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Article

Feedback Control in Swedish Multi-Family Buildings for Lower Energy Demand and Assured Indoor Temperature—Measurements and Interviews

Daniel Olsson [1,*], Peter Filipsson [1] and Anders Trüschel [2,*]

[1] CIT Renergy, 41258 Gothenburg, Sweden; peter.filipsson@chalmersindustriteknik.se
[2] Division of Building Services Engineering, Department of Architecture and Civil Engineering, Chalmers University of Technology, 41296 Gothenburg, Sweden
* Correspondence: daniel.olsson@chalmersindustriteknik.se (D.O.); anders.truschel@chalmers.se (A.T.)

Abstract: Europe needs to save energy, and lowered indoor temperature is frequently promoted as part of the solution. To facilitate this, heating control systems with feedback from indoor temperature sensors are often required to avoid thermal discomfort and achieve long-term temperature reductions. This article describes a measurement- and interview-based study on feedback control where 107 Swedish multifamily buildings were analysed. The obtained results show that buildings with lowered indoor temperatures had reduced annual heating demand by 4 kWh/m^2 and a reduced indoor temperature of 0.4 °C. There were, however, significant individual differences and even buildings with increased indoor temperatures, which harmed the energy savings. Temperature fluctuation was most often significantly reduced, but the impact on heating power demand during cold weather was, on average, only 2%. An interview with different actors indicated higher energy savings, possibly due to their stock's original room temperature levels. Several interviewees also mentioned other advantages of temperature mapping. Most of the results obtained in this study were in line with several previous investigations. The study's novelty lies in the large number of investigated buildings with mature commercial heat control technology, including PI-control for adjusting supply temperature, indoor temperature sensors in almost every apartment and a parallel analysis of additional affected parameters.

Keywords: indoor temperature; feedback control; demand heat control; multi-family buildings; energy efficiency

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1. Introduction

Europe's energy situation is strained. In several EU countries, campaigns have been launched with messages similar to those adopted by the Swedish Energy Agency: Every kilowatt-hour counts! Dwellings account for a large proportion of the total energy used, especially heating. Therefore, comprehensive building-related measures such as improved wall insulation, better windows, ventilation heat recovery, etc., are often required to reduce the heating demand. Since such arrangements are often expensive and demand extensive work, they are only done in practice in connection with major renovations. Therefore, the Swedish Energy Agency also urges additional cost-efficient measures, such as improved window sealing, additional roof insulation, more efficient tap water systems and lowered room temperatures.

The potential of lower indoor temperatures has been supported by previous studies [1–5], which show that the average temperature in Swedish multi-family buildings is around 22.0–22.5 °C during winter. Compared with the Swedish Public Health Agency's (Folkhälsomyndigheten) guidelines of an air temperature of at least 20.0 °C [5], it is thus established that most multi-family buildings are significantly overheated, resulting in unnecessarily high use of energy. Lowering indoor temperatures to the desired level is however more complex than it might appear. Inadequate adjustment and heating control within one and the same building mean that the apartments are often at different temperatures (spatial variability), and the indoor temperature constantly fluctuates (temporal variability). Therefore, there is an imminent risk that lowering without feedback will result in recurrently excessively low indoor temperature. While spatial variability is taken care of by proper adjustment and balancing, the temporal variability depends on the control system, which is the focus of this analysis.

This article, which aims to quantify the benefit of feedback control and capture experiences about it, shows that it almost always results in room temperatures fluctuating less and being at a better level with the desired setpoint. In addition, it leads to relatively significant energy savings, provided that the buildings are not insufficiently heated from the start. Given the energy situation, it is essential that the results and other knowledge from this study quickly reach the final users (mainly housing companies). Therefore, adapted result compilations have already been published at the beginning of 2023 in the relevant forums and seminars for Swedish operating managers, housing companies, energy service providers, etc.

Heating control is often divided into three categories:

(1) Feedforward: A traditional solution only considering the outdoor temperature
(2) Feedback: Controls towards the desired room temperature by also taking room temperatures into account
(3) Model-based: Partly the same as feedback, but this control strategy can, with algorithms/calculation models, also consider and process various other measurement data and conditions. In some modifications, this technique can also be adaptive. It then gradually learns to anticipate the required heating demand for different situations.

The latter two control strategies in Figure 1 can be defined as demand controlled. In both cases, indoor temperature sensors are essential. The heating system will always increase or decrease its heat output with respect to a continuous comparison of the indoor temperature to a specified setpoint. With feedback control, the influence of solar radiation, wind, internal heat generation, outdoor temperature, thermal inertia, insulation, infiltration, ventilation, etc., is handled indirectly through indoor temperature sensors. This type of heat control is slow but, on the other hand, considers the actual need. A more proactive heating control can be achieved with model-based control, especially if it uses weather forecasts. This type of heat control is faster but also generally more sensitive and requires correct weather forecasts and detailed information about the building envelope, etc. Therefore, it is essential that model-based heat control also takes measured indoor temperature into account. Without it, the central heating control lacks important information.

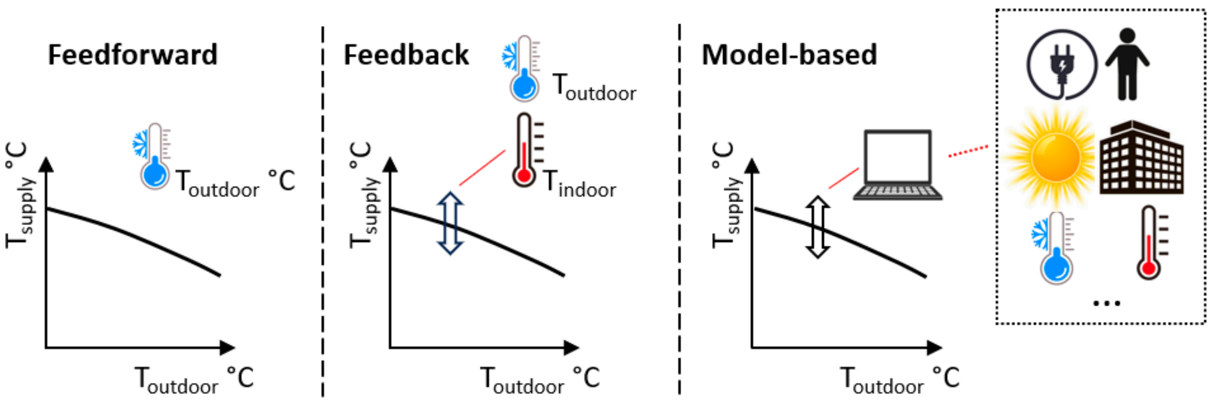

Figure 1. Illustrations of three heating control strategies. Icons: vectorstock.com, accessed on 20 September 2023.

