The 15th International Symposium on District Heating and Cooling,
September 4th to September 7th, 2016, Seoul, Korea

MAPPING ENERGY AND EXERGY FLOWS OF DISTRICT HEATING IN SWEDEN

Mei Gong and Sven Werner
School of Business, Engineering and Science, Halmstad University, PO Box 823, SE 30118 Halmstad, Sweden

Keywords: District heating, exergy, Sankey diagram, Sweden

ABSTRACT

District heating has been available in Sweden since the 1950s and used more than half of the total energy use in dwelling and no-residential premises in 2013. Energy and exergy efficient conversion and energy resources are key factors to reduce the environmental impact. It is important to understand energy and exergy flows from both the supply and demand sides. The exergy method is also a useful tool for exploring the goal of more efficient energy-resource use. Sankey diagrams together with energy and exergy analyses are presented to help policy/decision makers and others to better understand energy and exergy flows from primary energy resource to end use. The results show the most efficient heating method in current district heating systems, and the use of renewable energy resources in Sweden. It is exergy inefficient to use fossil fuels to generate low quality heat. However, renewable energies, such as geothermal and solar heating with relative low quality, make it more exergy efficient. Currently, about 90% of the energy sources in the Swedish district heating sector have an origin from non-fossil fuels. Combined heat and power is an efficient simultaneous generator of electricity and heat as well as heat pump with considering electricity production. Higher temperature distribution networks give more distribution losses, especially in exergy content. An outlook for future efficient district heating systems is also presented.

INTRODUCTION

District heating was introduced in 1948 and has been successfully expanded in Sweden since then. The district heating deliveries are mainly used to cover space heating and hot water demands in buildings, but have a low usage in the industrial processes. Currently, about 58% of total building heat demands for residential and service sector premises are covered by district heating [1].

Both the exergy concept and Sankey diagrams are used as tools for visualizing energy quality processes in this study. The exergy concept gains insights into its efficiency as well as the quantitative measure of quality, and the diagrams were used for mapping energy and exergy supplies, transformations and uses during 2014. Sankey diagrams together with energy and exergy analyses are presented to help policy/decision makers and others to better understand energy and exergy flows from primary energy resource to end use. The combined methods have been applied for national levels in a country [2-5] and industrial heating processes [6], as well as in company levels in industry [7]. To our knowledge, there is currently no exergy flow analysis available for a national district heating sector. The purposes of this paper are to:

- map energy and exergy flows from primary energy sources to customer usages in the Swedish district heating systems
- show the most efficient heat supply methods in current Swedish district heating systems
- visualize the utilization of renewable energy resources in Sweden.
- give an outlook for more efficient district heating systems in Sweden

METHOD

Exergy analysis

Exergy is a measure of how far a certain system deviates from equilibrium with its environment, a given state of reference or equilibrium. In this analysis, the average outdoor temperature is used as reference temperature T_0, and 100 kPa as reference pressure.

The exergy of material substances can be calculated as [8]:

$$E = \sum n_i(\mu_i^0 - \mu_{i0}^0) + RT_0 \sum n_i \ln \frac{c_i}{c_{i0}} \tag{1}$$

where n_i is the number of moles of different chemical materials i. μ_i^0 and c_i are the chemical potential and concentration of substance i in relation to its standard state. μ_{i0}^0 and c_{i0} are the chemical potential and concentration for the substance in the environment in relation to its standard state. R is the gas constant, 8.314 J mol^{-1} K^{-1}.

The exergy factor is defined as the ratio of exergy to energy. The exergy factor of energy transferred as heat at a constant temperature T, i.e., a heat reservoir becomes [8]:

$$\frac{E}{Q} = \left| \frac{T_0 - T}{T} \right| \tag{2}$$

Heat used for space heating and domestic hot water was calculated by Equation 2. The exergy factor of district heat was calculated as [8]:

$$\frac{E}{Q} = 1 - \frac{T_0}{T_s - T_r} \ln \frac{T_s}{T_r} \quad (3)$$

where T_s is the temperature of the supplied heat, i.e., the temperature of the hot water used by the consumer for space heating. T_r is the temperature of the return water.

