The Rebound Effect in District Cooling Systems: Analysis Based on Case Studies and Surveys in China

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ABSTRACT:

District cooling systems are widely promoted in China now because of their higher coefficient of performance (COP). However, through the investigation of case studies, it was found that the energy use of these systems is usually much higher than that of decentralized systems. The increase of energy use is caused by the change of occupancy behavior as people tend to use cooling more when the district cooling is used, or the so-called rebound effect.

This research intends to describe the difference of occupancy behavior in these two systems using quantitative analyses methods. Both case study and questionnaire surveys are used to find the relationship of usage patterns and energy consumption and analyze the reason of high energy use in district cooling systems.

The main reasons cause the rebound effect are also discussed based on the case study, including the adjustability of the system, the pricing scheme and the improvement of the requirement of the indoor thermal environment. The findings suggest that in order to save energy and to weaken the rebound effect, corresponding measures both on technology development and policy are urgently needed. Future research should focus on the careful analysis of the pricing scheme. For the improvement of living standards, cooling systems are surely needed in China, but it is important that the system is suitably scaled and designed.

1. Introduction

District cooling systems, which is usually using one system to cool several buildings, have been promoted widely in China in recent years. Some governments consider this system as an energy saving technique because of its high coefficient of performance (COP). But through the investigation of different systems, it seems that most buildings with this system are not “energy saving” residential buildings (BERC, 2013). Figure 1 shows the air conditioning (AC) energy use of decentralized and centralized systems from fourteen residential buildings in China. It can be seen that the AC energy use of buildings with centralized systems is much higher. For some buildings, it can even be ten times of that with a decentralized system.

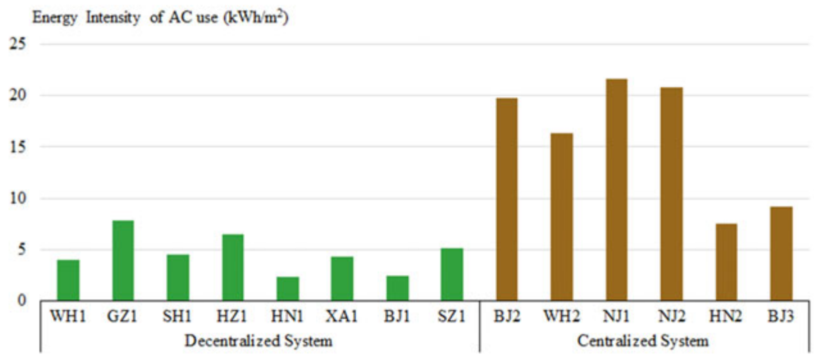

Figure 1 Energy Intensity of AC Use in Different Systems

Source: ZHOU et al. 2016

In theory, district cooling can offer better energy efficiency and save energy. But it seems that in China, this system does not work well. The most significant reason for this is that with district cooling systems, people prefer using more cooling (BERC, 2013). Therefore, despite higher energy efficiency, usage increases and so is the total energy use, which is referred to as the "rebound effect".

Existing research about the rebound effect in building energy use has focused on the existence of the effect (Haas and Biermayr, 2000; Galvin, 2014; Grossmann et al., 2016). Much of this work has explained the effect using economic or social theory. However, there still lacks research on the system performance and occupant behavior. This paper intends to analyze the rebound effect within district cooling to find the relationship between equipment and behavior in the residential cooling sector, and discuss the suitable trend of cooling equipment in China, which may be helpful for the future technology development and policy suggestions.

2. Method

In order to analyze the usage of different systems, case studies and questionnaire surveys have been done in China to compare different cooling usage, analyze the rebound effect in cooling use, and discuss the possible causes behind usage patterns observed.

The case studies include detailed data of the system and some interviews of the users. In this study, data from five district cooling systems gathered through primary data collection or literature review, are compared. The cases differ in their energy use, terminals, pricing schemes (by usage or by floor area), behaviors and other factors. Through these cases, some critical factors related to behavior can be recognized. The comparative study also includes comparisons of centralized and decentralized systems.