Parallel to the central heat control, where the heat supply is managed with the main supply temperature, each room usually has local heat control through thermostats on all radiators. Their function is to adjust the hot water flow through the radiators. With perfectly functioning thermostats, the central heating control would be less critical as long as it delivered a sufficiently high supply temperature. In practice, however, their function could be better, at least the mechanical ones, which can often be easily manipulated and put out of action. They are also relatively sluggish, often lose their function and may get stuck in one position. The study does not clarify whether electric thermostats work better than mechanical thermostats in the long term because they are still very unusual in apartment buildings.

For cost- and technology-related reasons, indoor temperature sensors for central heating control were previously only (generally) installed in a few representative apartments per building. Nowadays, however, it is common to have sensors in every apartment, of which some of the coldest and warmest are continuously excluded when averaging. Which ones are sorted out differs hour by hour. The temperature sensors nowadays are generally wireless, connected to cloud services and usually placed in the halls of the apartments.

Optimum placement in an apartment has been discussed among many actors for a long time. On the one hand, residents generally only pass through their halls, which would make them unrepresentative as living area. On the other hand, halls generally do not have the living room's heat-emitting devices and solar radiation, which risks affecting the heating control unduly. Another advantage of placing it in the hall is that the ventilation air from the bedroom and living room usually passes through the hall before it is extracted from the kitchen and bathroom.

In the future, temperature sensors may be installed in all rooms. How that would affect heating control is not investigated further here, nor does it seem to have been established in any other study. However, some studies address temperature differences between different rooms. According to Hunt and Gidman [6], living rooms are typically warmer than bedrooms and kitchens. This observation is also made by Summerfield et al. [7] based on measurements in 15 energy-efficient multi-family buildings in the UK. Oreszczyn et al. [8] found that living rooms are typically about 2 °C warmer than bedrooms. Finally, Yohanis and Mandol [9] rank indoor temperatures in different rooms of 25 Northern Irish households, where living rooms were the warmest, followed by kitchens, bedrooms, and halls.

Even though feedback control in various forms has been used in a large number of Swedish multi-family buildings for more than a decade, the benefits are not very well documented. Among the few studies that exist on the subject, there are differences in conditions compared to the situation today, not least regarding the access to indoor temperature sensors. Apelblat & Rydström [10] conducted short-term measurements during the 1970s where the exhaust air temperature was used as feedback to adjust the supply temperature of the heating system. The investigated multi-family building had 72 apartments and a one-pipe heating system supplied by district heating. It was concluded that the exhaust air temperature could be maintained within ±0.1 °C in contrast to ±0.5 °C when only taking the outdoor air temperature into account. The authors estimated that this made it possible to decrease the indoor air temperature setpoint by 0.5 °C, thereby reducing the heat demand by 2.5%.

The same building was further studied a couple of years later by Jensen & Lange [11]. Their study included the whole heating season, and the exhaust air temperature feedback implied a heat demand reduction of 12%. The savings were allocated to less overheating and less airing. The proportional gain was increased during the test, and the savings were assumed to be more significant if a higher gain was used already from the start. Another suggested improvement was adding an integral part to the control, i.e., implementing PI-control.

In a study from the late 80s, Hedin [12] studied exhaust air temperature feedback in five multi-family buildings. Overall, 600 apartments with district heating supplied hydronic heating without thermostatic radiator valves. The measurements agreed with the calculations, and the annual heat saving exceeded 10 kWh/m^2, corresponding to 5–6%

of the total annual demand for the district's heat. In addition, while the energy savings were building-specific, the authors introduced a more general indicator, called free heat utilization factor which improved from 40% to 90%. This factor represents how much of an internal heat gain can be compensated by the reduction from the heating system.

While previous investigations all used the exhaust air temperature as a proxy for the indoor air temperature, Dahlblom & Jensen [13] used measurements of the actual indoor air temperature (this study is also presented in Dahlblom et al. [14]). This was enabled by the introduction of individual measuring and billing of heat demand based on indoor air temperature in all bedrooms and living rooms. The study included 355 multi-family buildings in southern Sweden with 4282 apartments, of which 1177 were controlled by indoor air temperature feedback. It was shown that the indoor air temperature fluctuated less in the buildings with an enhanced control system, but no energy savings were observed. A lot of missing data, unfortunately, harmed the evaluation. Nevertheless, it was concluded that better results would have been achieved if the proportional gain was higher and if the heating supply temperature was allowed to be adjusted by more than 5 °C from the set point determined by only the outdoor air temperature. Suggested future research included investigation of control parameters such as proportional gain, dead-band and allowed range of adjustment, placement and number of indoor air temperature sensors and sampling interval.

Yeom et al. [15] investigated feedback control in a floor-heated building in South Korea. However, instead of the air temperature the return temperature was used for the feedback control. The study included both simulations and measurements. The heat energy reduction was 4.19% in the simulations and 3.98% in the measurements, compared to when only the outdoor air temperature was used to determine the heat supply temperature. A notable result is that the measured energy reduction was achieved at the same time as the average indoor air temperature was increased by 0.17 °C.

Sun et al. [16] investigated the heating control system of four district-heated buildings in Anyang, China, among which three used radiators and one used floor heating, with an overall area of 144,000 m^2. The investigation included both optimizing the heat control as a function of the outdoor air temperature and implementing indoor air temperature feedback. The achieved heat energy reduction was 6% due to the more stable indoor air temperature. The authors introduced a parameter called the indoor temperature non-uniformity index, which was reduced from 0.05 to 0.04, while the average indoor temperature was reduced from 20.3 to 20.1 °C.

Similarly, Yuan et al. [17] implemented indoor air temperature feedback simultaneously with optimizing the relation between the outdoor air temperature and heating supply temperature. The study included 17 multi-family buildings with 550 floor-heated apartments in Tianjin, China. As a result, the heat demand was reduced by 5.8%, and the average difference between highest and lowest indoor air temperature during one day was reduced from 0.46 to 0.29 °C.

Also, Sun et al. [18] did investigate improvements in the supply heat temperature control where indoor air temperature feedback was one crucial contribution. Compared to previous studies, the system boundaries were wider, and this investigation included controlling the supply heating temperature on the primary side of the district heating substation. This was carried out in northern China, in a district heating system supplying heat to 26 million m^2, of which 10% (top, bottom and middle floors included) had indoor air temperature sensors providing data to the control system. The results were better thermal comfort (the indoor temperature non-uniformity coefficient was reduced from 0.0310 to 0.0196) and an energy saving of 6.75%.

