In-situ validation of a new sizing methodology for combined production and distribution for domestic hot water and space heating

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Abstract

Collective heating systems are becoming more frequent due to their sustainable and economic benefits. Nevertheless, some aspects, such as how to size collective installations that provide heat for both space heating and domestic hot water, are not yet fully understood. Based on an initial evaluation and feedback from designers, it is found that current sizing methods are insufficient. Recently, a new method 'maximum sum of parts' was proposed that aims to achieve a more optimal design. A validation procedure is presented in this study, which is developed to validate this new method using (smart) heat meter readings. The validation procedure uses insight from an earlier study to cope with the limitations of this type of data to identify the peak heat demand of the system. The outcome of the procedure is characteristic, showing the different possible production capacity – thermal storage combinations required to meet peak heat demand. Furthermore, the validation procedure is demonstrated by examining two case studies and thereby providing a first validation of the new method. The results show that the desired characteristic can be obtained based on (smart) heat meter readings. Although, some limitations remain, in particular how to consider the influence of the outdoor conditions into the validation. Moreover, the first two case studies are not representative to give a first validation of the new sizing method. Due to, inter alia, changes to the heating system it is possible that the peak heat demand is underestimated.

Key Innovations

- Validation of a new sizing method.
- Using (smart) heat meter readings to identify the possible combinations of production capacity – thermal storage to meet peak heat demand.

Practical Implications

The study discussed the validation of a new sizing method that can be used to achieve a more optimal design of collective heating systems. The developed validation procedure shows a way to handle the limitations of data from (smart) heat meter readings to identify a peak heat demand profile.

Introduction

In recent years, the concern of climate change has increased considerably. In general, the global CO_2-emissions have to decrease, and more sustainable technologies should be used for the remaining energy demand. Recent studies show that district heating and cooling have the potential to decrease CO_2 emissions (Connolly et al.,2014) and offer flexibility to increase the amount of renewable energy sources in the overall energy supply (Lund et al.,2014). Also, in collective housing complexes such as apartment buildings, centralising the heat supply has advantages regarding CO_2 emissions and the integration of renewable energy.

In order to fully exploit these advantages, proper design of the collective heating system is crucial. The first step in the design is sizing. Several studies (Verhaert et al., 2019; Peeters et al., 2007) show that sizing influences the performance of different heat production systems. In short, the main conclusion is that oversized systems often tend to decrease in energy efficiency due to bad part load behaviour, while undersized systems result in a lack of comfort for the consumers. Moreover, sizing not only affect the production unit but also affects the distribution system, leading to higher heating losses and installations costs (Averfalk et al., 2019). As a result, oversizing affects the performance and costs of the entire heating system.

Problem statement

In order to achieve well-designed collective heating systems, following insight is essential. Collective heating systems, e.g. combilus systems and district heating, provide heat for both space heating purposes as for domestic hot water (DHW) preparation, so the system has to be designed considering both heat demands. With respect to the design philosophy of the standard NBN EN 12828 (equation 1), the total required heat capacity (Φ_{SU}) should be determined taking into account the possible simultaneous occurrence of the maximum of the heat demand for space heating (Φ_{SH}) and DHW (Φ_{DHW}). The factors f_{SH} and f_{DHW} consider that the design heat loads may not be cumulative.

$$\Phi_{SU} = f_{SH} \cdot \Phi_{SH} + f_{DHW} \cdot \Phi_{DHW} \qquad (1)$$

The existence and effect of this simultaneity phenomenon was demonstrated in several studies. E.g. Wang et al. (2020) showed that due to simultaneity, the maximum total heat demand is reduced as opposed to the sum of the individual maximum demands. Furthermore, condisering a good simultaneity factor in the calculation of the design heat demand, the risk of oversizing and the related disadvantages can be avoided (Koiv et al.,2014).

However, within the Belgian context, currently, no standards or design rules exist for the sizing of collective heating systems such as the combilus system and district heating. As a consequence, in practice, designers use a mix of foreign design guides and their own rules of thumb or manufacturers' specific design guides. In general, the following workflow is adopted:

- As a first step, the individual heat demands for space heating and DHW are calculated according to the appropriate standards.
- Secondly, the required total heat capacity is determined by combining the individual demands with calculation rules.

