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Thermal Characteristics and User Regulation of Household Heat Metering for Residential District Heating Systems in Northern China

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Abstract: Heat metering is an important measure of China's heating marketization reform as well as an energy-saving policy implemented in buildings nearly 20 years ago. However, this policy has not achieved the expected results due to various reasons. It is important to note that although northern China is dominated by large apartment buildings, resulting in unique thermal characteristics and user behavior, the measured results of these characteristics are not common. In this study, data from cities in northern China were obtained using household heat meters and field testing. Based on the three levels of station, building, and household, the effects of location, heat outages, and users' regulation behavior on energy consumption were analyzed. The results show that different locations lead to a considerable difference in heat consumption among users, and an outage leads to a significant increase in consumption by surrounding users. For typical buildings in northern China, it is challenging to realize energy savings with district heating systems based on user behavior, and household metering and charging are not fair and reliable. Adjusting the heat meter unit from the household to the building was suggested.

Keywords: northern China; heat metering; heat user behavior; district heating system

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Citation: Luo, A.; Li, C.; Xia, J.; Cheng, P. Thermal Characteristics and User Regulation of Household Heat Metering for Residential District Heating Systems in Northern China. *Energies* **2024**, *17*, 579. https://doi.org/10.3390/en17030579

Academic Editors: Ahmad Arabkoohsar and Meisam Sadi

Received: 1 December 2023
Revised: 12 January 2024
Accepted: 23 January 2024
Published: 25 January 2024

1. Introduction

District heating (DH) in northern China is a crucial component of building operations, energy consumption, and carbon emissions. It is also an important livelihood project to ensure a comfortable life for residents in winter. Due to the vast territory, the area of buildings with heating systems in northern China reached 15.6 billion m^2 in 2020, and the total energy consumption reached 214 Mt of standard coal equivalents (tce, 1 tce = 29.307 GJ), with a total carbon emission of 450 Mt CO_2 [1]. In the macro-energy strategic goal of "carbon peak and carbon neutrality," the carbon-reduction task for building operations is arduous, and the same is true for residential DH systems [2].

The energy use intensity (EUI) of DH in northern China has dramatically reduced over the past two decades. Control measures for the energy consumption and carbon emissions of DH have developed with technological advancements, including the use of efficient and clean heat sources, such as the utilization of thermal-power-plant waste heat [3], industrial waste heat [4], low-loss distribution pipeline networks, and building envelope improvement [5]. The reform of heating marketization has not achieved apparent consequences in the mechanism aspect. Implementing "heating metering" for users and charging according to the metered heat is key to the reform [6–8]. The main promotion method is installing a household heat meter, referring to experience from Northern Europe [9].

Despite the fact that approximately a 2 billion m^2 heating area in northern China had meters installed through financial investment, barely any households are charged with metered data [10]. The reasons are summarized as follows: heat transfer between households [11,12], stoppage by heat users [13], and meter quality [14]. This results in household meters malfunctioning. Thus, to understand the dilemma of heat reform and household heat metering in northern China, it is necessary to study the thermal characteristics of meter users and their regulation behavior.

1.1. Study of Heat Metering

The aim of promoting heat metering is to (1) promote the implementation of buildings' energy-saving standards and reduce heat energy consumption; (2) promote energy-saving behavior among users and reduce excessive heating caused by overheating or heating vacant rooms; and (3) improve the quality of heating services and achieve on-demand heating [15]. However, metering only involves data detection and cannot lead to energy savings directly.

As household metering is the leading heat metering technology promoted in northern China, many studies have focused on the heat transfer between households through experiments, simulations, and onsite surveys as a basis for correcting user heat fees. Zhan et al. [16] found that heat transfer between households accounts for 9.3–47.2% of the total heat consumption of typical users through onsite measurements. Ling et al. [17] proposed various location correction factors in seven cities that regulate metered heat data to achieve a fair distribution of heating costs among households. Liu et al. [18] analyzed the factors of heat cost allocation through simulation. They proposed that users in the building allocate the heating cost according to the accumulated time of valve opening. The data from household meters cannot be used directly [19], which significantly increases the cost of equipment and calculations, resulting in a lack of enthusiasm for heating companies and a low degree of user recognition.

Therefore, it is necessary to reexamine the heat metering technique, which is regarded as an energy-saving technology for buildings. In particular, the energy saved must be evaluated at the system level. For a DH system, energy saving is achieved only when the total energy consumption of the heat source (such as a boiler or a thermal power plant) decreases for the same area [20]. The heating station is the smallest unit in the secondary system, i.e., the energy-saving effect of heat metering should be fed back to the heating station. Meanwhile, the heating EUI is a key evaluation indicator for every DH system level.

1.2. Influence of User Regulation on Heat Energy Consumption

Owing to the continuous operation of heating systems, the energy-saving potential of regulating user behavior has always been a controversial topic. Canale et al. [21] conducted a comprehensive review of the technical means, energy-saving effects, charging methods, and cost effectiveness of heat metering in EU countries. It was pointed out that the energy-saving effect of metering is due to the combined influence of the temperature control valve, user behavior, and charging mechanism rather than the installation of heat meters [22]. For studying the actual energy savings of household meters, 105 household heat metering users were selected, and it was found that users can reduce their heat by 5% by reading the meter and can save 3% to 9% of their heat using other feedback methods [23]. Lynham et al. [24] found that energy consumption can be reduced by displaying real-time energy consumption information to residents. In addition, it is more cost effective to help residents understand the energy consumption of their daily behaviors through education and signs.

However, the policy attitudes of some EU countries have changed in recent years. The Swedish National Housing Administration recommends that households should meter no new buildings for heating or domestic hot water [25,26]. The Danish Energy Agency defines cost effectiveness as the life-cycle energy saving of heat meters being greater than their purchase and installation costs but found this largely impossible to inspect [25]. For the heat metering of existing apartment buildings in Finland, it was not possible to achieve cost effectiveness through behavioral energy savings, and investments to control and balance the heating network were proposed to be more effective than indirect measures [27].

