ON DISTRICT HEATING AND COOLING RESEARCH IN CHINA

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ABSTRACT

The growth of the Chinese district heating sector has been very rapid during recent years. No other country in the world can show the same rapid growth of district heating systems during the last decades. Heated building area increased six times between 1995 and 2008 according to the Chinese district heating statistics. China has also enjoyed strong growth of scientific articles and papers published about district heating in recent years. During 2010-2012, one third of all international scientific journal articles and conference papers about district heating came from Chinese scientists, while Swedish researchers accounted for one quarter. It is important to identify the Chinese district heating and cooling research to judge the potential for future collaborative research on district heating systems between Sweden/Europe and China. Until 2013, Chinese district heating and cooling scientists have published 205 international publications on district heating and 36 publications on district cooling. In this paper, these articles are mapped and summarised with respect to topics, active research institutions, and their technology focuses. Another approach is to grasp the Chinese interest for more diversified heat supply, since many new systems are established and thereby have more degrees of freedom when choosing by various heat supply and technology options.

INTRODUCTION/PURPOSE

China is the second largest building energy user in the world, ranked the first in residential energy consumption, the third in commercial energy consumption [1], and the highest ranks in CO_2 emission, about 27% of world's CO_2 emission in the world [2]. The average annual growth rate of CO_2 emission from urban district heating has been 10.3%, it was responsible for 4.4% of China's total CO_2 emission in 2009 [3]. Coal is the primary fuel in Chinese heat supply. About 40% of the air pollution in China came from coal dust [4]. In order to improve energy efficiency and reduce CO_2 emission, many scientists work within the field of district heating and cooling system.

The growth of the Chinese district heating sector has been very rapid during recent years. No other country in the world can show the same rapid growth of the district heating during the last 10-15 years. Heated building area and total pipe length increased 8 and 17 times, respectively, between 1995 and 2012 according to the Chinese district heating statistics [5]. In many respects, the technology used in China is similar to the technology in Scandinavian, which is characterized by high quality and has been a prerequisite for district heating high market shares in Sweden, Denmark and Finland.

In the 1950s, both China and Sweden started to build district heating systems. Denmark became the guiding example for Sweden, while the former Soviet Union became the guiding example for China. Both these guiding examples started their first district heating systems in the 1920s. One important feature of Danish district heating was customer heat demand control and flow control in each substation. This feature gave automatically a proper flow allocation. The Russian systems lacked this feature, and worked with balancing valves creating average constant flow in the system. This Russian principle is a major drawback in system functioning, giving severe flow allocation problems.

The huge amount of district heating comes from both Combined Heat and Power (CHP) and boilers in China, about half of each. The heat supply from CHP and boiler continues increased by year to year. In Sweden, the CHP accounted for 45% of the supplied district heating in 2011 [6]. In recent years, the interest on biofuel based CHP has increased in Sweden, while China will transfer coal boilers to natural gas boilers with higher efficiency. More than half of the heat supply to district heating systems in Sweden came from biofuel and waste, while the fuel used in China is still dominant by coal.

China has become the largest national air conditioning equipment market in the world, the annual growth rate of urban households have been very high during the last 10-15 years [7]. In Sweden, district cooling is used mainly in offices and business premises and for cooling some industrial processes.

To our knowledge there is no organised research cooperation between China and Sweden for district heating system and district heating technologies.

The purpose of this paper is to identify the Chinese district heating and cooling research to judge the potential for future collaborative research on district heating systems between Sweden/Europe and China.

STATE OF THE ART

Sweden has had district heating research since 1975 in various research programs, but most of them were written in Swedish, making them unknown for foreign researchers. Also many Chinese research projects are unknown in Europe. There should be a future value for the Swedish/European district heating sector to undertake a benchmarking against the rapidly growing district heating sector in China. Many newly built Chinese district heating systems have had more degrees of freedom to consider in their expansion, while old systems have been locked in their technology choices. The existing Swedish district heating systems have a very strong market position with more than half of all Swedish building spaces connected after 60 years of expansion, giving less degree of freedom for the future. An important issue for a benchmark is how the technical choices influence the district heating research in China and Sweden/Europe.

The two major research questions identified are:

- What can Sweden/Europe learn from Chinese district heating and cooling experiences?
- What can China learn from Swedish/European district heating and cooling experiences?

METHODS/METHODOLOGY

The Scope scientific search engine was used for the analysis of the current district heating and cooling research in China. Articles written by Chinese district heating and cooling scientists in international scientific journals have been mapped according to markets, demands, loads, supply, environmental impact, distribution technology, substations, system functioning, as well as economics and planning. These articles have been evaluated and summarised in order to draw conclusions.

RESULTS: PAPERS ON DISTRICT HEATING AND COOLING

International analysis

Between 1970 and 2013, 5627 international scientific publications have been written about district heating and 278 for district cooling, according to the scientific search engine Scopus, as shown in Figs 1-2.

