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Technical, economic and environmental investigation of using district heating to prepare domestic hot water in Chinese multi-storey buildings

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Abstract
The development of DH (District Heating) is an environmentally friendly and energy-efficient strategy in China. Currently, the vast majority of DH systems are SH (Space Heating) only and do not provide DHW (Domestic Hot Water). DHW is mainly produced by individual water heaters due to the cost-effective issues of the centralized DHW systems. From the perspective of long-term development, DHW produced via DH systems would be more sustainable because DH is an important precondition for an environmental safe use of domestic waste fuels. This paper presents an approach that uses flat stations meanwhile utilizes the industrial waste heat to prepare DHW via the DH network. A building model of a multi-storey building in Beijing was developed to investigate the technical feasibility. An economic evaluation was made using net present value to compare the annualized cost for individual water heaters and flat stations. The environment impact in terms of CO_2 emission when fossil fuels are used to produce DHW was quantified. The results show that flat stations are technically feasible if a few renovations are implemented, and that the use of flat stations is a more sustainable, economic and environmentally friendly approach than the existing DHW preparation technologies.

Key words: district heating, domestic hot water, flat station solution, hydraulic priority, industrial waste heat, China

1 Introduction
Many international research studies have shown that DH is playing an important role in the societal goal of realizing an effective and sustainable energy system [1][2][3][4]. For China, the development of DH in highly-populated and cold-climate regions is both an environmentally friendly and energy-efficient strategy [5] to cope with air pollution and provide energy supply security, which are the two most important challenges for China today [6]. The 12th Five-Year Guideline requires the use of DH in the northern heating area to achieve a 65% share of the heat market [7]. Currently, the vast majority of DH systems only supply SH without DHW.

Over the past 30 years, China has experienced unprecedented urbanization, modernization, and economic development. According to a report from the World Bank, the proportion of urban population rose from 34% in 1996 to 54% in 2014 (Figure 1) [8]. Over the next 20 years, an additional 350 million people are expected to

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migrate to the cities. The rapid urbanization has resulted in significant pressure to provide DHW that can fulfil hygiene and comfort requirements in an efficient, environmentally friendly and economical way.

Over the last decade, the popularity of private DHW systems has led to a substantial increase in DHW consumption. From 1996 to 2011, hot water consumption in Chinese urban areas increased at a significantly faster rate than can be explained by the urbanization process alone (Figure 1) [9]. In 2011, the total energy consumption for residential DHW was 426 PJ, which accounts for 9.5% of total residential energy consumption in China. Moreover, in 2011 the annual average DHW consumption per urban household reached 1.8 GJ having increased more than 8-fold since 1996. This growth trend means the gap between China and developed countries on DHW consumption is getting smaller. For instance, an average household in Denmark consumes 8.28 GJ per year for DHW [10]. Based on the experience and trends in other countries, it can be expected that the share of DHW consumption in urban building energy consumption will keep growing in the next decades. This means that China urgently needs an efficient and technically feasible solution for producing DHW.

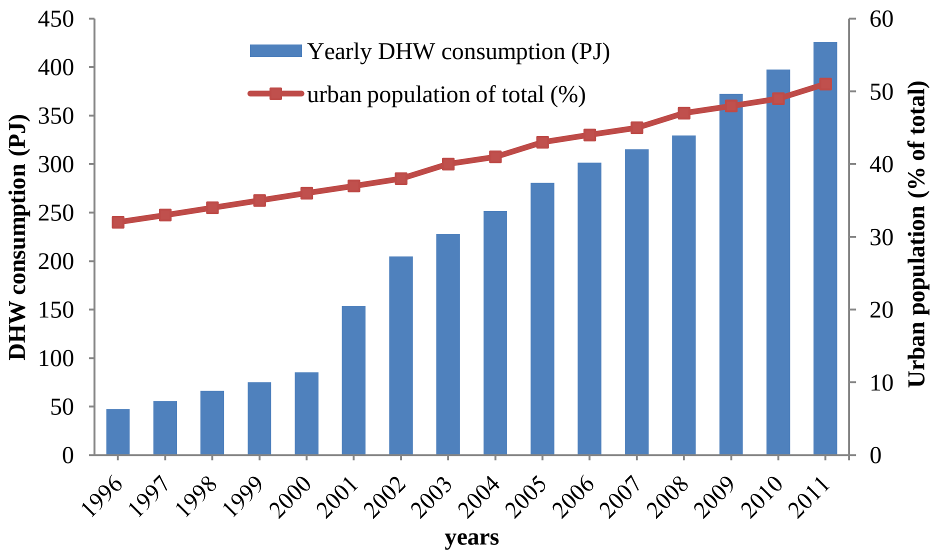


Figure 1. 1996-2011 China's yearly urban residential domestic hot water consumption (PJ)

Numerous studies have focused on producing DHW in an efficient, environmentally friendly and economical way. The 4th generation DH project [2] has studied technology for supplying DHW instantaneously and SH from DH networks with a low supply temperature [10][11][12]. In China, recent DHW research has mainly focused on decentralized DHW systems, such as the use of heat pumps and local renewable energy. For instance, Liu et al. [13] presented a hybrid heat pump system that uses solar energy as the initial heat source for heating shower water in public buildings. An electric heat pump recycles the exhaust heat from the used and drained shower water. Kong et al. [14] analysed the thermal performance of a direct-expansion solar-assisted heat pump water heater to supply DHW throughout the year. Liu et al. [15] studied the production of DHW by recovering the condensing heat from a solar thermoelectric air conditioner. Wu et al. [16] simulated the supply of heating, cooling and DHW combined by using a ground source absorption heat pump. Finally, Luo et al. [17] presented a retrofitted natural gas-based cogeneration system to heat DHW using the waste heat of condensing steam and exhaust gas.

All these studies focused on DHW production in China, but no relevant research has looked into the preparation of DHW using the flat station solution. There are numerous benefits in combining DH supply for SH with the DHW system because the economies of scale in DH make it possible to achieve higher efficiencies in heat plants than can be achieved in individual water heaters. Furthermore, DH can be coupled with environmentally friendly heat sources that cannot be used on an individual basis.

1.1 Background

Currently, individual water heaters are the predominant way of producing and supplying DHW in Chinese households (Figure 2), and DHW prepared via DH systems is rare. A study was made in 2011 to investigate the share of different DHW solutions applied in China, and the results are listed in Table 1 [18].

(a). Electric water heater (b). Natural gas water heater

(c). Solar water heaters

Figure 2. Individual water heater installations in Chinese households

Table 1. DHW preparation technologies in northern and southern China

DHW preparation technology	Share of total	
	Northern China	Southern China, Shanghai
Electric water heaters	63%	12%
Solar water heaters	21%	10%
Natural gas heaters	6%	77%
District heating	5%	1%
Other	5%	0%

Table 1 shows that electric and natural gas water heaters are the technologies most commonly used for DHW preparation in China: 69% in northern China and 89% in southern China respectively. DHW supplied via DH systems accounts for less than 5%. Since the individual water heaters can supply hot water with the desired temperature instantaneously, it seems they must be more cost-effective than DHW from the DH network. But from the perspective of long-term development, DHW produced via DH systems would be more sustainable, because DH has the advantage of being a fuel-independent technology, which means it can supply energy from any energy source that is connected to it [19]. Therefore, investigation is essential to work out the most economical way to produce DHW. This study will address the economic comparison.

1.2 Centralized DHW systems in China

Existing traditional DH systems in China that combine SH and DHW generally have large area substations or central DHW-only boilers that supply hot water to a number of multi-storey buildings via the distribution pipeline. The profile of the traditional DH system that supplies both SH and DHW is illustrated in Figure 3.

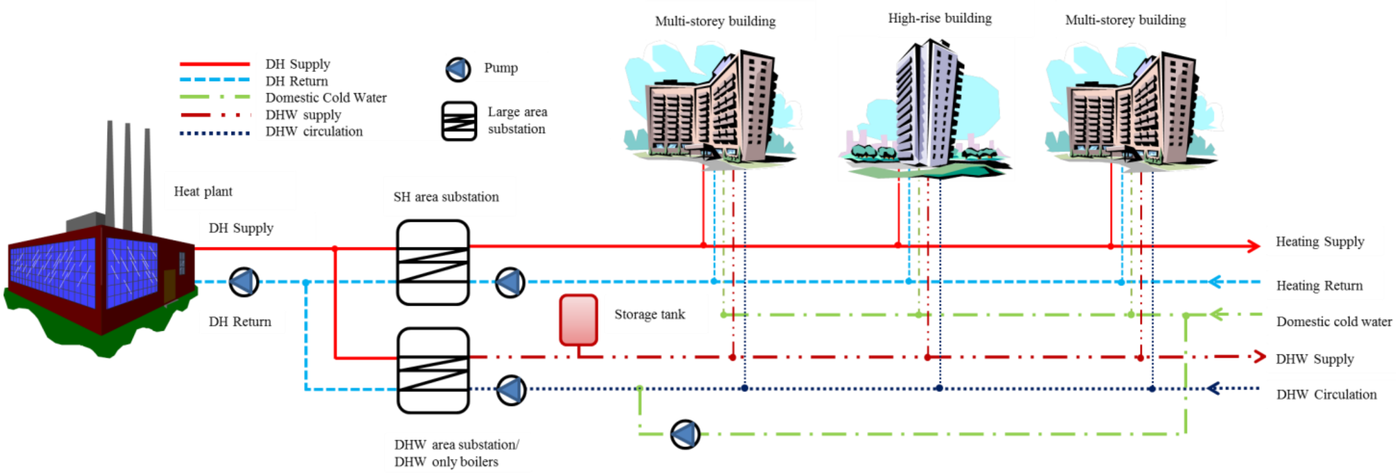


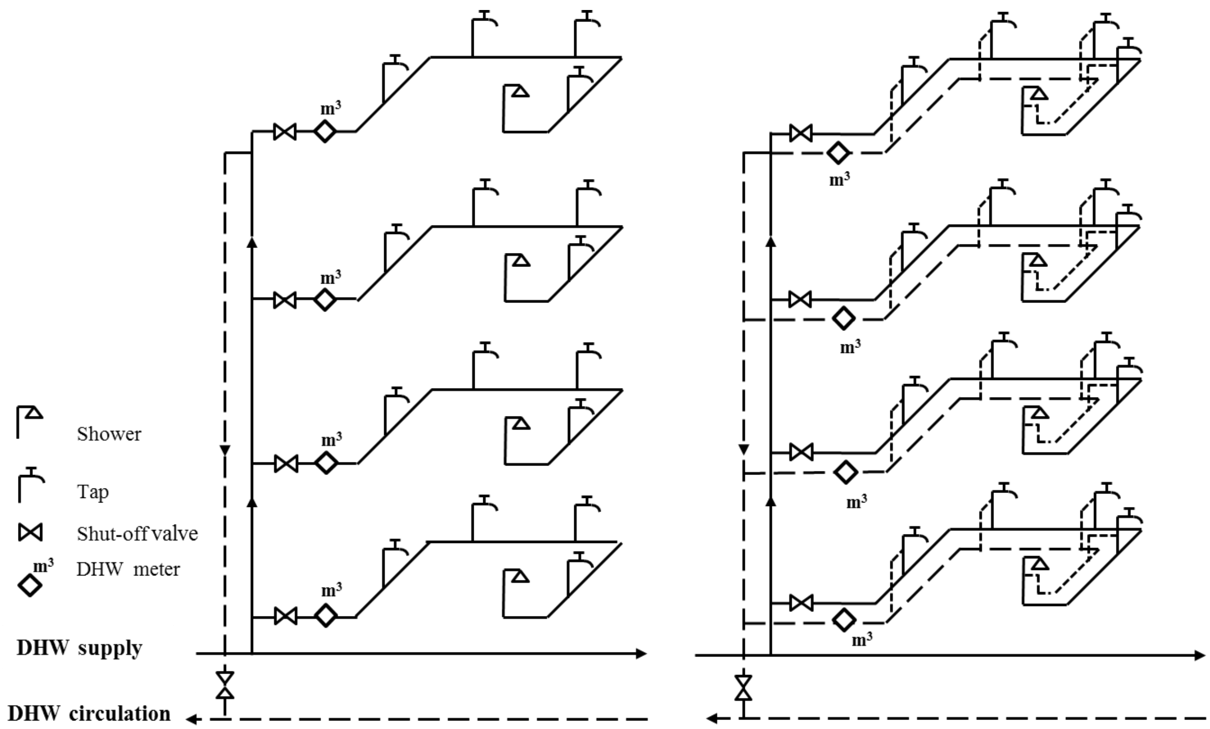
Figure 3. Traditional DH systems that combine SH and DHW supply

These facts have led to the following obstacles to applying DHW preparation via DH:

- High heat losses from the distribution and circulation pipes of centralized DHW systems;
- Unsatisfactory DHW comfort level, due to the arrangement form of the circulation pipes;
- Generally lower hot water consumption per capita than in European countries;
- Historically, SH seen as social welfare is the basis of the DH systems and DHW is excluded.

Figure 3 shows clearly how the central location of the large area substations or DHW-only boilers means that large-scale distribution pipelines are needed to reach all the connected multi-storey or high-rise buildings. Large circulation piping systems are also necessary to keep hot water circulating to ensure the appropriate hot water tapping temperature in terms of hygiene and comfort for DHW usage. Substantial heat losses occur from these distribution and circulation pipelines, which result in inefficient and uneconomic DHW production. Studies have indicated that heat losses from distribution and circulation pipelines account for over 50% of the total heat consumption when DHW is prepared in such a centralized manner [20].

Furthermore, to control costs in the centralized DHW networks, the circulation pipe is commonly only at the staircase level (Figure 4(a)), rather than reaching to each tap (Figure 4 (b)). When circulation pipes are arranged in this way, see Figure 4(a), the result is that a large amount of cold water has to be drained off before the hot water with the desired temperature can be tapped. Nevertheless, the drained-off cold water is still charged at the hot water price.



(a) (b)

Figure 4. Two different circulation pipe arrangements

Studies show that hot water consumption in China only amounts to 1/5 of the hot water consumption in other countries, such as Spain 200 litres/apartment·day, United States 270 litres/apartment· day, Japan 300 litres/apartment·day [20]. Furthermore, measurements from 7 centralized DHW systems in Beijing in 2012 show that the average hot water consumption is 45～133 litres per apartment per day [18]. With centralized domestic hot water systems, the greater the amount of hot water consumed, the more obvious are the economic benefits.

Historically, DH was originally planned as a social welfare service in China with the aim of only providing SH to urban residents during the winter period, and DHW was excluded from the DH systems. Today, the Chinese government is working towards modernizing DH systems by implementing the heat-metering reform of 2003 [21]. One of the aims is to commercialize or commodify heating in cities. That means that in the long run all heat consumption, both SH and DHW, will have to be paid for on the basis of real consumption in the future.

The above-mentioned issues interact with each other and constitute the main barriers to the development of centralized domestic hot water systems in China.

1.3 Key factors in centralized DHW systems

A hot water temperature of 55°C is commonly applied in DHW systems. It is sufficient to meet typical household demands. It is also high enough to kill off Legionella, which has a growth interval from 20 °C to 45 °C. Higher temperatures than 60 °C are not recommended because they can result in scalding of human skin and lime deposits in heat exchangers and other downstream equipment.

For the sake of health safety, Legionella prevention has to be given high priority in DHW systems. Breathing of Legionella-contaminated aerosol, which can occur when the water springs out of taps or shower heads, can cause "Pontiac fever" and "Legionnaires diseases", such as chronic lung disease, immunodeficiency, and can be fatal [22]. European countries have specific stipulations to cope with Legionella in DHW systems. For instance, Danish standard [23] states that, if the concentration of Legionella in contaminated hot water has reached 1000 cfu/l, sterilization treatments must be initiated. To minimize the risk of Legionella, some alternative disinfection methods have been introduced: such as thermal disinfection methods, photochemical (UV light) methods, and physical techniques (ultrafiltration) for pump operation. Other possibilities are to minimize Legionella growth potential by system design. According to the German standard w551 [24][25], DHW systems with volumes less than 3 litres are considered to be safe irrespective of the DHW temperature.

The Chinese design code [26] states that the hot water temperature should be 60°C when considering bacteria and lime precipitation issues. This means that to make DHW hygienically safe the centralized DHW systems need to supply 60°C to the furthest consumers. This causes high heat losses in the distribution and circulation pipelines. Experience from Denmark's DH systems could be relevant for China. They normally use building level or flat stations to produce SH and DHW from separate heat exchange units. To avoid the considerable heat losses caused by large-scale distribution pipelines, low DH temperatures are applied, such as 70/40°C (supply /return temperatures) in 3rd generation DH systems, or even 50/25°C in 4th generation DH systems [27]. Moreover, pre-insulated pipes are commonly used to minimize building distribution and circulation heat losses [28]. The trend today is to avoid DHW circulation altogether by applying a substation in each flat to prepare DHW instantaneously combined with a low-volume DHW installation. This means that the SH supply temperature can be lowered down to 50°C and DHW temperatures to 45°C [29], and that large-scale distribution systems are eliminated. Real flat station applications in Denmark show 8-16% savings can be achieved in terms of the distribution heat loss reduction when flat stations replace the traditional centralized DHW systems [30].

2 Proposed approach

This paper presents the flat station concept for providing both DHW and SH on demand via the DH system to end-users in Chinese multi-storey residential buildings. The flat station is a proven concept. In most European countries, individual heat metering is enforced by law and here flat stations have considerable advantages over vertical DHW riser systems because heat metering can be easily achieved at the same time and with the same heat meter as is used for metering heat consumption for space heating. This study used a building model to analyse the technical feasibility of this concept in a multi-storey residential building in Beijing. We compared the use of flat stations and individual water heaters in terms of both economic benefits and environmental impacts. The aim was to develop a sustainable approach to the production of DHW in Chinese multi-storey residential buildings. The main conclusions from the analyses are: 1) the flat station application is technically feasible in both existing residential building and new buildings; 2) it is economically competitive compared to existing individual DHW production methods in China; and 3) the utilization of sustainable energy or renewable/waste energy as fuel sources makes this approach environmentally friendly.

2.1 Flat station solutions

The flat station is a complete individual heat transfer unit. The energy is supplied from a central energy source and a flat station is installed in each flat or single-family house. A substation consists of three main elements: instantaneous preparation of DHW, differential pressure control of the heating and DHW system, and metering of the energy consumption. It is installed in the apartment with three centrally connected pipes: a heating supply pipe and a return pipe connected via the DH network to a central heat source, and a cold water supply pipe.