Table 1 lists some energy forms used in this study. The exergy factors for fuel are based on lower heating values (LHV), which are the data available in Swedish energy statistics. It must be noted that some factors are only approximate due to unknown moister and exact content. The exergy factor for current district heating grid is the average value for Swedish district heating system [9], and the outdoor temperature has a strong effect on the heat at room temperature, since the annual average temperature varies from -1°C in the north to 10°C in the south of Sweden.

Table 1 The exergy factor of some energy forms.

Energy form	**Exergy factor**
Oil, petroleum products [10]	1.06
Natural gas [10]	1.04
Electrical energy	1.0
Sunlight [8]	0.93
District heat (current generation) [9]	0.17
Heat at room temperature (20°C)	0.04-0.07

Both energy and exergy efficiencies are defined as the ratio between useful generation and used energy and exergy. The Coefficient of Performance (COP) of heat pump is the ratio of heat production to used electricity.

Sankey diagram

Schmidt [11] reviewed the importance in decision making and public policy. Sankey diagrams are the tools for indicating the flows in both energy and exergy from primary energy source to the end use. Left side of diagram shows incoming flows of primary energy, the middle part contains the conversion and transmission processes, the right side presents the end users, the energy losses go from up to down, while the exergy destructions disappear. The nodes indicated processes or distribution grids. The width of flow represented the amount of energy/exergy. Different colour represented different type of incoming and outgoing flows.

Data and assumptions

In this analysis the data are mainly from Statistics Sweden and the Swedish Energy Agency. In the Swedish statistics, the biomass energy flows are based on LHV, the value for exergy is not accurate since the precise moisture contents are hardly to determine for biomass and municipal waste. In this study the exergy factor of biomass was assumed about 1.

When calculating exergy factors of space heating and domestic hot water usage, the temperatures of indoor and hot water are set as 20°C and 50°C, respectively. Two thirds for space heating and one third for hot water usage was assumed for heat usage for the household, but a higher share of space heating for service sector [12]. The characteristics of district heating for industry are uncertain, in this analysis the temperature used by industry was assumed to be 50 °C. The temperature of incoming flue gases to flue gas condensation was assumed to be 150 °C.

MAPPING FLOWS OF DISTRICT HEATING SYSTEM

Mapping district heating system in 2014

The energy and exergy flow diagrams for district heating in Sweden during 2014 are shown in Figure 1 and Figure 2, respectively. The latter exergy diagram shows also the exergy usage for space heating and domestic hot water, while the rest was destroyed during heating process.

In the left side fossil fuels, peat, recovered gases, biomass and municipal waste produced 83% of total heat production though fuel boilers and combined heat and power (CHP) with flue gas condensation (FGC). The excess heat from industries and the large heat pumps contributed 8% and 9% of total heat production, respectively, and the electric boilers accounted for 0.5%. The supply sources besides industrial excess heat are high quality energy, there are not much difference in energy and exergy content. About 90% of primary energy or exergy supply came from renewable energy, excess heat, and waste.

The production of heat has large difference between energy and exergy since delivered heat have low temperature which means low energy quality. The average energy and exergy efficiency for CHP including FGC were 94% and 50%, respectively. The average conversion efficiency of fuel boilers were 91% in energy and 16% in exergy. Most of exergy content in fuel boilers and CHPs are mostly destroyed in the conversion processes. The average COP of heat pump was 3 and the average exergy efficiency was 50%.

Heat was delivered to the end users through the district heating grid. The distribution heat losses were 12% of heat production. The percentages of total heat demands were 89% in space heating and domestic hot water usage in the household and service sector, 10% in industrial sector, and less than 1% for ground heating.