Surveys for the cooling usage were also conducted as part of this study to analyze the energy use difference with district cooling and people's satisfaction with cooling use. Energy use simulation toolkit, DeST-h, is also used for this study to describe the usage difference in a quantitative way (YAN et al., 2008).

The overall methodology can be shown in Figure 2:

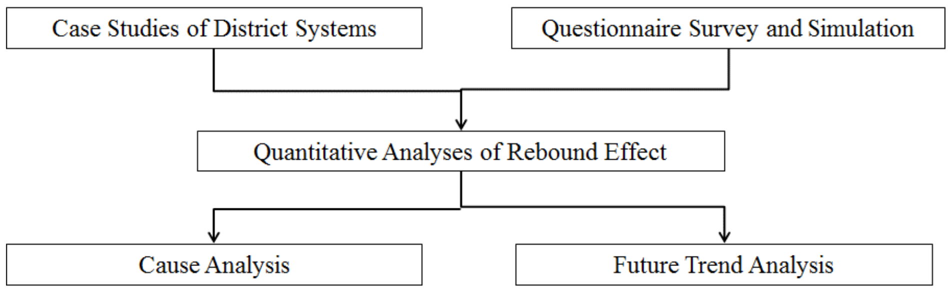

Figure 2 Overall Methodology

3. Case Study Results

3.1. Case 1

Case 1 is a district cooling system in Jiangsu Province, in hot summer and cold winter climate zone (HSCW climate zone) (Li, 2012). The floor area is around 10,000 m^2 and the occupancy rate is about 90%. Ground source heat pumps are used as the cooling source, while radiant ceiling and displacement ventilation are used as a terminal. The indoor environment is controlled by the district cooling operators to keep the constant temperature in every room throughout the cooling season. Occupants cannot make adjustments and pay for cooling based on floor area.

The energy use over the cooling season is 21.9 kWh_E/m^2, about 5 times that among decentralized systems, of which refrigerator uses 13.4 kWh_E/m^2, water pumps use 6.5 kWh_E/m^2, and the rest is used by the air supply unit. The average COP over the cooling season is around 4.4 while the EER is around 3, higher than the average among decentralized systems.

The reason for the high energy use of this case is that the operation mode of this system is "full time, full space", which is quite rare for households with an air-source heat pump.

3.2. Case 2

Case 2 is a district cooling system in Hubei Province, also in Hot Summer and Cold Winter (HSCW) climate zone. The floor area is around 50,000 m^2. The cooling source is ground source heat pumps and terminals are FCU. In this system, FCU can be adjusted with different speeds. The pricing scheme is based on the usage.

The energy use of a cooling season is 7.9 kWh_E/m^2. The average COP over the cooling season is around 3.9, while the EER is around 3.0, higher than the average among decentralized systems. Through the survey, it is found that although people keep using cooling equipment only when needed, opening time is longer than that with a decentralized system.

3.3. Case 3

Case 3 is a district cooling system in Jiangsu Province. The floor area is around 159,000 m^2. Ground source heat pumps are used as a cooling source while FCU as terminal. The equipment can be adjusted free. The pricing scheme is based on the usage.

The energy use of a cooling season is 6.9 kWh_E/m^2. The average COP over the cooling season is around 2.9, while the EER is around 2.4, similar to the average among decentralized systems.

3.4. Case 4

Case 4 is another district cooling system in Jiangsu Province. The floor area is around 48,700 m^2. Ground source heat pumps are used as a cooling source while FCU as terminal. The pricing scheme is based on the usage.

The energy use of a cooling season is 3.6 kWh_E/m^2, similar to that with decentralized systems. The average COP over the cooling season is around 4.6, while the EER is around 3.1, higher than the average among decentralized systems. Sixty percent of the households use less cooling than the set threshold. For this case, the energy use is low, while the efficiency is better than decentralized systems.

