heating networks. The temperature control was conducted using the HeatTO™ software provided by ENFOR that was installed to optimize the supply temperature from the heat exchanger to lower the supply temperature without breaking any restrictions, i.e. minimum supply temperature at the consumer.[1] The methodology behind the temperature controller will not be introduced here as it is quite complex. It can be found in Madsen et al. [5] and Madsen et al. [7]. However, the temperature controller needs feedback of the network to estimate the network's characteristics, i.e. time-delay in the network and heat losses. Here, data from smart meters are used directly as feedback to the production to optimize the temperature. Hence the data needs to be of high quality and represent the network such that the network characteristics can be estimated and used to optimize the supply temperature and minimize the production cost. To estimate the performance of the new controller, degree days are used to compare supply temperature between two seasons. Degree days are used to compare supply temperature between different heating seasons. The degree days, T^{dd} are computed by estimating the difference between the average ambient temperature, $\overline{T}_a$ over one day, and using 17 °C as the cut-off of heating demand from buildings,

$$T^{dd} = max(0, 17 - \overline{T}_a)$$

The degree days gives the possibility to quantitative the performance between operations as two controllers cannot be operated at the same time.

3. Description of case studies

3.1. Case study 1: Group of smart meters

In this case study, we apply the smart meter heating data to create an estimated network temperature to be used as temperature feedback of the network to the production. The data is from a district heating network in Brønderslev that is located in the northern part of Jutland in Denmark. The district heating utility, Brønderslev Forsyning has supplied smart meter data from one area in their network. The data set consists of measurements from 15 single-family houses that are also located close to a measurement well. They have also supplied data from the

[1] https://enfor.dk/services/heatto/.

measurement well. Thus, we can compare the result from the proposed algorithm to the measured supply temperature in the network. In order not to violate privacy and comply with GDPR, the smart meter data was anonymized as only Brønderslev Forsyning knows which houses the data belongs to. Hence, the location is unknown and the only information about their location is that each house in the data set is located close to each other. Fig. 1 shows the raw data from the smart meter data set, the plots to the left show the supply temperature and the flow in a winter period while the plots located on the right show the same in a summer period. The bold red line in the temperature plot is the supply netpoint temperature measured at a measurement well that is located close to the houses, or the supply netpoint temperature that is typically used to see how the network is performing. The other lines are the supply temperatures from the smart meters measured at the end-users. The flow is also measured at the end-user shown in the lower plots. We can see from the temperature plots that the smart meter temperatures follow the dynamic of the netpoint temperature but there is a temperature level offset. The offset can be explained as the temperature drop due to heat loss to the surroundings in the service pipe from the street to the end-user. The difference between winter and summer can be seen when the flow is compared between the seasons. During the cold months in the winter, houses usually have constant space heating, and thus have a constant flow. However, during summer periods in Denmark, there is no need for space heating. Therefore, the flow during the summer is frequently close to zero except for the peaks as the plot shows, which can be explained by consumers' domestic hot water usage.

