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Status Report on District Heating Systems in IEA Countries

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Content

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Abstract

The study presents an evaluation of district heating systems in IEA countries based on characteristic parameters such as the annual heat losses, the linear heat density in MWh/(a m) (where 1 m refers to the length of the pipeline), and the connection load. Data are available and presented for Austria, Denmark, Finland, Germany, and Switzerland covering a total of 800 district heating systems. An additional assessment is performed for the case of Switzerland where detailed information on 52 systems was collected and evaluated.

The evaluation reveals a strong dependence of the heat losses on the linear heat density. Thus the recommendation of a minimum linear heat density is confirmed. For the minimum value of 1.8 MWh/(a m) as proposed by QM Holzheiwerke in Switzerland, Germany, and Austria, typical heat losses of 13 % are achieved compared to the target value of QM of 10 %.

Although the linear heat density is confirmed to be an important parameter, the survey also shows that the heat losses are distributed over a range of more than a factor of three at a given linear heat density. Consequently, additional parameters also influence the heat distribution losses according to the following trends:

- The pipe diameter strongly affects the capital costs and the heat distribution losses. Application of pipes with significantly larger diameters than necessary to avoid cavitation pitting leads to strongly increased capital costs and heat distribution losses.
- Additional parameters like the network layout, the temperature spread, the temperature level, the insulation class, and the ratio between the operation hours of the district heating and the full load hours of the heat consumers also affect the heat losses and costs.
- While heat production plants exhibit strong economy of scale, the heat distribution is related to diseconomy of scale, which is not reflected in the linear heat density. Consequently, large district heating systems as, e.g. in Denmark, are economically feasible thanks to the economy of scale in the CHP, however related to higher distribution losses when compared to smaller systems as, e.g. common in Switzerland.

A detailed analysis of individual line sections for a selected number of district heating systems in Switzerland reveals that 80 % of the line sections are oversized mostly by one or two and maximally up to four nominal diameters. A theoretical comparison between real designs with a design including pipelines of minimum diameter in each section exhibits a potential to reduce the heat distribution losses of up to 20 % and the heat distribution costs up to 30 %.

Since the network layout is not reflected in the linear heat density but also highly relevant for the total cost, a method is introduced which enables a qualitative assessment of the local distribution of the heat consumers and an assessment of potential locations for the heat production site.

Keywords: District heating, linear heat density, heat distribution losses, heat distribution costs, pipe diameter.

1 Introduction

1.1 Relevance of district heating

The heat distribution by district heating (DH) networks enables the increased use of renewable energy carriers such as wood and ambient heat as well as waste heat. The introduction of single large heat generators may additionally offer benefits regarding cost, comfort, and air quality compared with small, decentralised plants. Hence the main advantages of district heating (and even emphasised for district heating and cooling) can be characterised as follows [1]:

- *Economy of scope* providing economical advantages because of the joint production of heat with related products in processes such as combined heat and power (CHP), waste incineration, industrial production and recycled heat.
- *Economy of scale* in the heat production (unlike the district heating system) due to lower specific investment and operation costs with increasing size for complex technologies such as biomass handling and combustion and more importantly for thermal cycles in power production as commonly applied in CHP applications.
- *Flexibility* due to the possible contribution of more than one energy source (e.g. waste heat, biomass, and solar energy) to heat production and by optimising the yield of different products such as electricity production depending on the current feed-in tariff.
- The *local environmental impact* especially with respect to air pollution can be reduced when replacing decentralised boilers for thermal heating by one large heating plant with lower emissions thanks to improved combustion, boiler operation, and the application of flue-gas cleaning for removal of particles and if necessary gaseous pollutants.

The advantages of district heating are however accompanied by additional costs for the district heating networks and heat losses in the network operation. As a consequence, district heating is only worthwhile for applications, where the advantages exceed the drawbacks which is typically the case in areas with a relevant specific heat demand.

Besides the distribution of directly useable heat, it may also be interesting to distribute heat at lower temperatures of 6°C to 20°C to be used in decentralised heat pumps. The use of waste heat from cooling units is thus put forward as well as the seasonal storage of waste heat from buildings in the ground and its extraction in winter. In order to reduce the primary energy use at defined useful energy demand, the reduction of exergy input needs to be addressed. The terms “LowEx district heating” and “multilevel district heating” are used accordingly [2]. The case of water distribution for heat removal is called “district cooling”, whereas the combination of heating and cooling is called “district heating and cooling”. The further interconnection between heat and cooling consumers thanks to networks with combined use offers additional potential to save primary energy. The majority of today’s networks however only covers heat supply and is operated at supply temperatures of more than 60°C for direct heat use only.

District heating is of high importance in Europe with a particularly significant share in the northern countries. In Europe (EU-27), 75 million customers are connected to a DH network whose heat supply covers 550 TWh or 10% of the total and 16% of the household annual heat demand and which generates a turnover of 19 million euro per year [3]. The technologies of heat production differ between the countries. Large areas in Europe are dominated by fossil-thermal power plants and by combined heat and power (CHP) plants. The share of energy wood has however highly increased over the past decades. In Germany, the majority of the 14% of the households connected to district heating are supplied with heat from large CHP plants of which 90% are fuelled by natural gas or coal and only 10% by renewable energy sources. In Poland, district heating supplies 50% of the heat demand and is mostly produced by coal. In Denmark, the share of district heating amounts to 50% to 60% and is supplied by biomass, waste, coal, and natural gas [3], [4]. Efforts are taken to supply the district heating networks entirely by renewable sources until 2060 [5]. In Austria, DH covers 20% of the residential heating demand and is mainly supplied by natural gas (44%) and biomass (38%) [6]. In Switzerland, the share of district heating is declared to amount to 2%, but the statistics only cover large-scale plants and hence underestimate the effective importance [7].

1.2 Main characteristics and parameters

An important parameter characterising efficiency and profitability of district heating networks is the linear heat density, i.e. the ratio between the annual heat demand and the pipeline length [1], [8]. In order to evaluate the suitability of an area to be connected to district heating in the case of large projects, the heat demand density is another important parameter, i.e. the ratio between the annual heat consumption of all costumers in the area and its surface area. On the one hand, recommendations on the maximum flow velocities dependent on the diameter to prevent cavitation pitting and inadmissible noise emissions provide a basis for the network design. On the other hand, recommendations on specific pressure drops are given in order to anticipate oversizing. The comparison of the profitability is finally based on the resulting specific losses and the specific cost of the heat distribution.

While the mentioned parameters are easily determined for current situations, numerous trends in the energy market as well as the consumer side need to be taken into account for the evaluation of future developments in district heating. The continuous improvement of building efficiency for instance is a factor that may lead to reduced linear heat density and hence reduced attractiveness of district heating. Conversely, the share of domestic hot water supply in the energy consumption is continuously increasing which offers advantages with reference to the seasonal load. With increasing electricity demand with respect to increasing building efficiency as well as to increasing cooling demand, the rapport between the electricity and heat demands decreases on the consumer side. In Germany, a ratio between heat and power in buildings of 4:1 is assumed and forecasted to decrease to 2:1 by the year 2050 [9]. At given boundary conditions and hence predefined network and linear heat density, a sensitivity analysis illustrates that the profitability of the heat distribution increases with increasing temperature spread and decreasing pipe diameters [10]. Since only little systematic information on the sizing and on the characteristics of existing district heating networks is on hand, it is evaluated in the present work.

1.3 Aim

The aim of the present study is to evaluate typical district heating systems in IEA countries based on characteristic values such as the annual heat losses, the linear heat density in MWh/(a m) (where 1 m refers to the pipeline length), and the connection load. In addition, detailed information on a selected number of district heating systems in Switzerland is analysed more closely in order to investigate the influence of additional design and operation parameters on the heat distribution losses. Particular attention is given to the pipe diameter as it strongly affects the capital costs and the heat distribution losses. Furthermore, the theoretical potential of heat loss reduction and minimisation of the total heat distribution costs by application of the most economic pipe diameter shall be assessed. As a basic assumption for this evaluation, the finding of an economic evaluation is considered stating that for typical situations, the minimum heat distribution costs are achieved by application of the smallest technically feasible diameter without cavitation pitting [10].

2 Data survey

For the data collection in IEA countries, the members of the IEA Bioenergy Task 32 were invited to participate by collecting available data from their country or by denoting respective contacts. For this reason, a questionnaire was prepared and distributed. Furthermore, the IEA Implementing Agreement on District Heating and Cooling including Combined Heat and Power (IEA-DHC, Task leader Andrej Jentsch) was invited to contribute and distribute the information among its members. The IEA-DHC assisted the survey by delivering literature on Germany. In parallel, a survey on electronically available statistical data was conducted. Table 1 shows a summary of the countries and contacts that provided data. In total, data from roughly 800 district heating systems in Austria, Denmark, Finland, Germany, and Switzerland are available for the evaluation.

Table 1 Data sources for district heating networks in IEA countries

Country	Contact	Info / Source
Austria	Franz Promitzer Alexandra Malik	QM-Holzheizwerke QM-Holzheizwerke
Denmark	Jesper Koch Internet	District Heating Association Statistical excel file
Finland	Internet	Statistical excel file
Germany	Sabine Hiendlmeyer Heiko Huther	C.A.R.M.E.N. Bericht AGFW-Hauptbericht
Switzerland	Stefan Thalmann	Survey on behalf of SFOE 2014 [11]
IEA-DHC	Andrej Jentsch (GER)	AGFW-Hauptbericht

In Switzerland, a specific data evaluation was performed in the framework of a project for the Swiss Federal Office of Energy (SFOE) [11]. For data collection purposes, a questionnaire was sent to contractors, operators, and design engineers of district heating networks. The considered networks operate since at least one year and fulfil one of the following conditions:

- DH network of at least 10 MW or
- DH network with a load between 400 kW and 10 MW put into operation or extended by at least 30% in the last 10 years.

The selection was done considering the members of the Swiss district heating association (Verband Fernwärme Schweiz VFS) as well as own contacts, though the analysis was carried out anonymously. In the case of contractors with a large number of networks, the networks were selected by statistical means in order to prevent a selection based on technical criteria. In order to consider lines made of plastic jacket pipes, design engineers were also included in the evaluation. This way, data of 52 plants owned by 22 companies were collected.