3.5. Case 5

Case 5 is also a district cooling system in Jiangsu Province. The floor area is around 159,000 m^2. Ground source heat pumps are used as a cooling source while FCU as terminal. The equipment can be adjusted free. The pricing scheme is based on the usage.

The energy use of a cooling season is 6.2 kWh_E/m^2. The average COP over the cooling season is around 2.7, while the EER is around 2.6, similar to the average among decentralized systems.

3.6. Comparative Analysis

Table 1 shows the key information from the five cases above.

Table 1 Key data on cases

	Case 1	Case 2	Case 3	Case 4	Case 5
Location	Jiangsu	Hubei	Jiangsu	Jiangsu	Jiangsu
Floor area (m^2)	10,000	50,000	48,700	340,000	159,000
Cooling source	Ground source heat pump	Ground source heat pump	Ground source heat pump	Sewage source heat pump	Ground source heat pump
Terminal	radiation ceiling and displacement ventilation	FCU	FCU	FCU	FCU
Energy use (KWh_E/m^2)	21.9	7.9	6.9	3.6	6.2
COP	4.4	3.9	2.9	4.6	2.7
EER	3	3.0	2.4	3.1	2.6
Cooling Load (KWh_H/m^2)	65.7	23.7	16.6	11.2	16.1
Usage mode	full time, full space	part time, part space	part time, part space	part time, part space	part time, part space
Pricing Scheme	by floor area	by usage	by usage	by usage	by usage

It could be seen for different district systems, the energy use, energy efficiency and cooling load can be quite different by usage mode, system design, pricing scheme, etc. Figure 3 show the energy use and cooling load comparisons of the above cases and decentralized systems (DS) in same climate zone (ZHOU et al., 2014).

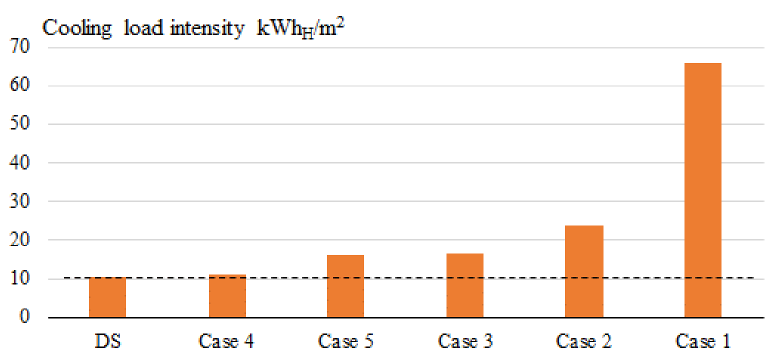

Figure 3 Energy use and cooling load of different systems

Through the case studies above, it can be seen that for most district systems, people use more cooling, which makes higher energy use with higher EER. But for some district systems when the occupants keep the operation mode of decentralized systems, the cooling usage may be not much higher, in some cases similar to that of decentralized systems, but the system should be designed carefully to fit the low load rate.

4. Survey and Simulation Results

4.1. Equipment, Usage Patterns and Cooling Load

In order to understand the energy differences caused by behavior change through the “rebound effect”, questionnaire surveys are also used in this research.

In 2015, 13,600 online questionnaires were completed to obtain data on the cooling equipment and usage mode distribution. The questionnaires include the cooling equipment, cooling usage patterns and cooling satisfaction.

The survey results show that air source heat pump is still the most popular in China, which is about 55%. Although only a tiny fraction (1%), district cooling has grown quite fast in recent years.