Indoor temperature feedback was also added by Li et al. [19]. In this case, in a district heating system in Dalian city, a cold region of China. It was concluded that the conventional predictive feed-forward control system is ineffective in improving the indoor temperature stability due to the thermal inertia of rooms. Adding room air temperature feedback reduced the fluctuations from 1.1 to 0.3 °C. It was estimated that this allowed an indoor air temperature setpoint reduction of 0.5 °C and thereby energy savings of 6.1%.

Whereas pure indoor air temperature feedback has attracted a limited amount of research, this is not the case for research on the control of heating systems in general. The control systems are taking more and more parameters into account and the complexity of the models is increasing [20–23]. In addition to using measured parameters, many systems are also fed with weather forecasts and to optimize costs, fluctuating energy prices can also be input into the control system. Many models require data about the thermal transmittance of the building envelope and novel methods of measuring this has recently been proposed [24,25].

Previous studies on pure feedback control are interesting and contribute to raising the level of knowledge on the subject. At the same time, it can be noted that there are only a few quantification and measurement-based studies on large building stocks. For good reasons, the mentioned studies did not have the opportunity to study the long-term impact over several years with temperature measurements in each apartment and heating systems with PI controllers for adjusting the supply temperature. The present study investigated operational situations equivalent to today's technical status in Swedish multi-family buildings over long, coherent periods (usually six years).

2. Materials and Methods

This study was carried out in collaboration with two housing companies: Poseidon and Familjebostäder i Göteborg. Both operate in Gothenburg, Sweden and have solid experience of feedback heating control where indoor temperature sensors control the radiator supply temperature. Together they manage more than 3.5 million square meters of building floor area. In principle, all their apartments are fitted with wireless room sensors of which the first were installed in 2012. Poseidon's heating control considers only indoor and outdoor temperatures. Familjebostäder's heating control is similar, yet a little more complex since the direct outdoor temperature is replaced either with a moving average of the outdoor temperature or the forecast outdoor temperature, depending on which is higher.

As is the case with the overwhelming majority of Swedish multi-family buildings, the buildings in this study are equipped with waterborne radiators, including thermostats, all connected to the local district heating system. In addition to the amount of purchased energy (kWh), most district heating companies' price models also consider power (W) and return temperatures. As a result, the price models vary significantly between different energy companies [26]. In general, however, lower heating power peaks in cold weather are economically favourable for the property owner. Therefore, the impact of this aspect is also quantified in this study.

The starting point was to examine several buildings not affected by any other energy efficiency measures at least two years before and two years after the feedback control was activated. Measurement data were provided on purchased energy for 71 district heating substations, which together supply 197 buildings and a total of approximately 7500 apartments. After some examination, however, the basis was reduced to 44 substations and 107 multi-family buildings with a total of approximately 250,000 square meters. The exclusions were due to various events occurring during the evaluation period, such as reconstruction, measures on building envelopes, replacement of tap water mixers, additional roof insulation, technical problems, etc.

As can be seen from Table 1, air temperature is the only investigated parameter in this study; no other thermal climate parameters were measured. The reason is that the sensors were placed in the halls of the apartments. From a thermal point of view, the hall is typically the most homogenous space in each apartment; there are no windows, the walls are interior and there are no supply air vents. Thus, the halls are minimally influenced by the outdoor temperature and solar irradiation. Consequently, most likely, in the studied apartments, the halls have air temperatures and surface temperatures that are practically the same. Thus, the air temperature and the mean radiant temperatures are about equal (and equal to the operative temperature). With this background, measurements of the operative temperature instead of the air temperature would not have given any different results in the halls of the studied apartments. Indeed, operative temperature and air temperature measurements will often differ in, e.g., living rooms, bedrooms, etc. If the thermal comfort was to be studied in such rooms, it would have been necessary to consider not only operative temperature but also draught, e.g., from supply air vents and downdraught at windows. A paper focusing on these issues would need to refer to, e.g., ISO 7730 [27] and EN 16798-1 and 2 [28,29].

Table 1. Measurement data included in the analysis.

What	Resolution	Source	For Analysis of the Impact on...
Energy (heat)	Month	Göteborg Energi *	Annual energy demand adjusted to a typical meteorological year
Energy (heat)	Day	Göteborg Energi *	Heat power demand at low outdoor temperature
Indoor temperature	Hour	EcoGuard **	Average temperature level Temperature fluctuations

* Energy company owned by the City of Gothenburg. ** Supplier of products, services, and support for measurement. Accuracy of temperature sensors: ±0.15 °C.

It turned out that several of the buildings had increased indoor temperatures. Unfortunately, there was no available information on the temperature setpoints to compare with. Still, it was assumed that the increases took place because they had been perceived slightly too cold and now reached the desired temperature level. From a comfort point of view, the increases in those cases were probably positive, but at the same time, it burdens energy use. To quantify the impact on energy, the buildings were therefore divided in two categories: one for buildings with a decreased indoor temperature and one where all relevant buildings were lumped together. The former is called Category A in the results section.

Both housing companies also provided basic information of the buildings, such as year and type of construction, size, number of apartments and ventilation system. To precisely study heating, all energy statistics from hot water and domestic hot water circulation were excluded. This was done by deducting the average summer demand and adjusting for seasonal variations in the incoming cold-water temperature and the use of hot water. Relationships measured by Ek and Nilsson [30] were used for seasonal adjustment regarding variation in the use of hot water. To adjust for variations in the incoming cold-water temperature, a sinusoidal seasonal oscillation over the year was assumed, with the water temperature oscillating between +5 and +15 °C, depending on the month, coldest in February and warmest in August. These assumptions were taken from a survey of Swedish multi-family buildings [31].

Adjusting for a typical meteorological year was done using two different methods: e-signature and SMHI Energy Index. Although these generally give similar results in absolute terms (kWh), their difference can still have a significant impact, as the heating energy savings are usually only around 5–15%. The difference between the methods is highlighted by adjusting for a typical meteorological year with the two different methods simultaneously. Therefore, the adjustment for a typical meteorological year has been given quite a lot of attention in this investigation.

The SMHI Energy Index is produced by the Swedish Meteorological and Hydrological Institute. The method considers the combined effect of the outdoor temperature, sunshine, and wind in combination with the building's location, characteristics, and use, which is handled automatically using several fictitious-type buildings. Another method, E-signature, is based on a comparison of energy statistics for the actual building, i.e., the relationship between the outdoor temperature and heat demand for certain periods [32]. The principle is as follows: non-adjusted energy use for a suitable period (here monthly) is converted to average heating power demand by dividing the number of hours for the current period.