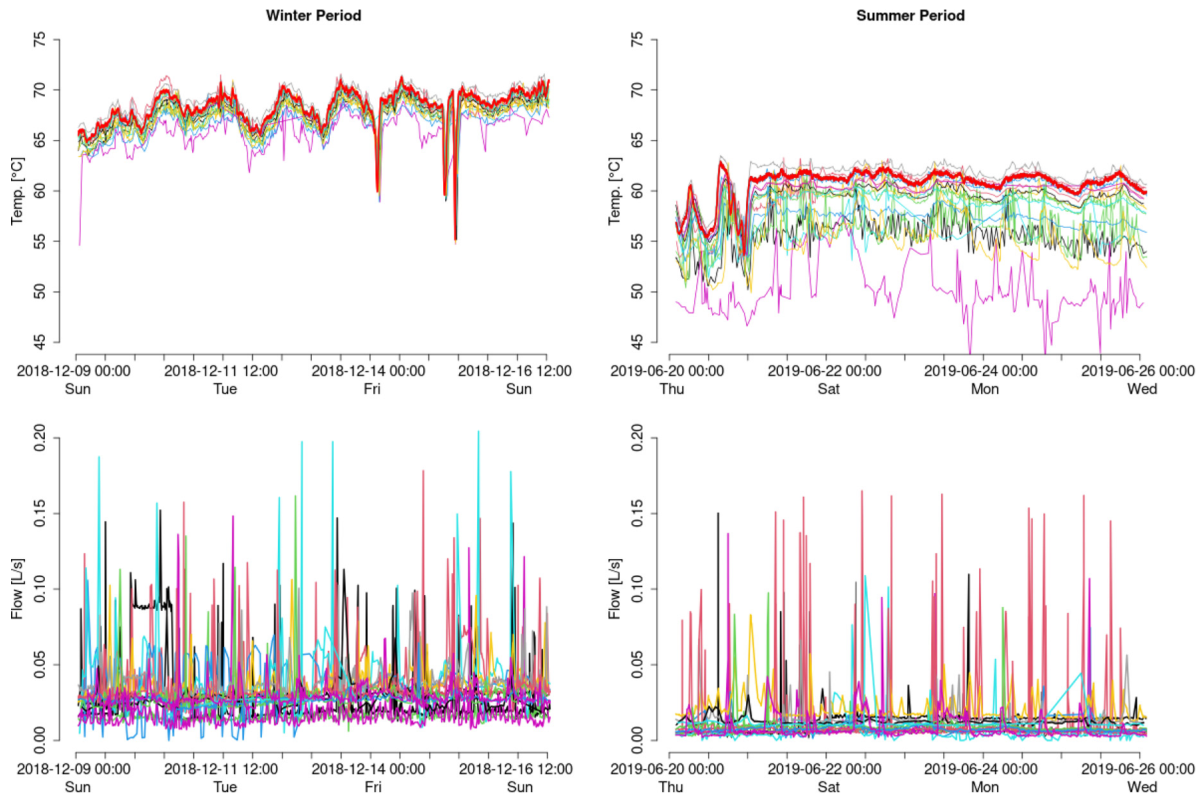

Fig. 1. The temperature and flow of 15 consumers from the district heating network in Brønderslev Forsyning for the winter and summer seasons. The bold red line shows the netpoint temperature measured at a measurement well in the network and used for feedback of the network. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

The readings from the smart meters occur with different frequencies and time-interval. This is more visible in Fig. 2 where the plots to the left show temperature and flow readings over two days from two different smart meters. We can see from the plots that readings come at different times, and the frequency is also different. The plot on the right side demonstrates this in more detail, visualizing temperature readings from all 15 m between 17:30 and 18:30. The frequency of the meter readings differs — some give multiple readings in this interval, while some just one, and from one of the smart meters there is no reading at this specific time interval. Hence, it is essential to aggregate the data to a specific resolution before using it to create an estimated supply temperature.

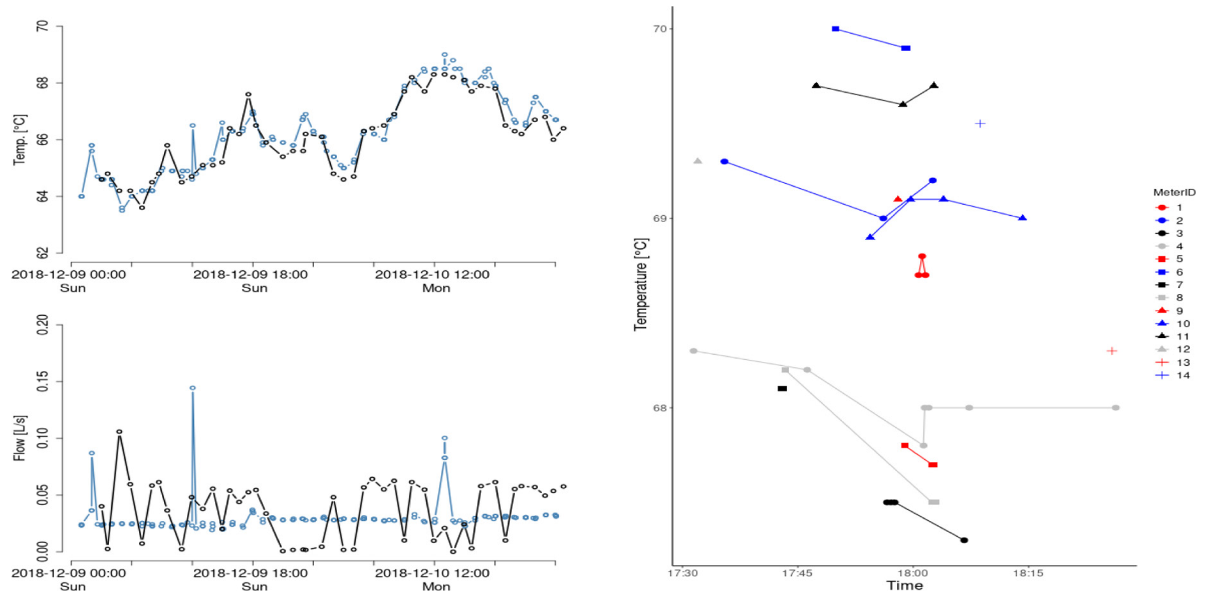

Fig. 2. Differences among the readings (frequency, time of the reading) from smart meters when compared to each other.