3 Efficiency of district heating systems

3.1 Evaluation of different countries

3.1.1 Austria

Information on Austria is derived from the database of the quality management system QM Holzheizwerke [8] which was developed in Switzerland, Austria, and Germany to ensure the quality in design and planning of biomass-fired heating plants. In Austria, the use of QM Holzheizwerke is compulsory for biomass boilers with a nominal heat output greater than 400 kW or in case of a total pipeline length of the DH network of more than 1000 m. Within this process, data are recorded in a database. The data presented here are based on design values and operating data of biomass-fired district heating systems that have requested governmental support in Austria since 2006. There are about 600 plants in the database with usable operational data for about 107 plants (Figure 1). Amongst the 107 plants are 34 plants built between 2006 and 2009. The remaining 73 plants were built between 1985 and 2005. The operating data represents the year 2010 [12].

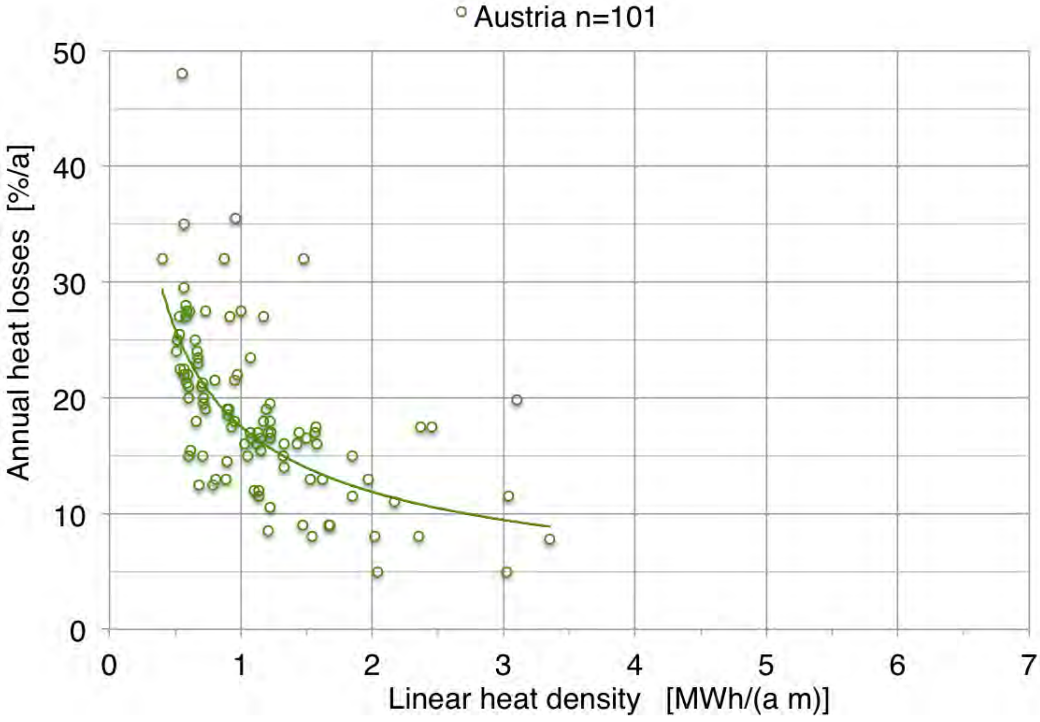

Figure 1 Heat distribution losses as function of the linear heat density of 101 biomass-fired district heating plants in Austria [12].

3.1.2 Denmark

The Danish District Heating Association (Dansk Fjernvarme) was founded in 1957 aiming at organising Danish district heating companies, facilitating cooperation between these members, and promoting their interests towards authorities and other organisations. It has slightly more than 400 members all over Denmark [13]. 55 are publicly owned district heating companies delivering around two thirds of all district heating whereas the others are predominantly consumer-owned cooperatives. Members supply 63% of Danish households (1.6 million) with district heating covering around half of the space heating demand in all buildings. 52% of delivered district heating is denoted as sustainable heat. The Danish District Heating Association provides statistical data on district heating on their website including an excel file with all main data. Based on the data in this file, the linear heat density and the annual heat losses for about 180 district heating networks in Denmark 2013 were analysed and are displayed in Figure 2 [13].

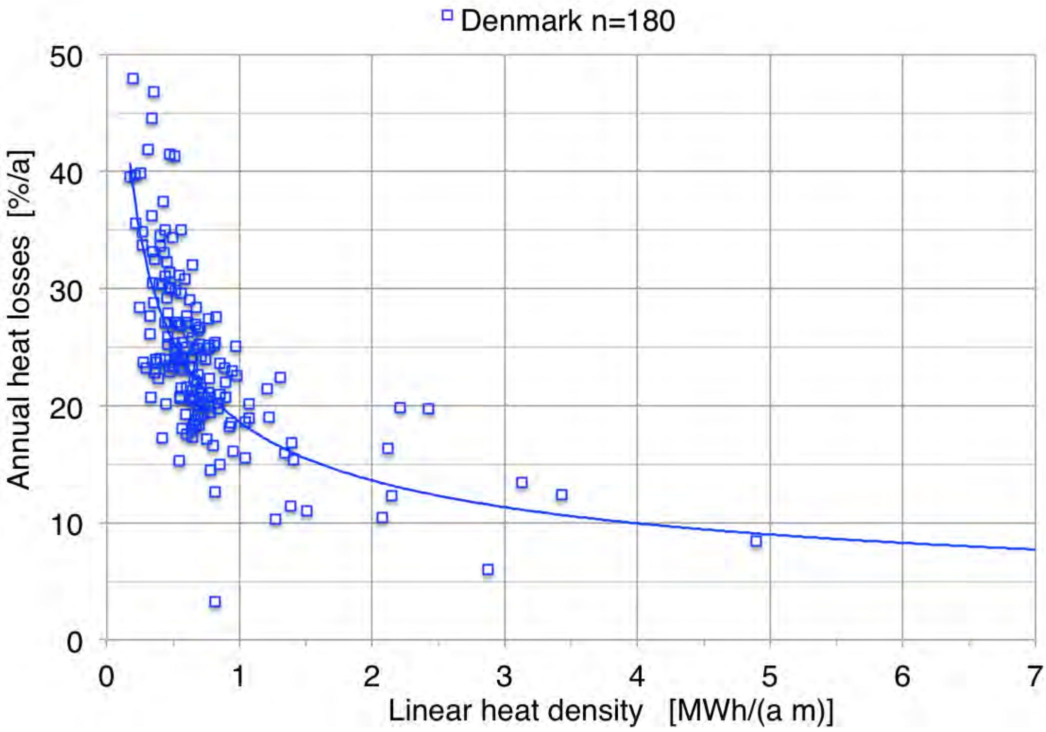

Figure 2 Heat distribution losses as function of the linear heat density in Denmark [13].
Data basis: 180 plants.

3.1.3 Finland

District heating is the most common form of heating in Finland and has been implemented since the early 1950s. It is available in almost all towns and population centres. About 2.6 million persons in Finland live in houses heated by district heat. District heating accounts for almost 50% of the total heating market [14]. Almost 95% of apartment buildings and most public and commercial buildings are connected to the DH network. In single-family houses, 7 % of the heating energy originates from district heat. In the largest towns, the market share of district heating is more than 90 %. Most heat for district heating is produced by combined heat and power or waste heat from industrial processes. District heating fuels include natural gas, coal, peat, and increasingly wood and other renewable energy sources such as biogas. The Finnish district heating association (Energiateollisuus) provides statistical publications on district heating and a master data excel file on their website. Based on the data in this file, the linear heat density and the annual heat losses for about 170 DH networks in Finland in 2012 were analysed and are displayed in Figure 3 [14].

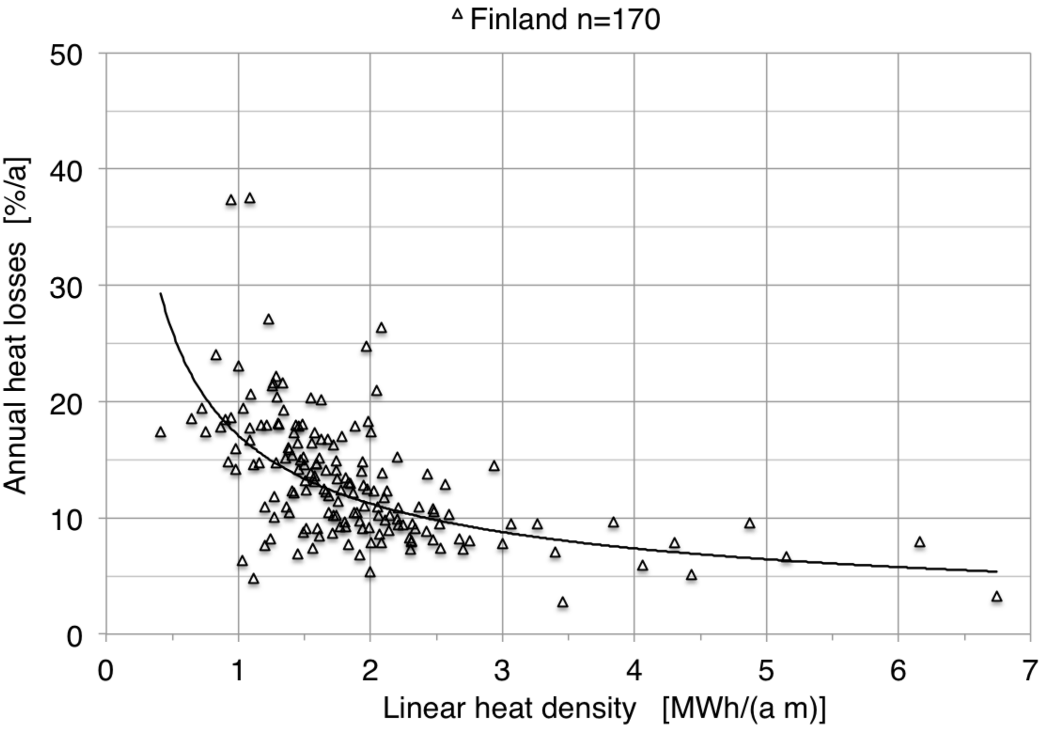

Figure 3 Heat distribution losses as function of the linear heat density in Finland [14]. Data basis: 170 plants.