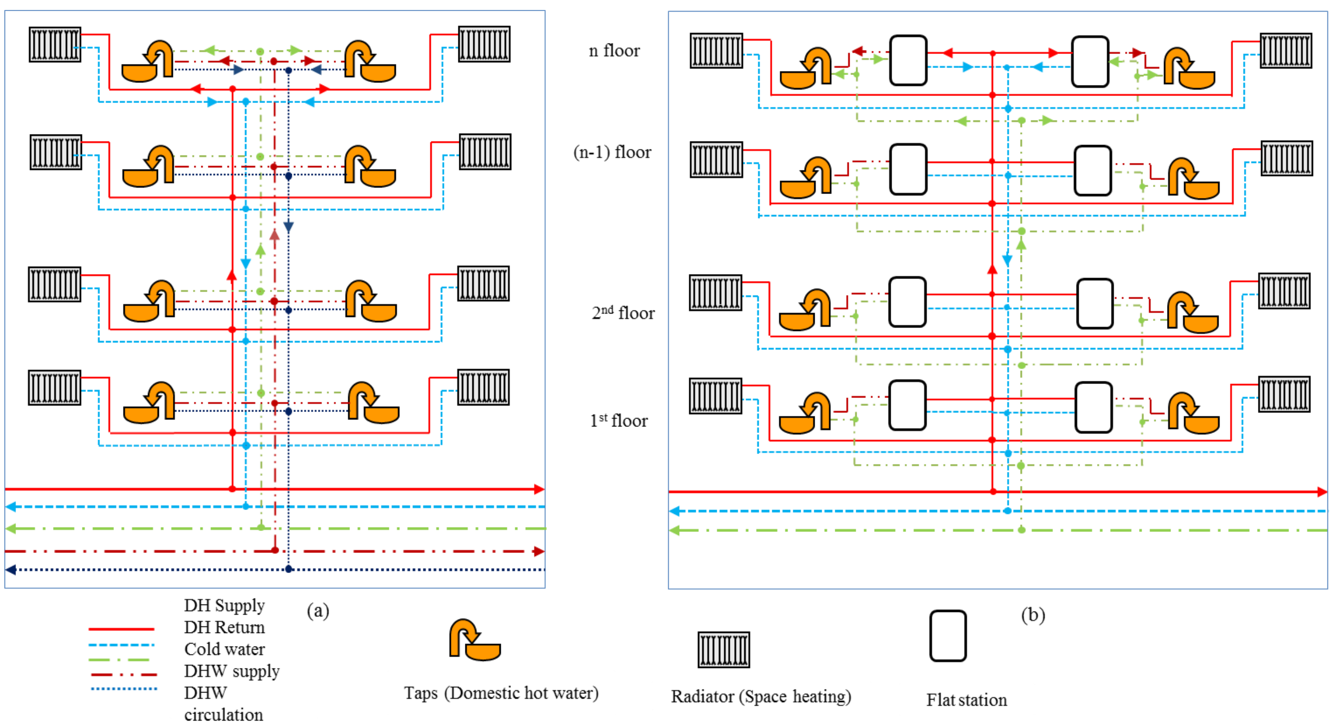


Figure 5. Traditional centralized DHW pipe system (a) and the flat station pipe system (b)

When flat station solutions are applied, the number of vertical pipes in the staircase is reduced. The traditional 5-pipe system (SH supply and return, DHW supply, circulation and DCW supply as shown in Figure 5 (a)) is replaced by 3-pipe flat stations (SH supply and return and cold water supply as shown in Figure 5 (b)). This reduction implies not only 40% less piping, but also 8-16% heat loss reduction.

With regard to Legionella, the flat stations minimize the risk, because the distance from the point of DHW preparation to the point of usage is considerably shortened. Furthermore, with every tapping the water in the pipe is flushed out and replaced with fresh hot water. During non-tapping periods, the water cools down to room temperature, typically below or at the border of the growth zone of Legionella.

Other advantages of the flat station concept are the comprehensive possibilities for individual control and energy consumption measurement at the level of the apartment. As flat station solutions take into account SH and DHW consumption measurements for individual apartments, the existing heat metering and billing methods, namely heat fees charged by floor area, and DHW fees charged by cubic metre, can be replaced. This could motivate the energy-saving consciousness of end-consumers, resulting in the achievement of reductions in energy consumption and emission [31].

2.2 The proposed approach

The proposed approach in this study is to integrate flat stations into existing heating systems with the aim of minimizing the necessary renovation work, but also taking into account the long-term development possibilities of the heating systems.

By integrating flat stations, the existing combined DHW/SH DH systems are simplified: the distribution and circulation pipes of the traditional centralized DHW systems can be removed (Figure 6). The indoor DHW system indirectly connects to the existing SH system via the heat exchanger embedded in the apartment substation. If the DHW is produced by an individual water heater, it is simply replaced by the flat station (Figure 6). In both cases, the existing SH system becomes the heat source of the flat stations.

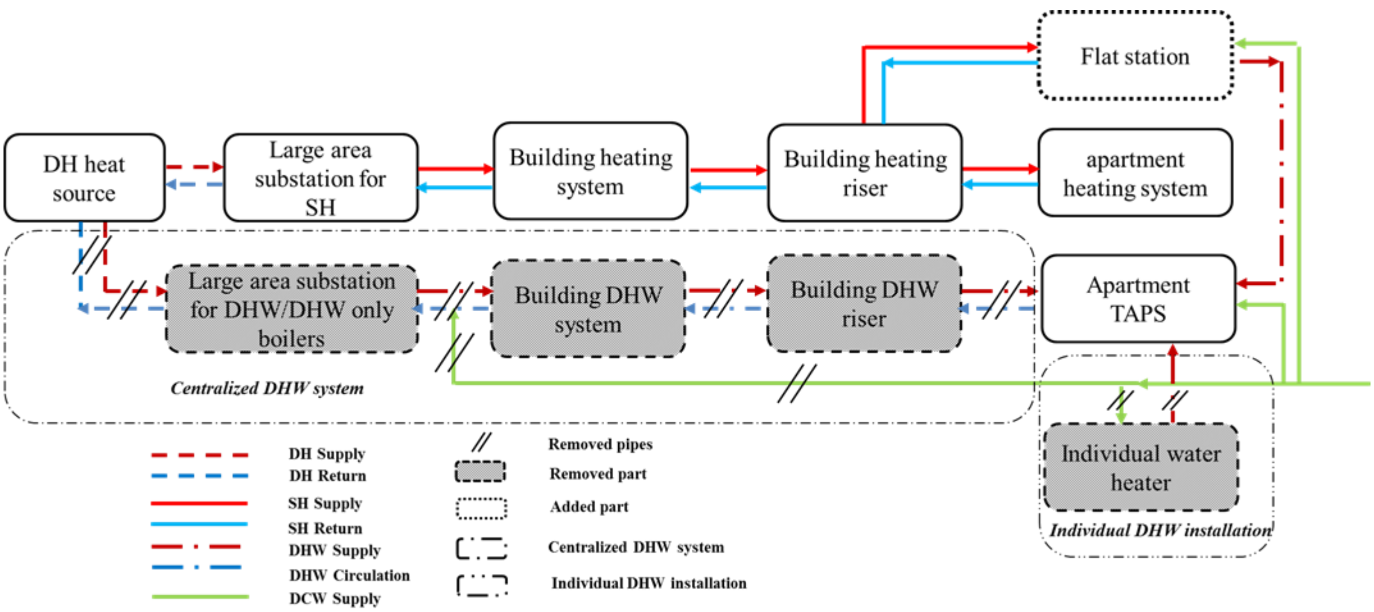


Figure 6. Renovating the existing DH system by integrating flat stations

From the long-term development point of view, the Chinese DH industry looks towards utilizing local renewable energy and surplus heat from industrial processing, which are currently being wasted into the atmosphere or unused as heat sources [32][33]. Moreover, studies have shown that in most cases waste heat from industrial processes can be found within a 30 km radius of cities in northern China that can meet almost 70% of the heat demand of northern China [9].Table 2 [34] lists the available industrial waste heat capacity from 13 cities around Beijing, together with each city's DH heat load. It is clear that some heavily industrial cities like Tianjin, Zhangjiakou, Tangshan, and Handan have sufficient waste heat capacity to supply the city's DH systems. Tsinghua University has proposed the integration of available industrial waste heat around Beijing and surrounding cities within a radius of 200km to be used as the DH source for these areas [26]. The research results indicate that the existing industrial waste heat in Beijing, Tianjin and Hebei Province could be used as the energy resource to power the DH systems of those areas during the winter for the next 10 years.

Table 2. DH heat load and industrial waste heat available in 13 cities around Beijing

	City	A: City heat load (MW)	B:Industrial waste heat capacity (MW)	Ratio A to B
1	Beijing	45666	8951	20%
2	Tianjin	15780	17515	111%
3	Shijiazhuang	13172	12729	97%
4	Chengde	3439	2435	71%
5	Zhangjiakou	5024	7556	150%
6	Qinhuangdao	3634	1988	55%
7	Tangshan	9859	16320	166%
8	Langfan	5415	2028	37%
9	Baoding	11112	4784	43%
10	Cangzhou	7457	5936	80%
11	Henshui	4244	2027	48%
12	Xingtai	7278	2405	33%
13	Handan	10204	11050	108%
	Total	142284	95724	67%

In China, the heating season generally has a fixed period, such as from November to the following March. Based on the assumption that industrial surplus waste heat can be utilized or recovered as the heat source for DH systems in China, and that DHW heat demand is significantly lower than that for SH, the industrial waste heat could be used to cover the DHW heat demand during the non-heating period. Moreover, the existing DH pipeline infrastructure, currently mostly used only for SH supply, can now be fully utilized operating for the whole year.

3 Methodology

A model was developed to evaluate the technical feasibility of implementing the flat station solution with instantaneous DHW preparation replacing the traditional centralized DHW system or existing individual water heaters in standard apartments in a multi-story building in Beijing.

3.1 Building model

According to the statistical data of Beijing city in 2014, the three-person family is the most common family size accounting for 30.9% in the urban area [35]. The same data shows that the housing area per capita in Beijing urban area is 31.5 m^2 [36]. This means that the standard apartment in Beijing can be defined as 95 m^2 with three occupants.

To accord with design code [26], the minimum pressure head needed to supply DCW (domestic cold water) to 1st storey apartments is 100 kPa. For the second storey, it is 120 kPa. For apartments above the 2nd storey, each storey needs an extra 40 kPa [37]. The DCW pressure head at the building service pipe is generally 300 kPa, which means the available pressure head is sufficient to deliver water to the sixth storey. So, in this study, we consider the supply pressure of DCW required for a 6-storey high residential building. Higher buildings will need DCW booster pumps. Here we assumed this 6-storey apartment building is attached to a few other building units. In each building unit, each floor has two apartments with the same area. The 12 apartments in each building unit are supplied heat via a common riser**.** The heating installation structure is shown in Figure 7.

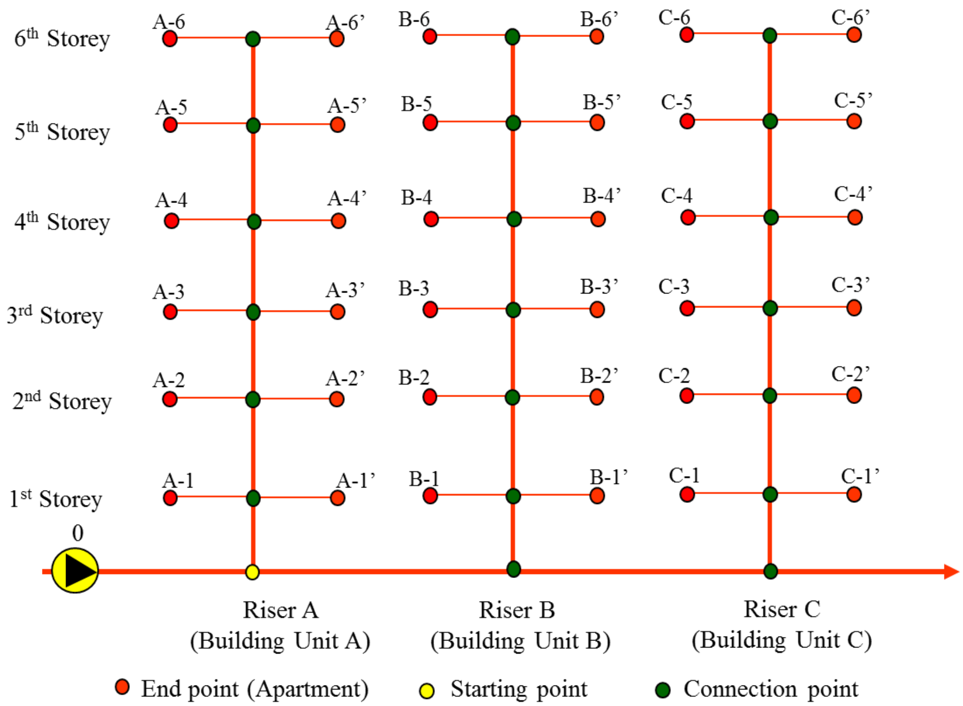


Figure 7. Graphic showing the heating installation structure in the multi-storey building model

3.2 The SH heat capacity and DHW demands

3.2.1 SH heat capacity and DHW demand for a single apartment

The existing buildings referred to in this study are mostly buildings built after 2000 with a two-pipe radiator heating system. Each apartment has its own horizontal heating loop. The peak heat load of the radiator heating system is considered to be 32 w/m^2 with a design outdoor temperature in Beijing of -9 °C [38]. Experience shows that many central heating systems are oversized, and were so even in the initial design phase. This was because the heating areas might be increased in the future or indoor thermal comfort might need to compensate for unsatisfactory operation. It is not unusual for the design heat capacity to be around 65 W/m^2 or even higher in some cases. So the design heat load for our standard apartment is 65W/m^2, and the heating capacity for the standard apartment with 95 m^2 will be 6.2 kW. The design temperatures for radiator heating systems are usually 75/50/18 °C (supply/return/indoor temperature) according to the national design code [39].

A 95 m^2 residential apartment in China usually contains a bathroom and a kitchen. The water installations are designed in accordance with the national design code [26], see Table 3. Here the average DCW temperature is considered 10 °C. For DHW installations in a single apartment, the necessary capacity usually meets the DHW demands of the shower and hand sink simultaneously. So for our standard apartment, the required DHW power is 21 kW.

Table 3. DHW consumption in a standard apartment in China

Item	Unit	Bath	Shower	Kitchen	Hand sink
Water flow	l/s	0.2	0.1	0.14	0.1
Appropriate tap temperature (Mixed water)	ºc	40	40	50	30
Capacity demand if T_{cold} water=10 ºC	kW	25.1	12.6	23.4	8.4

3.2.2 China's hourly variation coefficient and European coincidence factors

When a centralized DHW system is dimensioned in China, the hourly variation coefficient K_h is an important factor in determining the hot water flow rate and heat consumption. The hourly variation coefficient is defined as the ratio between the maximum hourly water consumption in the peak load day and the average hourly water consumption: see Eq. (1).

$$K_h = \frac{q_{hr}}{q_T} \tag{1}$$

where q_{hr} (l/h) stands for the maximum hourly water consumption in the peak load day and q_T (l/h) is the average water consumption, which can be calculated as in Eq. (2)

$$q_T = \frac{\mathrm{m} * q_r}{24} \tag{2}$$

where m is the number of DHW consumers and q_r (l/person・day) is the DHW usage quota per person per day. For residential buildings in China, the hot water consumption quota per person is recommended as 60 ~100 l/person・day [26].

So the actual K_h value depends on the personal hot water consumption quota, q_r (l/person・day) and the number of DHW consumers, m. The design code [37] states that when the number of consumers is less than 100, K_h is 4.8; and K_h is 2.75 when the number of the consumers is higher than 6000. Intermediate values can be obtained by using the interpolation method [37].

For an all-day DHW supply system in China, DHW demand power, Q_{DHW-CN} (kW) can be calculated by using Eq. (3).

$$Q_{DHW-CN} = K_h * \left(\frac{m * q_r * C * (T_h - T_c) * \rho_w}{3600 * t}\right) \tag{3}$$

where T_h, T_c are the temperatures of hot water and cold water, corresponding to 60 °C and 10 °C respectively, ρ_w (kg/l) is the density of water, and t is DHW daily supply hours (equals 24 here).

In contrast, when a European DHW system is dimensioned, coincidence/simultaneous factors are commonly used to estimate the number of the flats that might use hot water at the same time. Coincidence factors use a probability method to determine the size of centralized DHW systems. Briefly stated, only some of all tap points are used in actual practice, based on a 99.9% coincidence interval in a statistical probability distribution [40] . By using coincidence factors, a centralized DHW demand can be calculated for European countries as in Eq. (4).

$$Q_{DHW-EU} = n * f * \emptyset_{DHW} \quad (4)$$

where n is the number of apartments that require DHW, f is the coincidence factor for DHW, and $\emptyset_{\mathrm{DHW}}$ is the DHW demand per apartment.

Coincidence factors are related to the DHW consumption pattern of a "standard flat", which refers to the number of residents in the average flat. For instance, in Denmark, Germany and Sweden the standard flat is defined as having 3.5 residents, which constitutes the basis for the factors[40]. Deviations can occur if the consumption pattern is atypical and differs from the "standard flat. The curves in Figure 8 show the coincidence factors for DHW systems in Denmark, Germany and Sweden. For these European countries, the coincidence factors have similar values, so that the probability of DHW simultaneous use is less than 0.25 when the number of flats is 12, and less than 0.1 when the number of flats is 100.

According to the International Electrotechnical Commission [41], the coincidence factor is identical to the reciprocal of the diversity factor. This definition means that the Chinese DHW hourly variation coefficient and the European DHW coincidence factor are comparable in terms of centralized DHW system calculation. The comparison is shown in Figure 8, where it can be seen that, for China, the DHW coincidence factors, which are the reciprocal of the hourly variation coefficient K_h, are relatively constant around 0.2 when the number of apartment is less than 100.

The reason that the coincidence factors differ greatly between European countries and China could be that high-rise and multi-storey buildings are the main types of building in China, so a low simultaneous DHW usage probability is assumed from the economic point of view. Whereas in European countries, single-family houses and multi-storey buildings are the main building types, so that the coincidence factors have detailed values when the number of flats is small to take comfort into account. On the other hand, the K_h values stated in the Chinese design code are empirical data originally derived from Soviet DHW systems, so there may be errors arising from differences between the design and real conditions due to the lack of actual measurements from Chinese DHW systems [42].

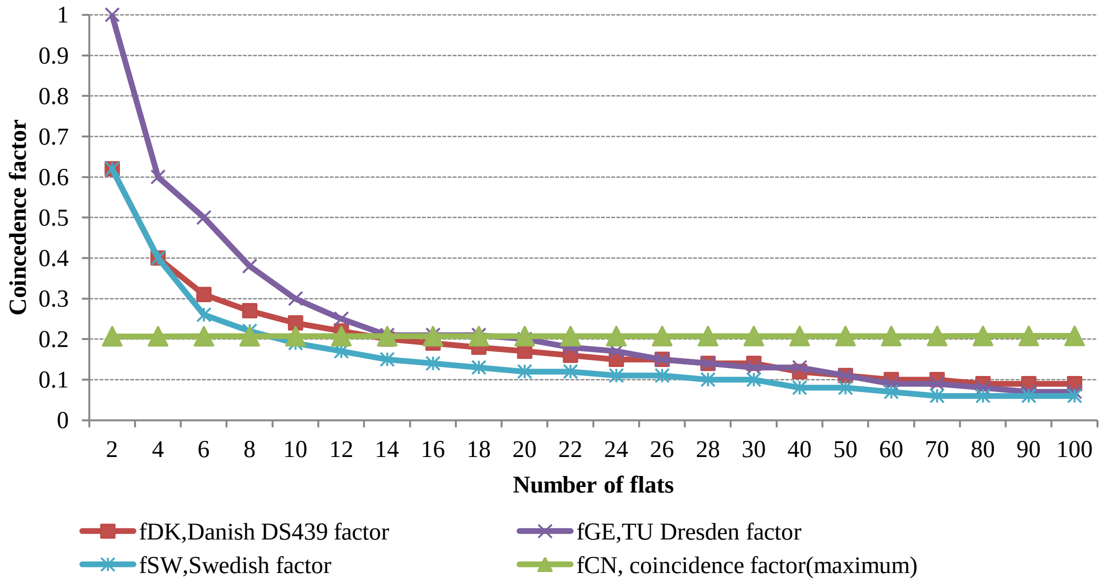


Figure 8. Comparison of coincidence factors used in different countries

Such errors are further confirmed when Eq. (3) is used to input the DHW usage quota, q_r as 100 l/person · day, together with the known data mentioned above, to calculate the DHW demand along the riser in the building model. The calculation results from the building model show that when the number of apartments is less than 6, as when the riser reaches the 4th, 5th and 6th floors, the DHW demand falls below the demand per standard apartment, 21 kW: see Table 4. It is clear that the K_h data are too rough to calculate the DHW demand when the number of apartments is small. To correct the calculation, f_{DK} and Eq. (4) can be used to obtain the accurate required DHW power. The corrected results are listed in Table 4. The SH demands of the building model per floor were calculated and are listed in Table 4 as well.