Smart meters and algorithm control could be effective in small-scale DH systems [28–30]. An algorithm, coupling downsized heat pumps to radiant emitters, based on thermal inertia control was studied and the seasonal performance of heat pumps increased by 10% [31]. Although there are control systems, the behavior of users opening windows is also worth considering. Even for retrofitted buildings, ventilation loss may still account for 70% of total heat loss [32]. In addition, users often worry about differences in heating costs, so a method that calculates minimum and maximum heating costs was studied to help allocate heating costs in multifamily buildings [33].

Typical residential buildings in the severely cold regions of northern China are large apartment buildings, whose number of households is much higher than that in European countries. Therefore, the characteristics and behavior of users in multifamily buildings in northern China need further study.

This study is focused on investigating the thermal characteristics of typical buildings in DH systems in northern China. Section 2 explains the analysis methods and research objectives of this study. The field tests and data collection were conducted at the scales of heating stations, buildings, and households in several heat metering pilot cities. Section 3 proposes the definition of the regulation behavior index of users to quantify regulation characteristics. Combined with the user behavior on installed heat meters, the actual regulation needs and regulation characteristics of users were analyzed from a microscopic perspective. In Section 4, the main influencing factors of the heat energy consumption of DH systems are summarized, and three factors, namely, household location, heat outages, and user adjustment, are analyzed in detail. Section 5 summarizes the significance of heat metering and the necessity of regulation based on the results. Finally, Section 6 discusses technical route ideas suitable for apartment buildings in northern China.

2. Method

District heating is the main form of heating in urban areas in northern China and is usually located north of the "Qinling-Huaihe" line. After extensive research in cities, it was found that poor-quality household heat meters are ubiquitous, mainly reflected in the severe lack of data during collection and transmission [34]. In this study, five cities with relatively superior measurement data quality were selected, and their heating data from the 2018–2019 heating season were used as objects, as shown in Table 1.

Table 1. Basic information about the research subjects.

City	Heating Duration (Day)	Average Outdoor Temperature (°C)	Total Quantity of Heating Stations	Sample Quantity of Meter Heating Station	Sample Quantity of Household Heat Meter
Chengteh	152	−4.7	185	13	5023
Qingdao	151	4.4	58	5	104
Tangshan	142	−0.9	760	4	548
Taian	136	3.3	398	6	868
Beijing	121	−0.4	3	3	356

In addition, this research selected the data from Chengteh as the primary analysis object, where heat metering has been implemented since 2004. Users in Chengteh widely accepted the metering and charging, with high positivity for participation in self-regulation, which is confirmed in Section 3. The local DH system is illustrated in Figure 1.

This study conducted a detailed investigation and field test of the heat metering user data from Chengteh, and some typical user data in several northern cities were comparatively researched. For convenience, users in different locations in a single building were divided into four categories: middle, side, top, and bottom. The framework of this study and the division of users into different locations are shown in Figure 2. The heating EUI, in units of GJ/m^2, was used as the index of energy consumption evaluation, and the analysis was carried out according to the three levels of heating stations, buildings, and households.

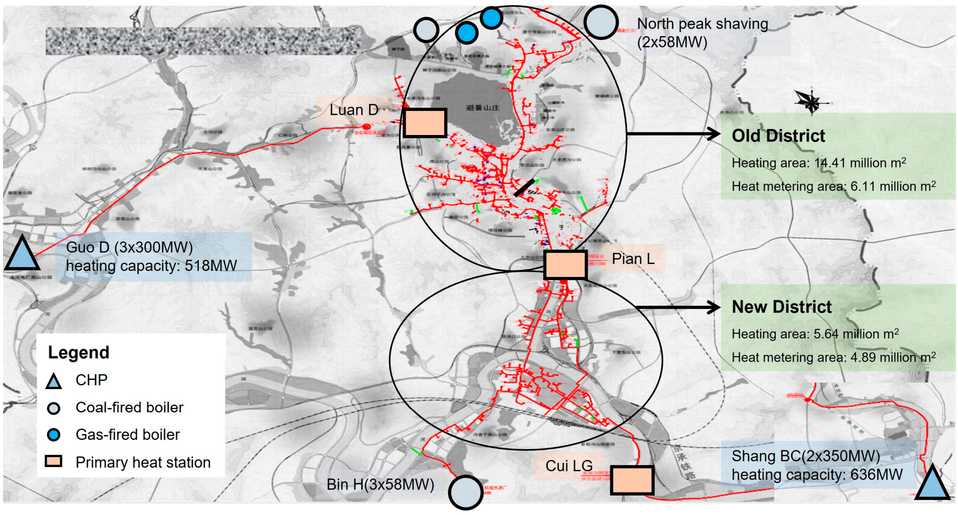

Figure 1. DH system in Chengteh.