3.1.4 Germany

The data for district heating systems in Germany are based on annual reports of 110 state-funded biomass-fired heating plants in Bavaria investigated in an evaluation by C.A.R.M.E.N. e.V. in 2009 [15]. Individual data from 330 reports are summarised in Figure 4. The reporting period covers the operating years from 1998 to 2008. The oldest of these heating plants went into operation in 1994. The net losses were calculated on the basis of figures provided by the operators and were not collected or measured. Thus reading errors, errors in the calorimeters or other inaccuracies may occur. The German district heating association (Fernwärmeverband Deutschland AGFW) additionally provided their main report 2011 [16]. Therefrom the data were taken for the different federal states (excluding Saarland) representing the average values of numerous plants.

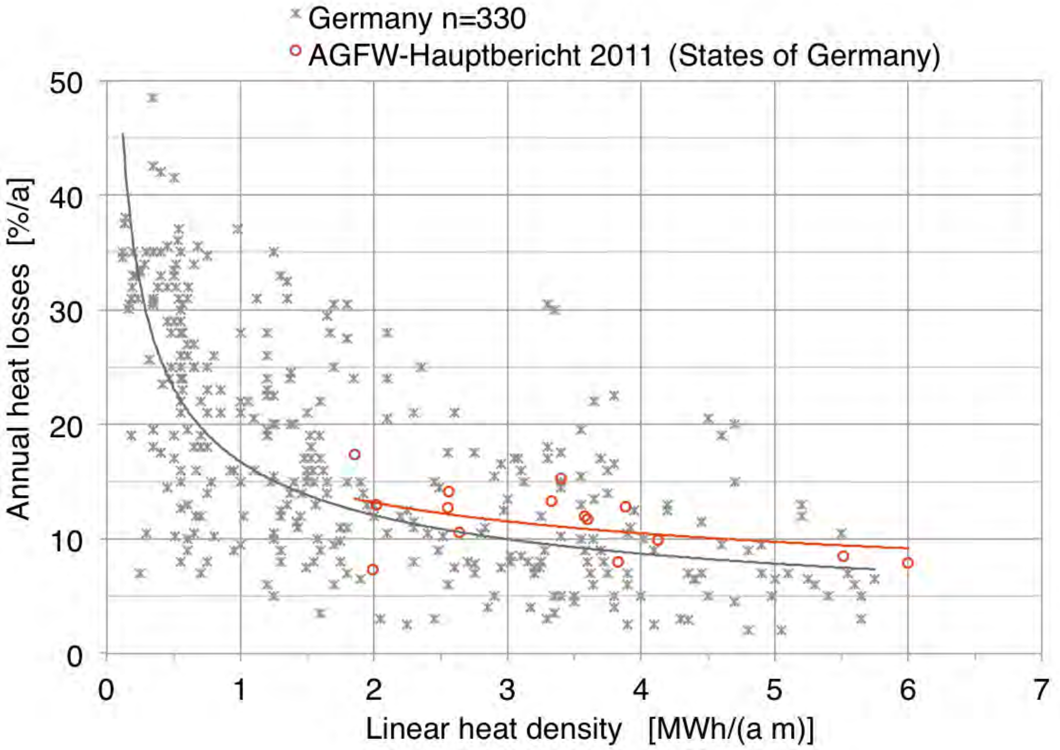

Figure 4 Heat distribution losses as function of the linear heat density in Germany. Data basis: 330 plants in Bavaria [15] and values for 15 German states (excluding Saarland) [16].

3.1.5 Switzerland

Figure 5 displays the annual heat losses as function of the linear heat density for 50 district heating systems evaluated in Switzerland [11]. In the graph, different heat sources are distinguished, i.e. furnace (biomass), CHP (municipal solid waste and biomass), heat pump, and heat recovery.

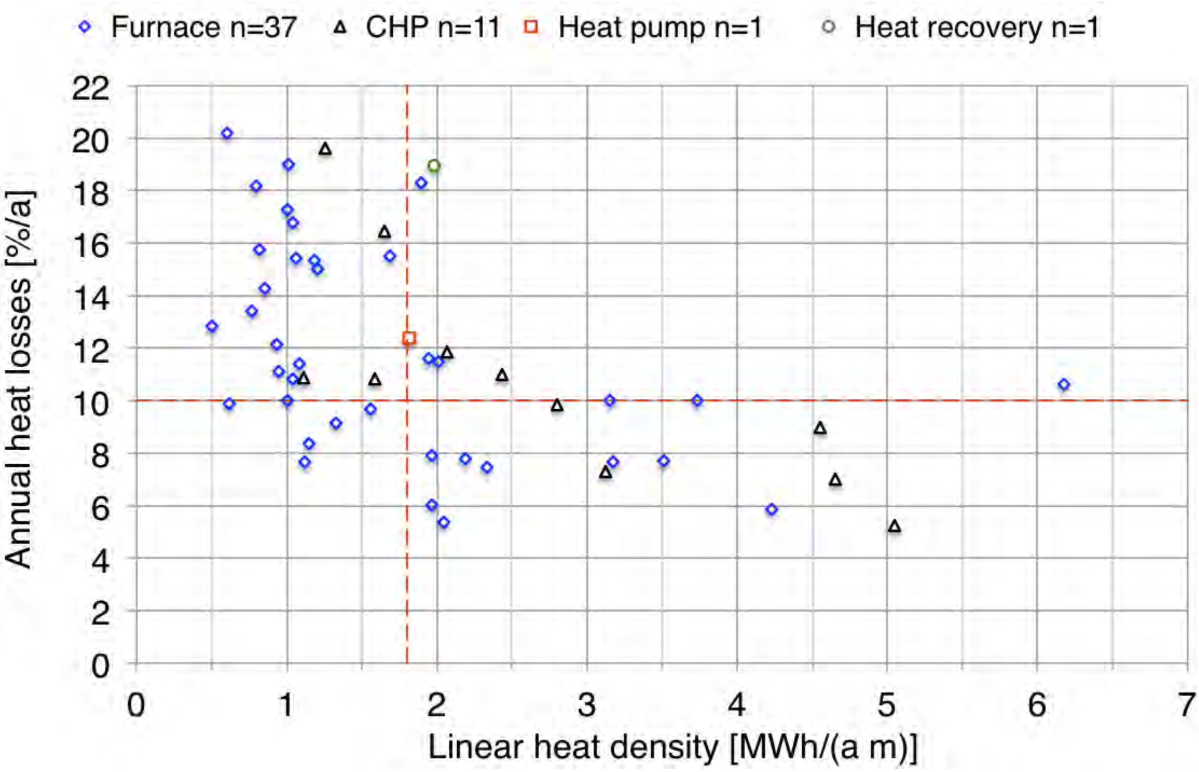

Figure 5 Heat distribution losses as function of the linear heat density for different heat production systems for 50 plants in Switzerland [11]. Dashed lines: target values as stated by QM Holzheizwerke [8] (data in the lower right quadrant comply with the target values).

3.2 Comparison of different countries

3.2.1 Influence of linear heat density

In Figure 6 the data from the five investigated countries are summarised. Figure 7 shows the trendline based on a potential fit for each individual country. Figure 8 summarises the results without distinction of the individual countries. For this data set, the following fit by a potential regression is introduced in the graph:

$$\text{Annual heat distribution losses in [\%/a]} = 17 \cdot (\text{linear heat density})^{-0.5}$$

According to the data represented by the correlation, the average annual heat losses at a linear heat density of 1.8 MWh/(a m) (which corresponds to the target value of QM [8] at final development) is approximately 13% which is higher than the target value for new district heating systems of 10% per year [8]. The value is however plausible for existing systems under operating conditions which might exhibit higher losses due to non-idealities in design and operation.

In all investigated countries, a clear and strong trend of decreasing annual heat losses with increasing linear heat density is found as expected by theoretical considerations [1], [10]. However, the evaluation also shows that for a given linear heat density the heat losses are distributed over a range of more than a factor three between the best documented system and the systems with the highest heat losses. Although this is true for all documented data, there are some specific factors to be considered:

- For a certain number of systems, heat losses significantly below the expected values are documented. This is valid, e.g. for one plant in Denmark with heat losses of less than 5 % for a low linear heat density of less than 1 MWh/(a m) according Figure 2. The worst systems at the same time exhibit heat losses larger by a factor of ten. For Germany, a less pronounced but still comparable situation is found with a relevant number of systems with very low heat losses (Figure 4). For Austria, Finland and Switzerland, the described trends are significantly less pronounced.
- Although a final assessment is not possible due to missing information on the systems, the exceptionally small heat losses are questionable, since they are barely achievable for typical temperature and operation conditions and only theoretically possible if several exceptional conditions are met at the same time. Very high heat losses, on the other hand, are possible, e.g. in case of low temperature spreads, weak insulation, or other negative parameters which however cannot be validated.
- Thus it is assumed that the documented data exhibit a relevant uncertainty. Nevertheless, the case study of Switzerland presented in chapter 4 enables a more detailed analysis of a limited number of individual data sets. This evaluation reveals that a relevant variation in the heat losses at constant linear heat density can be explained by the design and operating parameters according to the following trends:

  - – Oversizing of the pipeline by use of pipe diameters larger than the minimum diameter needed for fluid dynamic reasons can lead to significantly increased heat losses.

  - – A high ratio between the operation hours of the DH system and the full-load hours of the heat consumer (e.g. by summer operation for warm water only) can strongly increase the annual heat losses.

  - – Finally, the heat losses as well as the heat distribution costs exhibit a diseconomy of scale effect, since an increase in size of the DH system leads to higher heat losses and capital cost at constant linear heat density. This effect is not reflected in the linear heat density and thus assumed to be a potential reason for the relevant differences, e.g. between the documented district heating systems in Switzerland which have relatively small connection loads of typically 0.5 MW to 5 MW and the systems in Denmark with typically 5 MW to 200 MW and presented in Chapter 3.2.2.