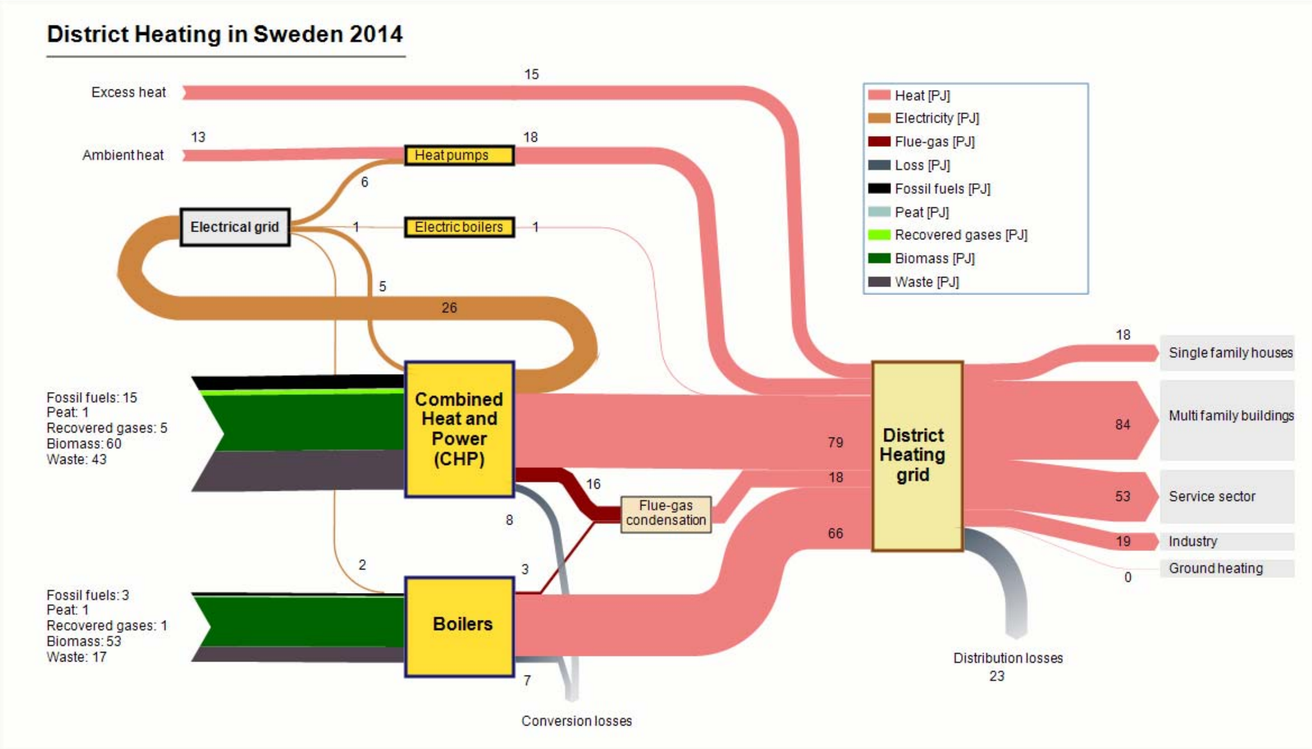

Figure 1 Sankey diagram of district heating, including corresponding part of electricity grid, in Sweden during 2014. Data source: [13].