Numbers of district heating publications from Germany are in first place since the journal Euroheat & Power (formerly Fernwärme International) has been published district heating articles for more than 40 years in Germany. The district heating articles from Sweden are still in the second place over countries since 1975, USA comes to the third place, and China is in the fourth place. However, one third of all international district heating journal articles came from Chinese scientists during 2010-2012.

Numbers of district cooling publications from USA are in the first place since ASHRAE Transactions is published in USA. China is in the second place during 1970-2013, followed by Malaysia, Germany and Sweden. This means that the Chinese academic researchers are supporting the expansion the Chinese district heating and cooling systems by their increased number of publications.

Analysis of Chinese district heating papers

Chinese authors have written 232 of the 5627 publications about district heating according to the Scopus scientific search engine. However, 16 are non-district heating papers and 11 are only about district cooling, since the Scope scientific research engine seems to regard the labels ‘heat generation’, ‘heat source’, and ‘heat load’ as ‘district heating’, so the total number of publications becomes 205 as shown in Table 1. 28% of the district heating papers have been published in conference proceedings and 27% in the international journals in Elsevier, of which 19% are published in the Elsevier energy journals, such as Energy, Energy policy, Applied Energy, and so on. Many universities in China have also their own journals, so 20% of the district heating papers have been published in these kinds of journals.

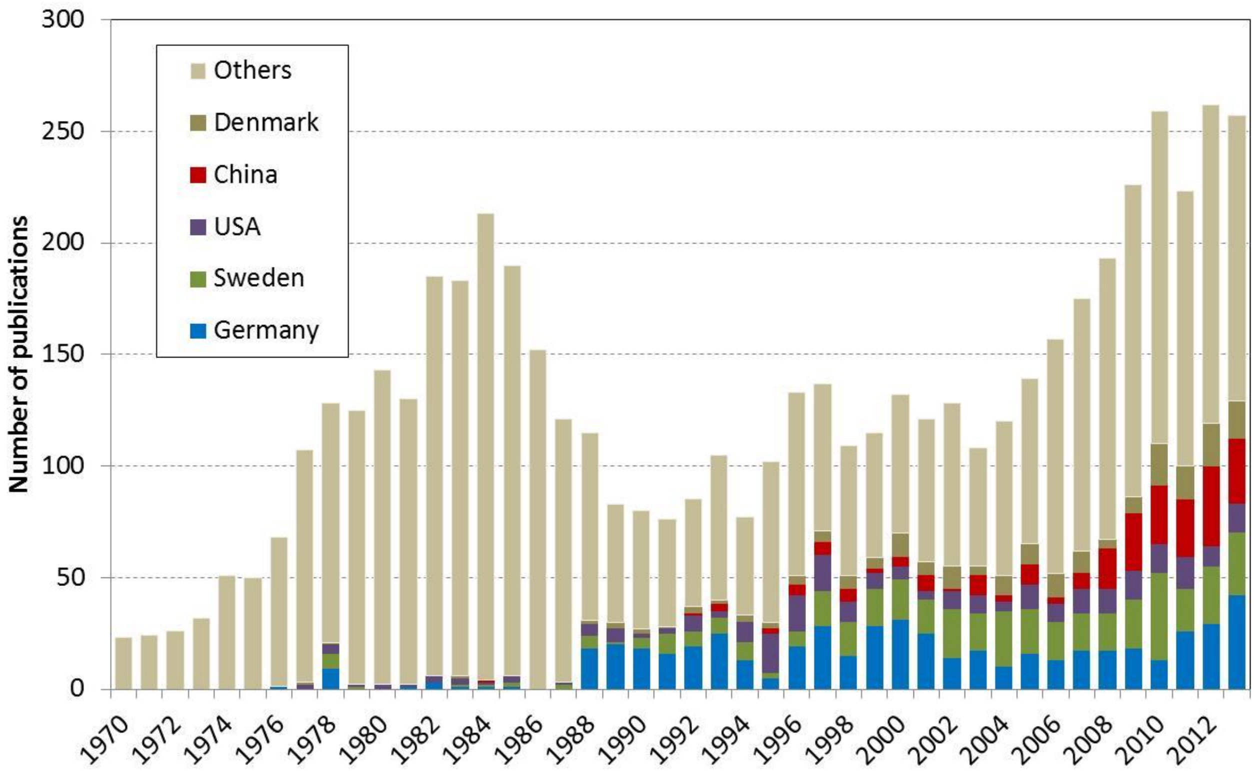

Fig. 1 Published articles and other papers with the ‘district heating’ label 1970-2013 by country affiliation. (Data from the Scopus scientific search engine)