The data are plotted in the diagrams. Regression lines and their equations are obtained with the outdoor temperature as a variable. Suppose the measurement data contain domestic hot water, the regression line breaks in two at the building's balance point temperature. The regression line would, in that case, be shaped as a "hockey stick". Without domestic hot water, the regression line typically remains unbroken, as shown in Figure 2.

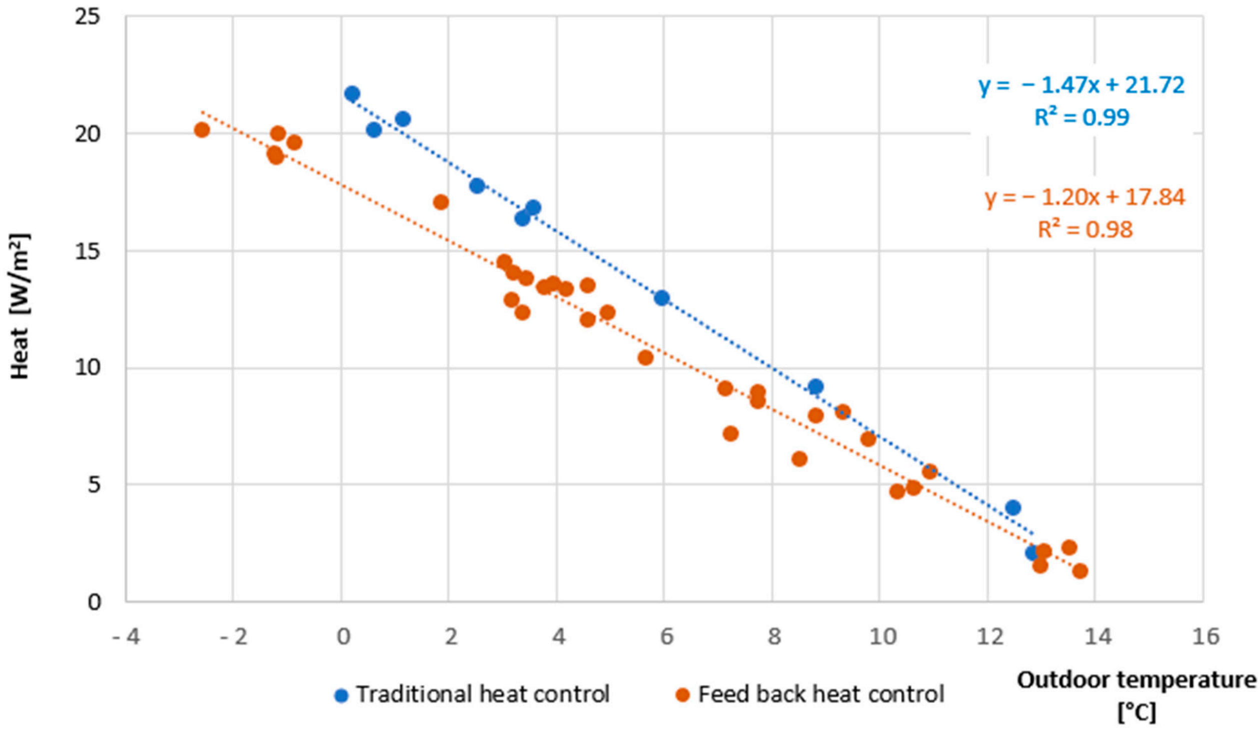

Figure 2. Example of E-signatures with regression lines and their equations for one of Poseidon's buildings. Deductions have been made for domestic hot water use and domestic hot water circulation. Time resolution: month.

Monthly temperature values from a meteorologically typical year are applied to the equations of the regression lines. The calculated average power is finally multiplied by the number of hours of the current month to re-convert it into energy.

The E-signature method was also used for the analysis of heating power demand at cold winter temperatures, see Figure 3. However, only outdoor temperatures lower than +5.0 °C and a 24 h resolution was applied in this case. According to the Swedish National Board of Housing, Building and Planning (Boverket), the design winter temperature in Gothenburg is −12.3 °C on a 24 h basis [33]. That temperature was therefore used when calculating the maximum power demand.

Finally, the impact on indoor temperature was also studied regarding the level and fluctuation, which was done by analysing the average temperatures of the apartments hourly. Fluctuations of the measured mean temperatures were quantified by weekly analysis of the standard deviations (deviations from the mean value) according to Equation (1).

$$\sigma = \sqrt{\frac{\sum(x-m)^2}{n}} \tag{1}$$

x: individual measured value,
m: mean value (weekly),
n: number of measured values (weekly).

Diagrams were used as a supplement to quickly identify seasonal differences, activation of the feedback control, etc., see Figure 4.

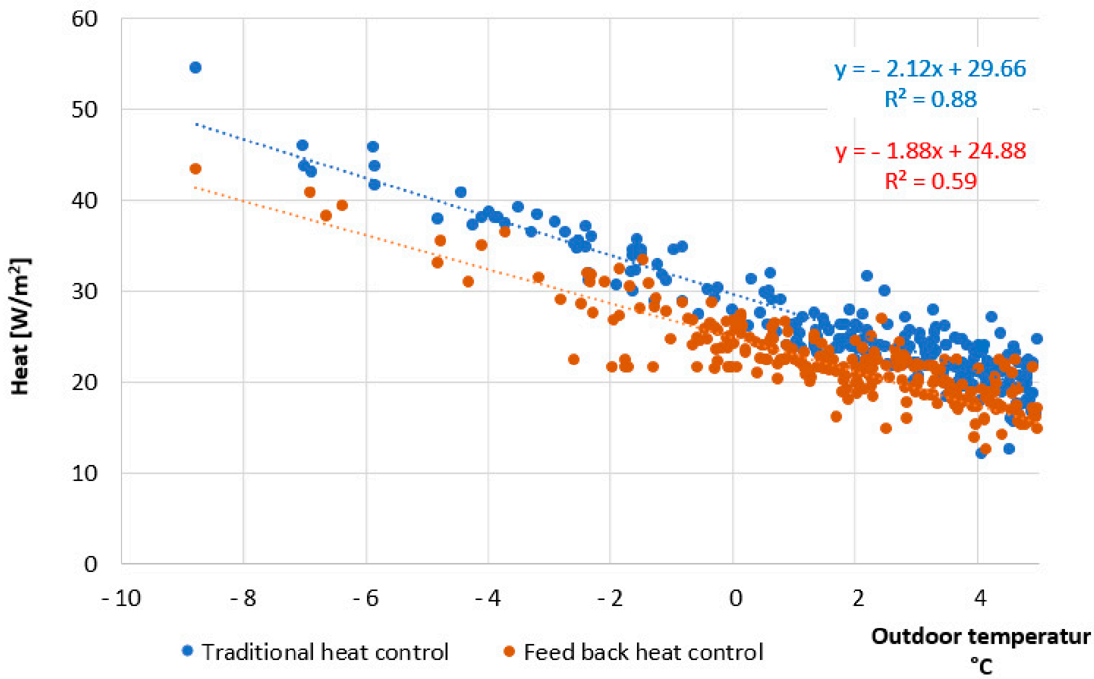

Figure 3. Example of E-signatures at outdoor temperatures lower than +5 °C. Deductions for hot water and domestic hot water circulation have been made. Time resolution: 24 h.