As a rule, the first step is clear: the individual heat demands for space heating and DHW are determined with the appropriate standards and to take simultaneity into account, the commonly used standards for DHW apply a simultaneity factor. In general, this simultaneity factor is determined based on either the number and type of tapping points or the number of dwellings connected to the heating network.

In the second step, in practice, two calculation rules are usually used to determine the required total heat capacity. A rule, mainly used to avoid undersized systems, is taking the sum of both heat demands for space heating and DHW. This rule is comprehensible for designing collective heating systems where both peak demands can occur simultaneously. However, in current state-of-the-art systems, i.e. combilus systems and district heating, the end-users are usually connected to the primary network with a so called flatstation or Heat-interface-unit (HIU). Generally, these HIU's cannot provide heat for space heating and heat for DHW simultaneously and thus work either in 'space heating mode' or 'DHW mode', with priority for DHW demand. As a result, when applying the summation rule this can lead to oversized systems. For this reason, another rule used in practice, i.e. taking the maximum of both individual heat demands of space heating and DHW. Nevertheless, this rule can result in undersized systems, e.g. when the heat demand for space heating is almost equal to the heat demand for DHW. To prevent the possibility to undersize the system, designers and manufacturers use 'customised rules' by applying adjustment factors or use their own calculation for the simultaneity factors for DHW and/or space heating. Consequently, this causes a lack of transparency and disables proper comparison. Moreover, this also prevents to incorporate new insights into calculating the heat demand of either space heating or DHW. Eventually, this leads to poorly designed systems and discussions between different stakeholders after installation.

Recently, a new sizing methodology 'Method of the maximum sum of parts' was introduced to tackle these issues (Verhaert, 2019). The general philosophy of the method is to divide all dwellings behind the point investigated into a group 'space heating' and a group 'domestic hot water'. Subsequently, the heat demand of each group is determined according to the used standards for space heating and DHW, after which the sum of both parts is calculated as possible overall heat demand. Naturally, there are various possibilities to divide the different dwellings into the groups. Therefore, the overall heat demand of all possibilities is calculated, whereas the maximum of these calculations is withheld as the required heat power for the investigated point in the installation.

In addition, the method is compatible with the 'power storage-method' introduced by Verhaert et al. (2016) making it possible to take the influence of the provision of thermal storage into account. As a result, not only variations in group but also variations in storage size are investigated. Consequently, a 'production capacity – thermal storage characteristic' is obtained which presents the required heat power as a function of the heat storage foreseen.

Scope of the paper

Based on a first assessment (Verhaert, 2019), the new rule, i.e. the method of the maximum sum of parts, seems to have potential. Nevertheless, the rule needs validation. Therefore, the objective of this paper is to present a validation procedure developed for the validation of this new sizing rule. The general aim is to use heat consumption data obtained from residential (smart) heat meters to validate the new sizing method. The introduction of residential (smart) heat meters in collective heating systems, mainly used for billing purposes and monitoring, provides large datasets regarding heat consumption. This data makes it possible to validate the new sizing rule based on multiple and different types of case studies at a low cost. Although, some problems arise using this type of data for the validation of sizing rules. More specifically, the poor quality and the measurement interval size pose some challenges. The procedure developed to tackle these challenges is presented in this paper. To demonstrate the validation procedure and thus the new sizing rule, the validation procedure was applied to two case studies. The results are discussed in this paper.

Methodology

Aim and insights of the validation procedure

The objective of the validation procedure is to evaluate the outcome of the 'method of maximum sum of parts' against the peak heat demand of the investigated case study. As mentioned in the introduction, the outcome of the sizing method is a production capacity – thermal storage characteristic. So as to validate the sizing method, each point on this characteristic has to be able to cover the peak heat demand. For this reason, the validation procedure intends to identify the 'real' production capacity – thermal storage needed to cover peak heat demand by analysing data from residential heat meters.

In order to obtain the 'real' production capacity – thermal storage characteristic, the validation procedure is based on insights from the design methodology for DHW production systems of Verhaert et al. (2016). Based on tap patterns, they determined a worst-case consumption graph or profile expressing the peak demand, volumes of hot water (in litres) as a function of the duration of the measurement interval. Subsequently, by assessing the possible hot water production at a certain production capacity with respect to this profile, a 'real' production capacity – thermal storage characteristic is obtained.