- Upon considering additional parameters influencing the heat losses such as the diseconomy of scale, the trends are assessed to be fairly similar in all investigated countries.

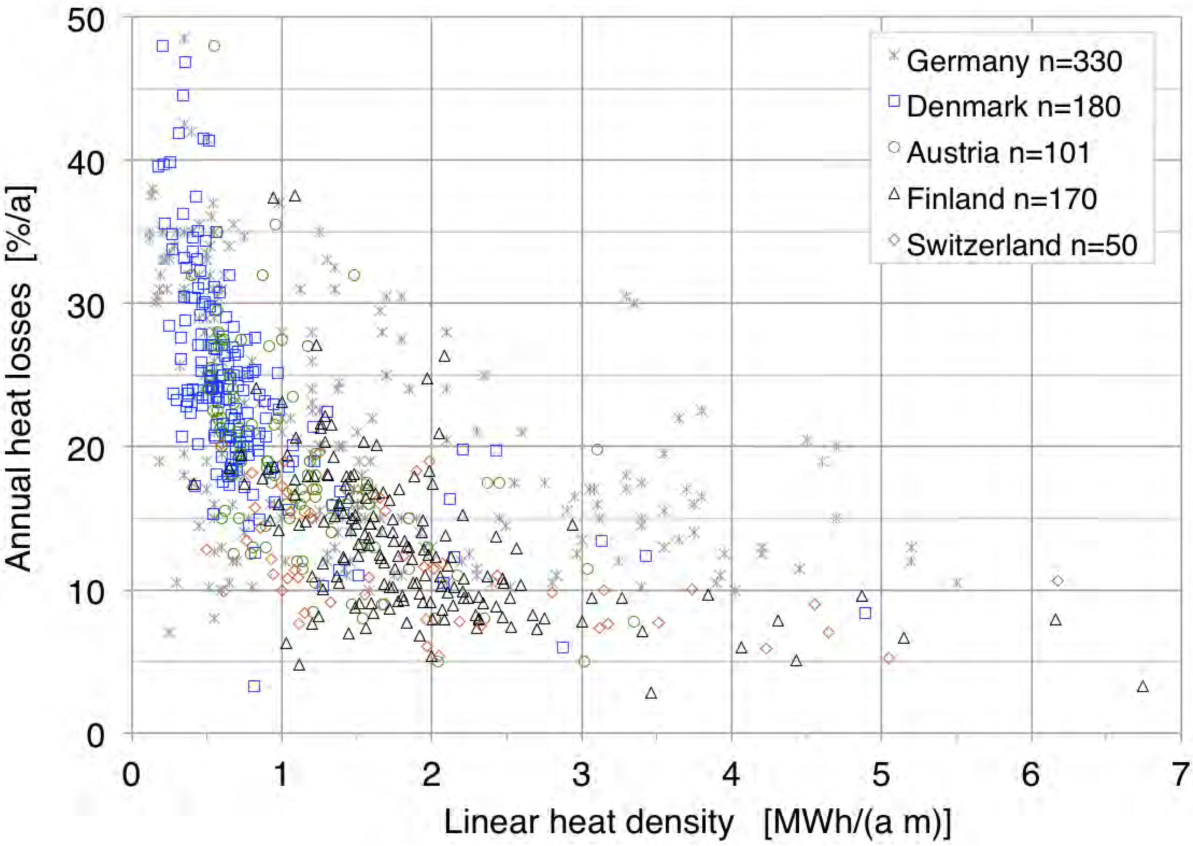

Figure 6 Heat distribution losses as function of the linear heat density for systems in Germany, Denmark, Austria, Finland and Switzerland. Data basis: between 50 and 330 plants per country.

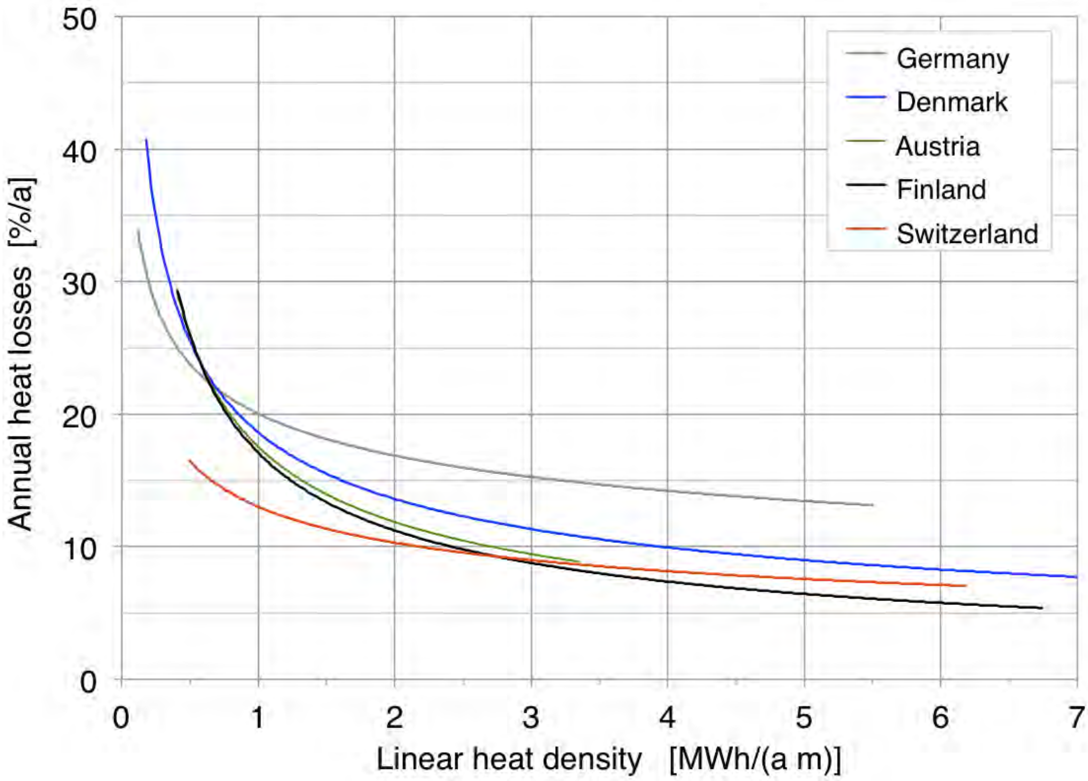

Figure 7 Heat distribution losses as function of the linear heat density for systems in Germany, Denmark, Austria, Finland and Switzerland. Only the potential trendlines are displayed.

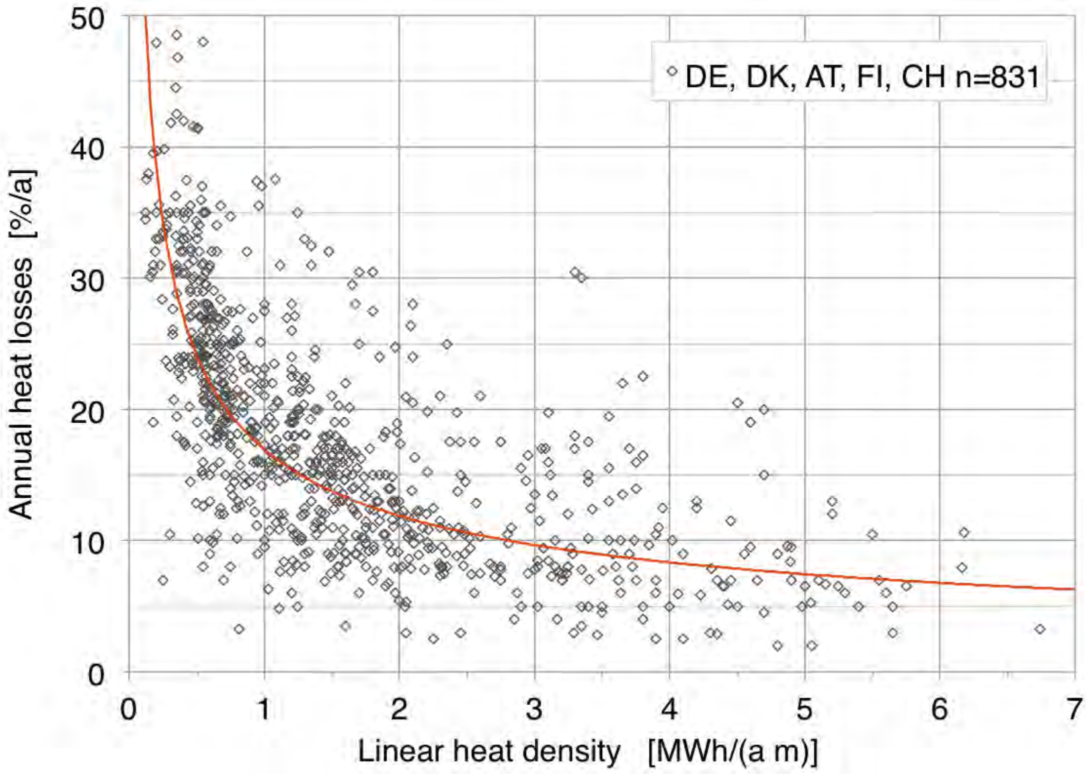

Figure 8 Heat distribution losses as function of the linear heat density. The district heating networks in Germany, Denmark, Austria, Finland and Switzerland were summarised in a potential trendline. Data basis: 831 plants.

3.2.2 Influence of connection load

For Denmark, Finland, and Switzerland information on the connection load is available. Figure 9 show the annual heat distribution losses as function of the connection load. Figure 10 shows the same date but in addition with a distinction of different ranges of the linear heat density introduced as parameter. The results indicate the following trends:

The majority of the investigated district heating systems in Switzerland is smaller than 5 MW with a relevant number of systems even smaller than 1 MW, while systems greater than 100 MW are scarce. Although the investigated networks cover only a small number of all DH systems in Switzerland, this distribution reflects the situation reasonably as the subset of plants even considers a disproportionally high number of large systems. The majority of the documented district heating systems in Denmark and Finland are larger than 10 MW with a relevant number of systems being larger than 100 MW and with rarely any system smaller than 2 MW. The comparison also illustrates that district heating systems in Denmark exhibit in average higher annual heat losses than in Switzerland and Finland at comparable connection load. One possible reason for this difference lies in the fact that systems in Denmark generally have significantly lower line heat densities as illustrated by Figure 6, Figure 10, Figure 11, and Figure 12. The significantly lower losses in Switzerland, however, are at least partially explicable by connection loads that are more than ten times smaller.