Table 4. Domestic hot water heat demands corrected by using coincidence factors from Denmark

The number of apartments	Calculation using K_h		Corrected calculation using f_{DK}		SH demands (kW)
	k_h	DHW demand power (kW)	f_{DK}	DHW demand power (kW)	
1	-	21	-	21	6.2
2	4.8	7.0	0.62	26.0	12.4
4	4.8	14.0	0.4	33.6	24.8
6	4.8	20.9	0.31	39.1	37.2
8	4.8	27.9	0.27	45.4	49.6
10	4.8	34.9	0.24	50.4	62
12	4.8	41.9	0.22	55.4	74.4

3.3 DHW hydraulic priority

3.3.1 Philosophy of DHW priority

The philosophy of DHW priority in European DH systems is generally used to dimension the service pipes that run from the street to a single-family house. This means that when the service pipes are designed, only the heat capacity for DHW is considered, because DHW priority assumes that the heat supplied to the SH system can be reduced or suspended during the short periods when DHW is drawn off. In fact, thermal comfort is not considered to be threatened by the lack of SH supply during the period of DHW use, since its duration is assumed not to exceed 10-15 minutes [43]. At a practical level, DHW priority could be achieved using sophisticated hydronic design or, in the case of a substation with electronic control, it can also be implemented electronically.

For this research, the hypothesis was that flat stations can be integrated into existing heating systems to prepare DHW with the minimum of renovation. However, the existing pipelines between the secondary side of the local large area substation and the primary side of the flat stations may need to be adjusted in accordance with the philosophy of DHW priority. Where the existing pipes are smaller than required for DHW, they need to be replaced with DHW size pipes; but where the existing pipes are the same size or bigger, they can be left as they are.

The dimensioning of pipes is determined by maximum flow rates in each section of pipeline. The normal criteria are a certain flow velocity and a certain pressure loss per running metre. In this case, the flow velocity in the pipes is typically less than 1m/s, and the pressure drop per metre has been recommended as 40-60 Pa/m for risers and less than 100 Pa/m for horizontal pipes [44]. The configuration of the renovated heating system is that the primary side of the flat station connects to the building riser, and the secondary side connects to the indoor DHW system. SH is still directly connected to the apartment heating system.

There are two preconditions for applying the philosophy of DHW priority: the first is that the DHW usage time needs to be short, e.g. 10-15 minutes; the second is that the philosophy can be realized at the practical level, in this study, electronically.

3.3.2 DHW usage in northern China

To find out about DHW consumption habits during the heating season on northern China, an investigation was launched using a questionnaire [20]. The questionnaire focused on three items: approximate tapping time, the usual time of day when the person takes a shower, how many times a week. The results show that the tapping time is less than 21 minutes for over 50% respondents; around 59% of the respondents take a shower in the evening; and the majority of respondents, 70%, take a shower once or twice per week (Table 5).

Table 5. Investigation into shower-taking in northern China

1. Tapping time		2. Time of day		3. Frequency of bathing	
< 7 mins	3%	Morning	9%	1-2 times a week	70%
7~ 9 mins	10%	Noon	3%		
9~ 16 mins	28%	Afternoon	14%	3-4 times a week	22%
16~ 21 mins	23%	Evening	59%		

21~ 32mins	17%	Midnight	1%	Every day	8%
> 36 mins	19%	Random	1%	Twice per day	0%

These data indicate that the philosophy of DHW priority is feasible from a realistic point of view. Even though the SH suspension interval could be 21 minutes, the time constant of buildings is typically so large that it would not make a noticeable difference to the indoor temperature.

3.3.3 Implementation of DHW priority

For the standard apartment with a two-pipe heating system considered in this study, a simple flat station like the Evoflat FSS [45] could be used. The Evoflat FSS is a complete unit for direct heating and indirect instantaneous DHW. Figure 9 shows the circuit diagram of the Evoflat FSS. The DHW temperature is controlled by a self-acting multifunctional controller, TPC-M [45], which implements DHW priority by using a zone valve.

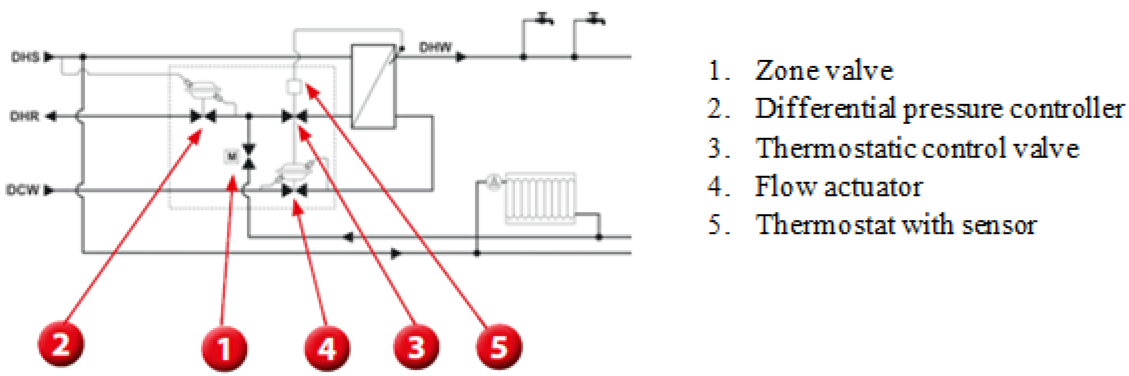


Figure 9. Circuit diagram of Evoflat FSS with self-acting multi-functional controller TPC-M

The TPC-M consists of 5 parts (Figure 9). When a DHW tap opens, the pressure drop that arises at the flow actuator (4) forces the thermostatic valve (3) towards an open position that is related to the flow rate on the secondary side. The desired DHW temperature is achieved by adjusting the opening of the thermostatic valve (3) in accordance with the difference between the desired temperature and the temperature that is measured with the thermostat (5). At the same time, the zone valve (1) ensures DHW priority over SH. There is a flow switch embedded in the secondary side. When a tap is opened, the flow switch detects the flow in the secondary pipe and transmits a “close” signal to the controller, which issues a command to the zone valve to close. When the DHW tapping stops, the flow actuator (4) ensures the immediate closing of the thermostatic control valve (3), and the zone valve (1) opens to allow supply to the SH system. The purpose of the differential pressure controller (2) is to ensure stable and optimum operating conditions for the DHW control valve and that the heating installation is not being affected by the external operation of the DH system. During non-heating periods, the zone valve (1) can be closed manually. In this way, the Evoflat FSS ensures the hydraulic priority of DHW.

4 Results and Discussion

4.1 Technical feasibility

Using the corrected coincidence factors and Eq. (4), the required DHW powers were calculated along the riser of the building model. The vertical DHW riser sizes were dimensioned on the basis of the calculation criteria, i.e. flow velocity less than 1m/s and a pressure drop per metre in the range of 40-60 Pa/m. The results are presented in Figure 10 and compared with the existing vertical SH riser sizes. The figure shows clearly that the riser needs to be replaced with DHW size pipes above the 4th floor, while the rest of the riser can still be used. For the horizontal pipes between the different risers, the required DHW powers are smaller than the SH demands due to the even smaller coincidence factors because of the increasing number of connected apartments. So the existing SH pipe dimensions should be sufficient to supply a flow rate to the buildings that can fulfil the partial SH and DHW demands simultaneously.

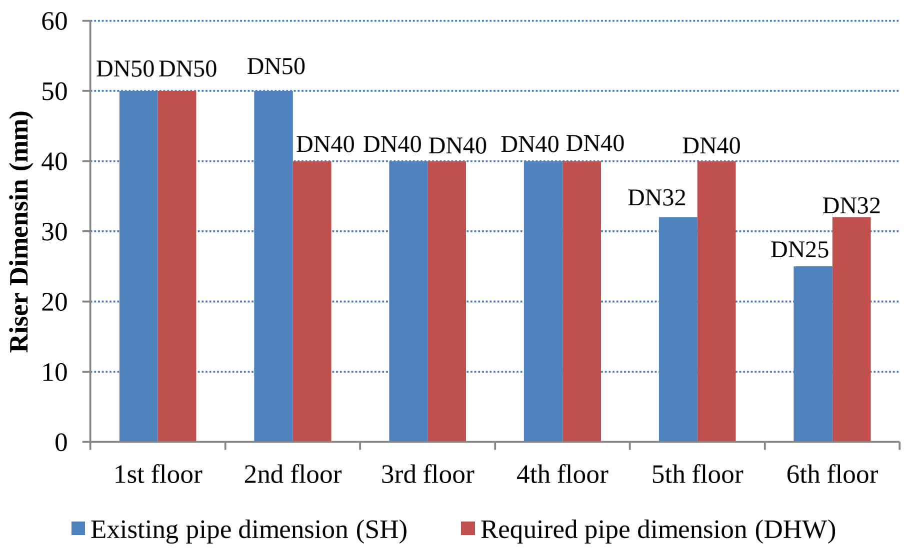


Figure 10. Comparison of existing SH pipe dimension with required pipe dimension for DHW

The philosophy of DHW priority over SH was applied to determine the dimensions of the riser. By explaining the functions of the multifunctional self-acting controller TPC-M, which is installed in the type Evoflat FSS flat stations, we have shown how the substations can implement the philosophy electronically. The other precondition for the application of this philosophy is that the DHW tapping should take no more than 10-15 minutes. Such short periods when SH is suspended will not affect the indoor temperature. The investigation into DHW consumption habits in northern China showed that 70% people take a shower once or twice a week, mostly in the evening, and have less than 21 minutes tapping time. This means that the impacts on indoor temperatures can be ignored. On the basis of these clarifications and data, the integration of flat stations into existing SH systems with the minimum of renovation is therefore technically feasible.

4.2 Economic evaluation

The main idea of economic evaluation is to compare the annual unit energy cost, which depends on the specific DHW preparation technologies, such as flat stations or individual water heaters. This economic comparison is based on the investment costs, operational costs, fuel costs, efficiency and the expected lifetime of the different DHW preparation units [46]. The calculation flow chart is presented in Figure 11. The uniform currency used in this economic evaluation is the Chinese Yuan (￥).

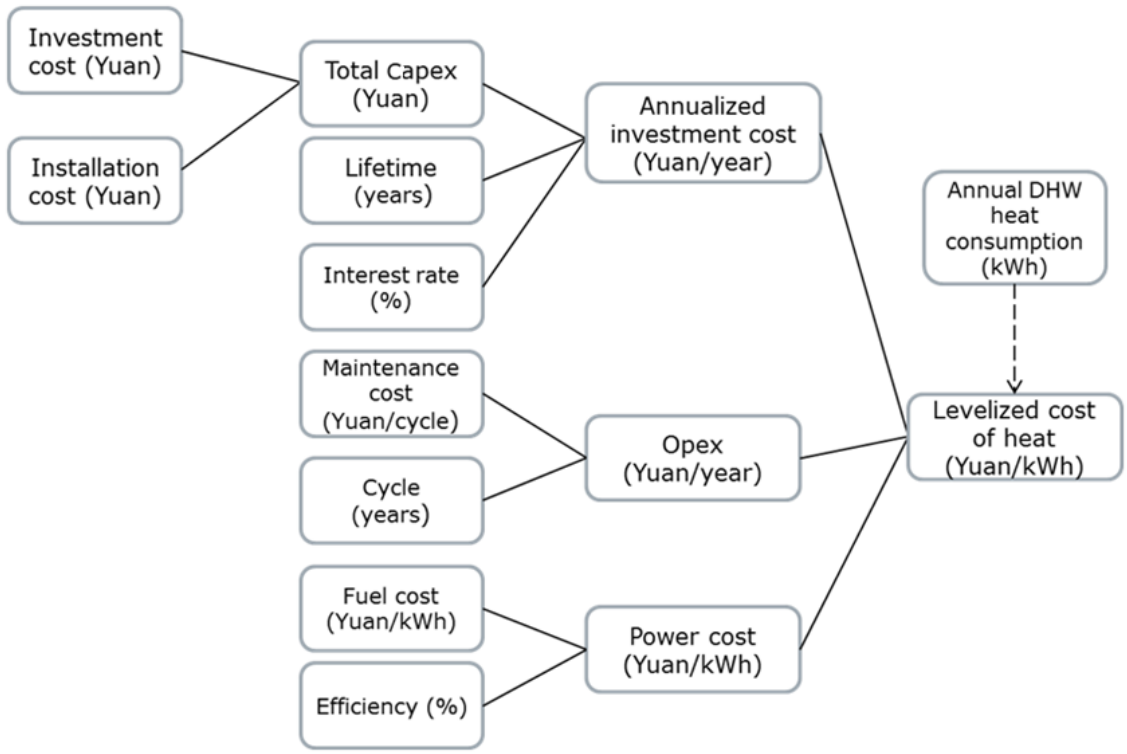


Figure 11. Flow chart to compare the economic evaluations between different DHW production equipment

The total Capex is the sum of investment cost and installation cost. To estimate the annualized investment cost, the net present value (NPV) concept [47] is utilized.

The annualized investment cost can be calculated using the following equation, which is a representation of the NPV concept with the NPV being zero at the end of the payment stream, with the time value and the money interest rate over the lifetime taken into account.

$$Anualized\ investment\ cost = \left(Total\ Capex * \frac{Interest\ rate}{1-(1+Interest\ rate)^{-Lifetime}}\right) \tag{5}$$

In Figure 11, Opex means the average annual cost for operating and maintaining the unit in a safe and reliable manner. Fuel cost represents the cost of the energy per kWh used in preparing the DHW. The fuel can be electricity, natural gas or any other fuel suitable for DH systems. The cost of the fuel is used as the actual cost for residential buildings in Beijing. The annualized cost of heat (Yuan/kWh) for different DHW preparation technologies, such as individual water heaters or flat stations, is the sum of the annualized investment cost, Opex per year divided by the annual DHW heat consumption (kWh) and the annual power cost.

The annual DHW heat consumption for a 95 m^2 apartment in China can be estimated to be 3990 kWh according to [48]. Basic information about the three DHW preparation technologies is listed in Table 6.

Table 6. Economic factors determining the annual cost of heat with different DHW preparation technologies

Items	Natural gas water heater	EL water heater	Flat stations
Annual DHW consumption for a family	3990 kWh	3990 kWh	3990 kWh
Nominal Heat/Electricity Power	21 kW (Heat)	9.5 kW (Electricity)	21 kW (Heat)
Fuels type	Natural gas	Electricity	Local waste heat
Investment cost (Yuan)*[1]	3500	4000	6000
Installation cost (Yuan)	500	500	500
Life time (years) *[2]	8	8	12
Interest rate (%)	5.25%	5.25%	5.25%
Maintenance cost (Yuan/cycle)	100	100	100
Fuel cost (Yuan/kWh)	0.23	0.5	0.09
Efficiency (%)	88%	88%	Flat stations:98%; DH heat source 60%; DH distribution pipeline 90%

*Prices are from Chinese local electronic commerce websites. Lifetime data are from the datasheet on DHW preparation units.

Based on the method discussed above, the levelized costs of heat (LCH) from the three DHW preparation technologies were calculated and are listed in Figure 12, which shows the economic advantage of flat stations over electric/nature gas water heaters. Electric water heaters have the highest LCH, and the LCH of flat stations is the lowest when all the economic factors are taken into account, including investment costs, operational costs, fuel costs, efficiency and expected lifetime. Although, only a small economic gap exists between the flat station solution and using a natural gas water heater, it is noticeable that the efficiency of the DH heat source used in flat station solution was estimated to be 60%. This is relatively low and is an average level, but it has great potential to be improved in the future (Table 6).

Convenience and safety are the two most important factors for residential DHW usage. This was shown by a questionnaire survey carried out in northern China [18]. According to the questionnaire interview data, the centralized DHW systems have the highest resident acceptance of 90% due to the convenience and high safety performance. On the other hand, the disadvantages of centralized DHW systems were mainly reflected in the high DHW price and long waiting-time because of the circulation system traditionally used. Moreover, the same questionnaire showed that individual water heaters have relatively low satisfaction compared to a centralized DHW solution: e.g. 80% said that electric water heaters have the disadvantages of high electricity consumption and the fast formation lime scale, 70% said that natural gas water heaters have risks of gas emission and explosion, and 73% said that solar water heaters have limited use time, provide an insufficient amount of DHW, and limitations in installation position. It seems that the disadvantages of both traditional centralized DHW system and individual water heaters can be avoided by applying flat station solution. So the result is positive in terms of the residents' acceptance of the flat station solution.

Under the national policy, the commercialization of heat, the implementation of household heat-metering based on the real consumption, the modernization of DH system, and the integration of more renewable energy into DH systems are imperative. This situation will drive the DH utilities to provide qualified heat to achieve high satisfaction among heat consumers. On the other hand, cost-effective DH applications are sought to expand profits and increase capacity. In these circumstances, the flat station is a win-win solution. Moreover, compared to renovated buildings, the flat station solution is more easily implemented in new buildings, especially if integrated in the initial design phase.

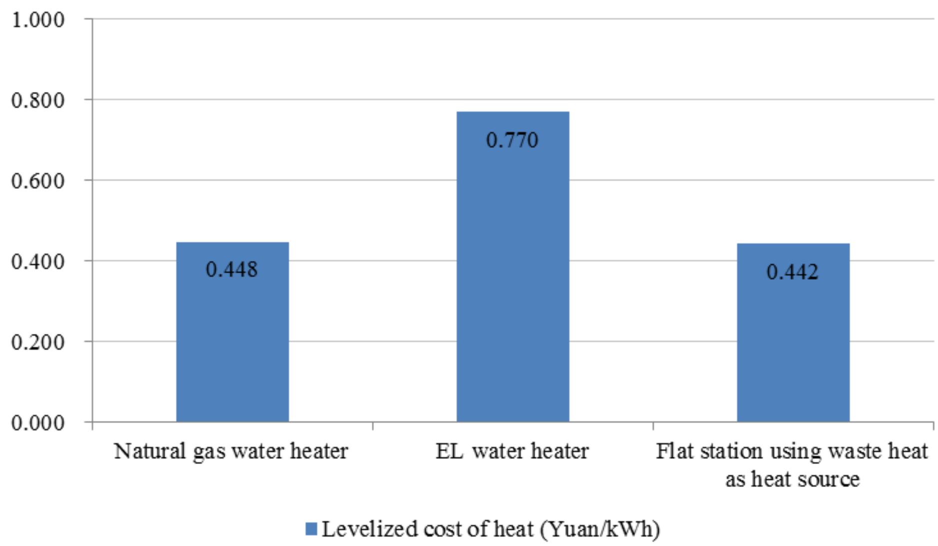


Figure 12. The annualized heat cost comparison between individual water heaters and flat stations

4.3 Quantification of environmental impact

The environmental impact of flat stations compared to individual water heaters can be accessed by considering CO_2 emissions from the different fuels.