However, some challenges arise to use the method for the validation of the new sizing rule. Firstly, since data from residential heat meters are used, the data resolution or measurement interval size has to be taken into account. These heat meters often register the cumulative heat consumption on an hourly basis. As a result, nothing is known about the peak consumption that can occur in the interval sizes smaller than one hour, which can significantly influence the determination of the 'real' production capacity – thermal storage characteristic. Secondly, heat consumption of both DHW and space heating is investigated, rather than DHW tap patterns. Since the heat consumption of space heating is influenced by outdoor conditions, these conditions should be considered. Furthermore, also the poor quality of the data from the residential heat meters needs to be addressed. Accordingly, to tackle these challenges, the validation procedure, as presented in Figure 1, is developed. In general, the procedure exists out of 4 steps.

Resulted workflow

- **Data Pre-processing**

First of all, to cope with the poor data quality, the step 'data pre-processing' is performed. This step includes the standardisation of the consumption according to fixed measurement times, the filling of missing values, and outliers' removal (incorrect values). For the standardisation and filling of the missing data, linear interpolation is used. Nevertheless, when data is missing for a long period, e.g. one day, these periods are removed from the dataset. To simplify the identification and removal of outliers and, also, for the use in further steps, the heat consumption per interval size ΔQ(t) is derived from the cumulative heat consumption as follows:

$$\Delta Q(t) = Q(t) - Q(t-x) \qquad (2)$$

Q(t) is the registered cumulative consumption at time t, and Q(t-x) the cumulative consumption at the previous registration timestamp.

Subsequently, to identify and remove outliers from the derived data, different statistical methods were investigated: standard deviation around the (moving) mean and median, generalised extreme studentised deviate and based on percentiles. However, none of these methods has been found appropriate to identify and remove outliers from the data. The large measurement interval, being one hour, in combination with the fact that heat consumption is only registered when one watt-hour is consumed, caused the removal of too many valuable data when using the mentioned methods. For this reason, outliers were removed by applying boundary values. Evidently, the lower boundary value is zero, whereas the upper boundary value is defined by taking the 98-percentile of the daily maximum values of ΔQ(t).

- **Data-analysis**

As mentioned, similar to the approach for domestic hot water profiles by Verhaert et al. (2016), a worst-case or peak consumption profile is determined. This profile presents visually the maximum cumulative heat demand that can occur during a specific time or measurement interval. However, the measurement interval size of the heat meters prevents the determination of a complete profile. The data for small intervals are lacking. To deal with this problem another visualisation is made. More specific, the visualisation of the average heat capacity or power Φ(x) required to cover the maximum heat consumption that can occur within a specific time or measurement interval size x. This average power Φ(x) can be determined as follows:

$$\Phi(x) = MAX\left(\frac{\Delta Q(t)}{x}, \forall t\right) \qquad (3)$$

By visualising this graph, it may be possible to identify a so-called 'critical interval'. During this interval, the average power Φ(x) does not differ that much. Due to the fact that the demand is of a collective nature, the peak heat demand may occur for a longer period. The existence of such an interval for DHW consumption was addressed in the study of Verhaert et al. (2016) consumption. However, the study of Wang et al. (2020) noted that for examining collective peak heat consumption, data with a half hourly to hourly measuring frequency is sufficient enough to identify the peak head demand, thus indicating that it may be possible to identify a critical measurement interval for collective heating systems that provide heat for DHW purposes as well as for space heating. If such critical interval can be observed, it can be concluded that the maximum average power Φ(x) of the smallest measurable interval size is representative for smaller interval sizes.