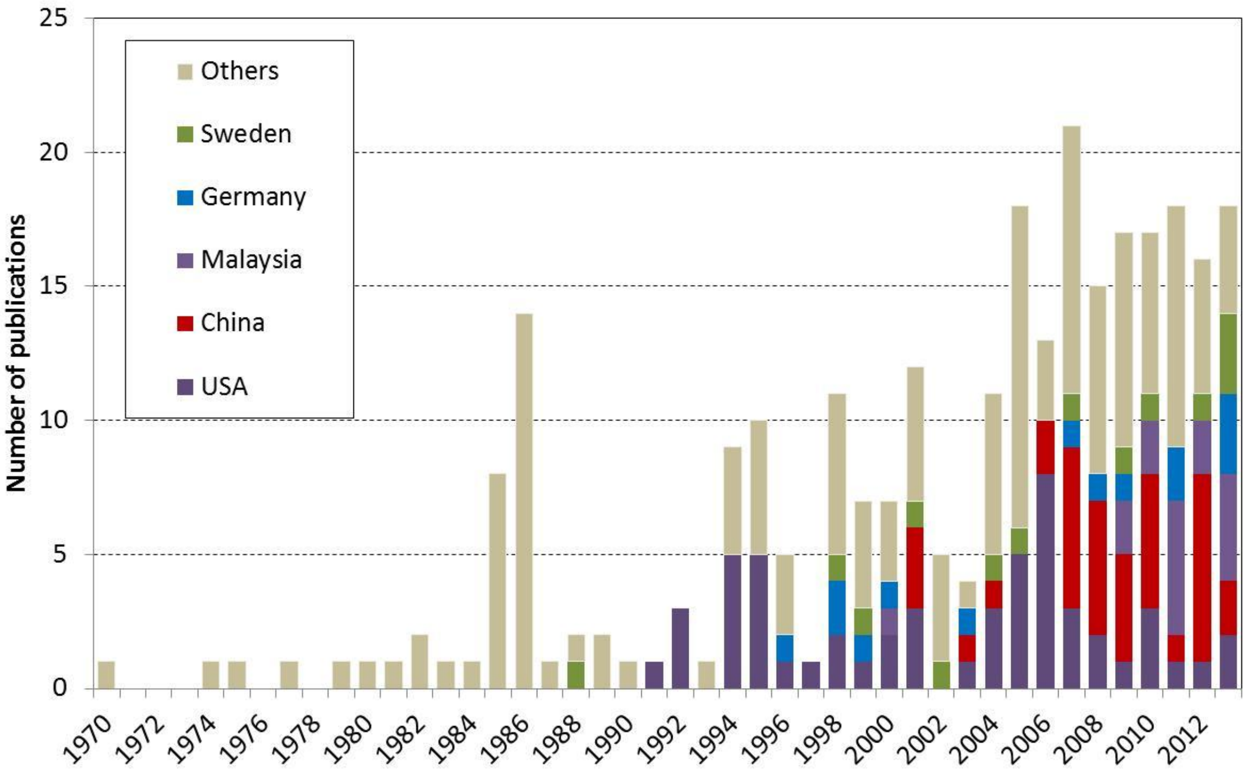

Fig. 2 Published articles and other papers with the 'district cooling' label 1970-2013 by country affiliation. (Data from the Scopus scientific search engine)

The first international district heating paper [8] by Chinese researcher was published in the special workshop issue of The International Journal of Energy in 1984. Eight years later, the second international district heating journal paper [9] was published. These two papers focused on heat from nuclear energy for district heating.

The chapters in the textbook "District Heating and Cooling" [7] have been used as subject classification to analyse these papers. The chapter numbers in Table 1-2 are:

Chapter 3: Energy, heat, and cold markets

Chapter 4: Heat and cold demands

Chapter 5: Heat and cold loads

Chapter 6: Heat and cold supply

Chapter 7: Environmental impact and opportunities

Chapter 8: Heat and cold distribution technology

Chapter 9: Substations

Chapter 10: System functioning

Chapter 11: Economics and planning

The identified papers are dominated by 81 papers about heat and cold supply methods, since many old inefficient and high pollution coal-fired boilers need to be replaced, and 49 papers focus on system functioning, as shown in Table 1.

Publications on energy, heat, and cold market are very few, since the Chinese district heating systems by tradition have been part of the welfare system without competition in heating market. Another low focus research field is on heat and cold distribution technology; all 5 papers have been published since 2009. The earlier technology was based on former Soviet Union standards, and this need to be improved with new enhanced technology. Recently, three papers on heating meter reform have been published, since Chinese district heating systems are expected to turn from public welfare systems into commercialized systems.