China typically converts all its energy statistics into "metric tons of standard coal equivalent" (tce), one tce equal 29.31 GJ (low heat) [49]. In terms of energy equivalence, to generate 1 kWh electricity is equivalent to 0.123 kg standard coal consumption. Regardless of the conversion losses, the corresponding emissions are: 319 g carbon dioxide (CO_2), 2.95 g (SO_2), and 0.86 g nitrogen oxide (NO_X). For natural gas, the two principal combustion products are CO_2 and water vapour. Burning 1 standard cubic metre natural gas with 35.84 MJ/m^3 low heat value emits 1.88 kg CO_2. As mentioned above, a standard apartment annually consumes 3990 kWh for the production of DHW. The consumed energy is equivalent to 3990kWh electricity, and 401 m^3 natural gas.

Table 7. Emissions when using EL water heater and Natural gas water heater to produce DHW

Annual DHW consumption for a standard flat	Energy consumption		Unit emissions	Annual emissions for annual DHW consumption
3990 kWh	Electricity	3990 kWh	CO_2:0.319 kg/ kWh_e	1273 kg CO_2

3990 kWh	Natural gas	401 m^3	CO_2: 1.88 kg/m^3_{gas}	753 kg CO_2
3990 kWh	Waste heat	-	-	-

The flat station solution can use a variety of fuels including waste heat from local industrial processing. Moreover, urbanized areas in northern China already have a well-developed DH pipeline infrastructure. Surplus heat from industrial processes is a great pollution-free resource for fulfilling residential heat demand [50]. According to Fang et al. [51], if 34% of available industrial waste heat had been recovered in 2009, it would have been enough to meet the whole DH heat demand that year. So it is entirely realistic for the flat station solution to use industrial waste heat as the heat source. If surplus heat from industries that is currently being wasted is utilized, there will be practically no extra particle or GHG emissions at all.

Based on the annual energy required to produce DHW for a standard apartment, the emissions (mainly CO_2) when electricity and natural gas are the power fuels were calculated. Based on the assumption that flat stations use local waste heat as the heat source, the CO_2 emission reduction could be 1273 kg per flat per year compared to using electricity as the power source and 753 kg per flat per year compared to using natural gas as the power source (see Table 7).

5 Conclusions

In this paper, we have analysed the current situation of DHW applications in China by using real data, and we have summarized the main reasons why centralized DH systems are not the main technology used to prepare DHW. Based on the current circumstances, the technical approach proposed is that flat stations should be integrated into the existing heating systems to produce DHW instantaneously. The technical advantages of the flat station solution can solve the problems in existing traditional centralized DHW systems and the individual water heaters currently in use can be removed.

Based on the model we developed of the building in Beijing, the proposed approach has been confirmed as technically feasible, and the renovation work required is limited to enlarging the riser pipe dimensions. During the technical feasibility analysis, the hourly variation coefficients commonly used to size centralized DHW systems in China were corrected by using coincidence factors from Denmark. Furthermore, we used the Net Present Value method to evaluate and compare the LCH from flat stations with that of individual water heaters, which showed the economic benefits of applying flat stations.

Real data evidences that massive industrial waste heat source is available around Beijing. Utilizing the industrial waste heat as DH fuel, rather than emitting into atmosphere, is a main tendency also an effective way to abatement the air pollution. On the assumption that flat station solutions can utilize industrial waste heat as the heat source, the environmentally friendly influences of flat stations were quantified and highlighted in comparison with individual water heaters.

A reliable and adequate supply of DHW for daily use has become an important factor for increasing life quality in China against the background of the rapid urbanization and modernization of Chinese society. At the same time, air pollution and security of energy supply are derivative challenges that could compromise the rapid development of the whole of society. The flat station solution presented in this study provides a sustainable alternative for DHW preparation in China; it is wise to have a long-term DHW application to balance the conflict between current opportunities and current challenges. The flat station solution can produce hygienic, comfortable and economic DHW in an environmentally friendly way, thus reducing the burning of fossil fuels and other non-renewable sources of energy and improving the quality of life for residents in China.

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Technical, economic and environmental investigation of using district heating to prepare domestic hot water in Chinese multi-storey buildings

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Abstract

The development of DH (District Heating) is an environmentally friendly and energy-efficient strategy in China. Currently, the vast majority of DH systems are SH (Space Heating) only and do not provide DHW (Domestic Hot Water). DHW is mainly produced by individual water heaters due to the cost-effective issues of the centralized DHW systems. From the perspective of long-term development, DHW produced via DH systems would be more sustainable because DH is an important precondition for an environmental safe use of domestic waste fuels. This paper presents an approach that uses flat stations meanwhile utilizes the industrial waste heat to prepare DHW via the DH network. A building model of a multi-storey building in Beijing was developed to investigate the technical feasibility. An economic evaluation was made using net present value to compare the annualized cost for individual water heaters and flat stations. The environment impact in terms of CO_2 emission when fossil fuels are used to produce DHW was quantified. The results show that flat stations are technically feasible if a few renovations are implemented, and that the use of flat stations is a more sustainable, economic and environmentally friendly approach than the existing DHW preparation technologies.

Key words: district heating, domestic hot water, flat station solution, hydraulic priority, industrial waste heat, China

1 Introduction

Many international research studies have shown that DH is playing an important role in the societal goal of realizing an effective and sustainable energy system [1][2][3][4]. For China, the development of DH in highly-populated and cold-climate regions is both an environmentally friendly and energy-efficient strategy [5] to cope with air pollution and provide energy supply security, which are the two most important challenges for China today [6]. The 12th Five-Year Guideline requires the use of DH in the northern heating area to achieve a 65% share of the heat market [7]. Currently, the vast majority of DH systems only supply SH without DHW.

Over the past 30 years, China has experienced unprecedented urbanization, modernization, and economic development. According to a report from the World Bank, the proportion of urban population rose from 34% in 1996 to 54% in 2014 (Figure 1) [8]. Over the next 20 years, an additional 350 million people are expected to

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migrate to the cities. The rapid urbanization has resulted in significant pressure to provide DHW that can fulfil hygiene and comfort requirements in an efficient, environmentally friendly and economical way.

Over the last decade, the popularity of private DHW systems has led to a substantial increase in DHW consumption. From 1996 to 2011, hot water consumption in Chinese urban areas increased at a significantly faster rate than can be explained by the urbanization process alone (Figure 1) [9]. In 2011, the total energy consumption for residential DHW was 426 PJ, which accounts for 9.5% of total residential energy consumption in China. Moreover, in 2011 the annual average DHW consumption per urban household reached 1.8 GJ having increased more than 8-fold since 1996. This growth trend means the gap between China and developed countries on DHW consumption is getting smaller. For instance, an average household in Denmark consumes 8.28 GJ per year for DHW [10]. Based on the experience and trends in other countries, it can be expected that the share of DHW consumption in urban building energy consumption will keep growing in the next decades. This means that China urgently needs an efficient and technically feasible solution for producing DHW.

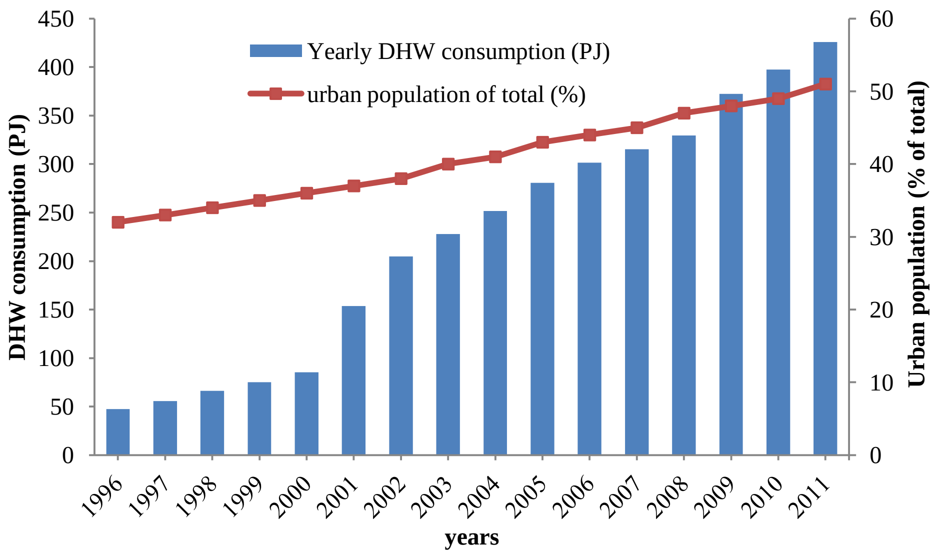


Figure 1. 1996-2011 China's yearly urban residential domestic hot water consumption (PJ)

Numerous studies have focused on producing DHW in an efficient, environmentally friendly and economical way. The 4th generation DH project [2] has studied technology for supplying DHW instantaneously and SH from DH networks with a low supply temperature [10][11][12]. In China, recent DHW research has mainly focused on decentralized DHW systems, such as the use of heat pumps and local renewable energy. For instance, Liu et al. [13] presented a hybrid heat pump system that uses solar energy as the initial heat source for heating shower water in public buildings. An electric heat pump recycles the exhaust heat from the used and drained shower water. Kong et al. [14] analysed the thermal performance of a direct-expansion solar-assisted heat pump water heater to supply DHW throughout the year. Liu et al. [15] studied the production of DHW by recovering the condensing heat from a solar thermoelectric air conditioner. Wu et al. [16] simulated the supply of heating, cooling and DHW combined by using a ground source absorption heat pump. Finally, Luo et al. [17] presented a retrofitted natural gas-based cogeneration system to heat DHW using the waste heat of condensing steam and exhaust gas.

All these studies focused on DHW production in China, but no relevant research has looked into the preparation of DHW using the flat station solution. There are numerous benefits in combining DH supply for SH with the DHW system because the economies of scale in DH make it possible to achieve higher efficiencies in heat plants than can be achieved in individual water heaters. Furthermore, DH can be coupled with environmentally friendly heat sources that cannot be used on an individual basis.

1.1 Background

Currently, individual water heaters are the predominant way of producing and supplying DHW in Chinese households (Figure 2), and DHW prepared via DH systems is rare. A study was made in 2011 to investigate the share of different DHW solutions applied in China, and the results are listed in Table 1 [18].

(a). Electric water heater

(b). Natural gas water heater

(c). Solar water heaters

Figure 2. Individual water heater installations in Chinese households

Table 1. DHW preparation technologies in northern and southern China

DHW preparation technology	Share of total	
	Northern China	Southern China, Shanghai
Electric water heaters	63%	12%
Solar water heaters	21%	10%
Natural gas heaters	6%	77%
District heating	5%	1%
Other	5%	0%

Table 1 shows that electric and natural gas water heaters are the technologies most commonly used for DHW preparation in China: 69% in northern China and 89% in southern China respectively. DHW supplied via DH systems accounts for less than 5%. Since the individual water heaters can supply hot water with the desired temperature instantaneously, it seems they must be more cost-effective than DHW from the DH network. But from the perspective of long-term development, DHW produced via DH systems would be more sustainable, because DH has the advantage of being a fuel-independent technology, which means it can supply energy from any energy source that is connected to it [19]. Therefore, investigation is essential to work out the most economical way to produce DHW. This study will address the economic comparison.

1.2 Centralized DHW systems in China

Existing traditional DH systems in China that combine SH and DHW generally have large area substations or central DHW-only boilers that supply hot water to a number of multi-storey buildings via the distribution pipeline. The profile of the traditional DH system that supplies both SH and DHW is illustrated in Figure 3.

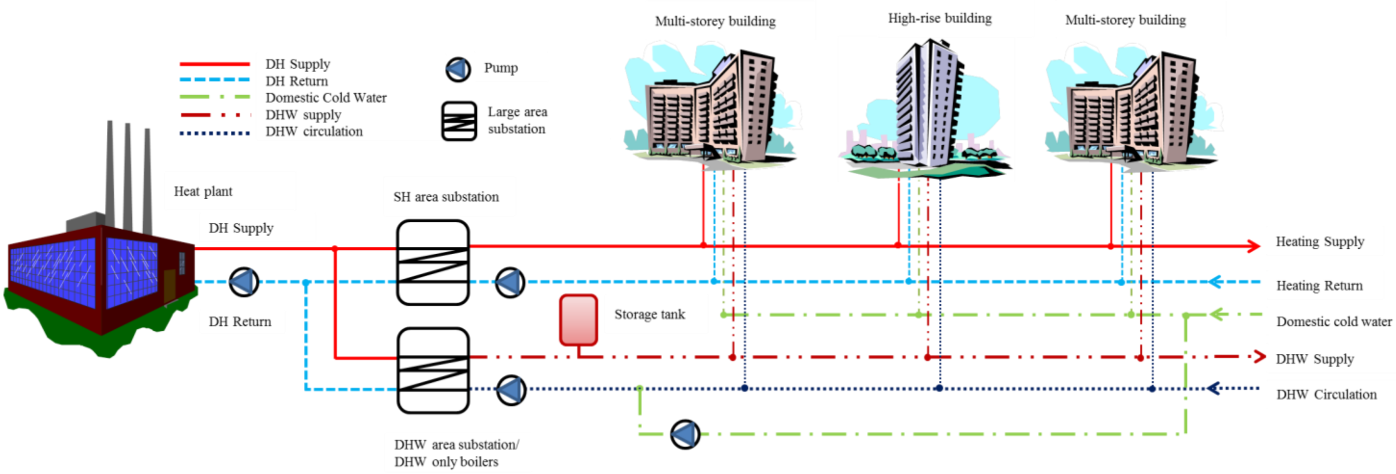


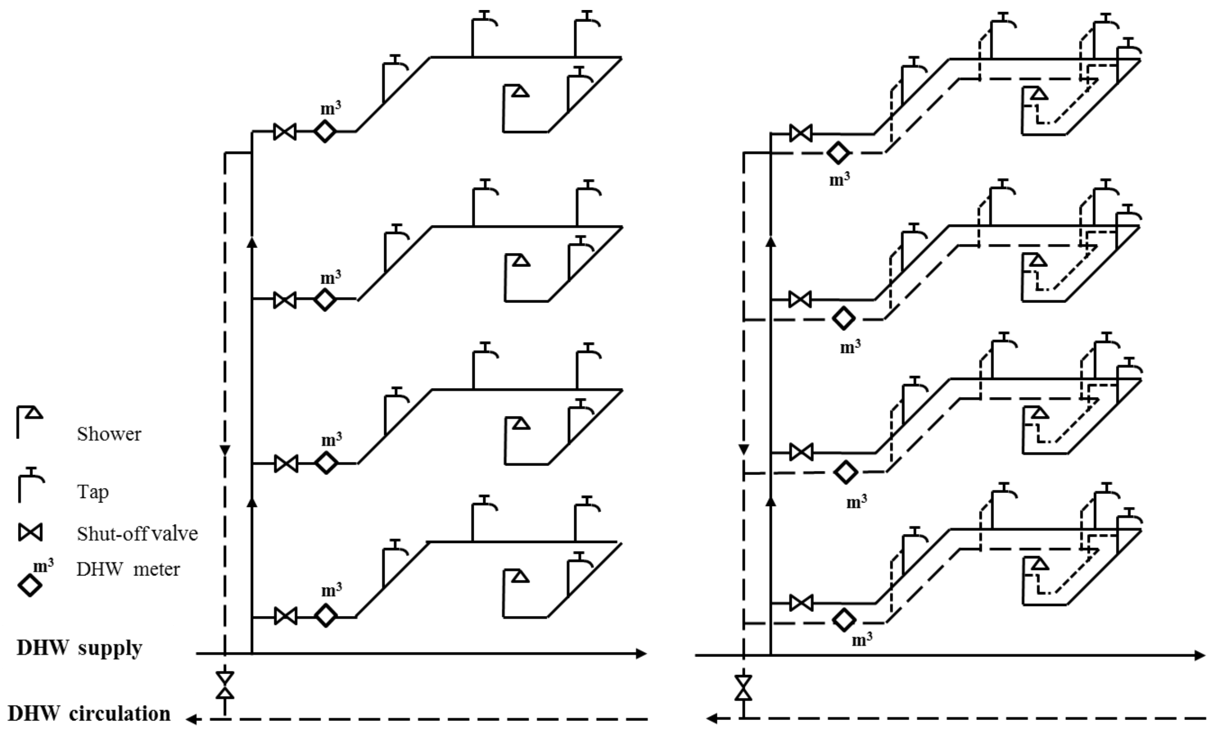
Figure 3. Traditional DH systems that combine SH and DHW supply

These facts have led to the following obstacles to applying DHW preparation via DH:

- High heat losses from the distribution and circulation pipes of centralized DHW systems;
- Unsatisfactory DHW comfort level, due to the arrangement form of the circulation pipes;
- Generally lower hot water consumption per capita than in European countries;
- Historically, SH seen as social welfare is the basis of the DH systems and DHW is excluded.

Figure 3 shows clearly how the central location of the large area substations or DHW-only boilers means that large-scale distribution pipelines are needed to reach all the connected multi-storey or high-rise buildings. Large circulation piping systems are also necessary to keep hot water circulating to ensure the appropriate hot water tapping temperature in terms of hygiene and comfort for DHW usage. Substantial heat losses occur from these distribution and circulation pipelines, which result in inefficient and uneconomic DHW production. Studies have indicated that heat losses from distribution and circulation pipelines account for over 50% of the total heat consumption when DHW is prepared in such a centralized manner [20].

Furthermore, to control costs in the centralized DHW networks, the circulation pipe is commonly only at the staircase level (Figure 4(a)), rather than reaching to each tap (Figure 4 (b)). When circulation pipes are arranged in this way, see Figure 4(a), the result is that a large amount of cold water has to be drained off before the hot water with the desired temperature can be tapped. Nevertheless, the drained-off cold water is still charged at the hot water price.



(a) (b)

Figure 4. Two different circulation pipe arrangements

Studies show that hot water consumption in China only amounts to 1/5 of the hot water consumption in other countries, such as Spain 200 litres/apartment·day, United States 270 litres/apartment· day, Japan 300 litres/apartment·day [20]. Furthermore, measurements from 7 centralized DHW systems in Beijing in 2012 show that the average hot water consumption is 45～133 litres per apartment per day [18]. With centralized domestic hot water systems, the greater the amount of hot water consumed, the more obvious are the economic benefits.