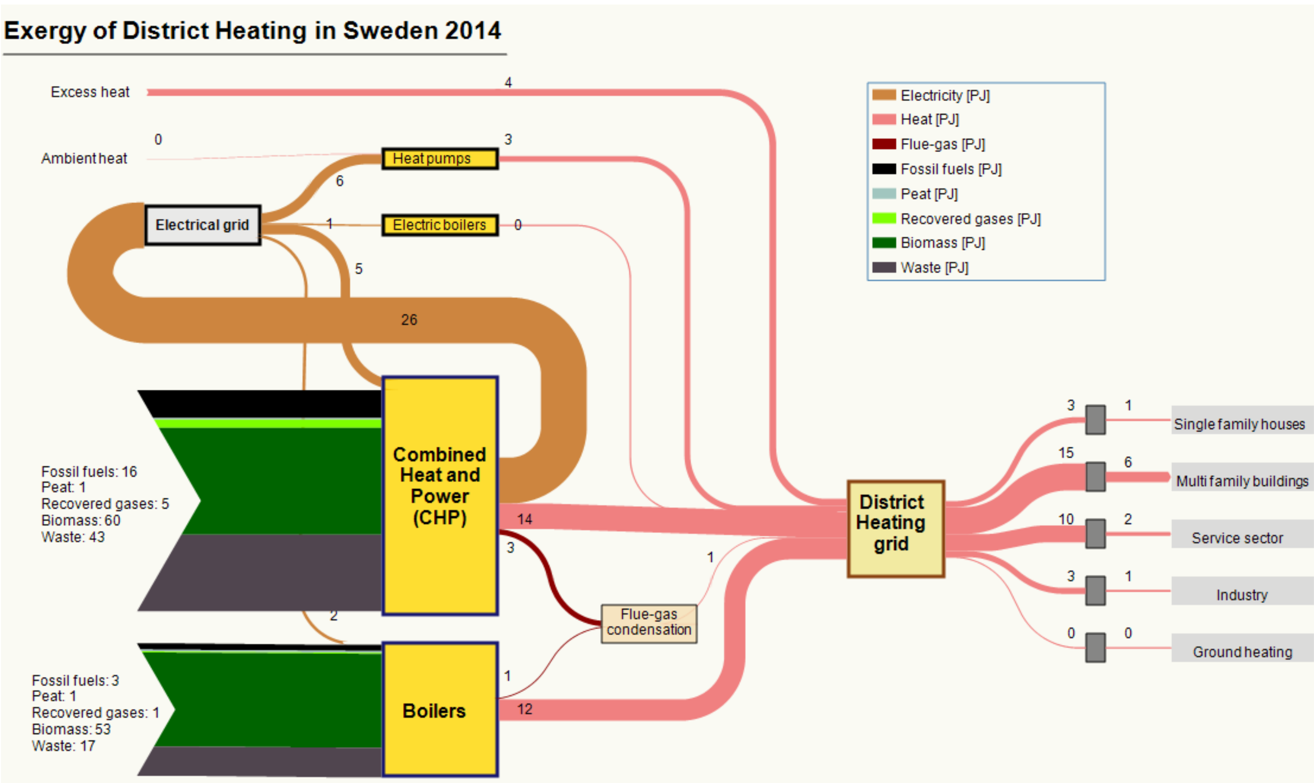

Figure 2 Sankey diagram of district heating, including corresponding part of electricity grid, based on exergy in Sweden during 2014. Data source:[13].

The right side of Sankey diagram based on exergy also showed exergy utilized in the end use. The left side of grey box was exergy from district heat grid to the end user, the right side of grey box was exergy finally used for space heating and hot water usage. Two thirds of incoming heat is destroyed by mixing hot water and cold water, and heat exchanger through substation and radiator.

The main differences between diagrams based on energy and exergy are the heat production and utilization, since the heat with lower temperature is low quality energy, this makes great exergy destruction in the district heating system.