Table 1 Publications of district heating by Chinese research according to the chapters in [7]. (Data source: the Scopus scientific search engine)

Count of CH										
Year/Chap.	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**Total**
1984				1						1
1992				1						1
1993	1			2						3
1995				2						2
1996				3				1	1	5
1997				4				2		6
1998				5	1					6
1999				1				1		2
2000				2				2		4
2001				3				2	2	7
2002									1	1
2003	1	2		6						9
2004				1				2		3
2005			3		1		2	3		9
2006				2				1		3
2007		1		2				2		5
2008			2	5			3	1	1	12
2009		1	3	7		2	3	5		21
2010			1	12	2			5		20
2011	1	2		7	4		3	5	1	23
2012	1	3		9	1	1	6	10	2	33
2013		3	2	6	7	2		7	2	29
Total	**4**	**12**	**11**	**81**	**16**	**5**	**17**	**49**	**10**	**205**

Analysis of Chinese district cooling papers

According to the Scopus scientific search engine, 37 of 278 publications on district cooling were written by Chinese researchers, one of them was a non-district cooling paper, so the total number of papers by Chinese researcher became 36, as shown in Table 2. The number of papers on heat and cold supply method and system functioning are equal, about 28% each, together account for more than half of publications. The publications on substations and planning are the third and fourth places.

Table 2 Publications of district cooling by Chinese research according to the chapters in [7]. (Data source: the Scopus scientific search engine)

Count of CH Year	4	6	7	8	9	10	11	Total
2001		3						3
2003			1					1
2004						1		1
2006				1	1			2
2007		2			1	1	2	6
2008					1	3	1	5
2009		1		2			1	4
2010	1	2			1	1		5
2011						1		1
2012		2			2	1	1	6
2013						2		2
Total	**1**	**10**	**1**	**3**	**6**	**10**	**5**	**36**

Most active district heating and cooling research institutions

However, the Chinese researchers working on district heating and cooling systems are spit into many affiliations. During the recent four years, the total publications from the top five universities are almost equal to the rest of the universities. Figure 3 and Figure 4 show the top five most published district heating and cooling university affiliations in China during 1990-2013, respectively.

District heating researchers at Tsinghua University are the leader in this field, accounting for 28% of total Chinese district heating publications. They were dominant five years ago. However, during recent five years, the publications at other universities have expanded faster, especially at Harbin Institute of Technology. The total number of publications at Harbin institute of technology has grown from third place during all years to the second place during 2010-2013.

Out of 64 papers totally from Tsinghua University in Beijing, 39 papers were related to heat and cold supply, 9 papers on system functioning, and 7 papers on substations.

Out of 24 papers totally form Harbin Institute of Technology, 10 papers were related to system functioning, and 7 papers on heat and cold supply.

The total number of district cooling publications is low compared to district heating. Most publications came from Tongji University in Shanghai, followed by Tsinghua University. Prof. Long Weiding took part in all 8 publications on district cooling at Tongji University. Most of these publications were related to optimization of pipe networks and community energy planning. A district cooling and heating system named regional distributed heat pump energy bus system was introduced by [10, 11] in order to achieve maximum urban energy efficiency, and to use clean energy, renewable energy sources, and end-use energy saving.

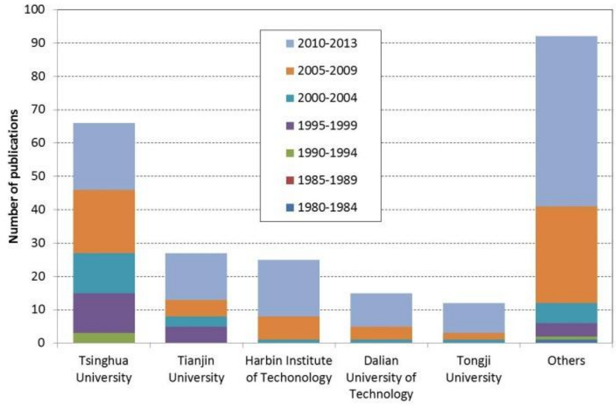

Fig. 3 Published articles and other papers with the 'district heating' label 1970-2013 by University affiliation. (Data from the Scopus scientific search engine)

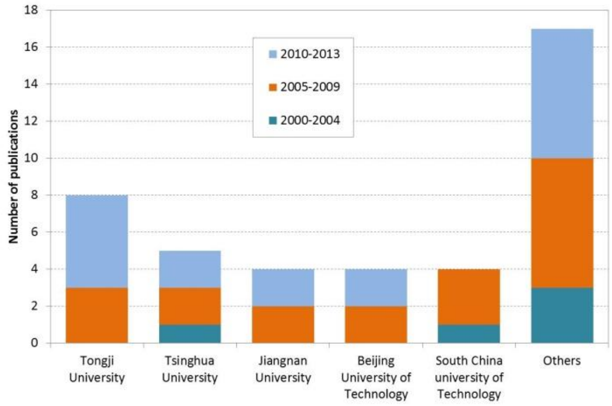

Fig. 4 Published articles and other papers with the 'district cooling' label 1970-2013 by affiliation. (Data from the Scopus scientific search engine)

RESULTS: RESEARCH AREAS

The topic of heat and cold supply methods are the most interesting subject for Chinese researchers during the analysed years. The system functioning topic was the second most interesting area after 1996. Recently, substation technologies grasp the Chinese researchers' interest as well.