Historically, DH was originally planned as a social welfare service in China with the aim of only providing SH to urban residents during the winter period, and DHW was excluded from the DH systems. Today, the Chinese government is working towards modernizing DH systems by implementing the heat-metering reform of 2003 [21]. One of the aims is to commercialize or commodify heating in cities. That means that in the long run all heat consumption, both SH and DHW, will have to be paid for on the basis of real consumption in the future.

The above-mentioned issues interact with each other and constitute the main barriers to the development of centralized domestic hot water systems in China.

1.3 Key factors in centralized DHW systems

A hot water temperature of 55°C is commonly applied in DHW systems. It is sufficient to meet typical household demands. It is also high enough to kill off Legionella, which has a growth interval from 20 °C to 45 °C. Higher temperatures than 60 °C are not recommended because they can result in scalding of human skin and lime deposits in heat exchangers and other downstream equipment.

For the sake of health safety, Legionella prevention has to be given high priority in DHW systems. Breathing of Legionella-contaminated aerosol, which can occur when the water springs out of taps or shower heads, can cause "Pontiac fever" and "Legionnaires diseases", such as chronic lung disease, immunodeficiency, and can be fatal [22]. European countries have specific stipulations to cope with Legionella in DHW systems. For instance, Danish standard [23] states that, if the concentration of Legionella in contaminated hot water has reached 1000 cfu/l, sterilization treatments must be initiated. To minimize the risk of Legionella, some alternative disinfection methods have been introduced: such as thermal disinfection methods, photochemical (UV light) methods, and physical techniques (ultrafiltration) for pump operation. Other possibilities are to minimize Legionella growth potential by system design. According to the German standard w551 [24][25], DHW systems with volumes less than 3 litres are considered to be safe irrespective of the DHW temperature.

The Chinese design code [26] states that the hot water temperature should be 60°C when considering bacteria and lime precipitation issues. This means that to make DHW hygienically safe the centralized DHW systems need to supply 60°C to the furthest consumers. This causes high heat losses in the distribution and circulation pipelines. Experience from Denmark's DH systems could be relevant for China. They normally use building level or flat stations to produce SH and DHW from separate heat exchange units. To avoid the considerable heat losses caused by large-scale distribution pipelines, low DH temperatures are applied, such as 70/40°C (supply /return temperatures) in 3rd generation DH systems, or even 50/25°C in 4th generation DH systems [27]. Moreover, pre-insulated pipes are commonly used to minimize building distribution and circulation heat losses [28]. The trend today is to avoid DHW circulation altogether by applying a substation in each flat to prepare DHW instantaneously combined with a low-volume DHW installation. This means that the SH supply temperature can be lowered down to 50°C and DHW temperatures to 45°C [29], and that large-scale distribution systems are eliminated. Real flat station applications in Denmark show 8-16% savings can be achieved in terms of the distribution heat loss reduction when flat stations replace the traditional centralized DHW systems [30].

2 Proposed approach

This paper presents the flat station concept for providing both DHW and SH on demand via the DH system to end-users in Chinese multi-storey residential buildings. The flat station is a proven concept. In most European countries, individual heat metering is enforced by law and here flat stations have considerable advantages over vertical DHW riser systems because heat metering can be easily achieved at the same time and with the same heat meter as is used for metering heat consumption for space heating. This study used a building model to analyse the technical feasibility of this concept in a multi-storey residential building in Beijing. We compared the use of flat stations and individual water heaters in terms of both economic benefits and environmental impacts. The aim was to develop a sustainable approach to the production of DHW in Chinese multi-storey residential buildings. The main conclusions from the analyses are: 1) the flat station application is technically feasible in both existing residential building and new buildings; 2) it is economically competitive compared to existing individual DHW production methods in China; and 3) the utilization of sustainable energy or renewable/waste energy as fuel sources makes this approach environmentally friendly.

2.1 Flat station solutions

The flat station is a complete individual heat transfer unit. The energy is supplied from a central energy source and a flat station is installed in each flat or single-family house. A substation consists of three main elements: instantaneous preparation of DHW, differential pressure control of the heating and DHW system, and metering of the energy consumption. It is installed in the apartment with three centrally connected pipes: a heating supply pipe and a return pipe connected via the DH network to a central heat source, and a cold water supply pipe.

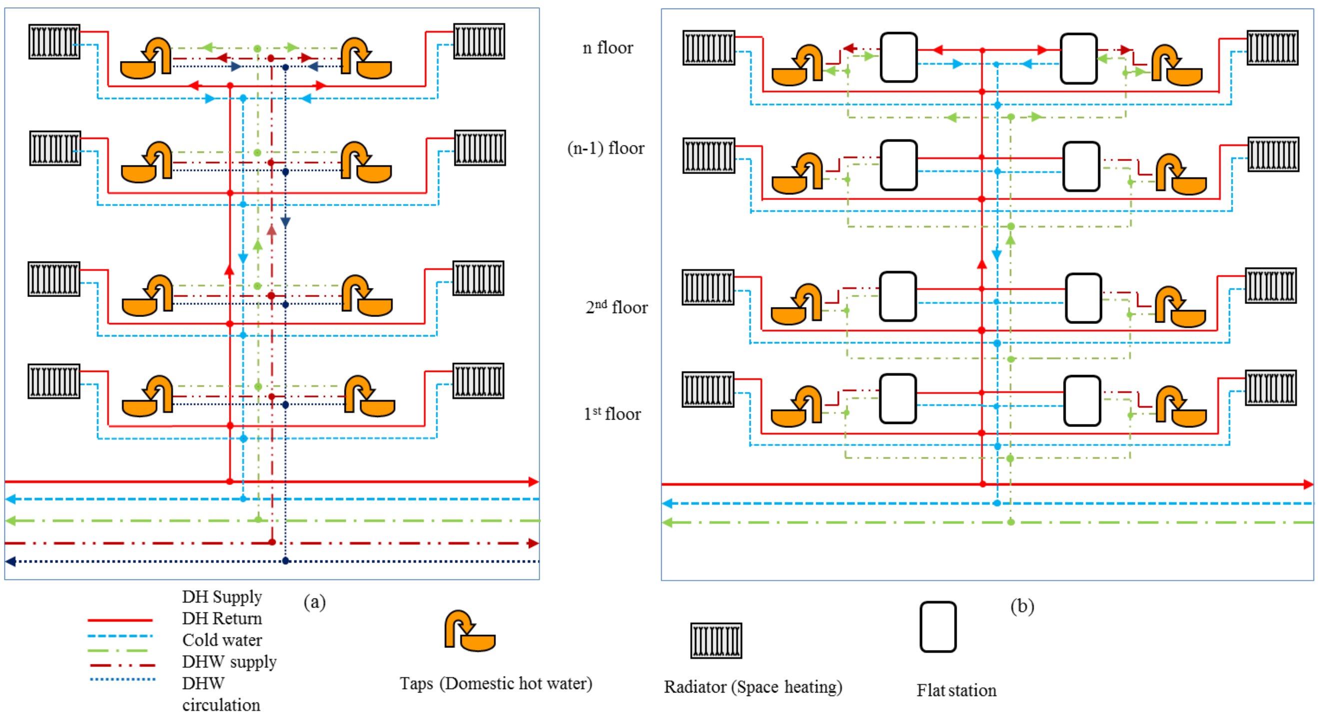


Figure 5. Traditional centralized DHW pipe system (a) and the flat station pipe system (b)

When flat station solutions are applied, the number of vertical pipes in the staircase is reduced. The traditional 5-pipe system (SH supply and return, DHW supply, circulation and DCW supply as shown in Figure 5 (a)) is replaced by 3-pipe flat stations (SH supply and return and cold water supply as shown in Figure 5 (b)). This reduction implies not only 40% less piping, but also 8-16% heat loss reduction.

With regard to Legionella, the flat stations minimize the risk, because the distance from the point of DHW preparation to the point of usage is considerably shortened. Furthermore, with every tapping the water in the pipe is flushed out and replaced with fresh hot water. During non-tapping periods, the water cools down to room temperature, typically below or at the border of the growth zone of Legionella.

Other advantages of the flat station concept are the comprehensive possibilities for individual control and energy consumption measurement at the level of the apartment. As flat station solutions take into account SH and DHW consumption measurements for individual apartments, the existing heat metering and billing methods, namely heat fees charged by floor area, and DHW fees charged by cubic metre, can be replaced. This could motivate the energy-saving consciousness of end-consumers, resulting in the achievement of reductions in energy consumption and emission [31].

2.2 The proposed approach

The proposed approach in this study is to integrate flat stations into existing heating systems with the aim of minimizing the necessary renovation work, but also taking into account the long-term development possibilities of the heating systems.

By integrating flat stations, the existing combined DHW/SH DH systems are simplified: the distribution and circulation pipes of the traditional centralized DHW systems can be removed (Figure 6). The indoor DHW system indirectly connects to the existing SH system via the heat exchanger embedded in the apartment substation. If the DHW is produced by an individual water heater, it is simply replaced by the flat station (Figure 6). In both cases, the existing SH system becomes the heat source of the flat stations.

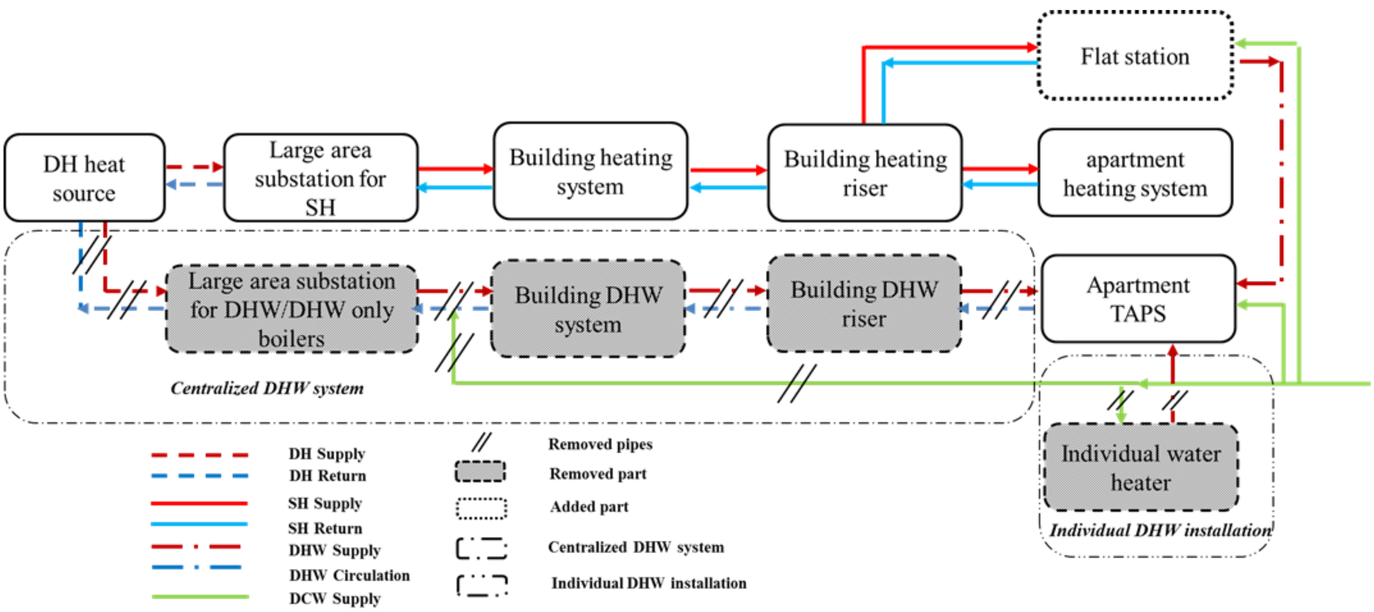


Figure 6. Renovating the existing DH system by integrating flat stations

From the long-term development point of view, the Chinese DH industry looks towards utilizing local renewable energy and surplus heat from industrial processing, which are currently being wasted into the atmosphere or unused as heat sources [32][33]. Moreover, studies have shown that in most cases waste heat from industrial processes can be found within a 30 km radius of cities in northern China that can meet almost 70% of the heat demand of northern China [9].Table 2 [34] lists the available industrial waste heat capacity from 13 cities around Beijing, together with each city's DH heat load. It is clear that some heavily industrial cities like Tianjin, Zhangjiakou, Tangshan, and Handan have sufficient waste heat capacity to supply the city's DH systems. Tsinghua University has proposed the integration of available industrial waste heat around Beijing and surrounding cities within a radius of 200km to be used as the DH source for these areas [26]. The research results indicate that the existing industrial waste heat in Beijing, Tianjin and Hebei Province could be used as the energy resource to power the DH systems of those areas during the winter for the next 10 years.

Table 2. DH heat load and industrial waste heat available in 13 cities around Beijing

	City	A: City heat load (MW)	B:Industrial waste heat capacity (MW)	Ratio A to B
1	Beijing	45666	8951	20%
2	Tianjin	15780	17515	111%
3	Shijiazhuang	13172	12729	97%
4	Chengde	3439	2435	71%
5	Zhangjiakou	5024	7556	150%
6	Qinhuangdao	3634	1988	55%
7	Tangshan	9859	16320	166%
8	Langfan	5415	2028	37%
9	Baoding	11112	4784	43%
10	Cangzhou	7457	5936	80%
11	Henshui	4244	2027	48%
12	Xingtai	7278	2405	33%
13	Handan	10204	11050	108%
	Total	142284	95724	67%

In China, the heating season generally has a fixed period, such as from November to the following March. Based on the assumption that industrial surplus waste heat can be utilized or recovered as the heat source for DH systems in China, and that DHW heat demand is significantly lower than that for SH, the industrial waste heat could be used to cover the DHW heat demand during the non-heating period. Moreover, the existing DH pipeline infrastructure, currently mostly used only for SH supply, can now be fully utilized operating for the whole year.

3 Methodology

A model was developed to evaluate the technical feasibility of implementing the flat station solution with instantaneous DHW preparation replacing the traditional centralized DHW system or existing individual water heaters in standard apartments in a multi-story building in Beijing.

3.1 Building model

According to the statistical data of Beijing city in 2014, the three-person family is the most common family size accounting for 30.9% in the urban area [35]. The same data shows that the housing area per capita in Beijing urban area is 31.5 m^2 [36]. This means that the standard apartment in Beijing can be defined as 95 m^2 with three occupants.

To accord with design code [26], the minimum pressure head needed to supply DCW (domestic cold water) to 1st storey apartments is 100 kPa. For the second storey, it is 120 kPa. For apartments above the 2nd storey, each storey needs an extra 40 kPa [37]. The DCW pressure head at the building service pipe is generally 300 kPa, which means the available pressure head is sufficient to deliver water to the sixth storey. So, in this study, we consider the supply pressure of DCW required for a 6-storey high residential building. Higher buildings will need DCW booster pumps. Here we assumed this 6-storey apartment building is attached to a few other building units. In each building unit, each floor has two apartments with the same area. The 12 apartments in each building unit are supplied heat via a common riser**.** The heating installation structure is shown in Figure 7.

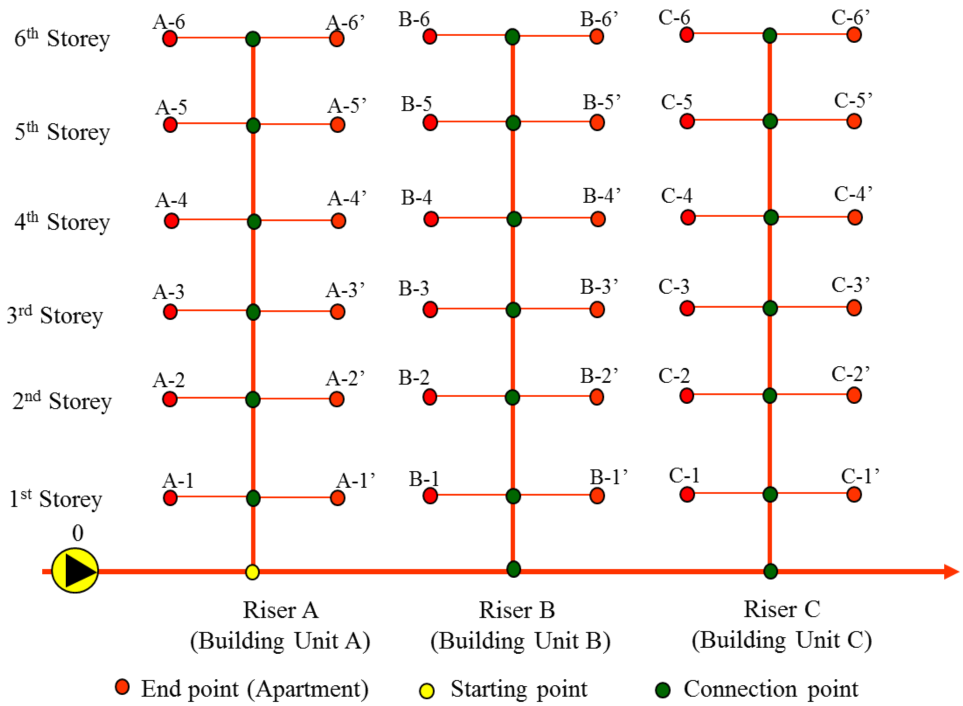


Figure 7. Graphic showing the heating installation structure in the multi-storey building model

3.2 The SH heat capacity and DHW demands

3.2.1 SH heat capacity and DHW demand for a single apartment

The existing buildings referred to in this study are mostly buildings built after 2000 with a two-pipe radiator heating system. Each apartment has its own horizontal heating loop. The peak heat load of the radiator heating system is considered to be 32 w/m^2 with a design outdoor temperature in Beijing of -9 °C [38]. Experience shows that many central heating systems are oversized, and were so even in the initial design phase. This was because the heating areas might be increased in the future or indoor thermal comfort might need to compensate for unsatisfactory operation. It is not unusual for the design heat capacity to be around 65 W/m^2 or even higher in some cases. So the design heat load for our standard apartment is 65W/m^2, and the heating capacity for the standard apartment with 95 m^2 will be 6.2 kW. The design temperatures for radiator heating systems are usually 75/50/18 °C (supply/return/indoor temperature) according to the national design code [39].

A 95 m^2 residential apartment in China usually contains a bathroom and a kitchen. The water installations are designed in accordance with the national design code [26], see Table 3. Here the average DCW temperature is considered 10 °C. For DHW installations in a single apartment, the necessary capacity usually meets the DHW demands of the shower and hand sink simultaneously. So for our standard apartment, the required DHW power is 21 kW.

Table 3. DHW consumption in a standard apartment in China

Item	Unit	Bath	Shower	Kitchen	Hand sink
Water flow	l/s	0.2	0.1	0.14	0.1
Appropriate tap temperature (Mixed water)	ºc	40	40	50	30
Capacity demand if T_{cold} water=10 ºC	kW	25.1	12.6	23.4	8.4

3.2.2 China's hourly variation coefficient and European coincidence factors

When a centralized DHW system is dimensioned in China, the hourly variation coefficient K_h is an important factor in determining the hot water flow rate and heat consumption. The hourly variation coefficient is defined as the ratio between the maximum hourly water consumption in the peak load day and the average hourly water consumption: see Eq. (1).

$$K_h = \frac{q_{hr}}{q_T} \tag{1}$$

where q_{hr} (l/h) stands for the maximum hourly water consumption in the peak load day and q_T (l/h) is the average water consumption, which can be calculated as in Eq. (2)

$$q_T = \frac{\mathrm{m} * q_r}{24} \tag{2}$$

where m is the number of DHW consumers and q_r (l/person・day) is the DHW usage quota per person per day. For residential buildings in China, the hot water consumption quota per person is recommended as 60 ~100 l/person・day [26].