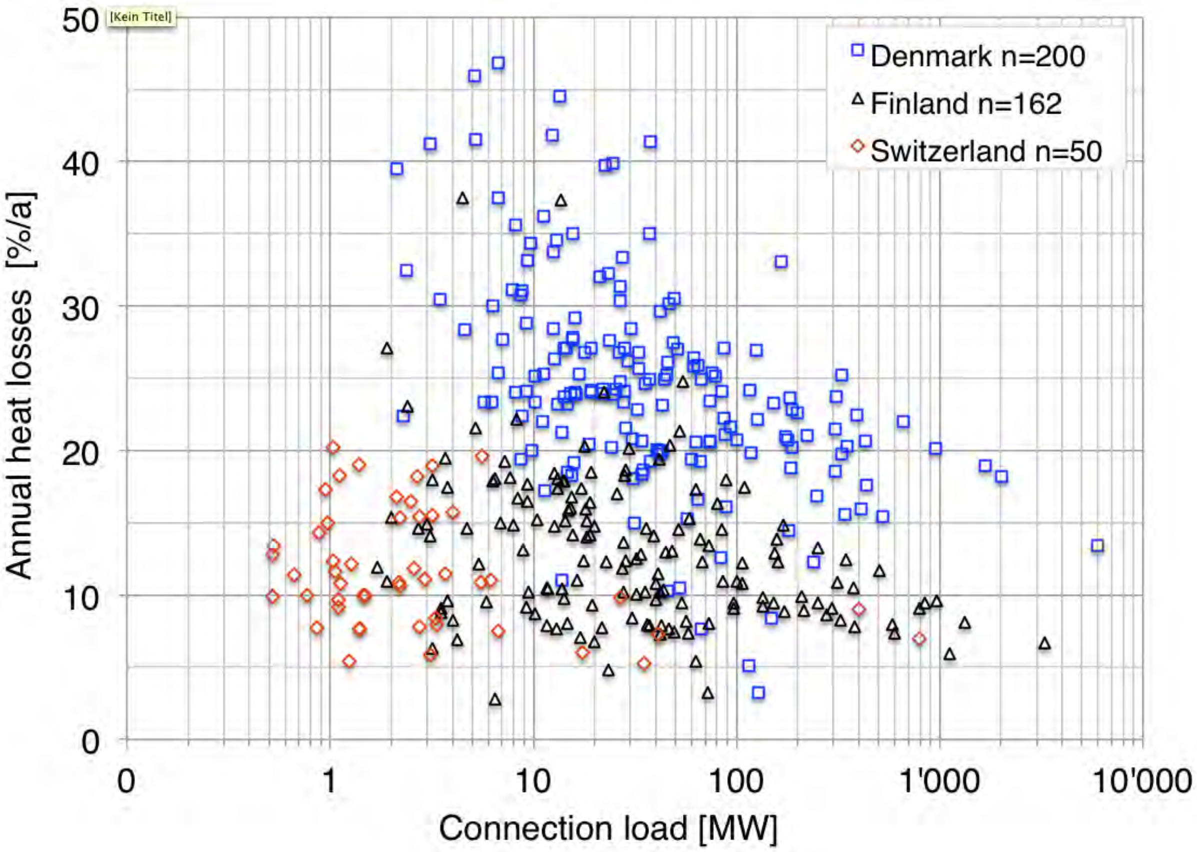

Figure 9 Heat distribution losses as function of the connection load. The district heating networks in Germany, Denmark, Austria, Finland and Switzerland were summarised in one potential trendline. Data basis: 831 plants.

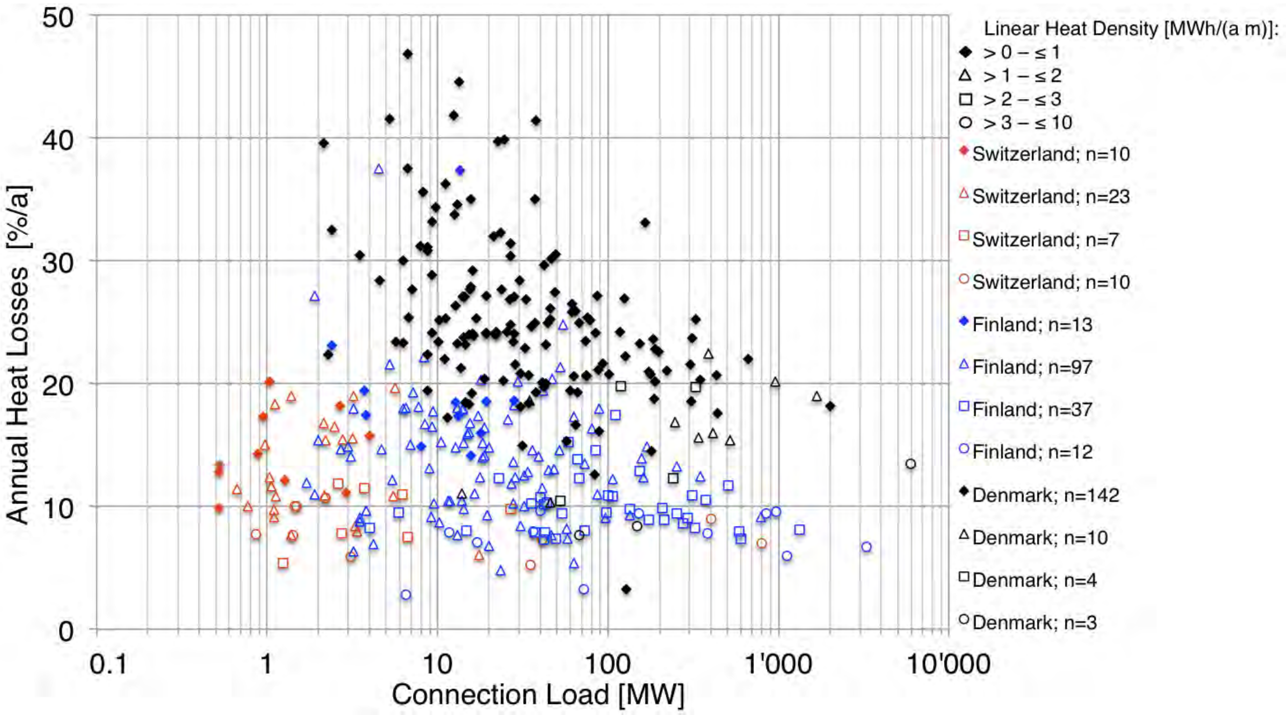

Figure 10 Linear heat density as function of the connection load for district heating networks in Denmark, Finland and Switzerland with additional distinction of the linear heat density introduced as parameter. Data basis: 412 plants.

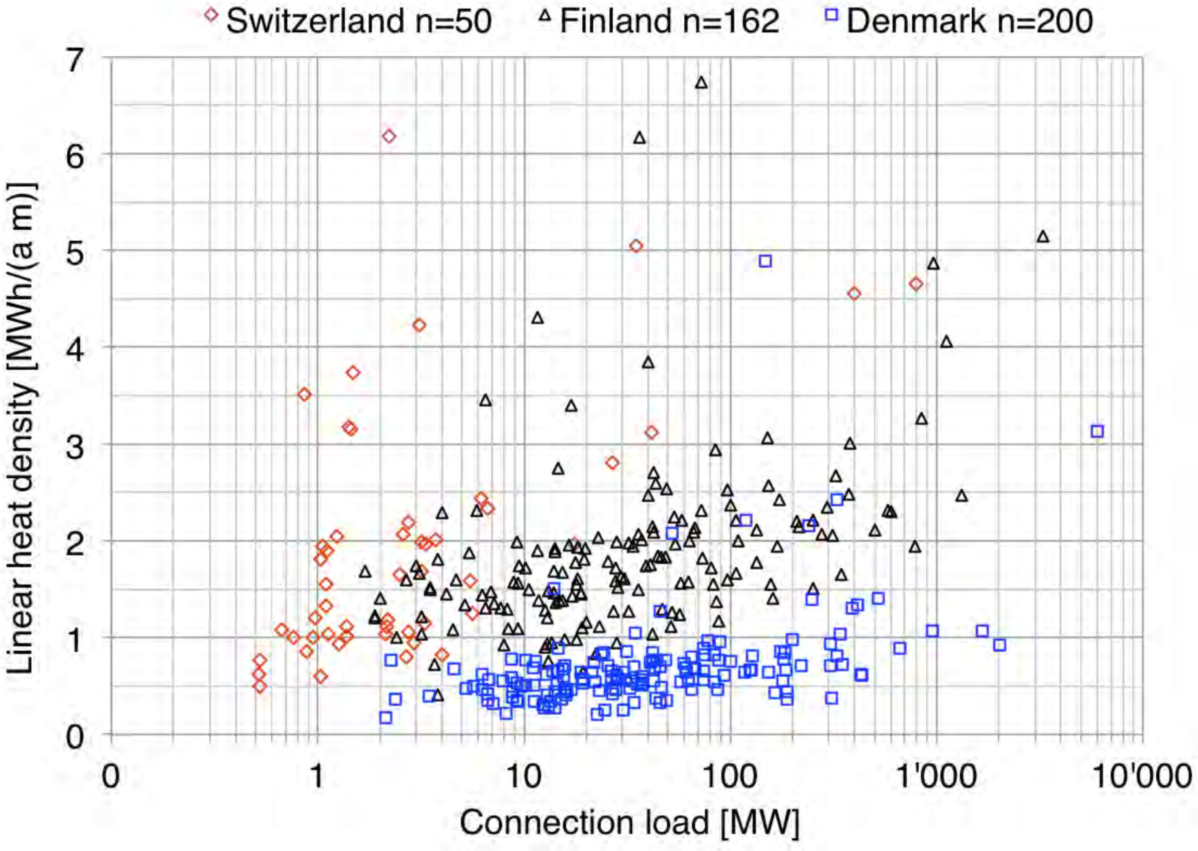

Figure 11 Linear heat density as function of the connection load for district heating networks in Denmark, Finland and Switzerland. Data basis: 412 plants.