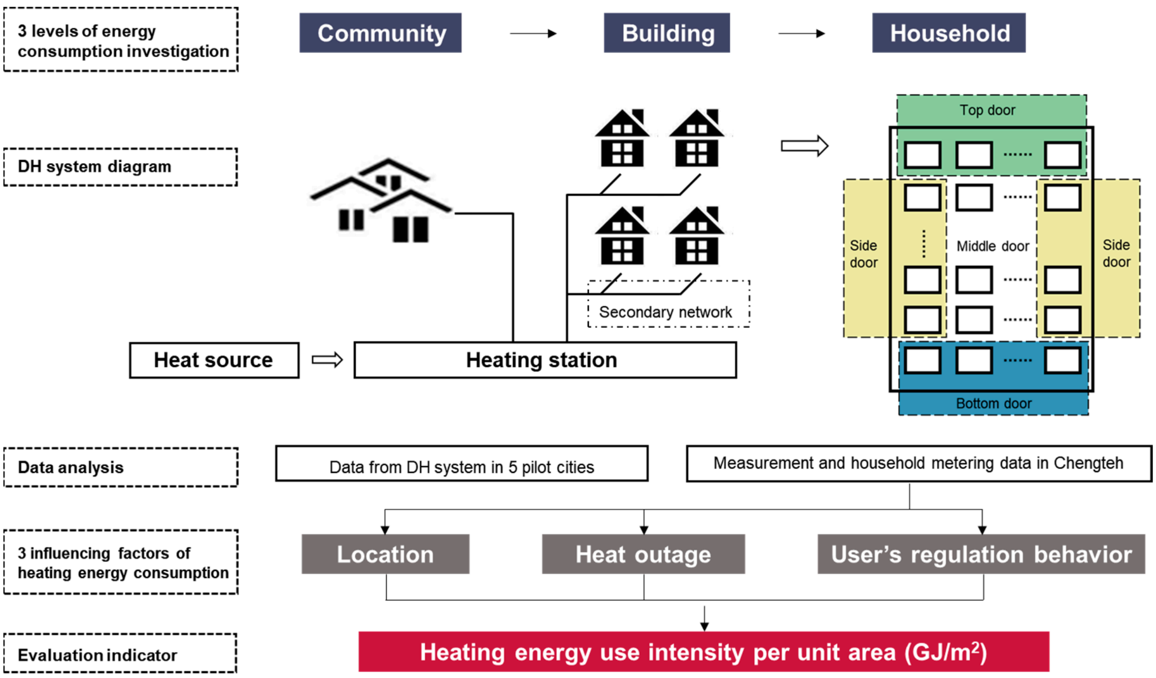

Figure 2. Framework of the study method.

3. Definition and Analysis of User Regulation Behavior Indicators

3.1. Thermal Characteristics of DH Systems

A heat metering system usually includes a meter and a regulating device. An indoor regulating device is a primary option for users to freely adjust the household heat. A general DH system in northern, urban residential buildings operates continuously due to the significant temperature difference between indoor and outdoor environments in winter, the thermal inertia of buildings, and the hysteresis of the heating pipe network. The building releases stored heat during heat outage periods and heating the EUI of the building significantly increases when turned on again. Hence, the energy savings that can be achieved by intermittent heating are negligible. The DeST model predicts that the energy saving of a whole building achieved through a heat outage of 2 h is only 1%. This phenomenon is called the "heat storage transfer effect" [35]. In addition, the equipment capacity must be increased to recover the room temperature quickly. Therefore, heat outages for vacant rooms have little energy-saving effect on typical apartment buildings and DH systems in the severely cold regions of China.

Owing to the continuous operation of DH systems, for some heat metering users who installed indoor control devices, their regulation behavior is based on "days" in comparison to the split air conditioners used in non-district heating areas, which are measured in "hours or minutes", as shown in Figure 3. The residents in the winter regions use air conditioners on heating mode in a discrete fashion with multiple start–stop cycles throughout the day [36]. In contrast, metering users in Chengteh only turn down the valve five times and open the valve six times during the entire heating season. Owing to the continuous operation characteristics of the system and the time scale regulated by the heat metering user, the data from existing heat metering devices are usually stored once a day or 2–3 times a day to reduce the storage capacity.

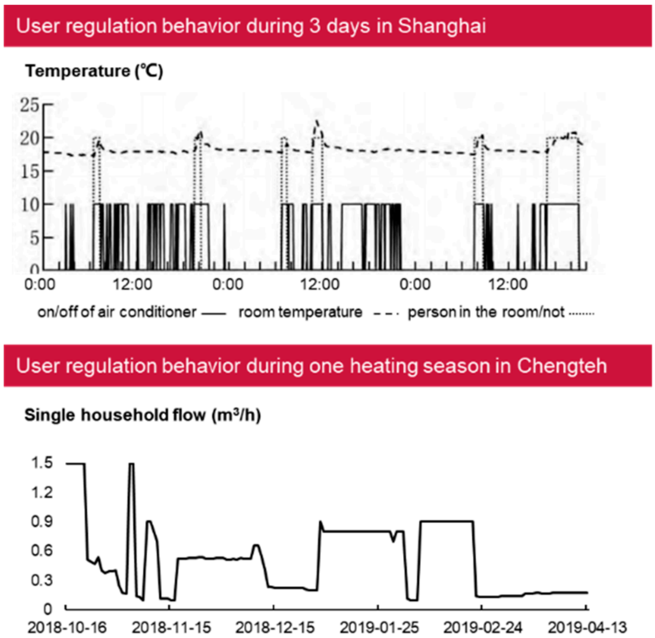

Figure 3. Comparison of the user regulation behavior between air conditioners and DH systems in the heating season.

3.2. Regulation Behavior of Heat Metering Users in Northern Chinese Cities

To further understand the regulation behavior of heat metering users, data from four typical household heat meters in the same building and community in Chengteh, Taian, Qingdao, and Beijing were selected. The daily flow and its distribution of the daily flow are shown in Figure 4. Owing to the different behaviors of metering users in Chengteh City, the flow curves for each user were entirely different, and the boxplots of their flow distributions also varied significantly. Because of the flow adjustment of the secondary pipe network in Taian City, the daily flow for each user had a slight fluctuation. However, the trend was completely consistent, making the distribution of the daily flow in the heating season almost the same. Users in Qingdao and Beijing showed little change in flow throughout the heating season, with a minimal difference between the upper and lower quartiles.

The results are summarized in Figure 4. It was observed that, except for Chengteh, metering users rarely participated in adjusting the valve to change the household flow, which confirms that the household meter is installed without regulation. For users in Chengteh, the indoor personnel will not adjust frequently, and there are about five regulation times during the entire heating season.