So the actual K_h value depends on the personal hot water consumption quota, q_r (l/person・day) and the number of DHW consumers, m. The design code [37] states that when the number of consumers is less than 100, K_h is 4.8; and K_h is 2.75 when the number of the consumers is higher than 6000. Intermediate values can be obtained by using the interpolation method [37].

For an all-day DHW supply system in China, DHW demand power, Q_{DHW-CN} (kW) can be calculated by using Eq. (3).

$$Q_{DHW-CN} = K_h * (\frac{m * q_r * C * (T_h - T_c) * \rho_w}{3600 * t}) \tag{3}$$

where T_h, T_c are the temperatures of hot water and cold water, corresponding to 60 °C and 10 °C respectively, ρ_w (kg/l) is the density of water, and t is DHW daily supply hours (equals 24 here).

In contrast, when a European DHW system is dimensioned, coincidence/simultaneous factors are commonly used to estimate the number of the flats that might use hot water at the same time. Coincidence factors use a probability method to determine the size of centralized DHW systems. Briefly stated, only some of all tap points are used in actual practice, based on a 99.9% coincidence interval in a statistical probability distribution [40] . By using coincidence factors, a centralized DHW demand can be calculated for European countries as in Eq. (4).

$$Q_{DHW-EU} = n * f * \emptyset_{DHW} \tag{4}$$

where n is the number of apartments that require DHW, f is the coincidence factor for DHW, and $\emptyset_{\mathrm{DHW}}$ is the DHW demand per apartment.

Coincidence factors are related to the DHW consumption pattern of a “standard flat”, which refers to the number of residents in the average flat. For instance, in Denmark, Germany and Sweden the standard flat is defined as having 3.5 residents, which constitutes the basis for the factors[40]. Deviations can occur if the consumption pattern is atypical and differs from the “standard flat. The curves in Figure 8 show the coincidence factors for DHW systems in Denmark, Germany and Sweden. For these European countries, the coincidence factors have similar values, so that the probability of DHW simultaneous use is less than 0.25 when the number of flats is 12, and less than 0.1 when the number of flats is 100.

According to the International Electrotechnical Commission [41], the coincidence factor is identical to the reciprocal of the diversity factor. This definition means that the Chinese DHW hourly variation coefficient and the European DHW coincidence factor are comparable in terms of centralized DHW system calculation. The comparison is shown in Figure 8, where it can be seen that, for China, the DHW coincidence factors, which are the reciprocal of the hourly variation coefficient K_h, are relatively constant around 0.2 when the number of apartment is less than 100.

The reason that the coincidence factors differ greatly between European countries and China could be that high-rise and multi-storey buildings are the main types of building in China, so a low simultaneous DHW usage probability is assumed from the economic point of view. Whereas in European countries, single-family houses and multi-storey buildings are the main building types, so that the coincidence factors have detailed values when the number of flats is small to take comfort into account. On the other hand, the K_h values stated in the Chinese design code are empirical data originally derived from Soviet DHW systems, so there may be errors arising from differences between the design and real conditions due to the lack of actual measurements from Chinese DHW systems [42].

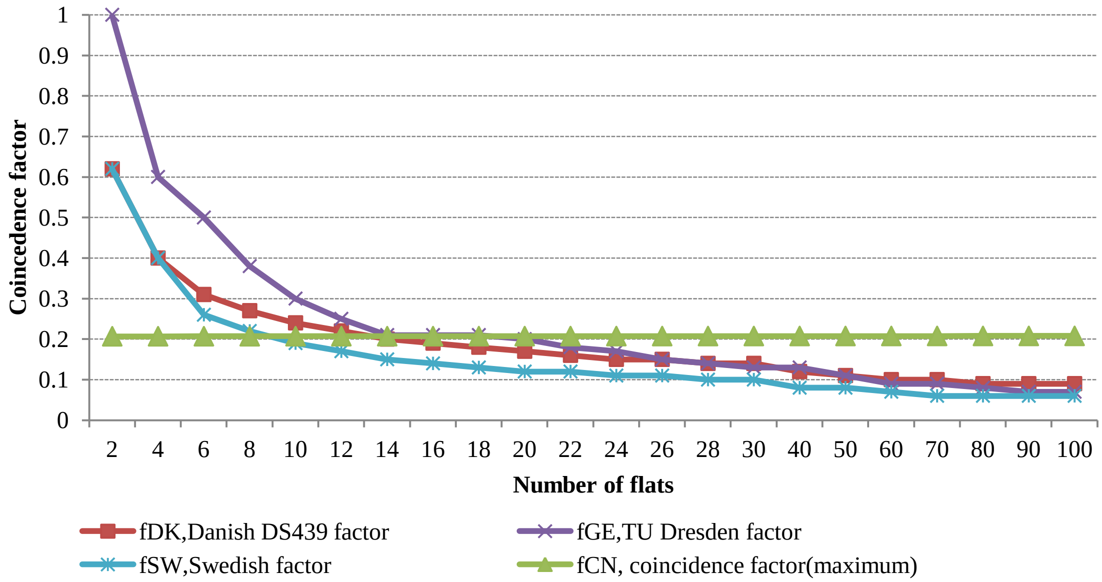


Figure 8. Comparison of coincidence factors used in different countries

Such errors are further confirmed when Eq. (3) is used to input the DHW usage quota, q_r as 100 l/person · day, together with the known data mentioned above, to calculate the DHW demand along the riser in the building model. The calculation results from the building model show that when the number of apartments is less than 6, as when the riser reaches the 4th, 5th and 6th floors, the DHW demand falls below the demand per standard apartment, 21 kW: see Table 4. It is clear that the K_h data are too rough to calculate the DHW demand when the number of apartments is small. To correct the calculation, f_{DK} and Eq. (4) can be used to obtain the accurate required DHW power. The corrected results are listed in Table 4. The SH demands of the building model per floor were calculated and are listed in Table 4 as well.

Table 4. Domestic hot water heat demands corrected by using coincidence factors from Denmark

The number of apartments	Calculation using K_h		Corrected calculation using f_{DK}		SH demands (kW)
	k_h	DHW demand power (kW)	f_{DK}	DHW demand power (kW)	
1	-	21	-	21	6.2
2	4.8	7.0	0.62	26.0	12.4
4	4.8	14.0	0.4	33.6	24.8
6	4.8	20.9	0.31	39.1	37.2
8	4.8	27.9	0.27	45.4	49.6
10	4.8	34.9	0.24	50.4	62
12	4.8	41.9	0.22	55.4	74.4

3.3 DHW hydraulic priority

3.3.1 Philosophy of DHW priority

The philosophy of DHW priority in European DH systems is generally used to dimension the service pipes that run from the street to a single-family house. This means that when the service pipes are designed, only the heat capacity for DHW is considered, because DHW priority assumes that the heat supplied to the SH system can be reduced or suspended during the short periods when DHW is drawn off. In fact, thermal comfort is not considered to be threatened by the lack of SH supply during the period of DHW use, since its duration is assumed not to exceed 10-15 minutes [43]. At a practical level, DHW priority could be achieved using sophisticated hydronic design or, in the case of a substation with electronic control, it can also be implemented electronically.

For this research, the hypothesis was that flat stations can be integrated into existing heating systems to prepare DHW with the minimum of renovation. However, the existing pipelines between the secondary side of the local large area substation and the primary side of the flat stations may need to be adjusted in accordance with the philosophy of DHW priority. Where the existing pipes are smaller than required for DHW, they need to be replaced with DHW size pipes; but where the existing pipes are the same size or bigger, they can be left as they are.

The dimensioning of pipes is determined by maximum flow rates in each section of pipeline. The normal criteria are a certain flow velocity and a certain pressure loss per running metre. In this case, the flow velocity in the pipes is typically less than 1m/s, and the pressure drop per metre has been recommended as 40-60 Pa/m for risers and less than 100 Pa/m for horizontal pipes [44]. The configuration of the renovated heating system is that the primary side of the flat station connects to the building riser, and the secondary side connects to the indoor DHW system. SH is still directly connected to the apartment heating system.

There are two preconditions for applying the philosophy of DHW priority: the first is that the DHW usage time needs to be short, e.g. 10-15 minutes; the second is that the philosophy can be realized at the practical level, in this study, electronically.

3.3.2 DHW usage in northern China

To find out about DHW consumption habits during the heating season on northern China, an investigation was launched using a questionnaire [20]. The questionnaire focused on three items: approximate tapping time, the usual time of day when the person takes a shower, how many times a week. The results show that the tapping time is less than 21 minutes for over 50% respondents; around 59% of the respondents take a shower in the evening; and the majority of respondents, 70%, take a shower once or twice per week (Table 5).

Table 5. Investigation into shower-taking in northern China

1. Tapping time		2. Time of day		3. Frequency of bathing	
< 7 mins	3%	Morning	9%	1-2 times a week	70%
7~ 9 mins	10%	Noon	3%		
9~ 16 mins	28%	Afternoon	14%	3-4 times a week	22%
16~ 21 mins	23%	Evening	59%		

21~ 32mins	17%	Midnight	1%	Every day	8%
> 36 mins	19%	Random	1%	Twice per day	0%

These data indicate that the philosophy of DHW priority is feasible from a realistic point of view. Even though the SH suspension interval could be 21 minutes, the time constant of buildings is typically so large that it would not make a noticeable difference to the indoor temperature.

3.3.3 Implementation of DHW priority

For the standard apartment with a two-pipe heating system considered in this study, a simple flat station like the Evoflat FSS [45] could be used. The Evoflat FSS is a complete unit for direct heating and indirect instantaneous DHW. Figure 9 shows the circuit diagram of the Evoflat FSS. The DHW temperature is controlled by a self-acting multifunctional controller, TPC-M [45], which implements DHW priority by using a zone valve.

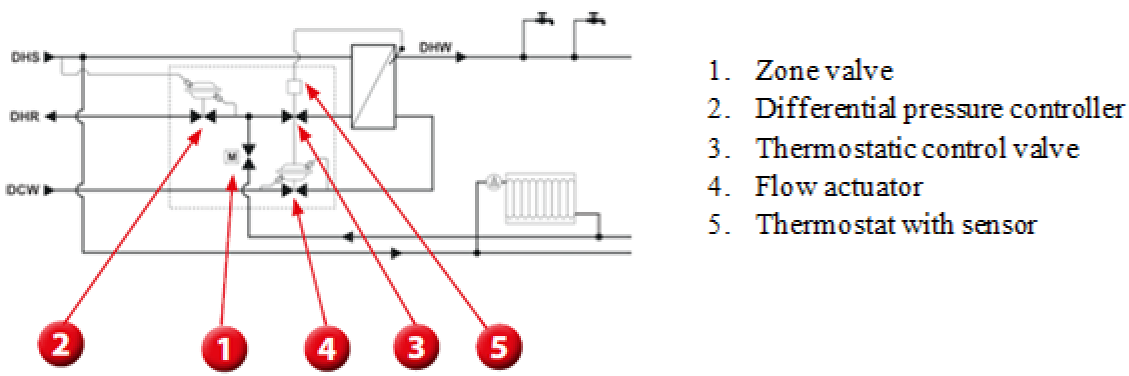


Figure 9. Circuit diagram of Evoflat FSS with self-acting multi-functional controller TPC-M

The TPC-M consists of 5 parts (Figure 9). When a DHW tap opens, the pressure drop that arises at the flow actuator (4) forces the thermostatic valve (3) towards an open position that is related to the flow rate on the secondary side. The desired DHW temperature is achieved by adjusting the opening of the thermostatic valve (3) in accordance with the difference between the desired temperature and the temperature that is measured with the thermostat (5). At the same time, the zone valve (1) ensures DHW priority over SH. There is a flow switch embedded in the secondary side. When a tap is opened, the flow switch detects the flow in the secondary pipe and transmits a “close” signal to the controller, which issues a command to the zone valve to close. When the DHW tapping stops, the flow actuator (4) ensures the immediate closing of the thermostatic control valve (3), and the zone valve (1) opens to allow supply to the SH system. The purpose of the differential pressure controller (2) is to ensure stable and optimum operating conditions for the DHW control valve and that the heating installation is not being affected by the external operation of the DH system. During non-heating periods, the zone valve (1) can be closed manually. In this way, the Evoflat FSS ensures the hydraulic priority of DHW.

4 Results and Discussion

4.1 Technical feasibility

Using the corrected coincidence factors and Eq. (4), the required DHW powers were calculated along the riser of the building model. The vertical DHW riser sizes were dimensioned on the basis of the calculation criteria, i.e. flow velocity less than 1m/s and a pressure drop per metre in the range of 40-60 Pa/m. The results are presented in Figure 10 and compared with the existing vertical SH riser sizes. The figure shows clearly that the riser needs to be replaced with DHW size pipes above the 4th floor, while the rest of the riser can still be used. For the horizontal pipes between the different risers, the required DHW powers are smaller than the SH demands due to the even smaller coincidence factors because of the increasing number of connected apartments. So the existing SH pipe dimensions should be sufficient to supply a flow rate to the buildings that can fulfil the partial SH and DHW demands simultaneously.

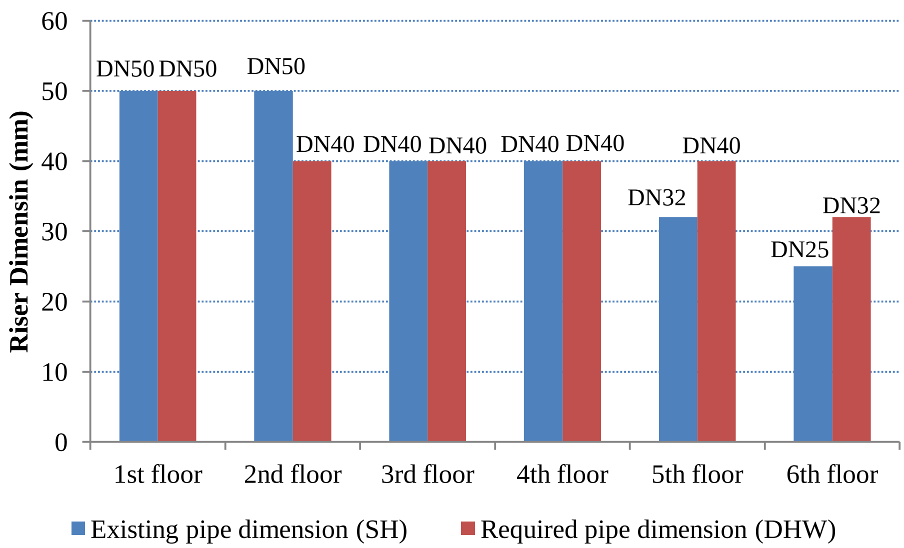


Figure 10. Comparison of existing SH pipe dimension with required pipe dimension for DHW

The philosophy of DHW priority over SH was applied to determine the dimensions of the riser. By explaining the functions of the multifunctional self-acting controller TPC-M, which is installed in the type Evoflat FSS flat stations, we have shown how the substations can implement the philosophy electronically. The other precondition for the application of this philosophy is that the DHW tapping should take no more than 10-15 minutes. Such short periods when SH is suspended will not affect the indoor temperature. The investigation into DHW consumption habits in northern China showed that 70% people take a shower once or twice a week, mostly in the evening, and have less than 21 minutes tapping time. This means that the impacts on indoor temperatures can be ignored. On the basis of these clarifications and data, the integration of flat stations into existing SH systems with the minimum of renovation is therefore technically feasible.

4.2 Economic evaluation

The main idea of economic evaluation is to compare the annual unit energy cost, which depends on the specific DHW preparation technologies, such as flat stations or individual water heaters. This economic comparison is based on the investment costs, operational costs, fuel costs, efficiency and the expected lifetime of the different DHW preparation units [46]. The calculation flow chart is presented in Figure 11. The uniform currency used in this economic evaluation is the Chinese Yuan (￥).

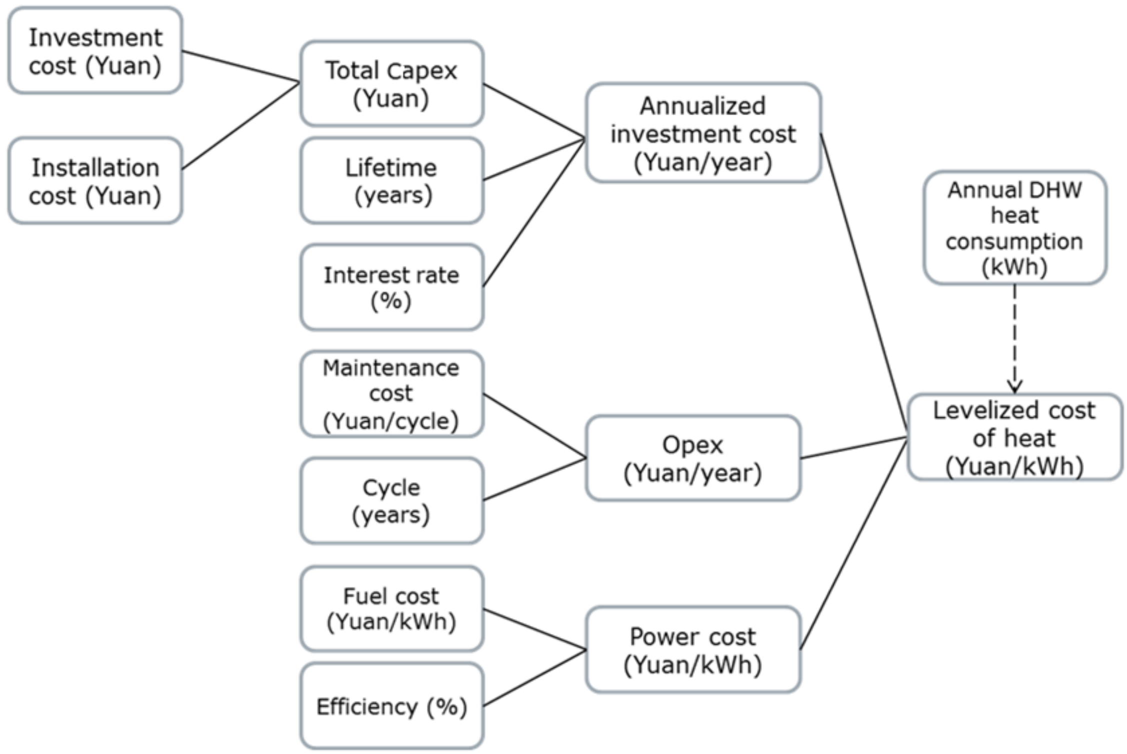


Figure 11. Flow chart to compare the economic evaluations between different DHW production equipment

The total Capex is the sum of investment cost and installation cost. To estimate the annualized investment cost, the net present value (NPV) concept [47] is utilized.