Heat and cold supply

Table 3 summarise papers about heat supply methods during 1984-2013. Early papers on heat and cold supply are mostly related to nuclear energy, later research focus more on renewable energy sources, such as geothermal and solar heat. Waste heat from thermal power plants (combined heat and power) and industrial processes are recently focused on. Boilers generate about half of all heat supply in district heating systems, but there was only one paper [12] published in 2011 on analysing 472 heating boilers in Tianjin. The statistics from these boilers showed very low energy efficiency. Heat pumps and CHP are the main direction of the development, as well as Combined Cooling Heating and Power (CCHP). The recently published papers on heat supply method align with most of the five current, suitable, strategic local heat and fuel resources for district heating. These five strategies are CHP (usable upgraded excess heat from thermal power station) plants, waste-to-energy plants (usable heat obtained from waste incineration), usable excess heat from industrial processes and fuel refineries, fuels that are difficult and bulky to handle and manage in small boilers, and natural geothermal heat sources [7].

Recent publications on heat pumps are the number one topic among the heat supply methods. Li et al. [13] proposed a district heating system based on distributed absorption heat pumps in order to supply low-grade renewable heat directly in the substations. It can save primary energy supply by 23-46% compare to conventional district heating systems. Ying & Yufeng [14] describes the dilatancy technology of district heating system with high-temperature heat pump to enhance the capacity of district heating system, to increase the temperature difference, to reduce the diameters and the initial investment of primary side network, and to save the operation consumption of circulating pumps.

Table 3 Summary of papers about heat supply methods in district heating systems during 1984-2013.

Heat supply	1984	1992	1993	1995	1996	1997	1998	1999	2000	2001	2003	2004	2006	2007	2008	2009	2010	2011	2012	2013	Total
absorption							1														**1**
bioenergy																	1		1		**2**
boiler																		1			**1**
CCHP									1	1										1	**3**
CHP			1						1						2	2	2	2	2	1	**13**
flue gas condensation															1						**1**
geothermal					1	2	2	1			2	1	1		2		1		1		**14**
heat pump											2		1	2		4	8	3	4	1	**25**
industrial waste heat																		1		1	**2**
mulitiple heat sources											1								1		**2**
nuclear	1	1	1	2	2	2	2			2	1					1				1	**16**
solar																				1	**1**
Total	**1**	**1**	**2**	**2**	**3**	**4**	**5**	**1**	**2**	**3**	**6**	**1**	**2**	**2**	**5**	**7**	**12**	**7**	**9**	**6**	**81**

Zhang et al. [15] proposed an ejector heat pump-boosted district heating system with CHP in order to recover waste heat from circulating cooling water in the CHP plant and to improve the heating capacity of existing district heating systems with CHP. Sun et al. [16] developed a new waste heat district heating system with CHP based on absorption heat exchange cycle in order to increase the heating capacity of CHP through waste heat recovery and reduce district heating cost.

A number of heat pump district heating systems using renewable/free energy source have been analysed, such as geothermal [17-19], seawater [20-25], lake water [26], ground water and sewage [27].

Chen et al. [28] proposes that heat pump heating serves as a replacement for urban district heating, in result the replacing coal-based urban district heating with heat pump heating decreases energy consumption and CO_2 emission by 43% in the heating sector, however, there is no explanation on how to calculate CO_2 emissions in this paper.

Geothermal is one of the important research topics on the heat supply method. Six early publications on geothermal are related to indirect geothermal district heating systems and plate heat exchangers. Later, Lei & Valdimarsson [29] used a dynamic simulation model to optimize geothermal energy with temperature 70-90°C heating system in Tianjin. Gao et al. [30, 31] applied large-scale ground-source/coupled heat pump to access geothermal energy for a district heating and cooling system in Shanghai. Zheng et al. [32] propose a comprehensive and systematic operation strategy for a geothermal step utilization heating system in order to utilize geothermal energy efficiently.

Two papers on industrial waste heat are related to low temperature industrial waste heat sources. The universal design approach to industrial-waste-heat based district heating is proposed by Fang et al. [33] with a case study.

No paper was found with search word “waste incineration” and “district heating” from Chinese researchers according to the Scopus scientific search engine.

System functioning

First international paper on system functioning [34] was published on water leakage and blockage detection in 1996 according to the Scopus scientific search engine.