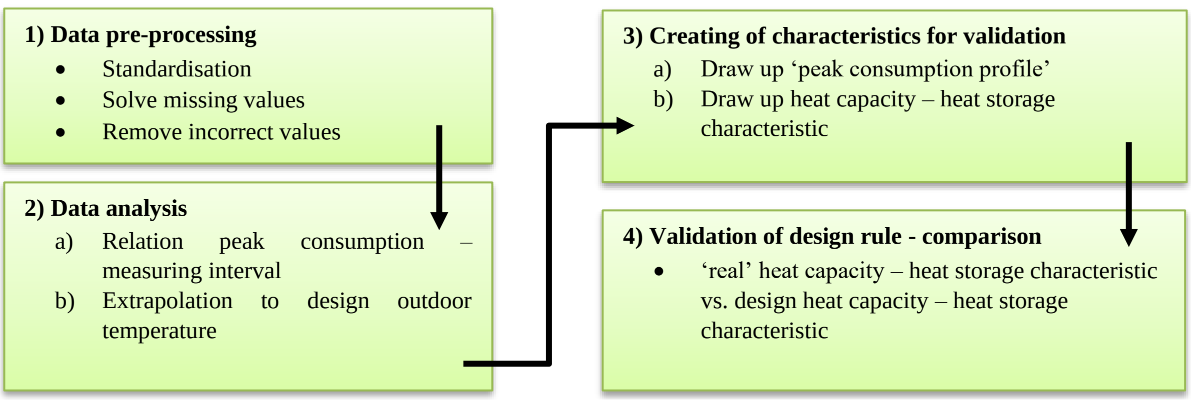

Figure 1: Overview of the validation procedure

Consequently, solving the problem of the measurement interval size.

In addition, to cope with the influence of the outdoor conditions, the maximum average power curve is visualised as a function of the outdoor temperature. In other words, for every temperature Φ(x) is calculated. Then for every value of x, the relation between Φ(x) and the outdoor temperature is determined. As a result, this relation can be used to extrapolate Φ(x) to the outdoor temperature which was used to determine the demand for space heating. The decision to use only the outdoor temperature to account for the outdoor conditions was made for two reasons. On the one hand, so as to not overcomplicate the determination of the influence of the outdoor conditions on the peak heat consumption. On the other hand, the study of Wojdyga (2008) showed the outdoor temperature as the most influencing factor of the outdoor conditions.

- **Creation of validation characteristics**

Once the average power curve Φ(x) is determined for the design outdoor temperature, the 'peak consumption profile' can be determined as follows:

$$C(x) = \Phi(x) \cdot x \quad (4)$$

To avoid misinterpretation, the symbol C(x) represents the worst-case consumption in Watt-hour [Wh] that can occur within a specific time interval or measurement interval x.

Furthermore, C(x) is also determined according to the following equation:

$$C(x) = MAX(\Delta Q(\mathrm{t}), \forall t) \quad (5)$$

In contrast to the heat consumption resulting from space heating, the consumption resulting from DHW is not as strongly influenced by the outdoor conditions (Gerin et al., 2014). Therefore, it is possible that for certain values of x, C(x) calculated according equation 5 is greater than C(x) determined according equation 6. Especially, this can occur at the smaller interval sizes, as the peak DHW consumption is of a short time nature. Consequently, in order to obtain the 'peak consumption profile' the maximum of both equations should be taken.

An essential aspect of this procedure is the observation of the so-called 'critical interval'. However, it is possible that this critical interval is not observed and, as a result, causing the 'peak consumption profile' to be incomplete for the interval sizes smaller than the measuring interval. When this should occur, the peak consumption profile is filled using an approximation equation. Given the fact that this peak consumption profile is an ever-increasing curve, and taking into account the observations of Verhaert et al. (2016), a second degree equation seems to be a proper approximation.

$$A(x) = a \cdot x^2 + b \cdot x + c \quad (6)$$

The coefficients of this second-degree equation can be determined based on the following: First of all, at the time interval size of zero, naturally, the heat consumption is zero. Thus c equals zero. Furthermore, coefficients a and b can be determined given the fact that, on one hand, the value of C(x) and A(x) should be the same for the smallest known value of x, and on the other hand, the slope of the tangents at this point must also be equal.

Once the peak consumption profile is determined, the 'real' production capacity – thermal storage characteristic can be determined. By comparing the possible heat production P(x) that a certain production capacity or power can provide within a certain time interval x, with respect to every point on the 'peak consumption profile', the required thermal storage can be derived as follows:

$$Q_{storage} = MAX\big(C(x) - P(x)\big) \quad (7)$$

The way of working is graphically shown in Figure 2. As long as the possible heat production P(x) is greater than the peak demand C(x), no thermal storage is required to cover the peak heat demand.

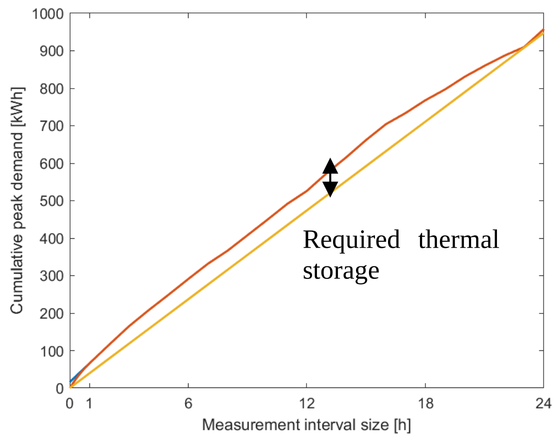

Figure 2: evaluation of the possible heat production of certain thermal capacity P(x) (yellow line) against the 'peak consumption profile' C(x) (orange line). The maximum positive difference between C(x) and P(x) represents the required thermal storage.