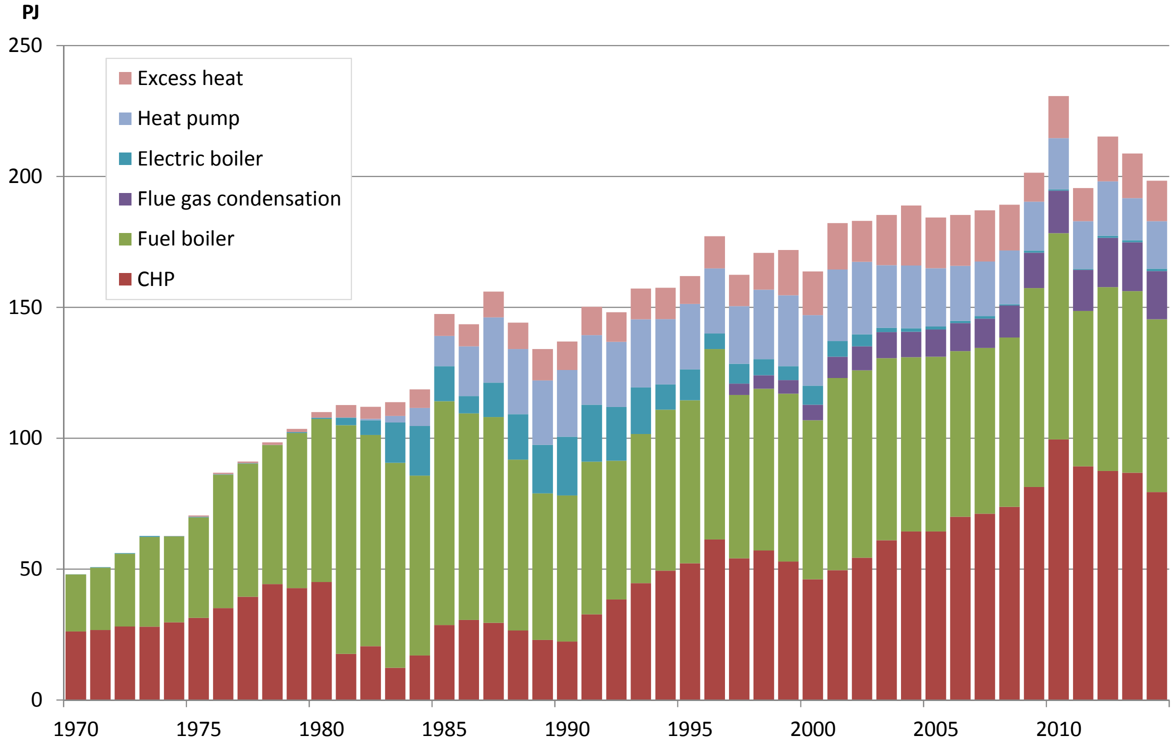

Figure 3 Heat produced per year by heat supply method during 1970-2014. Data source: Statistics Sweden and the Swedish Energy Agency.

Heat supplies

Figure 3 shows heat production from 1970 to 2014. The heat production was increased steadily with the average rate of 11% from 1970 to 1980 and 2% from 1980 to 2014. The peak of heat supplies appeared in 2010 due to a very cold winter.

CHP and fuel boilers dominate in heat supply. Almost all heat productions were from CHPs and fuel boilers during 1970s and early 1980s, and now one forth came from large heat pump, electric boiler and industrial excess heat. The heat supply became more diversified.

In 1981, more than half of heat production from oil fuel CHP plant was reduced due to the second oil crisis and commissioning of new nuclear power stations. In the early 1990s, the biofuels started to play an important role in district heating. The primary energy input started to transfer from fossil fuels to biomass including waste. Investments of biofuel based CHP have good economic benefit since the green certificates for renewable electricity were introduced in 2003, the production from CHP increased steadily until 2011, then the development is stagnating. Several cities produced heat from waste incineration plants as base loads, since the landfilling of combustible waste and organic waste were prohibited from 2002 and 2005, respectively.

Flue gas condensation is a method for increasing the efficiency of heat utilisation of a CHP or boiler plant by partially condensing flue gas vapour at low temperature to recover latent heat. In Sweden, Fagersta became the first to install FGC in 1980 to save energy and reduce emission. However, the national district heating statistics included FGC firstly from 1997. Today this technology is widely used in the Swedish biomass boilers and CHPs.

Several large-scale electric boilers and heat pumps were installed for district heating during the 1980s, since a national electricity surplus from new nuclear power stations became higher than the electricity demand increase and need to be absorbed within the country [14].

Industrial excess heat is mainly available from energy intensive industries, such as pulp and paper industry, steel industry, and chemical industry. In this study, the temperature of industrial excess heat is assumed to be 100 °C for the exergy analysis.

Table 2 shows the average energy and exergy efficiencies since 1997 in Sweden. The efficiency of CHP includes electricity production and heat from FGC. The efficiency of boilers also included heat from FGC. The energy efficiencies are much higher than exergy efficiencies. Among them, the average energy efficiency is between 90% and 98%. The heat pumps have highest exergy efficiency, then CHPs. Both types of boilers have lowest exergy efficiency. However, the electricity used in heat pump is secondary energy resource, the amount of the primary energy source will be degraded in order to produce electricity.

Table 2 The average energy and exergy efficiencies of CHPs, fuel and electric boilers and heat pumps in Sweden.