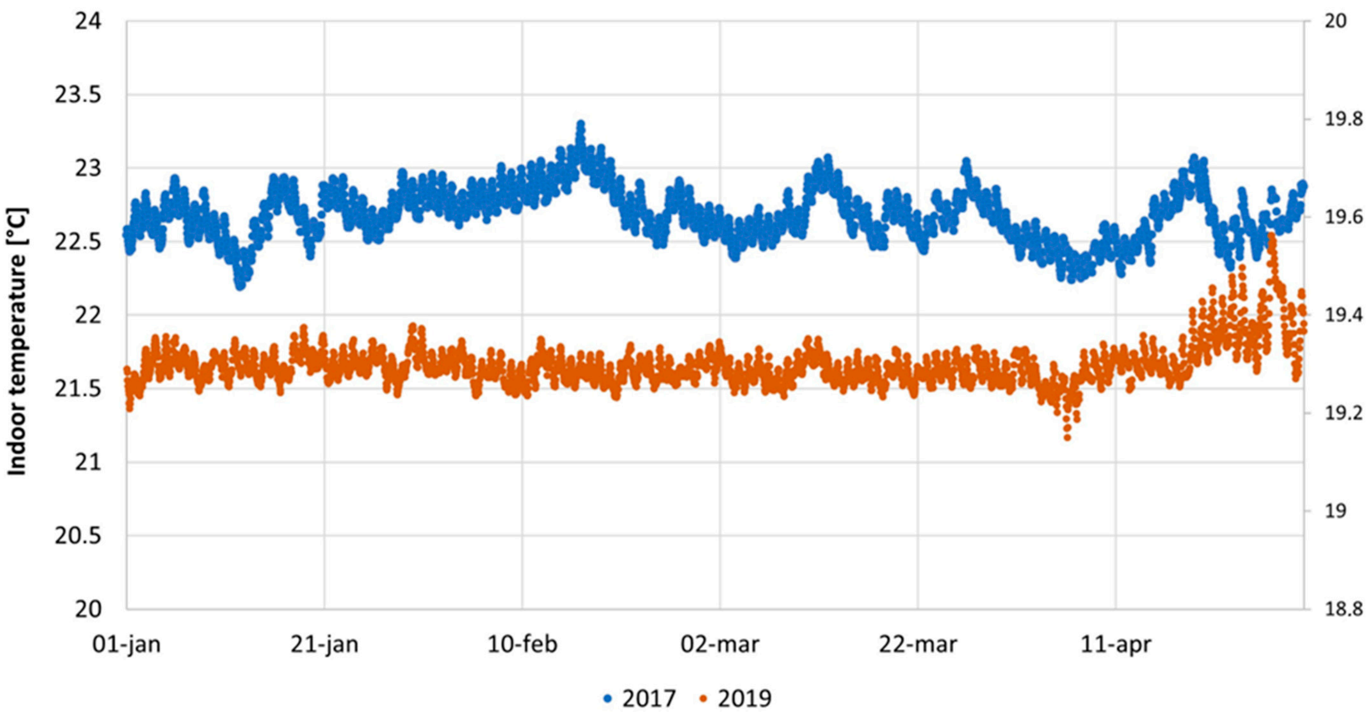

Figure 4. Example of average indoor temperatures. Time resolution: hour.

3. Results

In this section, measurements from the two housing companies, Poseidon and Familjebostäder, are reported. An interview study, including people from various housing companies, service providers and equipment manufacturer, is also reported here. The results from the measurements are compiled in Tables 2–4 and are commented on later in the Discussion section. However, the results of the interview study are commented on here.

Table 2. Summary of results—Poseidon.

What	Unit	Category A [1]	All
Changed annual energy use (heat) [2]	kWh/m^2	−6.9 (−12 to −2)	−0.1 (−12 to +13)
Changed indoor temperature level	°C	−0.4 (−0.8 to 0.0)	−0.1 (−0.8 to +0.3)
Changed indoor temperature fluctuation [3]	%	−26 (−67 to −2)	−21 (−67 to +4)
Changed heat demand at design low outdoor temperature	%	X [4]	X [4]
Substations	counts	13	30
Buildings	counts	50	93
Area	m^2	89,300	190,000

[1] Substations for buildings with reduced indoor temperature. [2] Mean value for typical meteorological year with SMHI energy index and E-signature respectively. [3] Change in standard deviation on a weekly basis. [4] Information on a daily basis was missing.

Table 3. Summary of results—Familjebostäder.

What	Unit	Category A [1]	All
Changed annual energy use (heat) [2]	kWh/m^2	+0.8 (−14 to +16)	Same [4]
Changed indoor temperature level	°C	−0.5 (−1.0 to −0.1)	Same [4]
Changed indoor temperature fluctuation [3]	%	0 (−18 to +21)	Same [4]
Changed heat demand at design low outdoor temperature	%	−2 (−14 to +13)	Same [4]
Substations	counts	10	Same [4]
Buildings	counts	14	Same [4]
Area	m^2	61,000	Same [4]

[1] Substations for buildings with reduced indoor temperature. [2] Mean value for typical meteorological year with SMHI energy index and E-signature respectively. [3] Change in standard deviation on a weekly basis. [4] All buildings showed reduced indoor temperature after feed-back control was installed.

Table 4. Summary of weighted results for both housing companies. Weighting with regard to the number of substations.

What	Unit	Category A [1]	All
Changed annual energy use (heat) [2]	kWh/m^2	−3.8 (−14 to +16)	−0.2 (−14 to +16)
Changed indoor temperature level	°C	−0.4 (−1.0 to 0.0)	−0.2 (−1.0 to +0.3)
Changed indoor temperature fluctuation [3]	%	−15 (−67 to +21)	−16 (−67 to +21)
Changed heat demand at design low outdoor temperature	%	Same as Table 3	Same as Table 3
Substations	counts	23	44
Buildings	counts	64	107
Area	m^2	150,300	251,000

[1] Substations for buildings with reduced indoor temperature. [2] Mean value for typical meteorological year with SMHI energy index and E-signature respectively. [3] Change in standard deviation on a weekly basis.