Subsequently, by evaluating a range of production capacities, the required thermal storage can be plotted as a function of the foreseen production capacity. As a result, this graph represents the 'real' production – thermal storage characteristic which shows the possible combinations of production capacity and thermal storage required to meet the peak heat demand.

- **Comparison real vs design characteristic**

In the final step of the procedure, the resulting characteristic is compared with the characteristic defined according to the sizing method. As long as the outcome of the new sizing method lies above this 'real' characteristic, it can be concluded that the outcome of the sizing method is sufficient to meet the peak heat demand. On the other hand, if the characteristic lies under the characteristic based on the consumption data, this would indicate that the result of the sizing method is unable to fulfil the peak heat demand. As a result, this may cause discomfort.

Case studies

To demonstrate the validation methodology and subsequently provide a first validation of the design rule, two apartment buildings were used as case studies. Both apartment buildings are constructed in the year 2018 and are part of a new city district, located in Antwerp, Belgium. The first building, referred to as Building 1, consists of 25 individual apartments. The second building, referred to as Building 2, consists of 30 individual apartments. The two buildings are equipped with a combilus system for the distribution of heat from the central boiler room to each individual apartment. Each individual apartment is equipped with a smart heat meter, used for billing purposes, which records the cumulative heat consumption with a measuring interval of one hour. Since the buildings are recently build, the period for which data is available is limited to July 2019 to February 2020.

As mentioned in the introduction, the first step in the design process of the new design rule is to determine the separate heat demand for space heating and DHW. The heat demand for DHW was calculated according to the standard DIN4708. The input conditions used for Building 1 and Building 2 are presented in resp. Table 1 and Table 2. Furthermore, for both apartment buildings, the sanitary facility of an individual apartment consists of a shower, a bath and four taps. This corresponds to a standard equipment according to the DIN standard.

Table 1: different apartment types of Building 1

# apartments	Heat demand space heating [W]	# occupants according to DIN4708	Heat demand classification according to DIN4708 [Wh]
5	4150	4,3	5820
6	2900	2	5820
1	4300	4,3	5820
6	3850	2,7	5820
7	3700	2,7	5802

Table 2: different apartment types of Building 2

# apartments	Heat demand space heating [W]	# occupants according to DIN4708	Heat demand classification according to DIN4708 [Wh]
5	3000	2,7	5820
4	2800	2	5820
1	3150	2,7	5820
3	2150	2	5820
1	1050	2	5820
3	3450	4,3	5820
5	3100	3,5	5820
3	2100	2	5820
3	3350	2,7	5820

Results

Establishment of the peak profile

As mentioned in the methodology, after the data pre-processing and the next step (2a) is to define the 'peak consumption profile', i.e. graphical presentation of the average power required to cover the peak heat consumption Φ(x) as a function of the measurement interval size x. The results of this step for Building 1 and Building 2 are shown in Figure 3 and Figure 4, respectively. By drawing up this graph, it was hoped to identify the critical interval, mentioned in the methodology. Should this critical interval be observed the curves would flatten out as the measurement interval size decreases. However, this is not visible on the graphs. In contrast, the average power increases as the measuring interval size decreases. Therefore, the critical interval is most likely to be less than one hour.

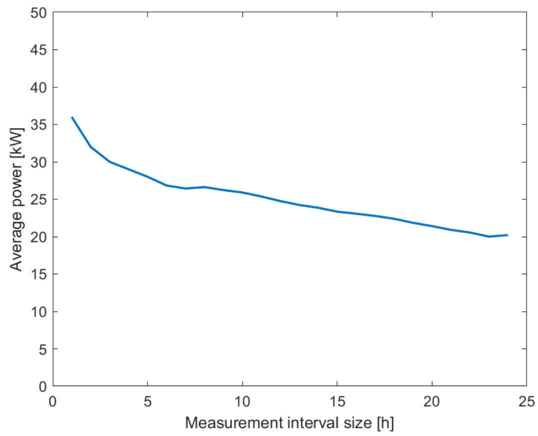

Figure 3: average power required to cover the peak consumption with respect to the measurement interval size x for Building 1