For cooling usage patterns, usage modes, cooling season and window situation are under consideration. 7 usage modes are defined, as shown in Table 2 (BERC, 2013):

Table 2 Usage modes

Mode 1	Never use
Mode 2	Turn on when feeling quite hot, turn off before sleeping
Mode 3	Turn on when feeling quite hot, turn off before leaving the room
Mode 4	Turn on when feeling hot, turn off before leaving the room
Mode 5	Turn on when in the room, turn off before leaving the room
Mode 6	Turn on all rooms once in the house, turn off when leaving
Mode 7	Turn on all the time with all rooms

With different modes, window habit and cooling seasons, there are sixty-one cooling usage patterns in all. Using DeST-h, the cooling load of these sixty-one patterns in a typical apartment in Shanghai are shown in Figure 4 and be classified into three levels.

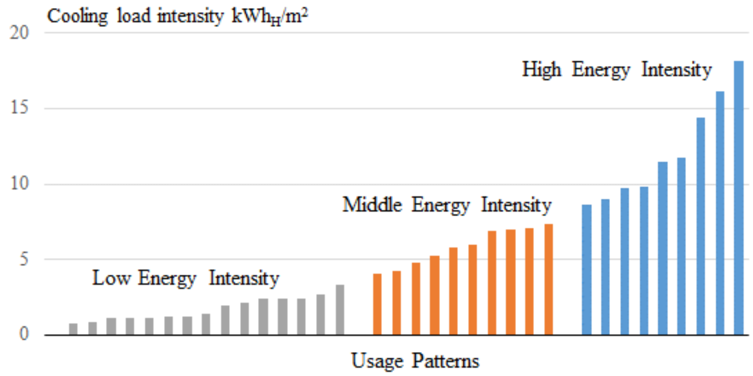

Figure 4 Cooling load of different modes

Figure 5 shows the distribution of usage mode with different cooling equipment. It could be seen that for district cooling systems, there will be more people use cooling in a high-intensity way.

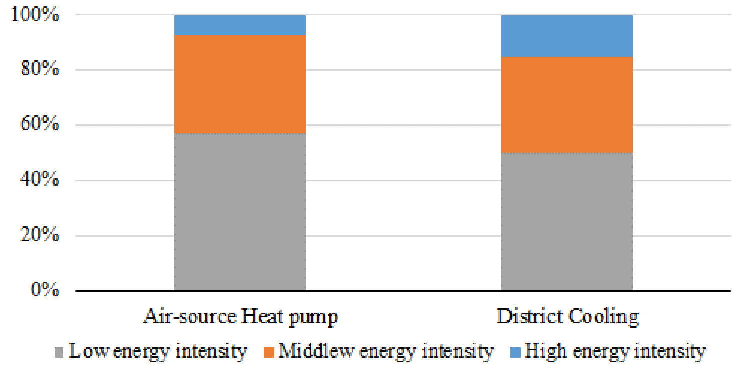

Figure 5 usage mode with different cooling equipment

4.2. Energy use of Different Systems

Using the distribution of usage patterns with different equipment and cooling load of different patterns, the average cooling load of different systems can be calculated. It is shown that the average cooling load of the air source heat pump is around 3.7 kWh_H/m^2, while that of district cooling systems 4.7 kWh_H/m^2.

Using the average COP of an air source heat pump as 2.5 and a good EER of district cooling system as 3, the rebound effect of district cooling systems can be seen in **Error! Reference source not found.**. Now the average cooling energy use of air source heat pump is 1.46 kWh_E/m^2. If cooling use stayed same, with a higher COP the energy use should have decreased by 23%. Because of the increase of cooling use, the real cooling energy use increase by 6%.