The heritage of the Russian principle with calculated balancing of heat distribution networks is still major problem in China, giving misallocations of heat deliveries to customers. Some buildings are overheated, solved by using open windows, while other buildings are underheated giving low indoor temperatures and critical customer viewpoints. These problems must be solved if payments for heat deliveries should be based on actual heat use based on heat meter readings. The number of articles about system functioning can be tracked to these major flow allocation problems in the Chinese district heating systems.

Some papers focused on analysis and optimization of networks, such as [35-38]. Some models on pipeline network with multiple heat sources were proposed, e.g. hydraulic model of looped pipeline network [39, 40]; object oriented based method [41].

The traditional regulation methods include quality regulation, quantity regulation, intermittent regulation etc. are all static regulation methods without considering the thermal inertia of the heating systems and buildings.

By tradition, Chinese district heat deliveries have been invoiced by the building spaces connected. Due to the heat meter reform, Chinese district heating systems are introducing heat meters and customer control systems in the buildings.

The application of thermostatic radiator valves has become popular. Yan et al. [42] investigated consumer behaviour including regulation of thermostatic radiator valves and opening of windows and its influences on the hydraulic performance and energy consumption of individuals and the whole system. They concluded that 30% deduction of the pump consumption with 10% deduction of the flow rate and 10% energy savings with the heat metering billing systems.

Liu et al. [43] compared the pros and cons of several metering methods, these methods charge fees according to heat-allocation meters on radiators, heated areas (traditional way), hot water meters in each household (volumetric meter), calorimeters in each household, and room temperature. After comparison, they proposed a new method that the total heating fee of a building is allocated according to the accumulated on-time (on/off valves) as well as the floor space of each household.

DISCUSSION AND SUMMARY OF RESULTS

Chinese researchers have achieved an impressive growth of number of papers published on district heating and cooling during the recent years compared to all papers published internationally.

Many Chinese research groups are represented in the literature survey. Tsinghua University is the dominant research group among Chinese district heating and cooling researchers, but Harbin Institute of Technology have expanded their publication rate rapidly during recent years.

The large Chinese interest of various heat and cold supply methods as CHP, CCHP, and heat pumps can be seen as an introduction to the required transfer from coal-fired CHP plants and boilers to other heat supply options, including using natural gas as fuel. However, no paper on waste incineration with heat recovery and only two papers on industrial heat recovery were identified in the literature analysis. Several Swedish cities use the heat from waste incineration as base load heat supply, since dumping combustible waste and organic waste was prohibited in 2002 and 2005.

With respect to system functioning, China has an important future challenge of installing customer heat control and flow control in substations in order to eliminate the flow misallocations in the heat distribution networks. New regulation methods are required considering all important parts: heat sources, heat networks, substations, and heat users.

A successful district heating and cooling manager must always minimise both the heat generation costs and the heat distribution costs in order to compete in the heating and cooling market. Earlier, the district heating systems in China were welfare systems, now with the implement of heat reform in 2003, new methods on heating fee are suggested. In Sweden, the district heating systems were commercial from the beginning and have very good market experience.

OUTLOOK

This paper is a short intermediate report from an ongoing assessment project. It will be followed by a study tour to China and discussions with four Chinese universities active in district heating and cooling research. The results from the Scopus scientific search engine show the structure of the district heating and cooling research in China. However, it is not the whole truth. More detailed studies should be made.

CONCLUSIONS

This paper has mapped scientific papers written by Chinese researchers about district heating and cooling. Some answers to the two corresponded research questions are:

What can Sweden/Europe learn from Chinese district heating and cooling experiences?

- Technologies on CCHP
- Hybrid systems of CHP and heat pumps

What can China learn from Swedish/European district heating and cooling experiences?

- Customer control systems for both heat demands and flow, giving automatic flow allocations in networks, are well developed in Sweden as well as the price of the district heat is competing with other source in the heating market.
- Multiple heat sources are easy to implement in district heating systems with customer control systems. Hence, almost perfect merit order heat supply can be applied. Hereby, various heat sources as waste incineration, biomass, heat pumps, and CHP at different locations can be utilised in the same distribution network.

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REFERENCES

[1] IEA, "Energy Balances of OECD/non-OECD Countries 2011," IEA, ed., 2011.

[2] U.S. Energy Information Administration. "International Energy Statistics," 20150505; http://www.eia.gov/cfapps/ipdbproject/IEDIndex3.cfm.

[3] L. Wang, X. Chen, L. Wang, S. Sun, L. Tong, X. Yue, S. Yin, and L. Zheng, “Contribution from Urban Heating to China’s 2020 Goal of Emission Reduction,” *Environmental Science & Technology,* vol. 45, pp. 4676-4681, 2011.

[4] L. Zhang, O. Gudmundsson, H. Li, and S. Svendsen, “Comparison of District Heating Systems Used in China and Denmark,” *EuroHeat&Power,* vol. 10, no. IV/2013, pp. 12-19, 2013.