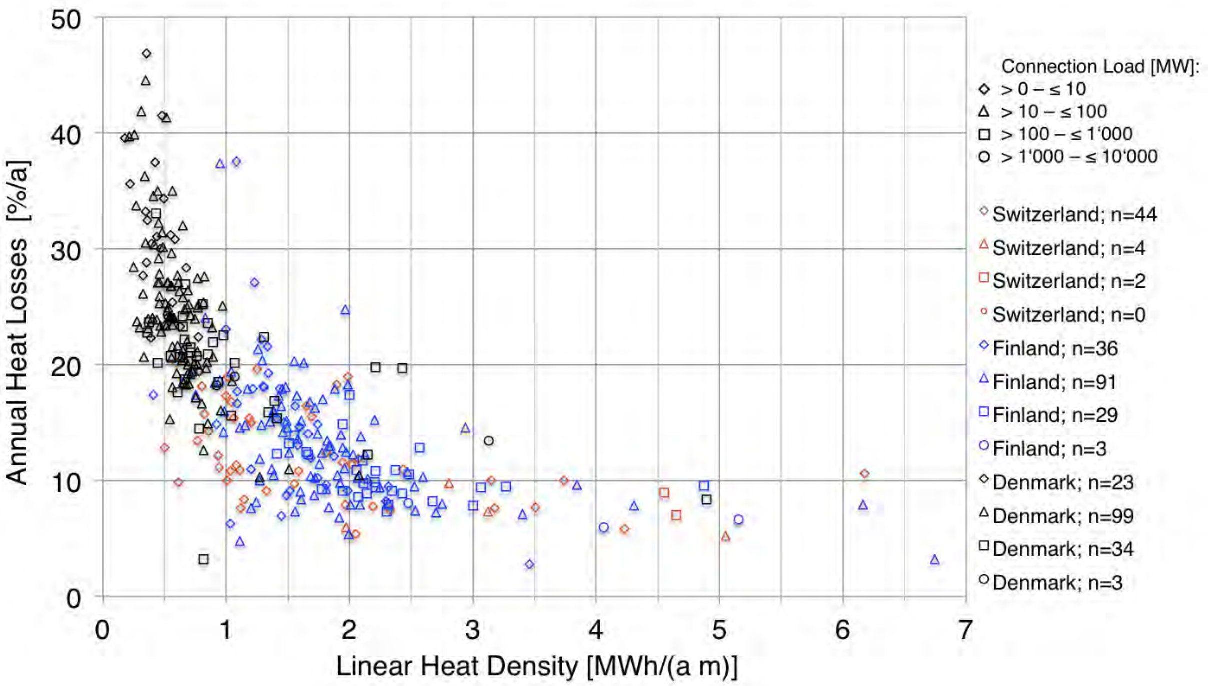

Figure 12 Linear heat density as function of the connection load for district heating networks in Denmark, Finland and Switzerland with additional distinction of the connection load introduced as parameter. Data basis: 412 plants.

In the following figures, the linear heat density, heat distribution losses, and connection load of each country are represented in the form of boxplot diagrams.

The box corresponds to the middle 50% of the data further divided in the upper and lower quartile. The height of the box as well as the median displayed as continuous line cutting the rectangle give an indication about the data distribution and its skewness coefficient. The whiskers indicate the position of the minimum and maximum values. Outliers are identified by the arithmetic average (white rhomb) and its difference to the median.

Figure 13 illustrates the repartition of heat distribution losses for each country. Denmark has the highest median with a value of 24%, whereas for all other countries it amounts to less than 20%. The evaluated networks in Switzerland have the lowest median (11%) and the lowest distribution range (5%-20%) of all data. Germany exhibits with 9%-24% the highest distribution range of the middle 50% of the data.

In Figure 14 is displayed the distribution of linear heat density for each country as well as the data published by Euroheat & Power [17]. This statistic evaluation only considered European countries enabling the determination of the linear heat density of 20 European countries.

The distribution of the linear heat density of the different countries exhibits large distribution ranges and also big differences in the absolute values. Danish networks nicely display the correlation between high distribution losses and low line heat densities. The evaluation of the data also illustrates small line heat densities between 0.5 and 3.0 MWh/(a m) for the middle 50% of the networks with many outliers with higher line heat densities. As already mentioned, QM Holzheizwerke considers year-round operated networks with a minimum linear heat density of 1.8 MWh/(a m) economically profitable.

The evaluation by Euroheat & Power needs to be considered with care since their country-specific data (red rhomb) differ considerably from the data evaluated in the present study for some countries (Switzerland, Germany, Austria), less for other countries (Finland, Denmark).

In Figure 15 are displayed the distribution of the connection loads in Finland, Denmark and Switzerland. Considering the connection load, the medium 50% of the networks in Finland and Denmark are 13 to 15 times larger than the ones in Switzerland that on the other hand are distributed over a smaller range than the Danish and Finnish ones.

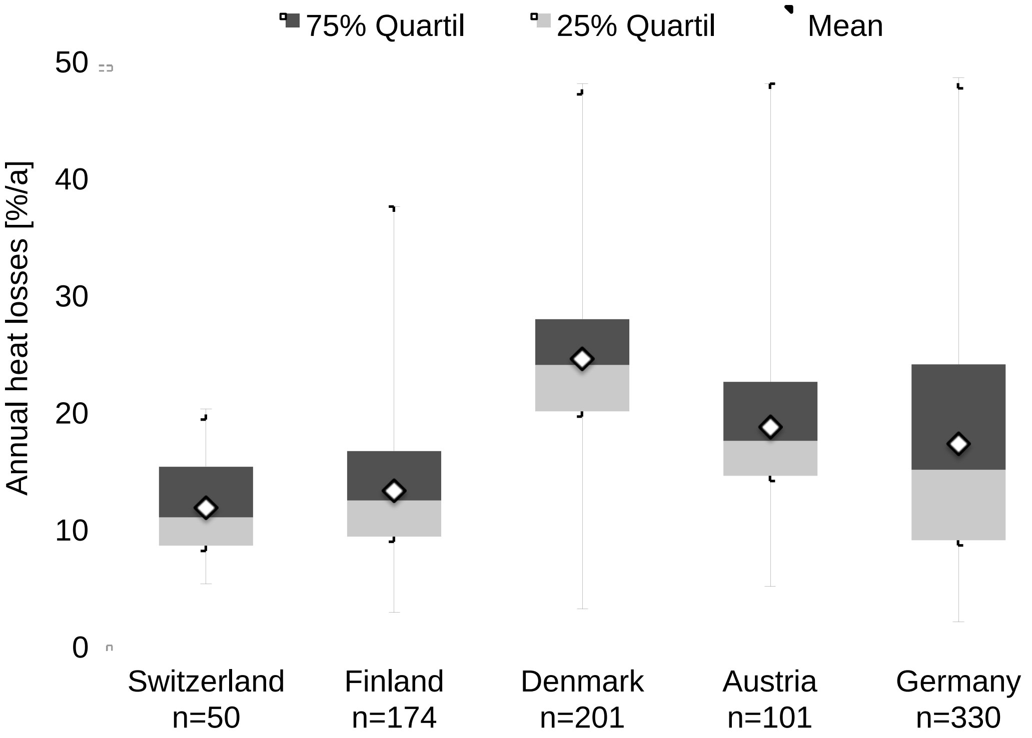

Figure 13 Distribution of the heat distribution losses in Germany, Denmark, Austria, Finland and Switzerland displayed as boxplots.

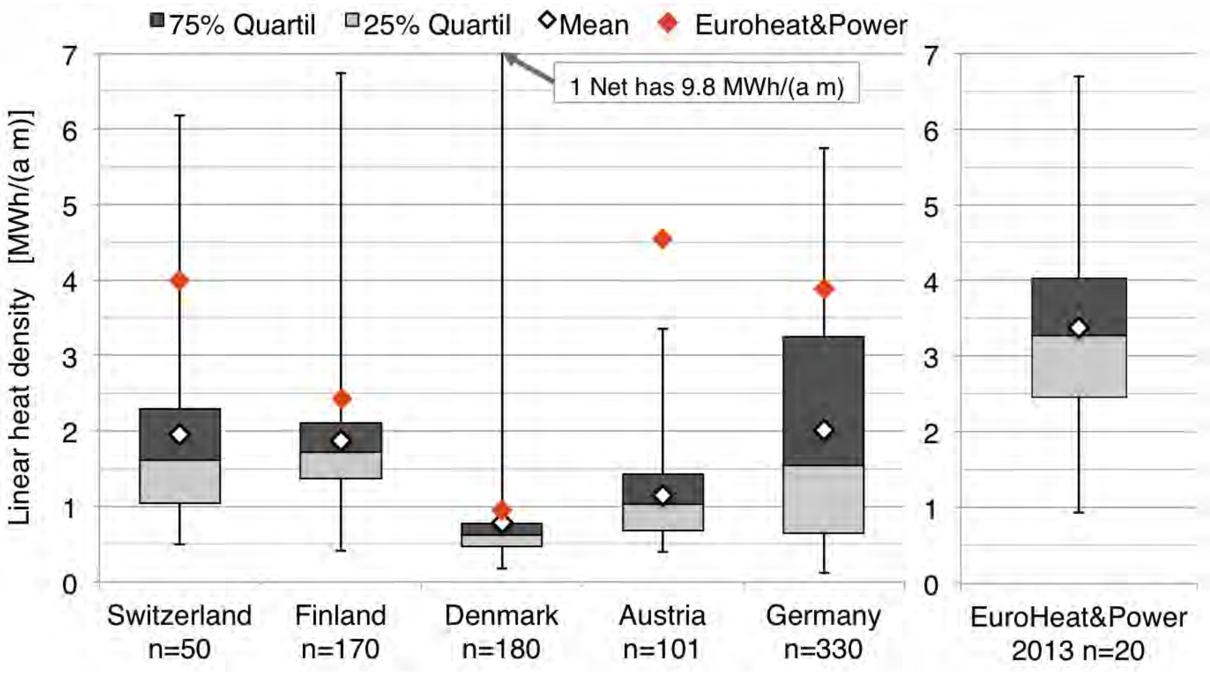

Figure 14 Distribution of the linear heat density of systems in Germany, Denmark, Austria, Finland and Switzerland displayed as boxplot. Data published by EuroHeat & Power [17] is additionally displayed as boxplot for comparison.