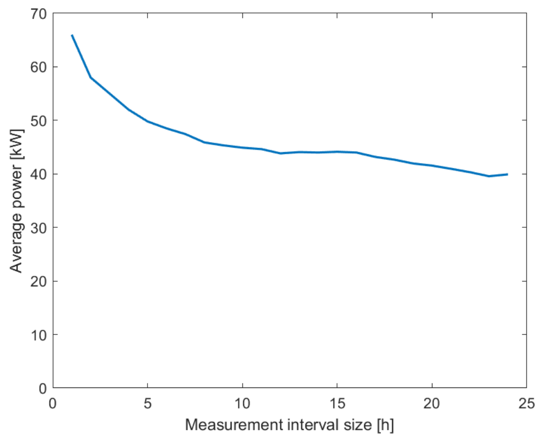

Figure 4: average power required to cover the peak consumption with respect to the measurement interval size x for Building 2

Subsequently, to take the outdoor conditions into account, the evolution of this graph is set out with respect to the outdoor temperature (Step 2b). Based on the results of this step for Building 1 (Figure 5) and Building 2 (Figure 6), it can be noted that these curves increase more or less linear as the outdoor temperature drops from 20°C to ±11°C. However, at lower outdoor temperatures this linear relation seems to disappear and Φ(x) seems to become independent of the decreasing outdoor temperature. This phenomenon is not in line with the expectations. On the one hand, at small interval sizes, it could be plausible that the relation between Φ(x) and the outdoor temperature is less pronounced, due to the fact that within these interval sizes the heat consumption from DHW, which is less influenced by outdoor conditions, is more decisive. On the other hand, for the larger interval sizes it was expected to observe a clear, and more or less linear, relationship with the outdoor temperature. Since it is assumed that at larger measuring interval sizes the share of space heating is likely to be higher.

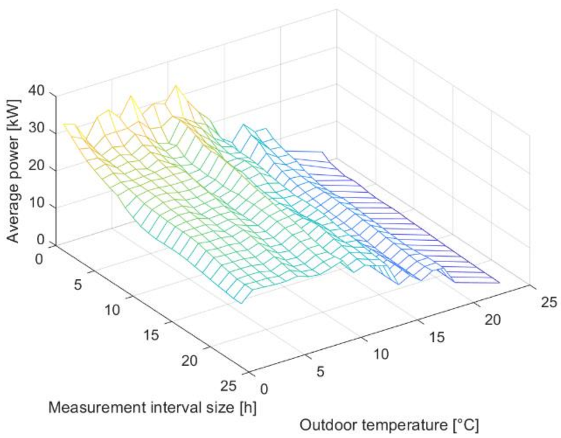

Figure 5: average power curve (lines parallel to the measurement interval size-axis) as a function of the outdoor temperature for Building 1.

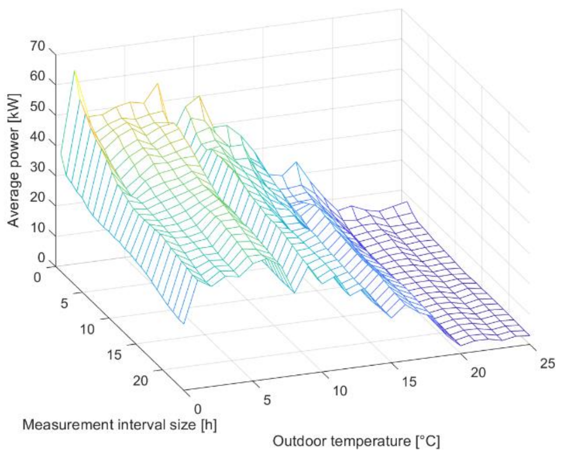

Figure 6: average power curve (lines parallel to the measurement interval size-axis) as a function of the outdoor temperature for Building 2

In order to find an explanation for the observed phenomenon, the daily individual consumptions of the different apartments were visualised over the period analysed. In addition, the total daily consumption of the two apartment buildings was visualised by summing up all the individual consumptions. On the basis of these visualisations, it was found that for both case studies, the heat consumption fell sharply from mid-December 2019. Part of this decrease could be explained by a changing occupancy rate, since the visualisation of the individual daily consumptions showed that some apartments became vacant during the period analysed. Nevertheless, the number of apartment that became vacant is limited so that this cannot be the only cause. Another possible (partial) cause may be an adaption to the combilus system itself. At the end of November 2019, hydronic adjustments to the combilus system in both buildings were made. In conclusion, the observed phenomenon in Figures 5 and 6 is most likely to be the result of a combination of causes. Furthermore, by visualising the daily individual consumptions it was found that a number of apartments were vacant during the entire period. Therefore, in order to not bias the design rule, a number of apartments were excluded from the design calculations.