Supplier	**Energy efficiency**	**Exergy efficiency**
CHP	92%	34%
Fuel boiler	90%	15%
Electric boiler	98%	17%
Heat pump	3.3 (COP)	56%

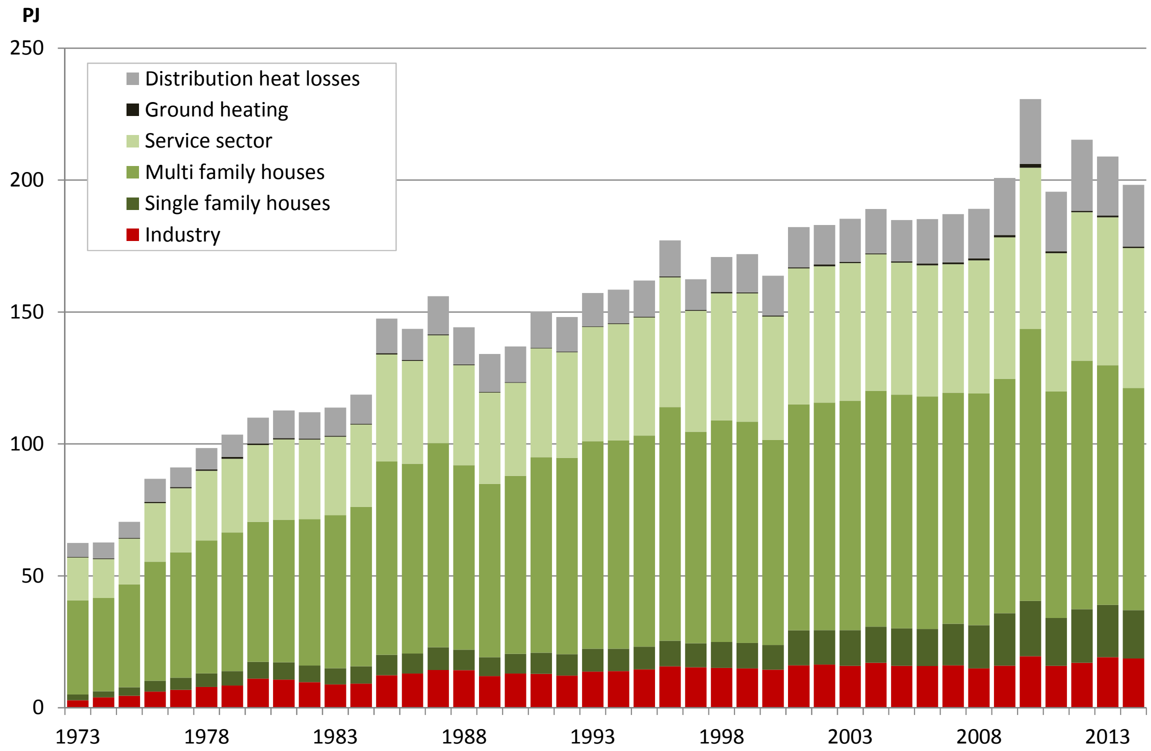

Figure 4 Heat demand by end user and distribution heat losses per year during 1973-2014. Data source: Swedish Statistics and Swedish energy Agency.

Distribution grid and Heat demands

The distribution heat losses were rising from 9% in 1970 to 12% in 2014 of total heat production with the increase of average linear heat density. The linear heat density is defined as the ratio between annual heat quantities utilised by customers to route length for the pair of pipes (normally half the pipe length) [12]. More and more single family houses were connected to the district heating grids, as shown in Figure 4, this caused the increase of the linear heat density.

In 2014, the exergy lost and destroyed in the district heating grid was 12% of total heat based on exergy supplied, the usage of space heating and hot water was about 30% of exergy of total heat delivered to building, the remaining exergy was destroyed.

About 10% of total heat usage was delivered to the industrial sector for space heating, hot water and low temperature processes with temperatures less than 100 °C. At present the district heating are more or less used for space heating and domestic hot water in Sweden.

DISCUSSION

Sweden aims to phase out fossil fuels in heating by 2020 and to have a sustainable and resource-efficient energy supply with zero net emissions of greenhouse gases by 2050. In order to achieve these goals, it should be to:

- use renewable energy and industrial excess heat with low quality energy source
- use biofuels including municipal waste
- improve technologies with more energy and exergy efficiency
- distribute heat with low temperature levels
- avoid mixing heat with high and lower temperature and use heat exchangers with long thermal lengths with less exergy destruction
- make policy in order to support these goals

Heat sources

At present the solar heating plants mainly contribute heat during summer. Large amounts of heat from industrial waste heat and waste incineration is enough to cover heat demand in many cities in Sweden, therefore, it is less attracted. However, several large-scale solar district heating systems with heat storage have been successful operated in Denmark [15]. In southern part of Sweden, the annual solar radiator and condition is similar to Denmark, it would be possible to install such systems when the economic is feasible in the future.