As will be shown, feedback control did not always result in reduced energy use. In fact, in some buildings, it even increased. In most cases, there are good reasons for it. This is discussed later and has already been briefly covered in Section 2, where it was also stated that buildings with a reduced indoor temperature are referred to as Category A.

3.1. Measurements

3.1.1. Energy

The analysis of the Category A buildings showed an annual average heating change of −7 and +1 kWh/m^2, respectively (Poseidon and Familjebostäder), with a weighted average of −4 kWh/m^2. Weighting with regard to the number of substations: if all buildings are considered (even the ones with increased indoor temperature), the average changes were, however, ±0 and +1 kWh/m^2, respectively, with a weighted average of ±0. March and April, when it is generally sunny but still cold, stand out as the period when the saving is most significant, while December and January only show minor differences compared to the traditional heating control.

The individual differences in energy saving between separate buildings were substantial. As mentioned, there were several cases where the heat demand increased, illustrated in Figure 5. The reason for the increased demand most often turned out to be that those buildings previously were too cool, now got warmer due to the feedback control. However, in some of Familjebostäder's facilities, the reasons have not been determined.

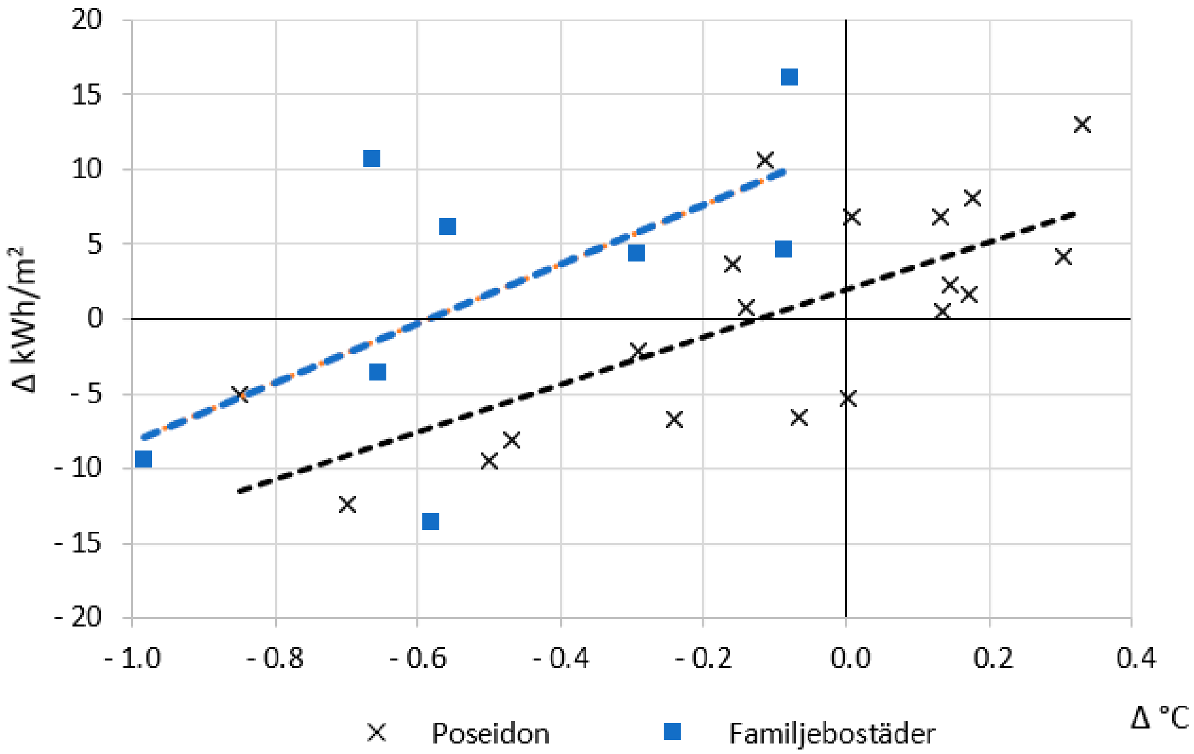

Figure 5. Relation between changed indoor temperature level and energy use. A positive value corresponds to an increase. All buildings are included except those sorted out early, according to the previous description. Each marker represents a substation. A total of 107 buildings are included in the figure.

3.1.2. Heat Power Demand during Cold Weather

In Category A, the heat power requirement at the design winter temperature on a 24 h basis, decreased on average by 2%. Here, it can be noted that power demand on a 24 h basis could only be analysed for Familjebostäder's buildings. Poseidon's buildings could only be analysed monthly, which was deemed irrelevant.

3.1.3. Indoor Temperature

Indoor temperature levels in Category A buildings were reduced during heating season on average by 0.4 and 0.5 °C, respectively (Poseidon, Familjebostäder), from 22.0 and 22.2 °C, respectively, to 21.6 and 21.7 °C. However, considering all buildings, the weighted average temperature level only dropped about 0.2 °C. Even though there is no information available on the set point values, it can be assumed that the feedback control brought the indoor temperatures closer to their respective set point levels.

The fluctuations expressed as the standard deviation of the weekly average temperature (according to Equation (1)) decreased by 26% in Poseidon's Category A facilities but 0% in Familjebostäder's. The weighted average fluctuation decrease in Category A for the two housing companies is 15%. If all buildings are considered, the weighted average fluctuation decrease is 16%.

3.1.4. Summary of Measurements

The results are summarized in Tables 2–4. It can be noted that in Familjebostäder's stock, there were buildings where the heat demand increased despite the reduced room temperature. The latter is further commented on in the Discussion section.

3.2. Interviews

The interviews showed positive experiences of demand heat control, partly due to the obtained heat demand reductions, and partly due to other added values. Several interviewees stated energy saving was the most common reason for acquiring demand heat control. Still, after a while, they realized that there were also other advantages connected to temperature mapping.

Depending on which housing company was asked, the energy savings amounted to approximately 5–20 kWh/m^2. The energy service providers, for their part, claimed savings in the range of 10–20 kWh/m^2, depending on the provider, which is slightly more than measured for Poseidon and Familjebostäder. The difference may depend on the heat control capacity, and perhaps the characteristics of the buildings. Still, it is probably more likely due to the original indoor temperature levels of the buildings or perhaps a combination.

As shown in Table 5, four suppliers of different control strategies were interviewed. The function of these control strategies is explained in a report from 2023 [34]. To summarize, they had varying complexities and capabilities, which made them difficult to compare. However, one thing that unites them is the crucial role of room temperature sensors, which the interviewees highlighted several times during the study. Many participants emphasized that temperature mapping facilitates the identification of local heating problems and the need to adjust radiator systems. But also, that it is a good basis for discussion with residents.