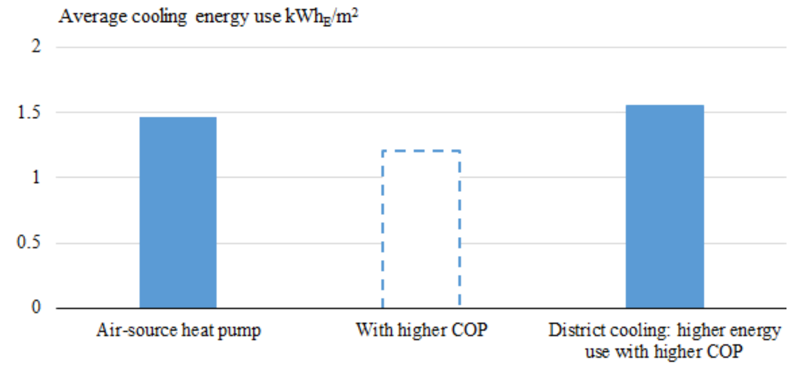

Figure 6 Cooling Energy Use of different equipment

It could be seen that without rebound effect, because of the increase of COP, the energy use can decrease. But as the change of usage patterns, the cooling use increase, which makes the energy use increase.

5. Discussion

5.1. The Reasons for the Rebound Effect

Through the case studies and analysis above, it can be seen clearly that the change of usage mode can affect the energy use. It is often claimed that high efficiency can only be achieved in district cooling systems when usage is high, but Case 4 shows that with a good design, low usage rates can also deliver cooling efficiently, without obviously behavior changes. So the most important to save energy and recede rebound effect is to decrease the change of behavior and get the reasons why behavior change.

Through the cases, it could be seen that the adjustment of the system is quite important. Through both case study and survey data collection, it can be seen that most Chinese households use cooling in “part space, part time” mode. And when the terminal is adjustable, occupants tend to adjust their usage downward when they leave the space. The systems that cannot be adjusted tend to have higher usage and consume more energy.

The case studies and literature review also revealed that pricing scheme also affects usage (ZHOU, 2015). When people need to pay for cooling by floor area, they tend to adjust the scope of the cooling. But when they need to pay by cooling usage, which is similar to the decentralized system, then people will keep the operation habit as a decentralized system.

With the increase of living standard, more cooling will be needed in residential buildings. It is true that in some places, the indoor thermal environment needs to be improved, but based on the existing research, using cooling at all times in all rooms does not equate to a better-living standard. Through 2,400 questionnaires made in Yinchuan, Chengdu and Beijing in 2013 and 2014, it shows that for more than 90% of people, the ideal mode of cooling usage is to use the equipment in the room when needed.

Above all, the reasons for the behavior change, or the rebound effect, include the adjustment of the system, pricing scheme and improvement of the indoor environment. Adjustment of the system and the pricing scheme can be promoted through careful design and suitable indoor thermal demand needs to encourage green lifestyle and suitable demand.

5.2. Possible Trend of Cooling System in China

Decentralized systems, or the air source heat pumps, are still the most popular equipment in China. And in the following years, this equipment will still be the most important for cooling. In order to increase the living standard and save energy, it is urgently needed to improve the related technology (BERC, 2013).

Centralized systems are still not so popular in China but have been promoted quite quickly in recent years. Through case studies, it can be seen that most district systems will use more energy than a decentralized system. But through careful design and operation, it is still possible to have some high-efficiency systems with low energy use, as case 4. But economic analysis shows that this case cannot afford its operation fee and initial investment in the current situation. If centralized systems are going to be promoted, they should use lower energy and higher efficiency than decentralized systems and the initial investment should be recovered in usually about five years. The new systems should be designed and operated quite carefully to avoid the rebound effect. Education is also important for the change of usage mode.

6. Conclusion

District cooling has been growing fast in China. Despite the claims, it is shown that these systems often uses more energy than decentralized systems. Through a case study, data collection and simulation, it can be shown that the change in occupant behavior is the main cause of the energy difference and the so-called rebound effect.

Through further analysis, it can be shown that adjustments to system use, pricing scheme and the increase of cooling demand may be the main reasons for the change. In China, decentralized systems are still the most popular and may be the most important equipment in the coming years. For centralized systems, it should be emphasized that the system design should allow for “part time, part space” usage and be able to achieve high energy efficiency even with low cooling loads.

Acknowledgements

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