3.2. Case study 2: Three large apartment buildings as feedback

This case study is located in the Tingbjerg area in Copenhagen, a small area with large apartment buildings. The network is thought of as an island within HOFORs district heating network as the area is isolated and only supplied with heat from a heat exchanger. HOFOR is Copenhagen's district heating supplier as it both produces heat and operates the distribution network. The network in Tingbjerg is small and has a short time delay, so a measurement well has not been deemed necessary for controlling the supply temperature from the heat exchanger. Consequently, the control of the supply temperature has been operated as an open-loop system, and the temperature is usually determined conservatively to ensure sufficient supply temperature to the consumers. Hydraulic simulation of the system and current ambient temperature were therefore used to optimize the temperature. Hence, no feedback of the network on how it adapts to changes at production and if the requirements are fulfilled. The Tingbjerg area is an ideal case study to demonstrate how to use the digitalization of the network to improve the network's operation as feedback for temperature control. In this study smart meters are used as feedback from large apartment buildings for the temperature control at the heat exchanger. HOFOR supplied smart meter data from 38 apartment buildings inside the Tingbjerg network to be considered as the network's feedback. The data collection started at the beginning of 2020 and data is still being collected as input for the controller that is still in operation. The data in an hourly temporal resolution was supplied once a day, containing readings from each meter since the previous data dump. In November 2020, the data collection changed — now the data is sent every hour with a 15 min temporal resolution. Thus, the controller relies on newer and more frequent data. Three smart meters were selected based on the measurements' reliability to give accurate temperature feedback of the network to the controller. The selected meters have relatively constant flow; therefore, the forward temperature signal is of high quality (i.e. the water does not become still in the pipe leading to the house), and measurements from these meters can be used for temperature control. Temperatures from the three meters to be used as feedback are shown in Fig. 3, where it can be seen that they are of good quality despite some peaks in the winter period.

4. Discussion and results

Fig. 4 shows the result from the first case study in Brønderslev where we use a group of smart meters to estimate the netpoint temperature. The gray lines represent the temperature from the end-users. The blue line is the netpoint temperature measured at a measurement well in the network. The well is located before the dwellings that supplied the smart meter data. The red line is the estimated network temperature using the smart meter data

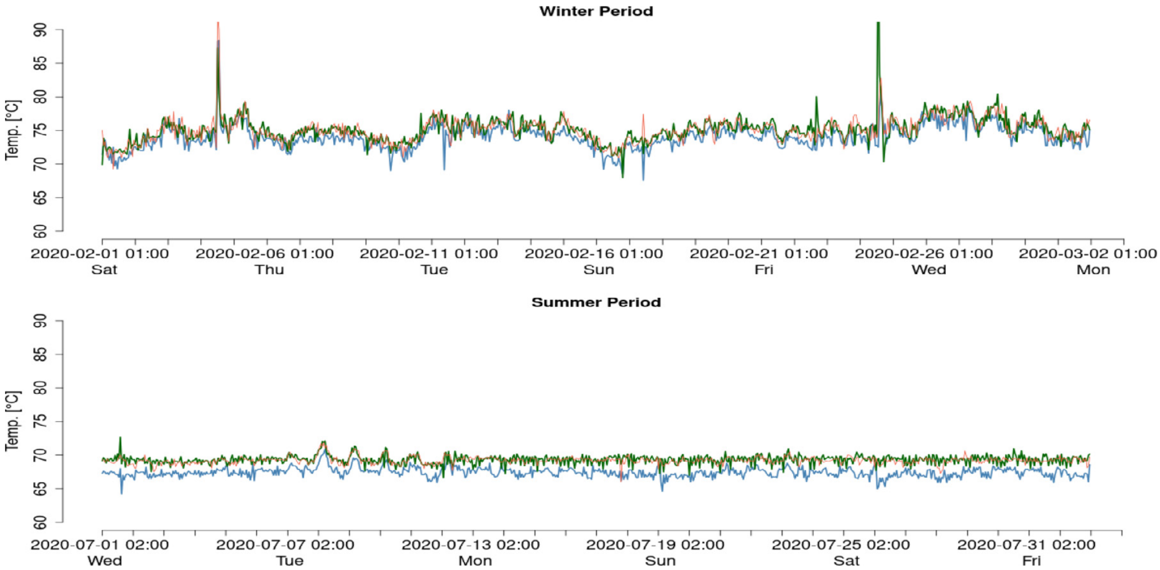

Fig. 3. Supply temperature from three smart meters in Tingbjerg used as feedback for temperature control. The upper and lower plots show the temperature at two different seasons, winter and summer.