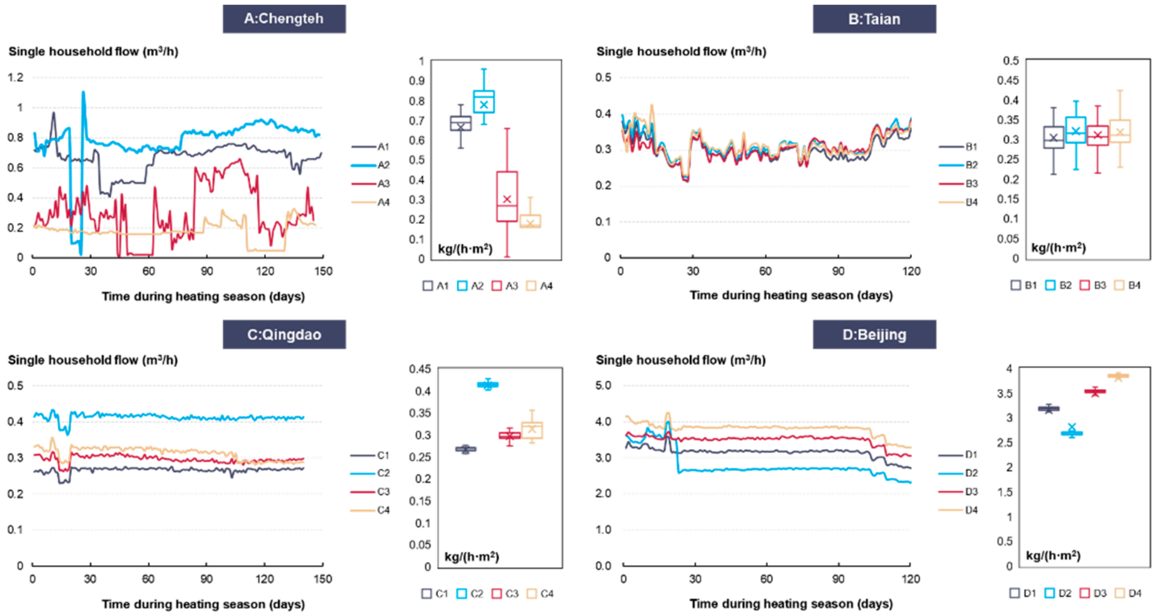

Figure 4. Flow curve and distribution of typical heat metering users (4 pilot cities).

3.3. Definition and Characteristics of User Regulation Degree

A scientific index is needed to quantify and evaluate the regulatory behavior of heat metering users. The relationship between the heating EUI and the flow rate of the two types of users in different locations is shown in Figure 5. It can be seen that there is an apparent positive correlation between the heating EUI and the average flow rate in the heating season. This correlation shows that the user regulation of the flow can effectively change the measured heat consumption, which means that the flow can represent the user regulation behavior. In conventional DH systems, heat stations operate at a constant flow rate. During the heating season, the controller changes the temperature of the supply water based on the outdoor temperature. And in this case, the correlation between the heating EUI and flow rate was not significant, and the heat consumption depended on the temperature difference between the inlet and outlet water. However, in systems where users can regulate the valve themselves, the higher flow rate results in higher heat consumption.

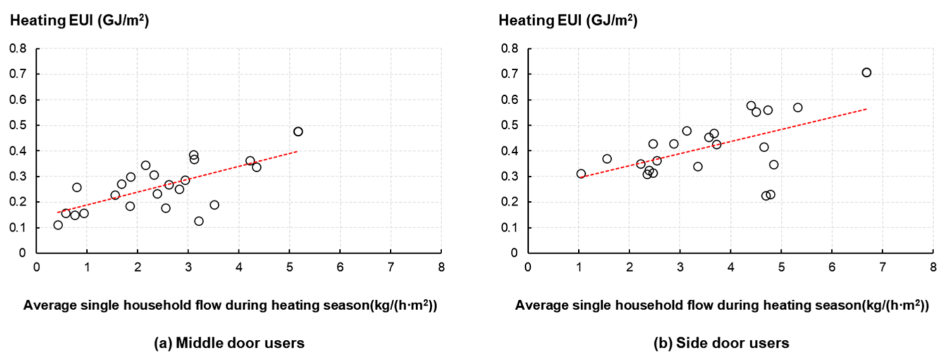

Figure 5. Heating EUI and flow of two types of users.

According to the above inference, the concept of a "regulation degree" is defined to evaluate the users' behavior and can be calculated using Equations (1)–(3).

$$\lambda = 1 - \frac{\overline{G}}{G_{n,max}} \tag{1}$$

$$\lambda_n = 1 - \frac{G_n}{G_{n,max}} \tag{2}$$

$$\lambda = \frac{\sum_{n=1}^{d} \lambda_n}{d} \tag{3}$$

where $\overline{G}$ is the average household flow per unit area, kg/(h·m^2); G_n is the household flow per unit area on the nth heating day, kg/(h·m^2); $G_{n,max}$ is the maximum daily household flow per unit area in the heating season, kg/(h·m^2); and d represents total heating days.

The value of the regulation degree does not reflect the frequency of adjustment by the heat metering user. However, it can reflect the proportion of the degree and duration of action in which users turn down the valve. The users in Chengteh were classified according to different regulation degrees, divided into three grades ($\lambda < 30\%, 30\% \leq \lambda < 50\%$, $\lambda > 50\%$). Three types of user flow curves and adjustment conditions in the same building were generated, as shown in Figure 6 and summarized in Table 2. When the regulation degree was greater than 30%, the users' adjustment times during the heating season ranged from four to ten times, and the behavior included turning down and completely closing the valve. The household meter data of heat metering users in the five cities were calculated, and the average regulation degree in each region was the mean value of the regulation degree of all statistical users. The calculation results are presented in Table 3.

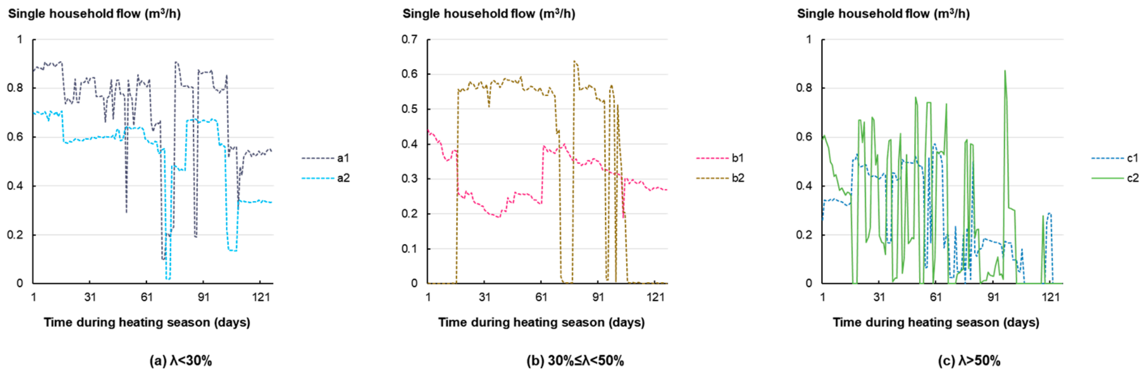

Figure 6. Single-household flow during the heating season for three ranges of regulation degree.