The annualized investment cost can be calculated using the following equation, which is a representation of the NPV concept with the NPV being zero at the end of the payment stream, with the time value and the money interest rate over the lifetime taken into account.

$$Anualized\ investment\ cost = \left(Total\ Capex * \frac{Interest\ rate}{1-(1+Interest\ rate)^{-Lifetime}}\right) \quad (5)$$

In Figure 11, Opex means the average annual cost for operating and maintaining the unit in a safe and reliable manner. Fuel cost represents the cost of the energy per kWh used in preparing the DHW. The fuel can be electricity, natural gas or any other fuel suitable for DH systems. The cost of the fuel is used as the actual cost for residential buildings in Beijing. The annualized cost of heat (Yuan/kWh) for different DHW preparation technologies, such as individual water heaters or flat stations, is the sum of the annualized investment cost, Opex per year divided by the annual DHW heat consumption (kWh) and the annual power cost.

The annual DHW heat consumption for a 95 m^2 apartment in China can be estimated to be 3990 kWh according to [48]. Basic information about the three DHW preparation technologies is listed in Table 6.

Table 6. Economic factors determining the annual cost of heat with different DHW preparation technologies

Items	Natural gas water heater	EL water heater	Flat stations
Annual DHW consumption for a family	3990 kWh	3990 kWh	3990 kWh
Nominal Heat/Electricity Power	21 kW (Heat)	9.5 kW (Electricity)	21 kW (Heat)
Fuels type	Natural gas	Electricity	Local waste heat
Investment cost (Yuan)*[1]	3500	4000	6000
Installation cost (Yuan)	500	500	500
Life time (years) *[2]	8	8	12
Interest rate (%)	5.25%	5.25%	5.25%
Maintenance cost (Yuan/cycle)	100	100	100
Fuel cost (Yuan/kWh)	0.23	0.5	0.09
Efficiency (%)	88%	88%	Flat stations:98%; DH heat source 60%; DH distribution pipeline 90%

*Prices are from Chinese local electronic commerce websites. Lifetime data are from the datasheet on DHW preparation units.

Based on the method discussed above, the levelized costs of heat (LCH) from the three DHW preparation technologies were calculated and are listed in Figure 12, which shows the economic advantage of flat stations over electric/nature gas water heaters. Electric water heaters have the highest LCH, and the LCH of flat stations is the lowest when all the economic factors are taken into account, including investment costs, operational costs, fuel costs, efficiency and expected lifetime. Although, only a small economic gap exists between the flat station solution and using a natural gas water heater, it is noticeable that the efficiency of the DH heat source used in flat station solution was estimated to be 60%. This is relatively low and is an average level, but it has great potential to be improved in the future (Table 6).

Convenience and safety are the two most important factors for residential DHW usage. This was shown by a questionnaire survey carried out in northern China [18]. According to the questionnaire interview data, the centralized DHW systems have the highest resident acceptance of 90% due to the convenience and high safety performance. On the other hand, the disadvantages of centralized DHW systems were mainly reflected in the high DHW price and long waiting-time because of the circulation system traditionally used. Moreover, the same questionnaire showed that individual water heaters have relatively low satisfaction compared to a centralized DHW solution: e.g. 80% said that electric water heaters have the disadvantages of high electricity consumption and the fast formation lime scale, 70% said that natural gas water heaters have risks of gas emission and explosion, and 73% said that solar water heaters have limited use time, provide an insufficient amount of DHW, and limitations in installation position. It seems that the disadvantages of both traditional centralized DHW system and individual water heaters can be avoided by applying flat station solution. So the result is positive in terms of the residents' acceptance of the flat station solution.

Under the national policy, the commercialization of heat, the implementation of household heat-metering based on the real consumption, the modernization of DH system, and the integration of more renewable energy into DH systems are imperative. This situation will drive the DH utilities to provide qualified heat to achieve high satisfaction among heat consumers. On the other hand, cost-effective DH applications are sought to expand profits and increase capacity. In these circumstances, the flat station is a win-win solution. Moreover, compared to renovated buildings, the flat station solution is more easily implemented in new buildings, especially if integrated in the initial design phase.

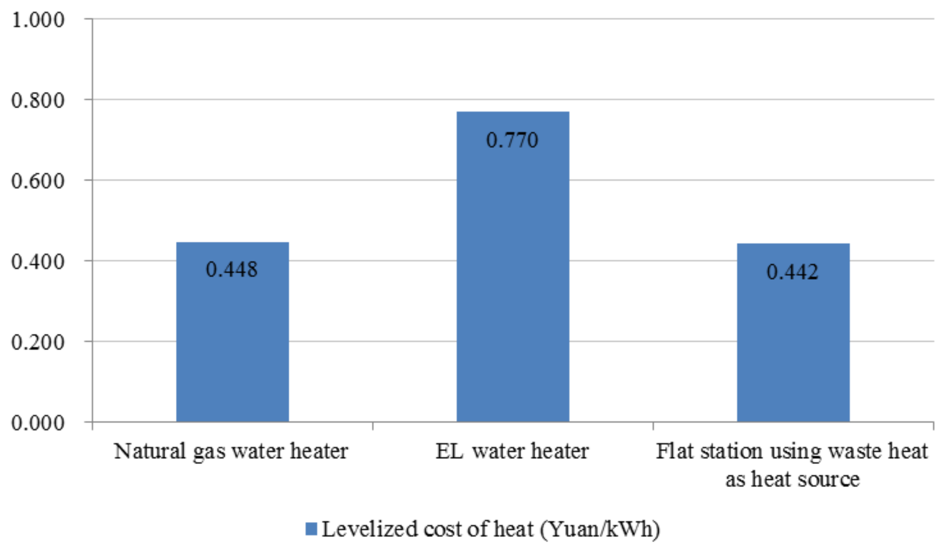


Figure 12. The annualized heat cost comparison between individual water heaters and flat stations

4.3 Quantification of environmental impact

The environmental impact of flat stations compared to individual water heaters can be accessed by considering CO_2 emissions from the different fuels.

China typically converts all its energy statistics into “metric tons of standard coal equivalent” (tce), one tce equal 29.31 GJ (low heat) [49]. In terms of energy equivalence, to generate 1 kWh electricity is equivalent to 0.123 kg standard coal consumption. Regardless of the conversion losses, the corresponding emissions are: 319 g carbon dioxide (CO_2), 2.95 g (SO_2), and 0.86 g nitrogen oxide (NO_X). For natural gas, the two principal combustion products are CO_2 and water vapour. Burning 1 standard cubic metre natural gas with 35.84 MJ/m^3 low heat value emits 1.88 kg CO_2. As mentioned above, a standard apartment annually consumes 3990 kWh for the production of DHW. The consumed energy is equivalent to 3990kWh electricity, and 401 m^3 natural gas.

Table 7. Emissions when using EL water heater and Natural gas water heater to produce DHW

Annual DHW consumption for a standard flat	Energy consumption		Unit emissions	Annual emissions for annual DHW consumption
3990 kWh	Electricity	3990 kWh	CO_2:0.319 kg/ kWh_e	1273 kg CO_2

3990 kWh	Natural gas	401 m^3	CO_2: 1.88 kg/m^3_{gas}	753 kg CO_2
3990 kWh	Waste heat	-	-	-

The flat station solution can use a variety of fuels including waste heat from local industrial processing. Moreover, urbanized areas in northern China already have a well-developed DH pipeline infrastructure. Surplus heat from industrial processes is a great pollution-free resource for fulfilling residential heat demand [50]. According to Fang et al. [51], if 34% of available industrial waste heat had been recovered in 2009, it would have been enough to meet the whole DH heat demand that year. So it is entirely realistic for the flat station solution to use industrial waste heat as the heat source. If surplus heat from industries that is currently being wasted is utilized, there will be practically no extra particle or GHG emissions at all.

Based on the annual energy required to produce DHW for a standard apartment, the emissions (mainly CO_2) when electricity and natural gas are the power fuels were calculated. Based on the assumption that flat stations use local waste heat as the heat source, the CO_2 emission reduction could be 1273 kg per flat per year compared to using electricity as the power source and 753 kg per flat per year compared to using natural gas as the power source (see Table 7).

5 Conclusions

In this paper, we have analysed the current situation of DHW applications in China by using real data, and we have summarized the main reasons why centralized DH systems are not the main technology used to prepare DHW. Based on the current circumstances, the technical approach proposed is that flat stations should be integrated into the existing heating systems to produce DHW instantaneously. The technical advantages of the flat station solution can solve the problems in existing traditional centralized DHW systems and the individual water heaters currently in use can be removed.

Based on the model we developed of the building in Beijing, the proposed approach has been confirmed as technically feasible, and the renovation work required is limited to enlarging the riser pipe dimensions. During the technical feasibility analysis, the hourly variation coefficients commonly used to size centralized DHW systems in China were corrected by using coincidence factors from Denmark. Furthermore, we used the Net Present Value method to evaluate and compare the LCH from flat stations with that of individual water heaters, which showed the economic benefits of applying flat stations.

Real data evidences that massive industrial waste heat source is available around Beijing. Utilizing the industrial waste heat as DH fuel, rather than emitting into atmosphere, is a main tendency also an effective way to abatement the air pollution. On the assumption that flat station solutions can utilize industrial waste heat as the heat source, the environmentally friendly influences of flat stations were quantified and highlighted in comparison with individual water heaters.

A reliable and adequate supply of DHW for daily use has become an important factor for increasing life quality in China against the background of the rapid urbanization and modernization of Chinese society. At the same time, air pollution and security of energy supply are derivative challenges that could compromise the rapid development of the whole of society. The flat station solution presented in this study provides a sustainable alternative for DHW preparation in China; it is wise to have a long-term DHW application to balance the conflict between current opportunities and current challenges. The flat station solution can produce hygienic, comfortable and economic DHW in an environmentally friendly way, thus reducing the burning of fossil fuels and other non-renewable sources of energy and improving the quality of life for residents in China.

Acknowledgements

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Figure

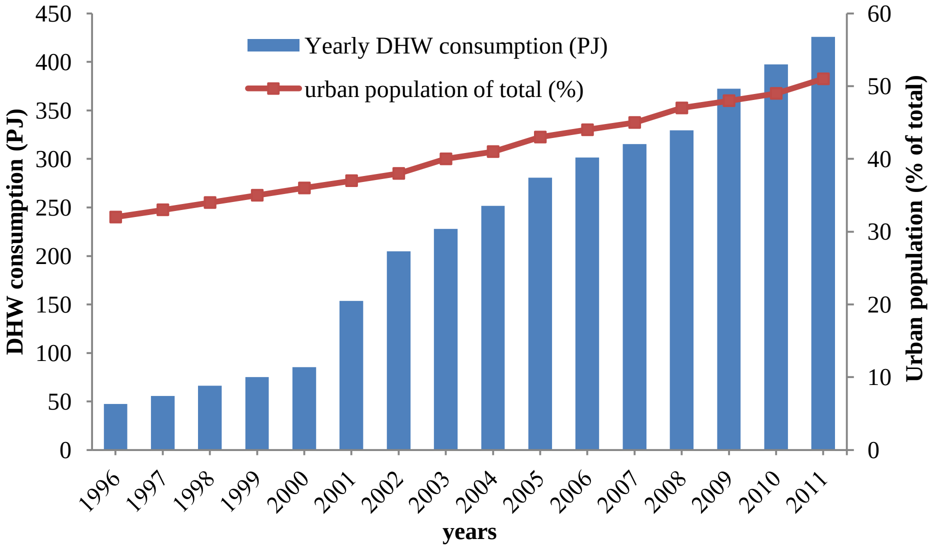


Figure 1. 1996-2011 China's yearly urban residential domestic hot water consumption (PJ)

Figure

(a). Electric water heaters

(b). Natural gas water heaters

(c). Solar water heaters

Figure 2. Individual water heater installations in Chinese households [19]

Figure

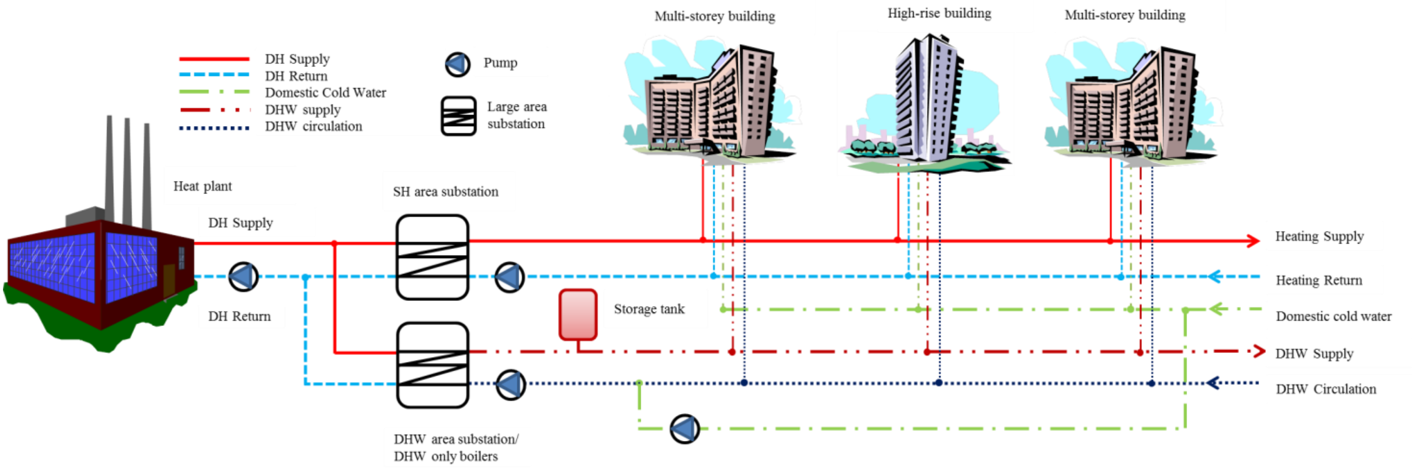


Figure 3. Traditional DH systems that combine SH and DHW supply

Figure

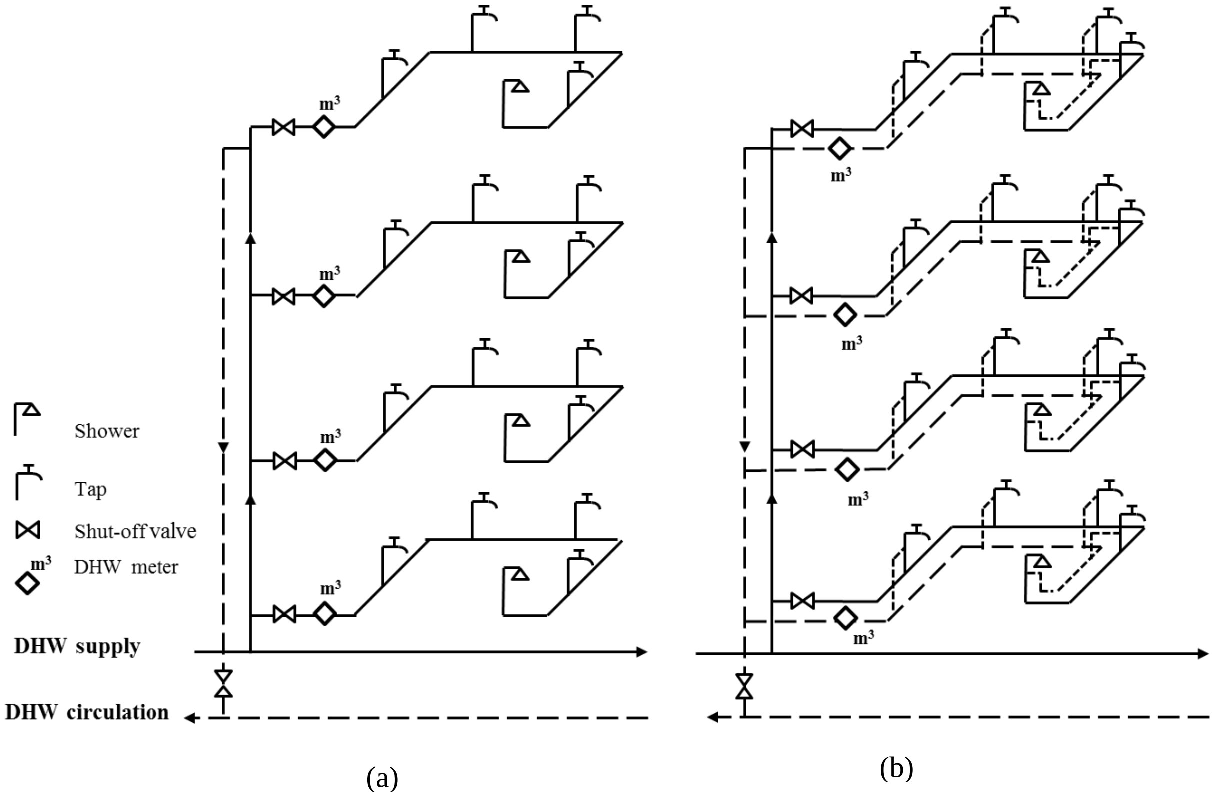


Figure 4. Two different circulation pipe arrangements

Figure

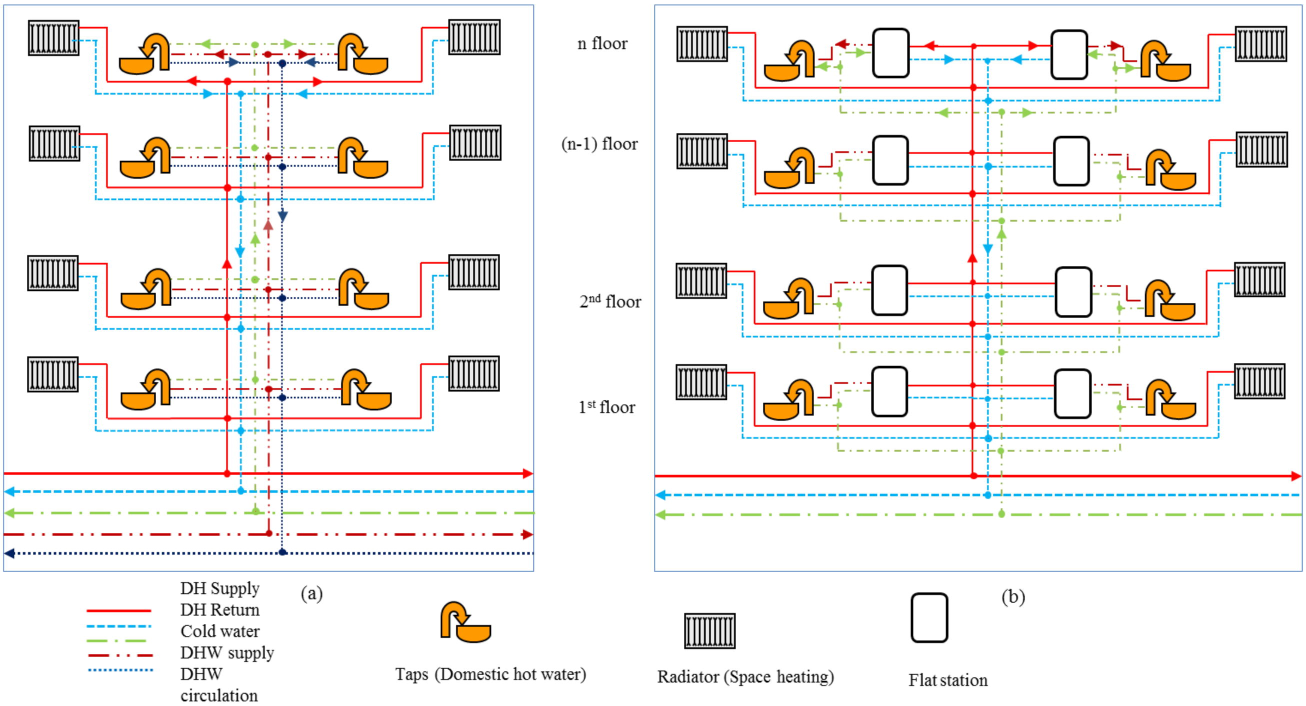


Figure 5. Traditional centralized DHW pipe system (a) and the apartment substation pipe system (b)