Table 5. Interviewed actors.

Housing Companies	Control System Providers	Measurement Service Providers
Familjebostäder i Göteborg	EnReduce	EcoGuard
Haningebostäder	Algeno	
Helsingborgshem	Kiona	
MKB	Riksbyggen	
Poseidon		
Stockholmshem		
Örebrobostäder		

Another thing that often came up in contact with the housing companies was their desire to avoid being locked into any single technology. They wanted to be able to expand and manage the entire process on their own. Open interfaces and APIs (connection of software functions) was considered increasingly important when choosing heat control technology in the future. However, it can be noted here that only large property owners were asked. The need for open technology solutions may seem different in smaller companies or for private property owners.

4. Discussion

An introductory remark in this context is that the indoor temperatures in the buildings of both housing companies studied were generally not very high and probably close to their desired setpoints right from the start. The savings would have been more significant if the analysis had been carried out in more overheated buildings. In several cases, it may be significantly larger.

This study underlines that the saving potentials for individual multi-family buildings cannot be precisely specified. But at a stock level where operation, design, etc., are similar to Poseidon's and Familjebostäder's situation, the range in Tables 2–4 is a good indication. It is, however, possible that more advanced heat control technologies can provide additional savings.

Tables 3 and 4 show that indoor temperature fluctuations were reduced significantly less in Familjebostäder buildings than in Poseidon's. What this could be due to could not be determined. Still, it was assumed it had to do with their heating control; instead of using the direct outdoor temperature, they automatically choose between a forecast outdoor temperature and a measured moving average temperature. Furthermore, as mentioned, the energy use increased in some of Familjebostäder's multi-family houses even though the indoor temperature decreased. A changed number of residents, increased ventilation flows, increased use of slit valves and window airing, and technical errors are examples of the reasons discussed with the housing companies. But the explanations could neither be established nor dismissed as the operational monitoring systems of those buildings did not date back to the relevant periods.

Initially, there was an ambition to distinguish the impact on lightweight buildings from heavy ones and to identify differences between different ventilation types. However, the building stocks were too homogeneous, with only a few light buildings and even fewer buildings with ventilation other than mechanical exhaust air. These aspects could not be evaluated.

AI and various types of intelligent control technologies with machine learning are now being implemented more often in the building stock. Some AI solutions will be able to optimize heat control regarding costs, power requirements, etc., rather than energy use and indoor temperature. In these cases, the indoor temperature levels and fluctuations are given lower priority. However, indoor temperature sensors will most likely have a crucial role also in the future in conjunction with the minimum permitted temperature levels as the mandatory boundary conditions. But there will still be a need to investigate the impact of intelligent control on thermal comfort and energy use as technology advances.

5. Conclusions

Most of the study's results regarding reduced energy use with lowered indoor temperature levels and fluctuation were expected and in line with previous investigations [10–19]. In this respect, the primary news value lies in the large base of multi-family buildings equipped with mature and commercial heating control technology, including indoor temperature sensors in almost every apartment and PI-control for the adjustment of the supply temperature.

The results underline the fact that saving potentials for individual multi-family buildings cannot be precisely specified. But at a stock level where operation, design, etc., are similar to Poseidon's and Familjebostäder's situation, the range in Tables 2–4 is a good indication. It is, however, possible that more advanced heat control technologies can provide additional savings.

With energy meters on radiator systems in each building, the precision of the energy statistics would increase. As it is now, it is somewhat disturbed by hot water and hot water circulation, although the described measures were taken to limit these disturbances. As a proposition for continued research, it is therefore suggested that the corresponding investigations are carried out on buildings with energy meters on radiator circuits. Furthermore, it is suggested that the influence on thermal comfort is investigated more broadly than just indoor temperature, for example, through survey studies among residents and measurement of comfort-related parameters in some individual rooms.

Finally, according to the Swedish Energy Agency (Energimyndigheten) [35], the country's total stock of multi-family houses is 222 million square meters. The stock's total energy demand for heating and domestic hot water is 29.3 TWh, corresponding to approx 132 kWh/m^2. Since most of the country's stock is overheated, we can assume that the total savings potential is equal to the level in Table 2 or higher. If implemented in all multi-family hoses, the savings potential at the Swedish national level is about 2

TWh, which brings us back to the Swedish Energy Agency's campaign that every kilowatt hour counts!