Table 2. Regulation indicator of typical users as a function of the regulation degree.

Regulation Degree	No.	Frequency of Regulation	Duration Ratio of Regulation	λ
λ < 30%	a1	4	9%	22.1%
	a2	2	6%	24.1%
30% ≤ λ < 50%	b1	4	24%	31.6%
	b2	3	37%	46.7%
λ > 50%	c1	10	46%	54.7%
	c2	13	55%	70.9%

Table 3. Average regulation degree of metering community in sample cities.

City	λ
Chengteh	44.50%
Tianjin	24.30%
Beijing	20.70%
Qingdao	14.40%
Taian	6.40%

4. Results

4.1. Heating EUI of Users in Different Locations

Users in the same building can have a difference in the number, area, and orientation of external walls. Even if all users are occupied, a large amount of heat is required to ensure the same room temperature. Figure 7 shows the heating EUI of several metering communities in Chengteh, and the difference is significant. Owing to the difference in the heat demand of users caused by the location, a vertical thermal imbalance is prone to occur in the absence of adjustments to the buildings' heating system [37].

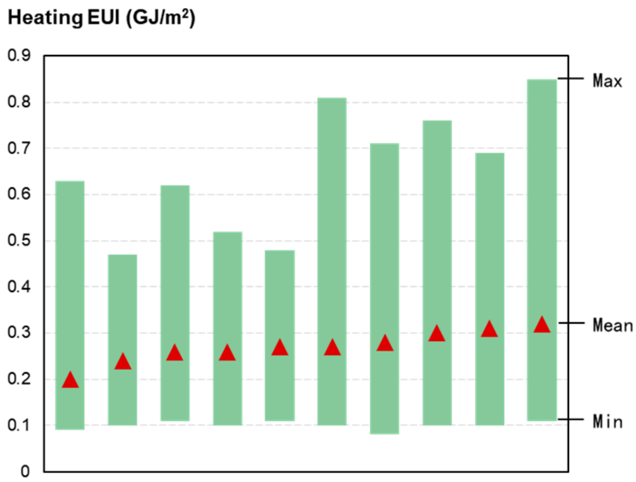

Figure 7. Heating EUI of household meters in 10 communities in Chengteh.

The average heating EUI of users in three types of locations in a total of 12 buildings was calculated, and the results are shown in Table 4. Regarding the average heating EUI, the heat consumption of the top and bottom households was the highest, followed by the side households. The heat consumption of the middle households was the lowest. The average heat consumption of the top/bottom households was 0.03–0.20 GJ/m^2, which is 11–77% higher than that of the middle households. The heat measured by household meters is inaccurate and complicated, making it difficult to use as an indicator to measure the actual heat consumption of users, and it is even more difficult to simply consider the measured values as the basis for charges.

Table 4. Heating EUI of household meters in different locations in case buildings in Chengteh.

Case	Heating EUI (GJ/m^2)			Statistics of Household		
	Top/Bottom	Side	Middle	Top/Bottom	Side	Middle
Ct 1	0.26	0.23	0.17	4	28	60
Ct 2	0.3	0.27	0.25	5	21	43
Ct 3	0.46	0.42	0.28	3	23	26
Ct 4	0.45	0.41	0.3	5	19	17
Ct 5	0.46	0.4	0.26	4	23	31
Ct 6	0.35	0.29	0.27	9	34	26
Ct 7	0.31	0.24	0.21	8	20	44
Ct 8	0.27	0.25	0.23	8	10	24
Ct 9	0.31	0.23	0.2	8	16	45
Ct 10	0.38	0.29	0.27	4	16	48
Ct 11	0.38	0.32	0.25	4	13	27
Ct 12	0.3	0.29	0.27	5	23	25
Ct 13	0.41	0.34	0.24	5	18	30

Because the heat consumption of users in Chengteh is also affected by regulations, the analyses of heat metering districts in the other five cities were used for comparison, and the results are shown in Table 5. The conclusions are similar. Due to the difference in location, the highest increase in the heating EUI of the top/bottom households was in a community in Taian, with a 78% increase, and the highest increase for side households was in Tangshan, with a 43% increase.

Table 5. Heating EUI of household meters in different locations in case buildings from sample cities.

City	Case	Heating EUI (GJ/m^2)		
		Top/Bottom	Side	Middle
Qingdao	Qd 1	0.44	0.41	0.4
	Qd 2	0.5	0.46	0.44
Taian	Ta 1	0.32	0.27	0.2
	Ta 2	0.41	0.27	0.23
Tangshan	Ts 1	0.37	0.4	0.28
	Ts 2	0.33	0.31	0.27
	Ts 3	0.31	0.31	0.28
	Ts 4	0.3	0.24	0.21

4.2. Influence of Heat Outages on Energy Consumption

It is ubiquitous for users in northern China to interrupt heating. Owing to the existence of heat transfer in adjacent rooms, heating outages will not only seriously affect the heating quality of the surrounding users but will also significantly increase the energy consumption supplied to meet the normal heating room temperature.

The relevant literature shows that the urban vacancy rate in China has reached 21.5%, much higher than that in Nordic countries. In 2017, the vacancy rate of commodity housing was 26.6%, accounting for 50.4% of the total vacant housing [38]. The main reasons for the vacancy of houses are the increases in investment and seasonal houses, and the housing vacancy rate in some northern district heating cities is as high as 40% [13].

An analysis of the heating EUI and occupancy rate in Chengteh is shown in Figure 8a. There is an apparent linear relationship between the heat consumption and occupancy rate. The heating EUI decreases by about 0.1 GJ/m^2 when the occupancy rate increases by 10%. Several buildings in the same community with large differences in occupancy rates were selected as representatives. The statistical results are shown in Figure 8b,c.