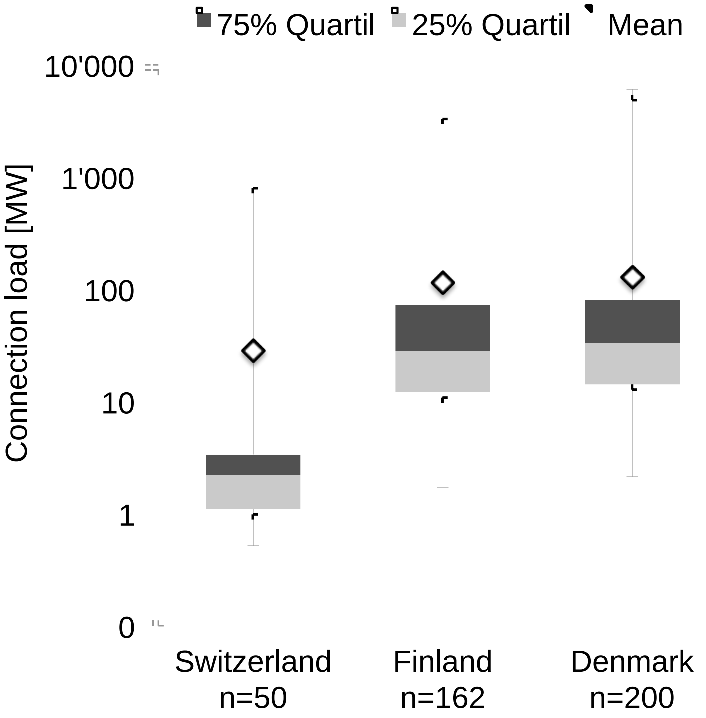

Figure 15 Distribution of the connection load in Switzerland, Finland and Denmark displayed as box-plot.

4 Case study Switzerland

4.1 Technology

In the evaluated DH networks, roughly three quarters of the heat is generated by wood firings and one quarter by CHP plants fuelled by waste (7 plants), natural gas (3 plants) and wood (2 plants). Two additionally considered plants generate district heat by heat recovery and heat pumps, respectively (Table 2). The base heat demand is covered by wood in 77% of the cases. This amounts to roughly 6% or 162 GWh/a of the total base heat allocation by district heating (Table 3). The remaining 94% and hence the biggest share of the base heat load are covered by the seven waste incineration plants. 78% of the evaluated DH networks are operated year-round. The peak load demand is covered by fuel oil (55.6%), natural gas (22.2%), wood (17.8%), and waste (4.4%). Most of the heat consumers just require space heating as well as domestic hot water (80.0%), whereas some additionally need process heat (17.8%) and a few exclusively require space heating (2.2%). 40 among the 45 district heating networks of which data is available dispose of leakage monitoring, and all of these 45 district heating networks take use of indirect heat exchange as well as a 2-pipe pipeline configuration.

Table 2 Technology and energy source for heat generation.

Technology	Energy source	Number	Share
Firing	Wood	38	73.1%
CHP	Waste	7	13.1%
	Natural gas	3	5.8%
	Wood (ORC)	2	3.8%
Heat recovery	Waste heat	1	1.9%
Heat pump	Ground water	1	1.9%
Total		52	100%

Table 3 Energy source for base load coverage.

Heat generation – Base load	Plants		Load	
	Number	Share	GWh/a	Share
Wood	40	76.9%	162	6.0%
Waste (CHP)	7	13.5%	2538	93.5%
Natural gas (CHP)	3	5.8%	8	0.3%
Ground water (Heat pump)	1	1.9%	2	0.1%
Waste heat (Heat recovery)	1	1.9%	4	0.1%
Total	52	100%	2714	100%

Three pipe systems are mainly used in the heat distribution:

- Rigid plastic jacket pipes with steel-medium pipe (KMR),
- Flexible plastic medium pipe (PMR),
- Flexible plastic jacket pipes with steel-medium pipe (MMR).

Figure 16 summarises the application areas of the pipe systems. The rigid KMR is the most laid pipe system thanks to its standardisation, robustness, and the low material prices. Flexible pipe systems, such as PMR and MMR, are mainly used in the sub-distribution and in house substations in case the pressure and temperature conditions actually allow their application. Their advantages are the laying from the reel resulting in a high laying speed and only few connections, the flexible line run, and the self-compensation [18]. All pipes are also available in twin-pipe format (Duo) for nominal diameters up to DN 200 (KMR) and DN 50 (PMR and MMR). Advantages thereof are slightly smaller heat losses and smaller trenches.

The evaluated district heating networks sometimes feature different pipe systems for individual sections (main, branch, and house connection pipelines). In order to simplify the assessment, the most used pipe system is assigned to each section of each district heating networks. The assessment reveals that KMR pipes have the biggest share with 60% to 70% followed by PMR and MMR (Figure 17). Other pipe systems in use include steel pipes in concrete ducts or steel jacket pipes for high temperatures and pressures.

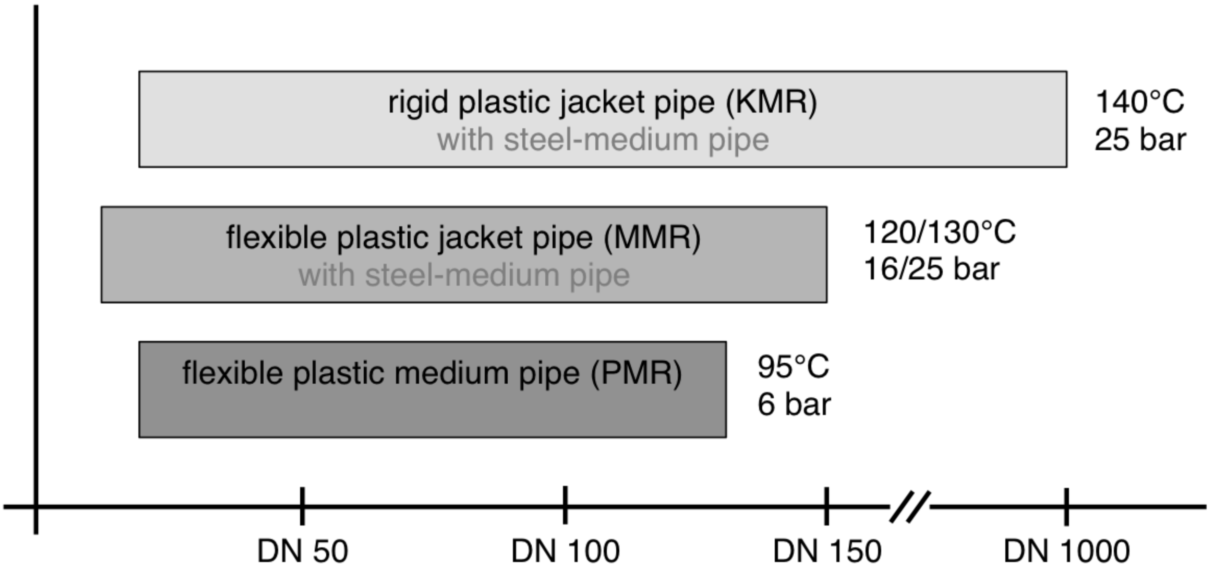

Figure 16 Characterisation of different pipe systems for district heating networks [18].