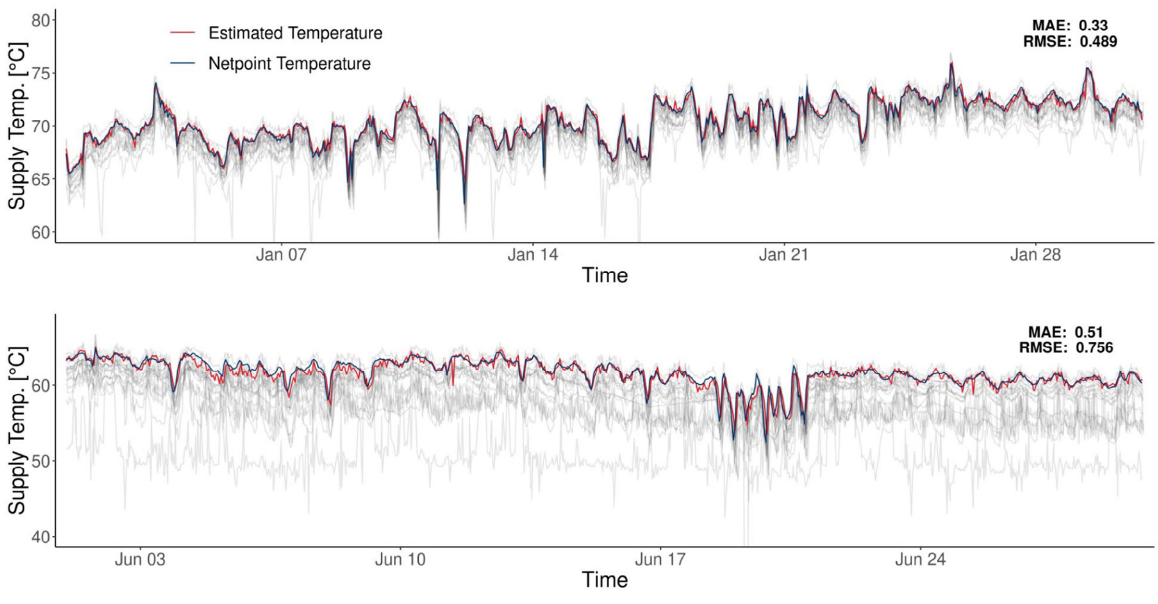

Fig. 4. The estimated network temperature from the proposed method as the red line and the measured netpoint temperature as the blue line. The gray lines are the temperature from the smart meters used in the proposed method. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

using the proposed algorithm from Section 2. We have aggregated the data to 30 min resolution and used the 90th quantile to estimate the netpoint temperature from the smart meters. The estimated temperature mimics the measured netpoint temperature adequately over the wintertime. However, it does not perform as well over the summer month. The metric scores, *Mean Absolute Error* (MAE) and *Root Mean Squared Error* (RMSE) are given in the plots to illustrate the performance of the algorithm and the difference between the two seasons. The accuracy difference between the heating season and the summer months can be due to fewer consumers that use space heating when the air temperature increases — the remaining usage is then domestic hot water, i.e. showering. Thus, the hot water in the pipe into the house is not in constant use; therefore, the water becomes still, and the temperature drops due to the heat loss to the surroundings. This can be seen in Fig. 1 when comparing the flow between the seasons and in Fig. 4 when looking at the different dynamics between the seasons. In the summertime, the temperature tends to drop exponentially and rise quite fast in a short time. The algorithm is however able to capture the street temperature accurately even though it has less information than the winter months due to infrequent usage of space heating. Notice that we are not trying to estimate the supply temperature measured at the well, it is only used to benchmark the performance of the estimated temperature in the street pipe outside the dwellings. Therefore, the algorithm is not optimized to have a perfect representation of the well measurement instead it is used to represent the temperature in the street, which can have different dynamics than the well because of heat loss between the well and dwellings.