Since no accurate relation could be established between the curve Φ(x) and the outdoor temperature, accordingly, the 'peak consumption profile' is mainly determined via equation 5. Furthermore, since the critical interval was not observed in step 2a, the 'peak consumption profile' is completed via an approximation by equation 6. By means of illustration, the result for Building 2 is shown in Figure 7. The orange line presents the approximation. Also, because an approximation is used, and uncertainty boundary has been included (blue line). This uncertainty boundary has been established by linear extrapolating the known peak consumption profile. Consequently, this uncertainty boundary presents the worst case.

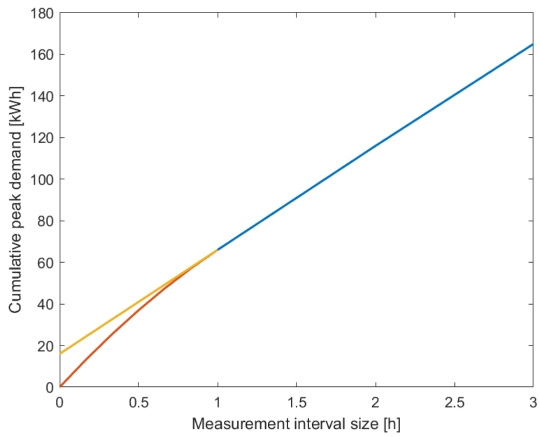

Figure 7: The completed 'peak consumption profile' for Building 2 with the approximation (orange line). The yellow line represents the uncertainty boundary

Subsequently, based on the obtained peak consumption profiles, the 'real' production capacity – thermal storage characteristic can be determined according equation 7 as shown in Figure 2.

Comparison of characteristics

The results of the final step in the validation procedure for Building 1 and Building 2 are shown in Figure 8 and Figure 9, respectively. The blue line represents the production capacity – thermal storage characteristic based on the consumption data (PV-data based). The dark red line represents the characteristic according to the sizing method (PV-design). Note, as shown in the results, this curve has a tipping point after which the required production capacity does not decrease with increasing thermal storage. The reason for this is that the sizing method only considers the possibility of thermal storage for DHW. This is in contrast to the characteristic based on the consumption data, whereas thermal storage includes storage for space heating as well as DHW. However, this is not a problem for the validation; the sizing method is simply stricter in the provision of thermal storage. For this reason, in order to validate the sizing method, it is sufficient that the characteristic of the sizing method lies above the one based on the consumption data.

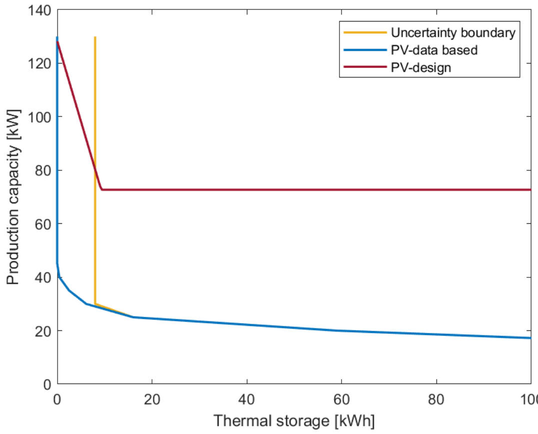

Figure 8: Comparison of the PV-curve according to the sizing method vs PV-curve based on the consumption data for Building 1 The yellow line represents an uncertainty boundary. The actual PV-curve is most likely to lie between the blue and yellow line.