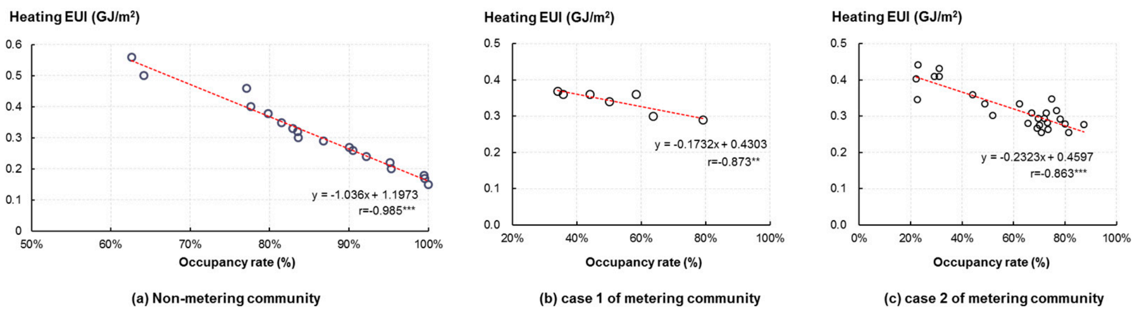

Figure 8. Heating EUI and occupancy rate of different communities in Chengteh (** and *** denote statistical significance at the 5% and 1% levels).

To analyze the effect of heat outages on heat consumption, users were divided according to the number of surrounding user outages. Taking the YL community as a case study, the heating EUI distribution of building 5# is shown in Figure 9. A darker color indicates higher heat consumption by users. In addition, in different locations, 96% of users with high heating EUIs were caused by heat outages nearby.

Figure 9. Distribution of household heating EUI in building 5# of YL community.

The heating EUI of the users at each location was classified and counted according to the number of surrounding user outages. As the existence and location distribution of users in the surrounding area of a single building is random, it is necessary to classify and analyze the users of multiple buildings in the same community. The results of this comparison are presented in Figure 10. With an increase in the number of outage households around the building, the heating EUI showed a progressive increase. When there were outage households around the middle households, heat consumption increased from 15% to 32%.

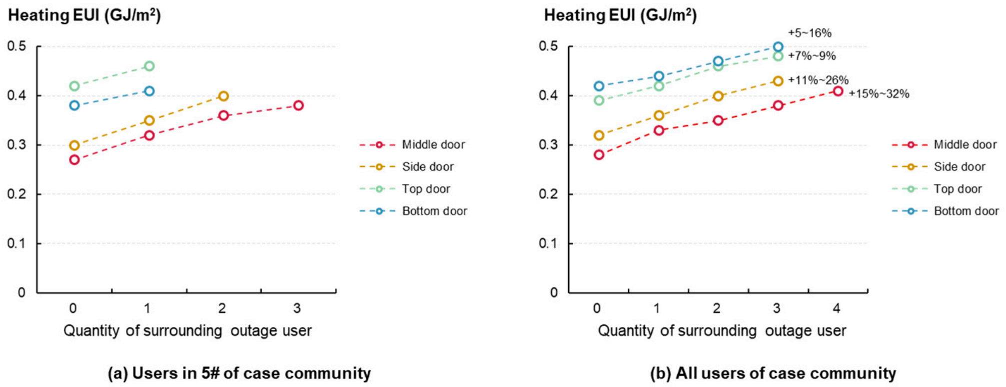

Figure 10. Household heating EUI with different quantities of surrounding user outages in building 5# and all users in the YL community.

Most northern cities do not charge heat outage users, which causes other users to bear more fees.. This causes great disputes in the settlements of these users, which seriously violates the fairness principle of metering and charging. User outages also increase the heating EUI of the entire building, which is an essential factor affecting energy conservation.

4.3. Influence of Users' Regulation Behavior on Heat Consumption

Seventeen metered and eleven non-metered communities were selected, and all samples were three-step energy-saving buildings (in line with the same building energy-saving design standards in northern China). The heating EUI was corrected based on the occupancy rate, and the results are shown in Figure 11. The regulation degree of the community averaged the statistics of all valid metered users, which ranged from 40% to 60%. By analyzing the average heating EUI of the two types of communities, we found that, although most users in the metering community had different degrees of regulation, the average heating EUI of the heating station was only reduced by approximately 0.01 GJ/m^2.

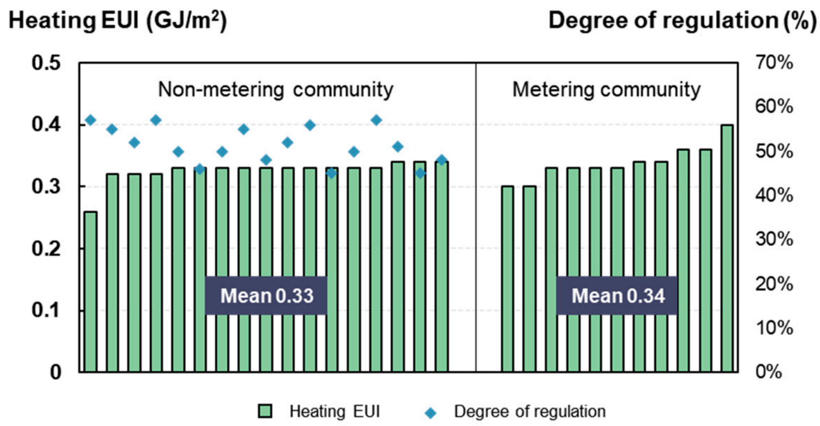

Figure 11. Comparison of heating EUI between various types of communities in Chengteh.

Users in 30 buildings in the YL community were divided into three categories, and the statistics of the heating EUI of each building under different regulation degrees are shown in Table 6. The average heating EUI of the two buildings with $\lambda > 50\%$ was 0.28 GJ/m^2, which is only about 0.03 GJ/m^2 lower than those with less regulation. The effect of reducing the heating EUI is still unclear.

Table 6. Heating EUI of buildings as a function of average regulation degree.