Most part of Sweden lacks geological suitable conditions for deep geothermal exploitation. Only one deep geothermal plant in Sweden has existed since 1984 and is still in operation to support about 20% of the heat demand to district heating system in Lund [16]. The usage of geothermal energy in Sweden is currently dominated by ground source heat pumps for space heating and domestic hot water for single family buildings.

In 2014, the excess heat for district heating was 15 PJ. In Sweden the theoretical volume of excess heat from all today’s industries have been estimated to between 22.3 PJ and 28.4 PJ, 70% of which come from energy-intensive industries, and low temperature excess heat from the premises are between 10.8 PJ and 18 PJ [17]. It is uncertain for supply and return temperatures in district heating, the estimated potential will be decreasing when the improvement of industrial process and increasing when transferring heat to the low temperature district heating systems. The estimated potential from excess heat can be covered about one fifth of today’s total district heat production.

Technology

- Heat supply

The average energy efficiency for CHPs and boilers are more than 90%, but heat pumps and CHPs have higher average exergy efficiency than boilers. Heat only plants should be transferred to bio-fuel based CHP plants. The share of CHPs in district heating production should be raised from current 41% to at least 80% up to 2030 [18], new CHPs will be invested and old CHPs will be modernised or replaced. At same time, the efficiency of bio-fuel CHP should be increased by the introduction of new technology with economic benefit.

The hybrid technology of CHP and absorption heat pump, first initiated in China, will be possible applied in Swedish biofuel CHP plants in order to improve heat capacity and efficiency [19, 20].

Heat from heat pump together with renewable energy, such as solar and geothermal energy, should be widely applied for single family house with no district heating in future, when surplus electricity from renewable sources will be available in Sweden.

- Low temperature grid

The authors [9] concluded that the two thirds of the current exergy content is lost in the heat distribution chain from heat supplied into networks to heat demands in building, in the future with low temperature grid it is possible to reduce to one third. The aim maybe achieved by lowing distribution temperatures, avoiding mixing heat with high and lower temperature, and using heat exchanger with long thermal lengths with less exergy destruction.

In the future, current buildings will be refurbished with lower heat demand. However, the temperature difference between supply and return will be reduced with future low exergy district heating system, and thus the radiator in the house would be kept same size.

Energy Policy

With the support of energy and climate policy, the Swedish district heating systems have been transformed towards more sustainability, from fossil dependent system into biomass dominant system. The use of biomass in heat production was inspired the investment subsides for construction of demonstration plants burning solid fuels from 1975 and 1980s, and further inspired through Solid Fuel Act with new boilers. The carbon tax was introduced in 1991. The local investment programme was funded during 1998 to 2002. A scheme for Tradable Renewable Electricity Certificate was introduced in 2003 in order to support electricity from renewable energy sources and peat, this lead fuel shifting in CHP plants from fossil fuels to biomass fuel.

Exergy is regarded as an essential tool in energy and environment policy making activates [21], and an exergy tax was introduced by Wall [22] in order to encourage the use of renewable resources and to improve the resource use. The differences between energy and exergy prices are small for almost all the energy sources except district heating. A good energy policy could speed up development towards efficient resource-saving and environmental friendly technology by ensuring exergy, rather than energy use.

CONCLUSION

In this paper, the flows based on both energy and exergy was mapped from primary energy source to customer usage with the aid of Sankey diagrams.

The diagrams viewed that more than half of exergy source was destroyed in CHP, even worse in boiler. In the current Swedish district heating system the most exergy efficiency methods is heat pump.

The utilization of renewable energy resource is high since biomass plays an important role in Sweden.

Future district heating systems with low distribution temperatures should use more low quality renewable energy and excess heat. It will be fossil fuel independent district heating system. CHPs and heat pumps in the aid of renewable energy will be possible dominant in future heat market.