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References

1. Jortsberg, M.; Svensson, O.; Thunborg, J.; Jönsson, B. *Teknisk Status i den Svenska Bebyggelsen*; Resultat från Projektet BETSI; Boverket: Karlskrona, Sweden, 2010.
2. Bagge, H.; Lindstrii, L.; Johansson, D. *Brukarrelaterad Energianvändning*; Resultat från Mätningar i 1300 Lägenheter; Lågan: Göteborg, Sweden, 2014.
3. Boman, C.; Jonsson, B.; Skogberg, S. *Mätning av Innetemperartur ELIB-Rapport 4*; Statens Institut för Byggnadsforskning: Stockholm, Sweden, 1992.
4. Teli, D.; Psomas, T.; Langer, S.; Trüschel, A.; Dalenbäck, J.O. Drivers of winter indoor temperatures in Swedish dwellings: Investigating the tails of the distribution. *Build. Environ.* **2021**, *202*, 108018. [CrossRef]
5. Carlsson, J. *Folkhälsomyndighetens Allmänna råd om Temperatur Inomhus*; FoHMFS 2014:17; Folkhälsomyndigheten: Solna, Sweden, 2014.
6. Hunt, D.; Gidman, M. A national field survey of house temperatures. *Build. Environ.* **1982**, *17*, 107–124. [CrossRef]
7. Summerfield, A.J.; Lowe, R.J.; Bruhns, H.R.; Caeiro, J.A.; Steadman, J.P.; Oreszczyn, T. Keynes Energy Park revisited: Changes in internal temperatures and energy usage. *Energy Build.* **2007**, *39*, 783–791. [CrossRef]
8. Oreszczyn, T.; Hong, S.H.; Ridley, I.; Wilkinson, P.; Warm Front Study Group. Determinants of winter indoor temperatures in low income households in England. *Energy Build.* **2006**, *38*, 245–252. [CrossRef]
9. Yohanis, Y.G.; Mondol, J.D. Annual variations of temperature in a sample of UK dwellings. *Appl. Energy* **2010**, *87*, 681–690. [CrossRef]
10. Apelblat, J.; Rydström, P. *Frånluftstemperaturreglering av Flerfamiljshus*; Rapport BKL 1977:12; Lunds Tekniska Högskola: Lund, Sweden, 1977.
11. Jensen, L.; Lange, E. *Energianvändning och Energibesparing i Malmö—Undersökning av ett Höghus (R9:1982)*; Byggforskningsrådet: Stockholm, Sweden, 1982.
12. Hedin, B. *Reglering av Inomhustemperaturen i Flerbostadshus med Central Återkoppling (R50: 1989)*; Byggforskningsrådet: Stockholm, Sweden, 1982.
13. Dahlblom, M.; Jensen, L. *Reglering av Värmesystem i Flerbostadshus med Individuell Värmemätning*; Final Report of Research Supported by CERBOF. (Rapport TVIT-11/3006); Building Services, Lund University: Lund, Sweden, 2011.
14. Dahlblom, M.; Nordquist, B.; Jensen, L. Evaluation of a feedback control method for hydronic heating systems based on indoor temperature measurements. *Energy Build.* **2018**, *166*, 23–34. [CrossRef]
15. Yeom, G.; Jung, D.E.; Do, S.L. Improving a heating supply water temperature control for radiant floor heating systems in Korean high-rise residential buildings. *Sustainability* **2019**, *11*, 3926. [CrossRef]
16. Sun, C.; Chen, J.; Cao, S.; Gao, X.; Xia, G.; Qi, C.; Wu, X. A dynamic control strategy of district heating substations based on online prediction and indoor temperature feedback. *Energy* **2021**, *235*, 121228. [CrossRef]
17. Yuan, J.; Huang, K.; Han, Z.; Zhou, Z.; Lu, S. A new feedback predictive model for improving the operation efficiency of heating station based on indoor temperature. *Energy* **2021**, *222*, 119961. [CrossRef]
18. Sun, C.; Liu, Y.; Cao, S.; Gao, X.; Xia, G.; Qi, C.; Wu, X. Integrated control strategy of district heating system based on load forecasting and indoor temperature measurement. *Energy Rep.* **2022**, *8*, 8124–8139. [CrossRef]
19. Li, Z.; Liu, J.; Yang, X.; Huang, X.; Jia, L.; Li, M. Novel effective room temperature-based predictive feedback control method for large-scale district heating substation. *Appl. Therm. Eng.* **2023**, *218*, 119241. [CrossRef]
20. Afram, A.; Janabi-Sharifi, F. Theory and applications of HVAC control systems—A review of model predictive control (MPC). *Build. Environ.* **2014**, *72*, 343–355. [CrossRef]

21. Mariano-Hernández, D.; Hernández-Callejo, L.; Zorita-Lamadrid, A.; Duque-Pérez, O.; García, F.S. A review of strategies for building energy management system: Model predictive control, demand side management, optimization, and fault detect & diagnosis. *J. Build. Eng.* **2021**, *33*, 101692. [CrossRef]
22. Dounis, A.I.; Caraiscos, C. Advanced control systems engineering for energy and comfort management in a building environment—A review. *Renew. Sustain. Energy Rev.* **2009**, *13*, 1246–1261. [CrossRef]
23. Balali, Y.; Chong, A.; Busch, A.; O'Keefe, S. Energy modelling and control of building heating and cooling systems with data-driven and hybrid models—A review. *Renew. Sustain. Energy Rev.* **2023**, *183*, 113496. [CrossRef]
24. Mobaraki, B.; Pascual FJ, C.; Lozano-Galant, F.; Lozano-Galant, J.A.; Soriano, R.P. In situ U-value measurement of building envelopes through continuous low-cost monitoring. *Case Stud. Therm. Eng.* **2023**, *43*, 102778. [CrossRef]
25. Mobaraki, B.; Pascual, F.J.C.; Garcia, A.M.; Mascaraque, M.Á.M.; Vázquez, B.F.; Alonso, C. Studying the impacts of test condition and nonoptimal positioning of the sensors on the accuracy of the in-situ U-value measurement. *Heliyon* **2023**, *9*, e17282. [CrossRef]
26. Persson, M.L.; Beggren, B.; Sjöqvist, D.; Rosén, M.; Wiederholm, J. Fastigheten Nils Holgessons underbara resa genom Sverige, en Avgiftsstudie 2022. Nils Holgersson Gruppen, Stockholm. Report. Available online: https://nilsholgersson.nu/wp-content/uploads/2022/11/NH2022_inkl_Bil1-4_v221115.pdf (accessed on 17 September 2023).
27. *ISO 7730:2005*; Ergonomics of the Thermal Environment—Analytical Determination and Interpretation of Thermal Comfort Using Calculation of the PMV and PPD Indices and Local Thermal Comfort Criteria. International Organization for Standardization: Geneva, Switzerland, 2005.
28. *EN 16798-1*; Energy Performance of Buildings—Ventilation for Buildings—Part 1: Indoor Environmental Input Parameters for Design and Assessment of Energy Performance of Buildings Addressing Indoor Air Quality, Thermal Environment, Lighting and Acoustics—Module M1-6. European Committee for Standardization: Brussels, Belgium, 2019.
29. *EN 16798-2*; Energy Performance of Buildings—Ventilation for Buildings—Part 2: Interpretation of the Requirements in EN 16798-1—Indoor Environmental Input Parameters for Design and Assessment of Energy Performance of Buildings Addressing Indoor Air Quality, Thermal Environment, Lighting and Acoustics—Module M1-6. European Committee for Standardization: Brussels, Belgium, 2019.
30. Ek, C.; Nilsson, D. *Varmvatten i Flerbostadshus: Erfarnehet, Kunskap och Mätning för en Klokare Användning*; Energiingenjörsprogrammet; Högskolan i Halmstad: Halmstad, Sweden, 2021.
31. Aronsson, S. Fjärrvärmekunders Värme- och Effektbehov—Analys Baserad på Mätresultat från Femtio Byggnader. Ph.D. Thesis, Institutionen för Installationsteknik, Chalmers, Göteborg, Sweden, 1996.
32. Schulz, L. *Normalårskorrigering av Energianvändningen i Byggnader en Jämförelse av två Metoder*; EFFEKTV: Göteborg, Sweden, 2003.
33. Karlsson, F.; Andersson, C. *Dimensionerande Vinterutetemperatur—DVUT 1981-2010, 310 orter i Sverige*; SMHI: Norrköping, Sweden, 2016.
34. Olsson, D. *Behovsanpassad Värmereglering. En Förstudie om Nyttan, Erfarenhter, m.m. 2022:052*; Bebo: Stockhol, Sweden, 2023.
35. Dyfvelsten, P. *Energy Statistics for Multi-Dwelling Buildings 2021*; Swedish Energy Agency: Stockholm, Sweden, 2022.