Fig. 5 shows the result from the second case study in Tingbjerg where it is presented by comparing supply temperature from the previous operation and trial using the new temperature controller and smart meters as feedback of the network. The top-left plot shows the supply and ambient air temperatures for the previous operation when an open-loop controller was in operation, and the middle-left plot shows it for a period when the new controller was used. The bottom plot shows the difference between current and previous supply temperature from the periods in the plots above. The difference plot shows that using the new controller gives a more robust temperature, i.e. the temperature is not changing rapidly as can be seen also when comparing the top and middle-left plots. The variance of the two difference time-series is also given in the plot to illustrate how stable the supply temperature has become using the controller. Hence, having a more stable supply temperature is beneficial for the control of the heating unit at the consumers' and the network's equipment. Large and frequent fluctuations in the supply temperature should be avoided as it increases the maintenance costs compared to stable operations [6].

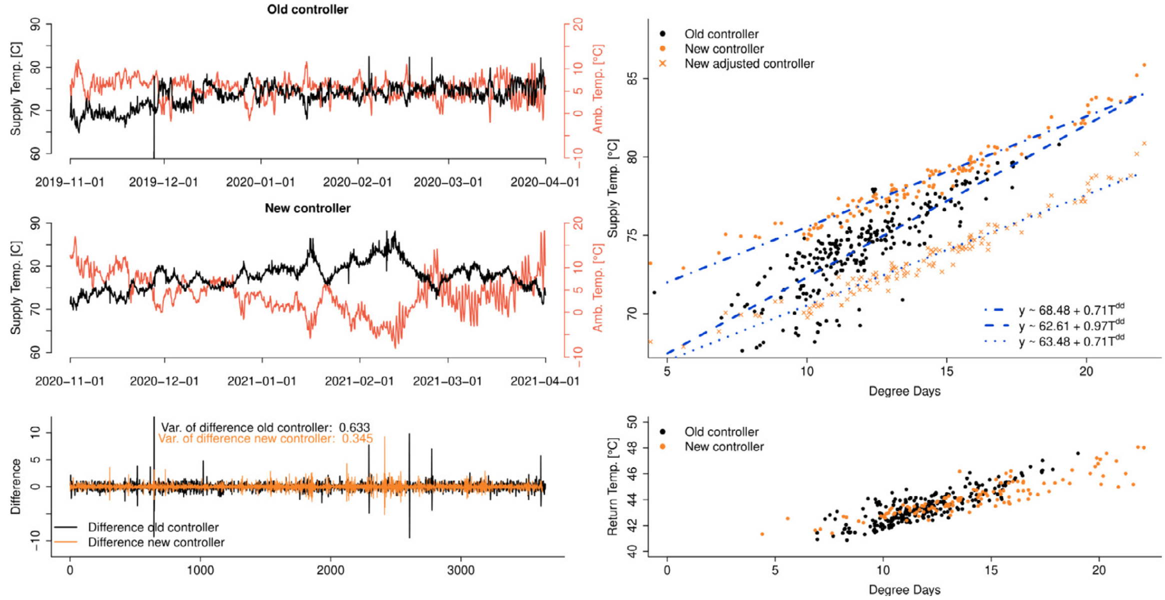

Fig. 5. The result of using temperature control using three smart meters as feedback of the network. The plots to the left show that the supply temperature at the production is more robust with the controller. The plots to the right demonstrate that the supply temperature at the production was higher when the new controller was in operation. The top right plot also shows the supply temperature adjusted by lowering them by 5 °C.

The plots on the right side of Fig. 5 demonstrate the performance of the control by comparing the supply and return temperature against the degree days. The average supply and return temperature for each day is then computed and plotted against its corresponding degree day as shown in the top and middle-left plots. We can see that the supply temperature is higher when the new controller is in operation as the regression lines also demonstrate. The regression lines (with intercept and slope) are used to highlight the difference between operations. This is a result of the reference curve that was used for the netpoint temperature was transferred from the previous open-loop operation to control the supply temperature to be used when the new controller was operating. The reference curve at the