Regulation Degree of Building	$\lambda < 30\%$	$30\% \leq \lambda < 50\%$	$\lambda > 50\%$
quantity of buildings	19	9	2
proportion	63%	30%	7%
heating EUI (GJ/m^2)	0.31	0.29	0.28

As shown in Table 7, it can be seen that the conclusions are different for the heating EUI measured by the users' household meters. Judging from the location distribution of users participating in regulation, 74% of the users with $\lambda > 50\%$ were middle households, indicating that the side households and the top/bottom households had less desire to regulate. With an increase in the degree of regulation, the metered heating EUI was significantly reduced. The average heating EUI of all users with $\lambda > 50\%$ was reduced by 0.16 GJ/m^2 compared with those with $\lambda < 30\%$, and the decrease rate reached 36%.

Table 7. Heating EUI of households with different regulation degrees.

Regulation Degree of User		$\lambda < 30\%$	$30\% \leq \lambda < 50\%$	$\lambda > 50\%$
Side households	proportion	33%	38%	74%
	Heating EUI (GJ/m^2)	0.31	0.31	0.28
Other households	proportion	67%	62%	26%
	Heating EUI (GJ/m^2)	0.52	0.40	0.32
All households	proportion	23%	25%	52%
	Heating EUI (GJ/m^2)	0.45	0.37	0.29

The results of the further classified users are shown in Figure 12. To integrate the three factors of user heat consumption, we found the following:

(1) For the middle and side households, regulation can only significantly reduce the metered heat when the number of surrounding heat-outage households is ≤ 1. There are still a few heating users under this condition. After regulating the valve, heat can be obtained from adjacent rooms, thereby reducing the heat measured by their household meters.

(2) When the number of surrounding heat-outage households is ≥2, regulation does not affect the heat of the household meter; the same is true when there are outages around the bottom and top households. When there are many nearby heat-outage households, users are unwilling to regulate to meet their everyday heating demands. Many users who participate in adjustments also find it difficult to reduce their consumption because they need to transfer heat to multiple users with outages.

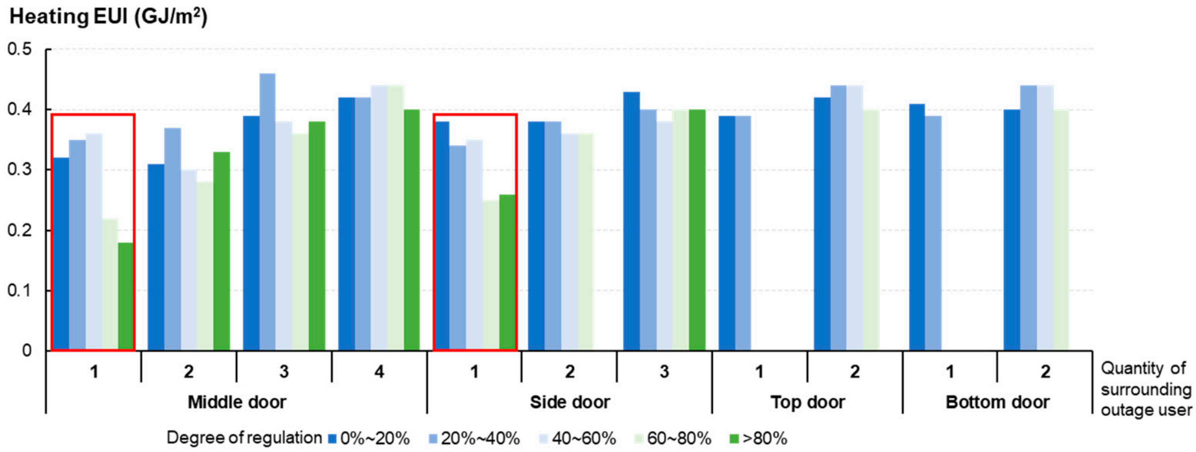

Figure 12. Heating EUI of users with different factors in the YL community.

5. Discussion

5.1. Metering, Charging, and Energy Saving

First, the measured heat consumption by the household heat meter is not equal to the actual heat consumption of the user. The analysis of the influence of the regulation behavior of metering users on the heating EUI in Chengteh showed that user regulation had almost no effect on the total heating EUI of buildings and heat stations. Only a few users achieved a reduction in household-metered heat through regulation. Because of the heat transfer in adjacent rooms, the actual heating EUI of each user in a large apartment building should be the sum of the household-metered heat and the heat transfer of adjacent users, as shown in Figure 13. Combined with the fact that the total heating EUI of the building did not change significantly, it can be considered that these users only reduced the heat provided by the pipe network through regulations so that the measured heat at their household heat meters is reduced. However, at the same time, regulation behavior increases the heat transfer from surrounding users. Therefore, even if there are some users in a building with a significant degree of regulation behavior, the total heating energy consumption of the entire building does not change significantly.

The data quality of household heat meters is generally poor, making the cost of ensuring adequate and reliable data for household meters very high. Even if a household meter can be accurately measured, many studies have pointed out that the actual heat transfer between households is difficult to calculate. Therefore, it is challenging to use household meter data as the basis for charging, as it only increases the burden and cost of communication with users in heating enterprises. Thus, the three original intentions of implementing the heat metering reform were to achieve user charging by heat, to promote building energy conservation, and to promote user behavioral energy conservation.

For the behavioral saving of DH systems, through the analysis of a large amount of measured data in this study, it was demonstrated that under the continuous operation of the system and the thermal characteristics of the users in the apartment building, it is difficult to realize energy saving with DH systems through user regulation behavior. The reform goals of charging with metered heat and promoting building energy conservation should adopt more suitable technical routes.

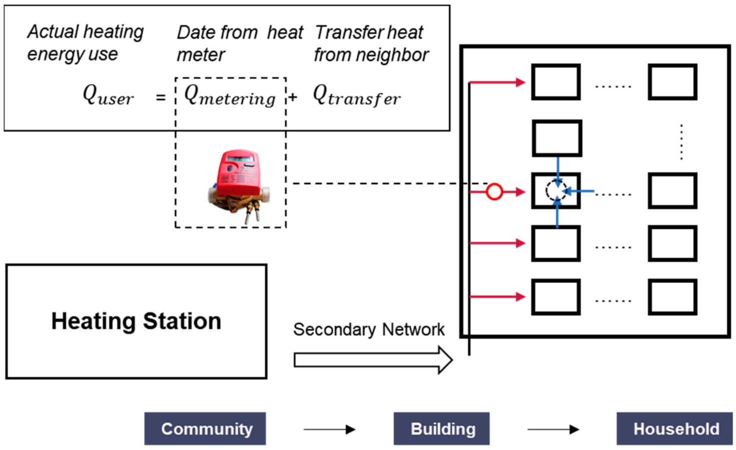

Figure 13. Schematic of actual heating energy consumption of households.