Figure

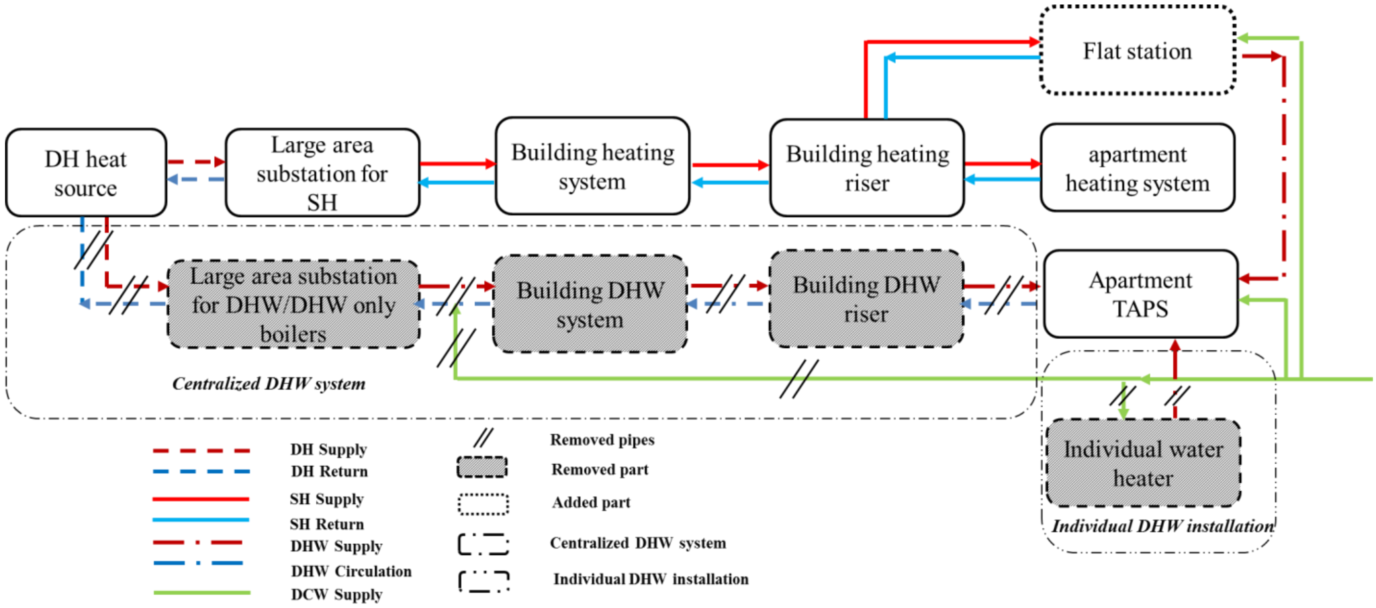


Figure 6. Renovating the existing DH system by integrating flat stations

Figure

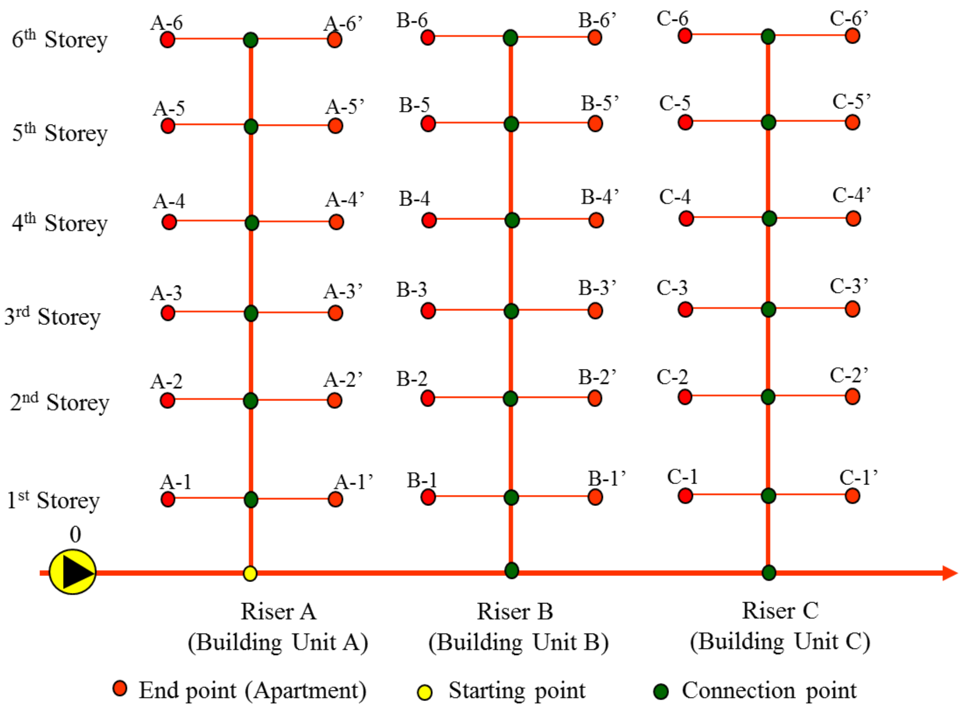


Figure 7. Graphic showing the heating installation structure

Figure

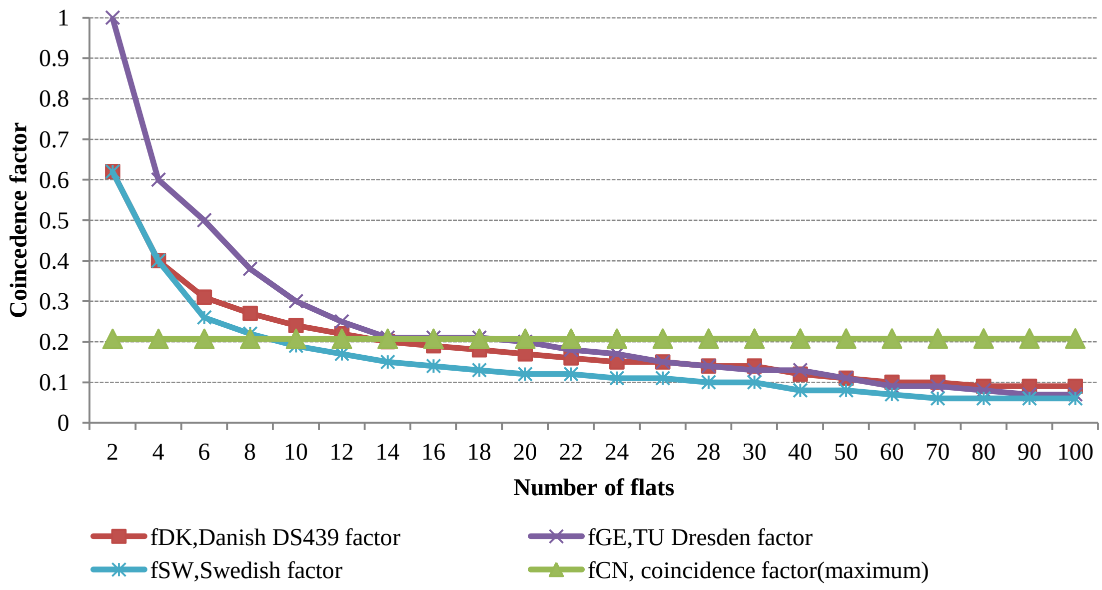
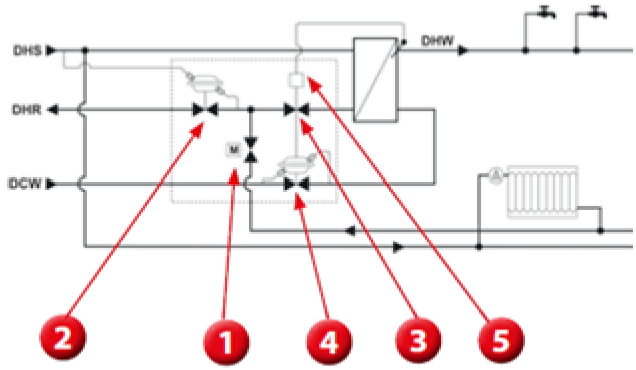


Figure 8. Comparison of coincidence factors used in different countries

Figure



1. Zone valve
2. Differential pressure controller
3. Thermostatic control valve
4. Flow actuator
5. Thermostat with sensor

Figure 9. Circuit diagram of Evoflat FSS with self-acting multi-functional controller TPC-M

Figure

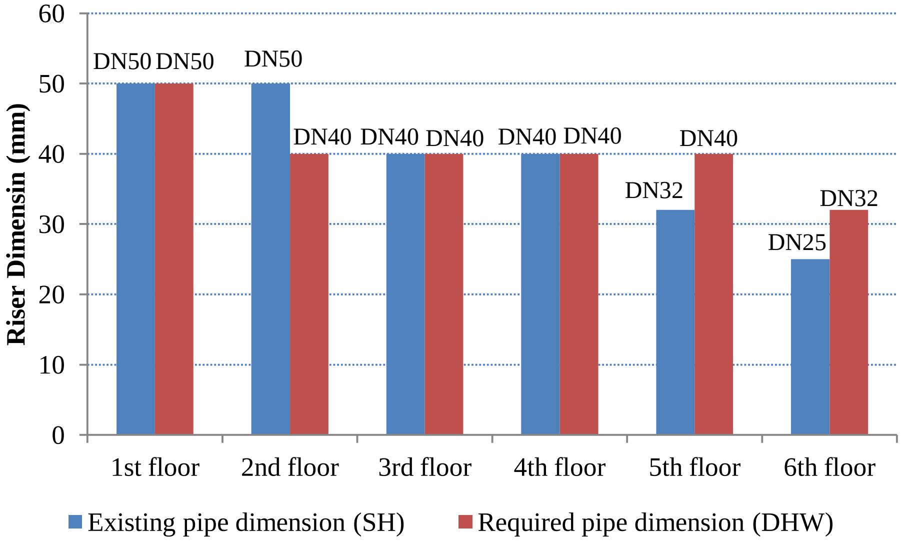


Figure 10. Comparison of existing SH pipe dimension with required pipe dimension for DHW

Figure

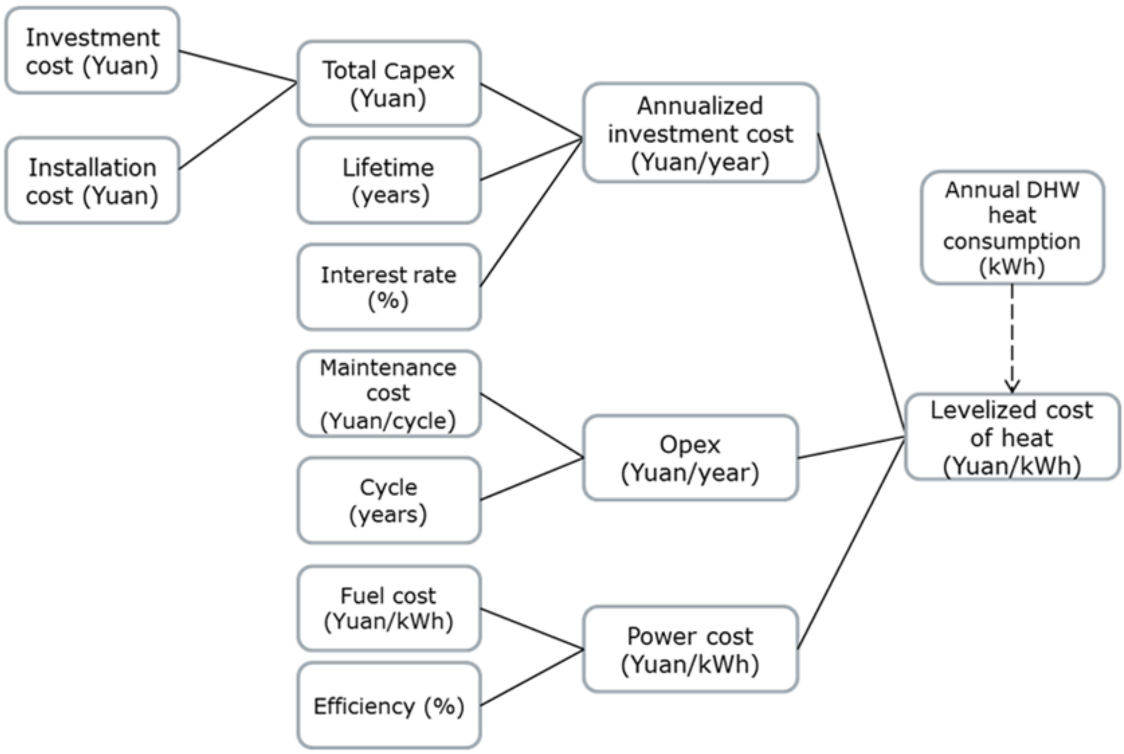


Figure 11. Flow chart to compare the economic evaluations between different DHW production equipment

Figure

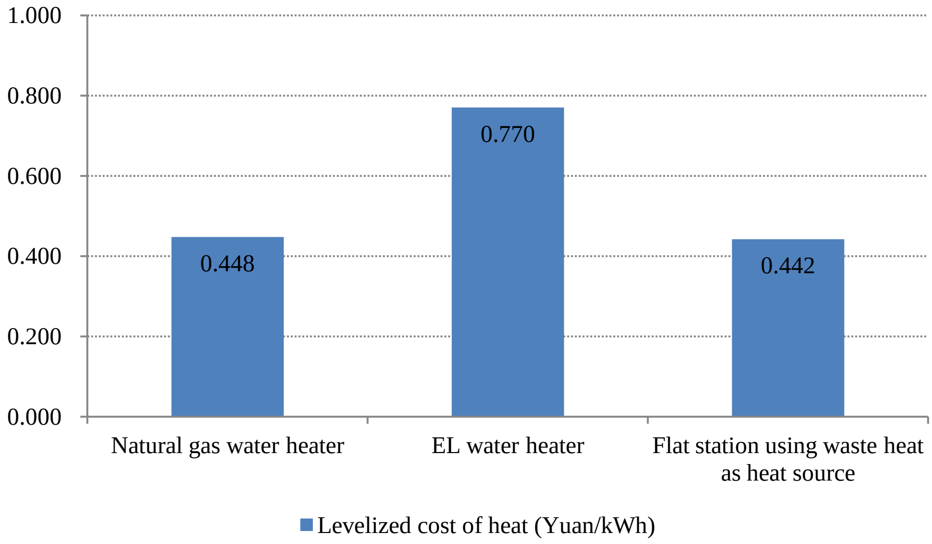


Figure 12. The annualized heat cost comparison between individual water heaters and flat stations

Table

Table 1. DHW preparation technologies in northern and southern China

DHW preparation technology	Share of total	
	Northern China	Southern China, Shanghai
Electric water heaters	63%	12%
Solar water heaters	21%	10%
Natural gas heaters	6%	77%
District heating	5%	1%
Other	5%	0%

Table

Table 2. DH heat load and industrial waste heat available in 13 cities around Beijing

	City	A: City heat load (MW)	B:Industrial waste heat capacity (MW)	Ratio A to B
1	Beijing	45666	8951	20%
2	Tianjin	15780	17515	111%
3	Shijiazhuang	13172	12729	97%
4	Chengde	3439	2435	71%
5	Zhangjiakou	5024	7556	150%
6	Qinhuangdao	3634	1988	55%
7	Tangshan	9859	16320	166%
8	Langfan	5415	2028	37%
9	Baoding	11112	4784	43%
10	Cangzhou	7457	5936	80%
11	Henshui	4244	2027	48%
12	Xingtai	7278	2405	33%
13	Handan	10204	11050	108%
	Total	142284	95724	67%

Table

Table 3. DHW consumption in a standard apartment in China

Data	Unit	Bath	Shower	Kitchen	Hand sink
Water flow	l/s	0.2	0.1	0.14	0.1
Appropriate tap temperature (Mixed water)	ºc	40	40	50	30
Capacity demand if T_{cold} water=10 ºC	kW	25.1	12.6	23.4	8.4

Table

Table 4. Domestic hot water heat demands corrected by using coincidence factors from Denmark

The number of apartments	Calculation using K_h		Corrected calculation using f_{DK}		SH demands (kW)
	k_h	DHW demand power (kW)	f_{DK}	DHW demand power (kW)	
1	-	21	-	21	6.2
2	4.8	7.0	0.62	26.0	12.4
4	4.8	14.0	0.4	33.6	24.8
6	4.8	20.9	0.31	39.1	37.2
8	4.8	27.9	0.27	45.4	49.6
10	4.8	34.9	0.24	50.4	62
12	4.8	41.9	0.22	55.4	74.4

Table

Table 5. Investigation into shower-taking in northern China

1. Tapping time		2. Time of day		3. Frequency of bathing	
< 7 mins	3%	Morning	9%	1-2 times a week	70%
7~ 9 mins	10%	Noon	3%		
9~ 16 mins	28%	Afternoon	14%	3-4 times a week	22%
16~ 21 mins	23%	Evening	59%		
21~ 32mins	17%	Midnight	1%	Every day	8%
> 36 mins	19%	Random	1%	Twice per day	0%

Table

Table 6. Economic factors determining the annual cost of heat with different DHW preparation technologies

Items	Natural gas water heater	EL water heater	Flat stations
Annual DHW consumption for a family	3990 kWh	3990 kWh	3990 kWh
Heat capacity	21 kW	9.5 kW	21 kW
Fuels type	Natural gas	Electricity	Local waste heat
Investment cost (Yuan)*[1]	3500	4000	6000
Installation cost (Yuan)	500	500	500
Life time (years) *[2]	8	8	12
Interest rate (%)	5.25%	5.25%	5.25%
Maintenance cost (Yuan/cycle)	100	100	100
Fuel cost (Yuan/kWh)	0.23	0.5	0.09
Efficiency (%)	88%	88%	Flat stations:98%; DH heat source 60%; DH distribution pipeline 90%

*Prices are from Chinese local electronic commerce websites. Lifetime data are from the datasheet on DHW preparation units.

Table

Table 7. Emissions when using EL water heater and Natural gas water heater to produce DHW

Annual DHW consumption for a standard flat	Energy consumption		Unit emissions	Annual emissions for annual DHW consumption
3990 kWh	Electricity	3990 kWh	CO_2:0.319 kg/ kWh_e	1273 kg CO_2
3990 kWh	Natural gas	401 m^3	CO_2: 1.88 kg/m^3_{gas}	753 kg CO_2
3990 kWh	Waste heat	-	-	-