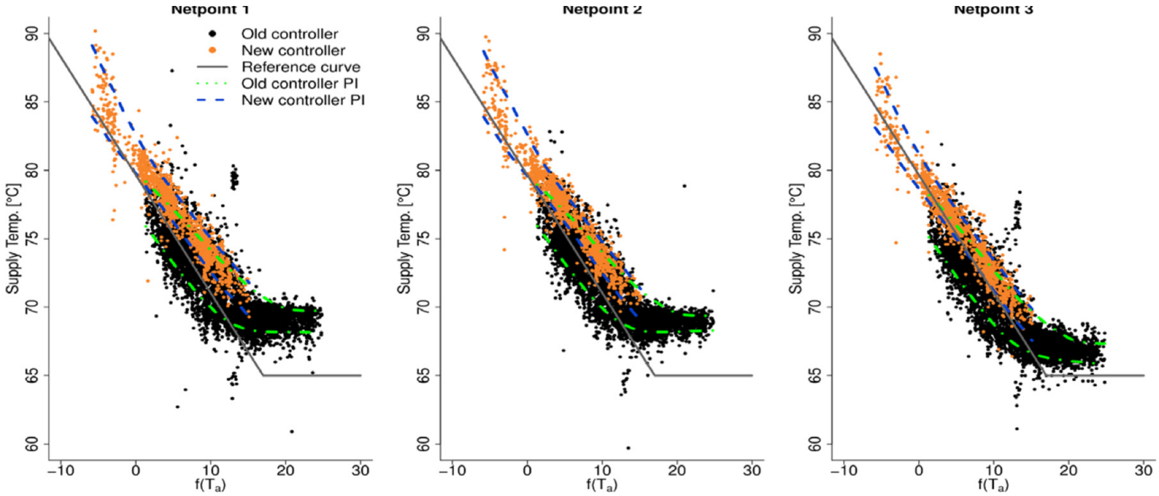

Fig. 6. Supply temperature at the three netpoints (the smart meters) plotted against the rolling average of the ambient air temperature with window length of 24. The reference curve constrains the controller to supply the consumer supply temperature for a given ambient temperature.

netpoint is to ensure that consumers will receive the required supply temperature as a function of the ambient air temperature.

In the past, the supply temperature control at production did not have any feedback from the network and therefore the reference curve was stated quite conservatively to ensure that the consumers would receive the required supply temperature. Notice that the slope is lower for the new controller hence for colder days the new controller will operate more efficiently even for suboptimal restrictions. The return temperature was also not affected by the new controller as shown in the right bottom plot in Fig. 5. Fig. 6 shows the supply temperature at the three netpoints for both periods. The plots demonstrate that the new controller can maintain the temperature at the netpoints with less spread and a better level of security than what was possible with the previous operation. This can be seen when comparing the prediction intervals (PI) between the two periods in Fig. 6. The intervals were estimated using nonparametric quantile regression using the 10th and 90th quantiles as the lower and upper bounds. The lower bound for the new controller rarely violates the restriction. Hence, it would have been possible to have a lower reference curve during the trial, and still maintain the same level of supply security at the consumer as with previous control. However, this potential for savings was not realized during the trial. The top right plot in Fig. 5 also shows an adjusted supply temperature for the new controller to demonstrate a "what if" situation. The adjusted supply temperatures are lowered by moving the reference curve down such that temperatures from previous operations are above it, we estimated it would by lowering it by 5 °C from Fig. 6. The supply temperature for the new control would therefore be 3 °C lower compared to the previous operation as can be seen in the regression lines.

5. Conclusion

In this paper, smart meters were used to demonstrate that they can add value to the district heating production and network. A novel algorithm was presented to create feedback of supply temperature from the network using smart meters located at single-family buildings. The estimated network temperature from the algorithm adequately mimics the netpoint temperature measured at measurement well located close to the buildings. Therefore, district heating utilities can reduce their cost by making measurement wells redundant and the corresponding maintenance of the well. The location of the predefined critical points becomes more flexible when using the smart meters as feedback. Using a few smart meters from large apartment buildings that have reliable measurement can be used as direct feedback to be used for temperature control. Results from an online operation of using three smart meters as feedback of the network to temperature control were presented. The results showed that the supply temperature is more robust than without the controller. Unfortunately, restrictions on the supply temperature at the consumer side were set slightly higher than without the new controller and as a result, the supply temperature at the production was higher when the controller was in operation. However, if the restrictions at the consumer were lower during the trial, then the supply temperature at the production side would at least perform with a similar temperature as when the controller was not in operation, and the temperature would also be more robust — with expected savings in network maintenance costs to follow in the longer term. Furthermore, using smart meters as feedback for network operation reduces the need of installing new measurement wells or maintaining the existing ones.

Future research on digitalization in district heating should focus on how to quantify the operational savings for district heating when incorporating digitalization into their operations. Digitalization can have s direct impact on the operational savings for district heating yielding better operation of the system, i.e. temperature optimization in the network, lowering return temperature by identifying bad coolers in the network, improving weather forecast with local climate stations, and leakage in the network.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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