5.2. The Necessity of User Regulation

Although there are many problems with household metering, user regulation in DH systems is necessary. Among heat users in northern China who have not installed metering facilities or even those who have installed meters, there is no method to regulate household heat. When the secondary pipe network for the community lacks balance adjustment, it leads to uneven heating and cooling between buildings and households. Some users feel uncomfortable because their room temperatures are too high. Under this condition, users cannot adjust the valve. They can only choose to open the window, and during this ventilation process, heat is wasted. When the outdoor temperature increases, the heat supply of the station remains unchanged, and heat waste occurs.

Suppose most users in a building are in a state of overheating. In that case, they can reduce the heat supply by adjusting and reducing room temperatures. However, when the user is overheated, a better solution is to send the heating company to conduct an initial balance adjustment and uniformly adjust the heating station to eliminate the overheating.

5.3. Summary of Influencing Factors

Based on the data from Chengteh and other northern cities, this research analyzed the heat consumption characteristics of the end users DH systems according to the three levels of "community/station-building household." This work considered the three aspects of location, heat outages, and user regulation, and the following conclusions were drawn:

(1) There are significant differences in heat consumption between users in different locations, which is mainly reflected in the fact that the heating EUI of users on the edge and at the top/bottom is higher than that of middle users.
(2) Heat outages by surrounding users significantly increase the consumption of heating users. From the perspective of buildings and heating stations, an increase in the rate of heat outages and vacant houses leads to a significant increase in heating energy consumption.

Based on the above analysis, the metered heat consumption of a single user is affected by three factors: location, surrounding heat outages, and user regulation. However, from the perspective of DH systems, the user outages are the main factor leading to an increase in heat energy consumption.

6. Conclusions

Through data analysis of several pilot cities implemented with a heat metering policy, this study found that the users' participation in regulation was low, and most indoor regulation devices were useless. Through a comprehensive analysis of household data in Chengteh and a comparison with northern cities, the following conclusions were drawn:

(1) There was a significant difference, about four to eight times, in heat consumption among metered users in Chengteh. The heating EUI of the side households and the top and bottom households was generally higher than that of the middle households. In Chengteh, the average heating EUI of the top/bottom households was 11–77% higher than that of the middle households. The average heating EUI of the side households was 7–54% higher than that of the middle households. In other cities, where users hardly regulate, the heating EUI of the top/bottom households had a maximum increase of 78% compared with that of the middle households and a maximum increase of 43% for the side households.
(2) Heat outages significantly impact the heat consumption of each level in the DH system. When a user turned off the supply, the heat consumption increases for heating users ranged from 5% to 32% in Chengteh. Through the analysis of communities and buildings with different occupancy rates, heat outages were found to be the main factor leading to increased heating EUIs. The phenomenon of heat outages is severe in DH systems in northern China. Users who have been out of service should be charged based on the increased heat consumption of surrounding users.
(3) For most DH systems in the northern cold and severely cold regions, the energy-saving potential of guiding users to regulate with household-metered data is small. By comparing the degree of regulation and consumption of multiple communities and buildings, only a few users reduced the metered heat by turning down their valves. However, these meters cannot reflect actual heat energy consumption. Even under the active regulation of users in metering communities in Chengteh, the total heat consumption of buildings and communities did not decrease. Considering metering and regulation separately, the indoor control device only allowed users to adjust the indoor temperature when overheated; therefore, household regulation is necessary.

The above three conclusions are based on the heat energy consumption characteristics of large apartment buildings in northern China. The different features of the external envelope cause the difference in users' consumption in various locations. In contrast, the characteristics caused by heat outages and regulation behavior are mainly due to heat transfer between adjacent rooms.

In summary, based on the analysis of the thermal characteristics of large apartment building residents in northern China, the technical route of the heat metering policy needs to be adjusted, following the objective and original intention of the policy. The district heating system in northern China is unsuitable for household metering. The basic metering unit of a heating system should be a building, and further research is needed on designing the relevant mechanism for metering and charging by building. Residents should install control devices to achieve adjustments throughout households. However, they are mainly used to improve indoor comfort when overheating rather than being directly related to the heating fee.

In addition, heat metering and charging are major and complex energy reform projects, and many issues, such as price mechanisms, fairness, the distribution of users' charges in the building, and how market-oriented mechanisms can promote energy conservation, require further research.

Author Contributions: Conceptualization, J.X.; Methodology, A.L.; Software, C.L.; Validation, A.L.; Investigation, C.L. and P.C.; Data curation, A.L., C.L. and P.C.; Writing—original draft, A.L., C.L. and P.C.; Writing—review & editing, A.L. and J.X.; Visualization, P.C.; Supervision, J.X.; Project administration, J.X.; Funding acquisition, A.L. and J.X. All authors have read and agreed to the published version of the manuscript.

Funding: This study was supported by the Ministry of Housing and Urban-Rural Development (MOHURD) R&D Project (Grant no. K20220771), the Natural Science Foundation of China (Grant No. 51521005), and the National Science and Technology Innovation Platform Foundation of Guangzhou Municipal Construction Group Co., Ltd. (grant number [2022]–KJ029). The authors thank the China District Heating Association and Chengteh Heat Group Co., Ltd., for helping with the detailed investigation and field tests. In addition, the authors would like to thank the MOHURD for organizing the survey of the heat metering pilot cities.

Data Availability Statement: Data are contained within the article.

Conflicts of Interest: Author Ao Luo was employed by the Guangzhou Municipal Construction Group Co., Ltd. Author Chunyang Li was employed by the Inner Mongolia Fulong Heating Engineering Technology Co., Ltd. Author Pengyue Cheng was employed by the Chengteh Heat Group Co., Ltd. The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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