REFERENCES

[1] Swedish Energy Agency, Energistatistik för småhus,flerbostadshus och lokaler 2014 (Summary of energy statistics for dwellings and non-residential premises for 2014), Eskilstuna, Sweden, 2015.

[2] G. Wall, "Exergy use in the Swedish society 1994," in International conference on thermodynamic analysis and improvement of energy systems, Beijing, China, 1997.

[3] G. Wall, E. Sciubba, and V. Naso, "Exergy use in the Italian society," Energy, vol. 19, no. 12, pp. 1267-1274, 12, 1994.

[4] M. Gong, and G. Wall, "On exergy and sustainable development—Part 2: Indicators and methods," Exergy, An International Journal, vol. 1, no. 4, pp. 217-233, 2001.

[5] B. Chen, G. Q. Chen, and Z. F. Yang, "Exergy-based resource accounting for China," Ecological Modelling, vol. 196, no. 3–4, pp. 313-328, 7/25/, 2006.

[6] K. Soundararajan, H. K. Ho, and B. Su, "Sankey diagram framework for energy and exergy flows," Applied Energy, vol. 136, no. 0, pp. 1035-1042, 12/31, 2014.

[7] M. Gong, "Exergy analysis of a pulp and paper mill," International Journal of Energy Research, vol. 29, no. 1, pp. 79-93, Jan, 2005.

[8] G. Wall, and M. Gong, "On exergy and sustainable development—Part 1: Conditions and concepts," Exergy, An International Journal, vol. 1, no. 3, pp. 128-145, 2001.

[9] M. Gong, and S. Werner, "Exergy analysis of network temperature levels in Swedish and Danish district heating systems," Renewable Energy, vol. 84, pp. 106-113, 12, 2015.

[10] I. S. Ertesvåg, and M. Mielnik, "Exergy analysis of the Norwegian society," Energy, vol. 25, no. 10, pp. 957-973, 10, 2000.

[11] M. Schmidt, "The Sankey Diagram in Energy and Material Flow Management," Journal of Industrial Ecology, vol. 12, pp. 82-94, 2008.

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

[13] Swedish Energy Agency, and Statistics Sweden, El-, gas- och fjärrvärmeförsörjningen 2014 (Electricity supply, district heating and supply of natural gas 2014), SCB, Sweden, 2015.

[14] A. Helge, P. Ingvarsson, U. Persson, and S. Werner, "On the use of surplus electricity in district heating systems," in The 14th International Symposium on District Heating and Cooling, Stockholm, Sweden, 2014.

[15] S. Furbo, J. Fan, B. Perers, W. Kong, D. Trier, and N. From, "Testing, Development and Demonstration of Large Scale Solar District Heating Systems," Energy Procedia, vol. 70, pp. 568-573, 5, 2015.

[16] S. Gehlin, O. Andersson, L. Bjelm, P.-G. Alm, and J.-E. Rosberg, "Country Update for Sweden," in Proceedings World Geothermal Congress 2015, Melbourne, Australia, 2015.

[17] L.-Å. Cronholm, S. Grönkvist, and M. Saxe, Spillvärme från industrier och värmeåtervinning från lokaler (Waste heat from industries and heat recovery from the premises), Stockholm, Sweden: Svensk Fjärrvärme AB, Sweden, 2009.

[18] CODE2, D5.1 Cogeneration roadmap member state: Sweden, 2014.

[19] M. Gong, and S. Werner, District heating research in China, Svensk Fjärrvärme AB, Sweden: Svensk Fjärrvärme AB, 2014.

[20] Y. Li, L. Fu, S. Zhang, Y. Jiang, and Z. Xiling, "A new type of district heating method with co-generation based on absorption heat exchange (co-ah cycle)," Energy Conversion and Management, vol. 52, no. 2, pp. 1200-1207, 2011.

[21] I. Dincer, "The role of exergy in energy policy making," Energy Policy, vol. 30, no. 2, pp. 137-149, 1, 2002.

[22] G. Wall, "Exergy, ecology and democracy - concepts of a vital society or a proposal for an exergy tax," in International conference on energy systems and ecology, Krakow, Poland, 1993, pp. 111-121.