[5] NBSC, *China Statistical Yearbook*, Beijing: China Statistics Press, various years.

[6] Swedish Energy Agency, *Energy in Sweden 2013*, Eskilstuna, Sweden: Swedish Energy Agency, 2014.

[7] S. Frederiksen, and S. Werner, *District heating and cooling*, Lund, Sweden: Studentlitteratur AB, 2013.

[8] L. Yingzhong, "The important roles of nuclear energy in the future energy system of China," *Energy,* vol. 9, no. 9–10, pp. 761-771, 1984.

[9] W. Dazhong, M. Changwen, D. Duo, and L. Jiagui, "Chinese nuclear heating test reactor and demonstration plant," *Nuclear Engineering and Design,* vol. 136, no. 1-2, pp. 91-98, 1992.

[10] P. Wang, and W. Long, "Research on energy consumption of regional distributed heat pump energy bus system," 4th International Conference on Technology of Architecture and Structure, ICTAS 2011, 2012, pp. 425-429.

[11] W. Long, "Smart Micro Energy Network for Eco-Communities," *REHAV Journal,* vol. 51, no. 2, pp. 12-17, 2014.

[12] L. Cong, X. Zheng, Y. Li, and S. Zhao, "Energy efficiency research and analysis on district heating boiler in Tianjin," *2011 2nd International Conference on Mechanic Automation and Control Engineering, MACE 2011.* pp. 3091-3094.

[13] Y. Li, L. Fu, S. Zhang, and X. Zhao, "A new type of district heating system based on distributed absorption heat pumps," *Energy,* vol. 36, no. 7, pp. 4570-4576, 2011.

[14] W. Ying, and Z. Yufeng, "Analysis of the dilatancy technology of district heating system with high-temperature heat pump," *Energy and Buildings,* vol. 47, no. 0, pp. 230-236, 2012.

[15] B. Zhang, Y. Wang, L. Kang, and J. Lv, "Study of an innovative ejector heat pump-boosted district heating system," *Applied Thermal Engineering,* vol. 58, no. 1-2, pp. 98-107, 2013.

[16] F. Sun, L. Fu, S. Zhang, and J. Sun, "New waste heat district heating system with combined heat and power based on absorption heat exchange cycle in China," *Applied Thermal Engineering,* vol. 37, no. 0, pp. 136-144, 2012.

[17] Z. Qiu, Y. Gong, W. Ma, and X. Bu, "Performance study of absorption/compression heat pump (ACHP) system by low-temperature geothermal tail water," *Taiyangneng Xuebao/Acta Energiae Solaris Sinica,* vol. 33, no. 4, pp. 653-657, 2012.

[18] Z. Wang, S. Lei, and Y. Peng, "Analysis of geothermal water sustainability for district heating in Xianyang City," *4th International Conference on Bioinformatics and Biomedical Engineering, iCBBE 2010*.

[19] P. C. Zhao, L. Zhao, G. L. Ding, and C. L. Zhang, "Temperature matching method of selecting working fluids for geothermal heat pumps," *Applied Thermal Engineering,* vol. 23, no. 2, pp. 179-195, 2003.

[20] S. Haiwen, D. Lin, L. Xiangli, and Z. Yingxin, "Quasi-dynamic energy-saving judgment of electric-driven seawater source heat pump district heating system over boiler house district heating system," *Energy and Buildings,* vol. 42, no. 12, pp. 2424-2430, 2010.

[21] H. W. Shu, L. Duanmu, Y. X. Zhu, and X. L. Li, "Critical COP value of heat pump unit for energy-saving in the seawater-source heat pump district heating system and the analysis of its impact factors," *Harbin Gongye Daxue Xuebao/Journal of Harbin Institute of Technology,* vol. 42, no. 12, pp. 1995-1998, 2010.

[22] H. Shu, L. Duanmu, C. Zhang, and Y. Zhu, "Study on the decision-making of district cooling and heating systems by means of value engineering," *Renewable Energy,* vol. 35, no. 9, pp. 1929-1939, 2010.

[23] S. Haiwen, D. Lin, L. Xiangli, and Z. Yingxin, "Energy-saving judgment of electric-driven seawater source heat pump district heating system over boiler house district heating system," *Energy and Buildings,* vol. 42, no. 6, pp. 889-895, 2010.

[24] X. l. Li, L. Duanmu, and H. w. Shu, "Optimal design of district heating and cooling pipe network of seawater-source heat pump," *Energy and Buildings,* vol. 42, no. 1, pp. 100-104, 2010.

[25] H. W. Shu, L. Duanmu, X. L. Li, and Y. X. Zhu, "Energy-saving criterion of seawater source heat pump district heating system," *Xi'an Jianzhu Keji Daxue Xuebao/Journal of Xi'an University of Architecture and Technology,* vol. 41, no. 4, pp. 561-565, 2009.