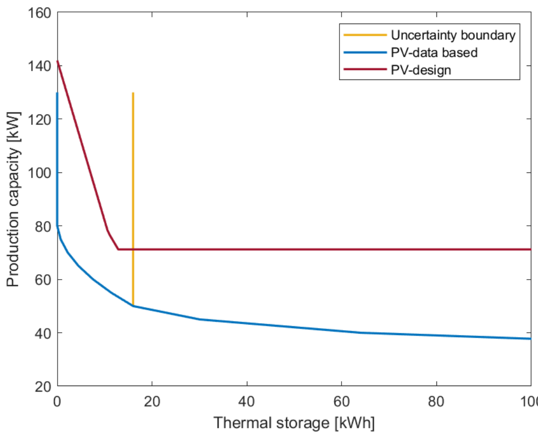

Figure 9: Comparison of the PV-curve according to the sizing method vs PV-curve based on the consumption data for Building 2 The yellow line represents an uncertainty boundary. The actual PV-curve is most likely to lie between the yellow and blue line.

In both cases it can be observed that the characteristic according the sizing method lies above the characteristic based on the consumption. As a result, it can be concluded that in both cases the output from the sizing method is capable of covering the peak heat demand. However, looking at the result for Building 2, a part of the characteristic according the sizing method lies within the uncertainty area, i.e. the area between the yellow and blue line. Therefore, that part of the characteristic cannot be validated with 100% certainty. Nevertheless, this uncertainty can be mitigated by considering the distribution network as an already existing thermal storage. Indeed, since the supply pipe line contains a certain volume of hot water so that it can be considered as thermal storage. However, the use of this 'extra' thermal storage is limited as it causes the network temperatures to decrease, which can result in discomfort.

Concluding Discussion

In this paper, as validation procedure is presented to validate a recently introduced sizing method for the collective heating systems which provide hot water for space heating as well as for DHW preparation (Verhaert, 2019). The validation procedure aims to establish a 'peak consumption profile' that represents the worst-case heat consumption that can occur within a specific period of time by using heat consumption data from residential heat meters. Based on this profile, a characteristic can be determined presenting the production capacity – thermal storage combinations required to cover this peak consumption profile, which can then be compared with the outcome of the sizing method.

To test the validation procedure and, subsequently, validate the sizing method the procedure was applied to two case studies. Based on the results of the case studies, it was concluded that the desired characteristics needed for the validation could be derived using the procedure. However, some limitations remain. Since some irregularities occurred in the consumption, no clear relation with the outdoor conditions, i.e. the outdoor temperature, could not be defined. Consequently, the peak heat demand cannot be determined at design outdoor conditions, i.e. the outdoor temperature used in the heat demand calculation for space heating. As a result, the peak consumption profiles, established through the validation procedure, are likely to underestimate the worst case consumption of both case studies. For this reason, it is not possible to validate the sizing method based on these case studies. Nevertheless, the results show that the outcome of the sizing method is capable of covering the peak heat consumption that has occurred during the period analysed.

Future research

In order to validate the sizing method, the validation procedure should be applied to more case studies. It is advisable to use buildings that have already been in use for some time and, moreover, have a stable occupancy rate as future case studies. Furthermore, it would be better to use heat consumption data with a higher measurement frequency, i.e. short measurement intervals, as the measurement interval size influences the peak heat demand measured significantly. Within the validation procedure, a way of coping with this fact is foreseen. However, this is based on the visualisation of a so-called 'critical measurement interval'. In addition, as it is possible that this critical interval cannot be observed, an approximation is foreseen within the validation procedure. However, this introduces an uncertainty level in the validation. By using consumption data with a shorter measurement interval, this approximation will become more precise and, moreover, will reduce the uncertainty level. Moreover, using data with a shorter measurement interval size, the critical interval might be observed so that the approximation becomes irrelevant.

Following the application of the validation procedure to the case studies, several concerns arose. First and foremost, for identifying the consumption at worst case outdoor conditions, taking only the outdoor temperature into account may be too limited. Therefore, in the future other parameters such as wind speed, heating degrees days, and internal heating gains should be considered. However, the latter is not evident regarding the privacy legislation concerning the data from residential (smart) heat meters.

Finally, it is essential to note that the measurement accuracy and resolution of the residential heat meters can be poor. The accuracy of the most recent heat meters is acceptable for the objective of the presented study. However, the resolution at which the heat consumption is calculated and recorded by the heat meter can cause concern. In most cases, the heat consumption is recorded on a kWh basis. This rather low resolution can lead to an underestimation, especially when the data from multiple heat meters are accumulated. On the other hand, also an overestimation is possible. In this study, this imprecision has been accepted. However, in the future research it is advisable to take this imprecision into account and also visualise it in the validation characteristics.

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