[26] X. Chen, G. Zhang, J. Peng, X. Lin, and T. Liu, "The performance of an open-loop lake water heat pump system in south China," *Applied Thermal Engineering,* vol. 26, no. 17–18, pp. 2255-2261, 2006.

[27] X. Chen, J. Han, and J. Zeng, "Performance and benefits evaluation of two water-source heat pump systems for district heating," 2012 International Conference on Civil, Architectural and Hydraulic Engineering, ICCAHE 2012, 2012, pp. 4225-4228.

[28] X. Chen, L. Wang, L. Tong, S. Sun, X. Yue, S. Yin, and L. Zheng, "Energy saving and emission reduction of China's urban district heating," *Energy Policy,* vol. 55, no. 0, pp. 677-682, 2013.

[29] H. Lei, and P. Valdimarsson, "Simulation of district heating in Tianjin, China," *GRC 2006 Annual Meeting: Geothermal Resources-Securing Our Energy Future.* pp. 201-206.

[30] J. Gao, X. Zhang, J. Liu, K. S. Li, and J. Yang, "Thermal performance and ground temperature of vertical pile-foundation heat exchangers: A case study," *Applied Thermal Engineering,* vol. 28, no. 17-18, pp. 2295-2304, 2008.

[31] J. Gao, X. Zhang, J. Liu, K. Li, and J. Yang, "Numerical and experimental assessment of thermal performance of vertical energy piles: An application," *Applied Energy,* vol. 85, no. 10, pp. 901-910, 2008.

[32] G. Zheng, F. Li, Z. Tian, N. Zhu, Q. Li, and H. Zhu, "Operation strategy analysis of a geothermal step utilization heating system," *Energy,* vol. 44, no. 1, pp. 458-468, 2012.

[33] H. Fang, J. Xia, K. Zhu, Y. Su, and Y. Jiang, “Industrial waste heat utilization for low temperature district heating,” *Energy Policy,* vol. 62, no. 0, pp. 236-246, 2013.

[34] Y. Jiang, H. Chen, and J. Li, “Leakage and blockage detection in water network of district heating system,” *ASHRAE Transactions,* vol. 102, no. 1, pp. 291-296, 1996.

[35] X. Qin, and Y. Jiang, “Accessibility analysis of district heating loop-networks based on genetic algorithms,” *Qinghua Daxue Xuebao/Journal of Tsinghua University,* vol. 39, no. 6, pp. 90-94, 1999.

[36] X. Qin, Y. Jiang, and Y. Zhu, "Optimization of Hydraulic Conditions in District Heating Networks," *ASHRAE 2001 Winter Meeting CD, Technical and Symposium Papers.* pp. 387-391.

[37] W. Q. Liu, J. H. Yang, and Y. Lin, “Intelligent control method on district heating network,” *Dalian Ligong Daxue Xuebao/Journal of Dalian University of Technology,* vol. 44, no. 3, pp. 464-468, 2004.

[38] P. H. Zou, X. X. Wang, X. L. Li, and Y. Q. Jiang, “Hydraulic simulation and analysis of heating loop network with multi-heat source in faulty condition,” *Tianjin Daxue Xuebao (Ziran Kexue yu Gongcheng Jishu Ban)/Journal of Tianjin University Science and Technology,* vol. 38, no. SUPPL., pp. 1-4, 2005.

[39] W. Na, Y. Song, and D. Li, "A hydraulic modeling of loop pipeline network with multiple heat sources based on graph theory," 4th International Conference on Technology of Architecture and Structure, ICTAS 2011, 2012, pp. 740-744.

[40] J. Pengfei, Z. Neng, N. Wei, and L. Deying, “Establishment and solution of the model for loop pipeline network with multiple heat sources,” *Energy,* vol. 36, no. 9, pp. 5547-5555, 2011.

[41] H. Wang, H. Y. Wang, and H. Z. Zhou, “Analysis of multi-sources looped-pipe network based on object-oriented methodology,” *Zhejiang Daxue Xuebao (Gongxue Ban)/Journal of Zhejiang University (Engineering Science),* vol. 46, no. 10, pp. 1990-1909, 2012.

[42] J.-j. Yan, S.-f. Shao, J.-p. Liu, and Z. Zhang, “Experiment and analysis on performance of steam-driven jet injector for district-heating system,” *Applied Thermal Engineering,* vol. 25, no. 8–9, pp. 1153-1167, 2005.

[43] L. Liu, L. Fu, Y. Jiang, and S. Guo, “Major issues and solutions in the heat-metering reform in China,” *Renewable and Sustainable Energy Reviews,* vol. 15, no. 1, pp. 673-680, 2011.