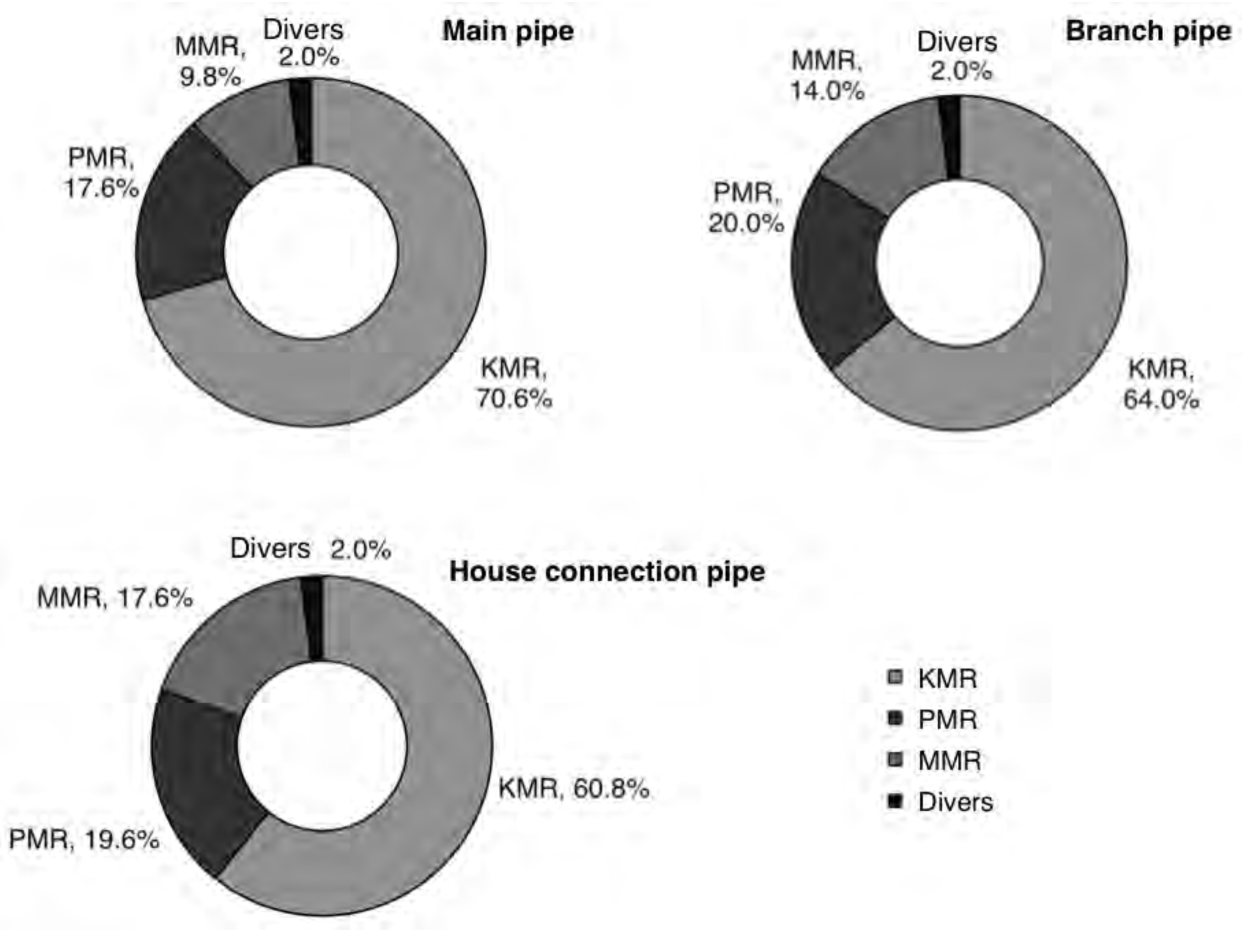

Figure 17 Share of the pipe systems in main, branch and house connection pipes.

42 plants or 93.3% of the 45 district heating networks dispose of a superior monitoring system. Yet they exhibit differences in the monitoring depth which describes the degree of tasks assumed by the monitoring. A DH network is sub-divided in heat generation, heat distribution and heat transfer. A monitoring system may hence supervise and control single tasks, a combination thereof, or the entire district heating network. Among the 42 plants with monitoring system, 16 plants (39%) dispose of a monitoring system for the entire network. Monitoring the combination of heat generation and heat transfer station also often occurs (in 23.8% of the cases) as well as the combination of heat generation and heat distribution network (in 16.7% of the cases). In more than 90% of the plants, at least the heat generation is monitored.

Amongst the 40 plants with wood firings, 22 plants representing 55% of all plants are supervised by QM Holzheizwerke. 13 or 59.1% of the ones under QM supervision have reached milestone 5.

Figure 18 summarises the maximum supply and return temperatures of 44 district heating networks. The temperatures correspond to the network temperatures at design conditions and outdoor temperatures of -10°C. Roughly 90% of the district heating networks have a supply temperature between 70°C and roughly 100°C and a temperature spread of 20 K to 40 K. Five networks dispose of a supply temperature of more than 100°C and accordingly of larger temperature spreads. In 37 of the 45 district heating networks, the supply temperature is controlled as a function of the outdoor temperature while the remaining eight networks work at year-round constant supply temperatures.

During the summer and the transition period, 12 of the 45 district heating networks dispose of a regulated hot water generation. Thereby, the supply temperature is increased to the level required for generating hot water several times a day. During the remaining time of day, the supply temperature corresponds at least to the maximum requirements of the heat costumers connected to the network. The majority of the networks is however operated at constantly high supply temperatures whereby the aseptic hot water generation is possible at all times.

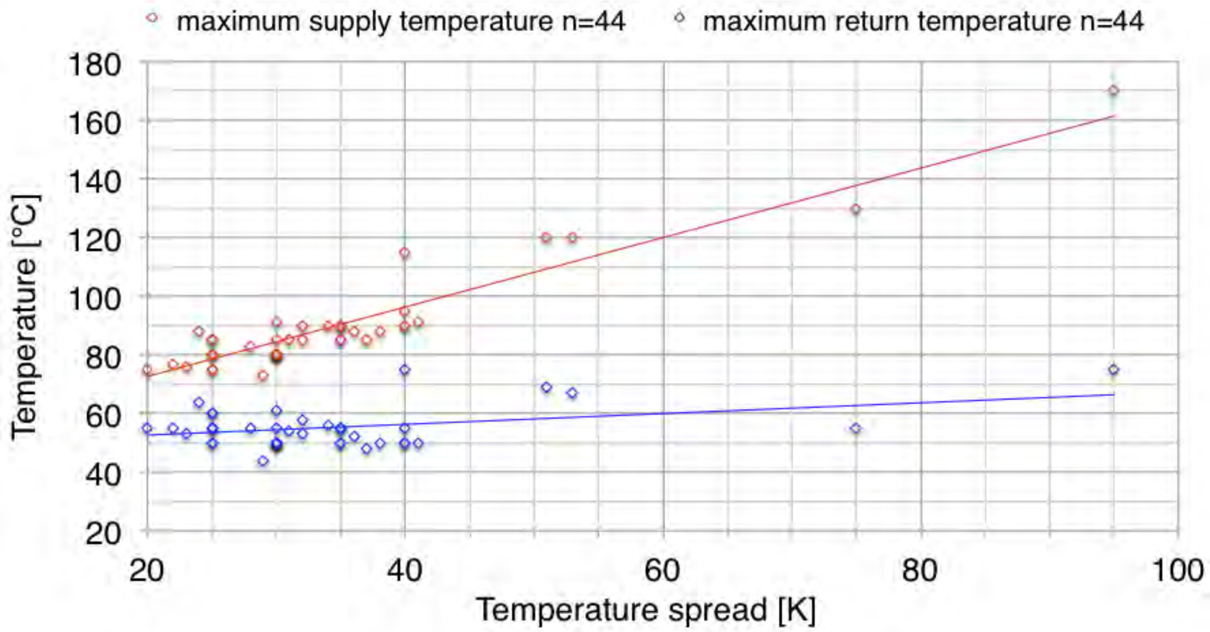

Figure 18 Maximum supply and return temperatures as function of the temperature spread of 44 evaluated district heating networks.

4.2 Efficiency

4.2.1 Heat distribution losses

The following diagrams display the heat distribution losses as function of the linear heat density in order to assess various influences on overall 50 plants. The following applies:

- The heat distribution losses are proportionally related to the heat supplied to the network.
- The linear heat density is determined using the annual heat demand of the heat costumers divided by the total pipeline length (main, branch, and house connection pipes).

The dashed lines represent the following target values as defined by QM Holzheizwerke [8]:

- Heat distribution losses ≤ 10%
- Linear heat density ≥ 1.8 MWh/(a m) in the case of a year-round operated district heating network with supply temperatures between 70°C and 90°C.

In Figure 5 is displayed the repartition of the plants according to the mode of heat generation. It is possible to state the trend that heat distribution losses decrease with increasing linear heat density. The evaluation simultaneously reveals a spread of the heat distribution losses of up to a factor three at equal line heat densities.

Figure 19 summarises the repartition of the wood-fired district heating systems according to annual or seasonal operation. The trendlines of three operation modes as defined by QM Holzheizwerke are complemented. The evaluation reveals that the heat distribution losses of annually operated plants with line heat densities below 1 MWh/(a m) lie in average roughly a third below the expected values by QM. The majority of plants with line heat densities above 2 MWh/(a m) contrarily exhibit significantly higher losses of up to a factor two compared to the expectations by QM.

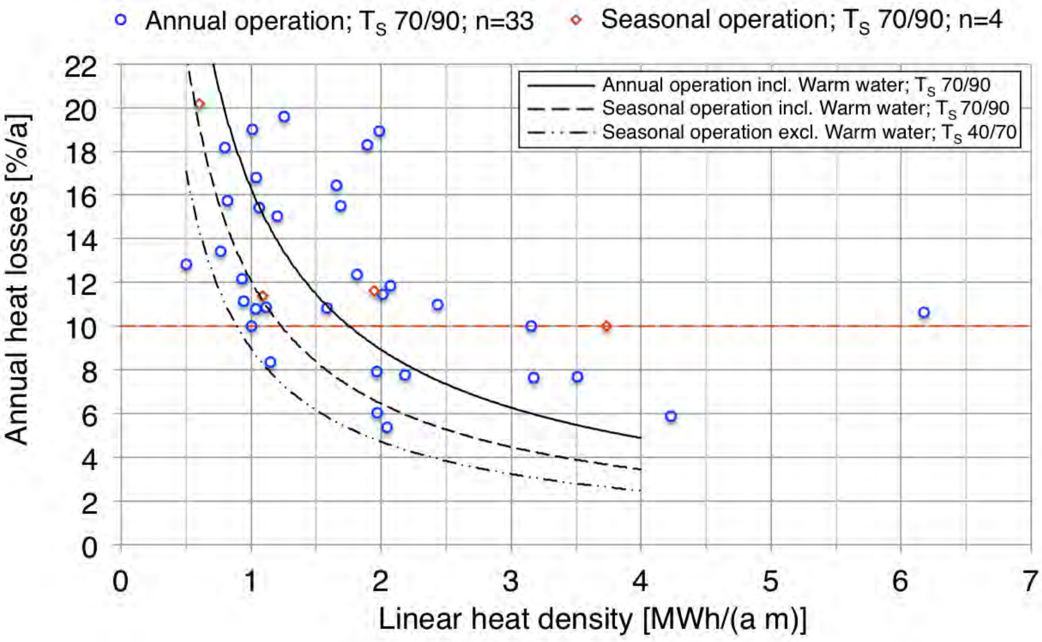

Figure 19 Heat distribution losses as function of the linear heat density including the trendlines of the values expected by QM Holzheizwerke for three network categories [8]. Data basis: 37 plants.

Figure 20 displays the distinction of the data according to pipe systems. It reveals that KMR systems cover the entire spectrum, whereas PMR are only used for smaller line heat densities. PMR systems are also rather used in smaller networks and hence mostly rural areas compared to larger networks where higher pressure levels are required.

The evaluation of the insulation class in KMR systems reveals much higher heat losses in the case of insulation class 1 compared to insulation classes 2 and 3 (Figure 21). In contrast, the difference in losses between insulation classes 2 and 3 is low, since these two insulation classes differ less hence increasing the influence of other factors.

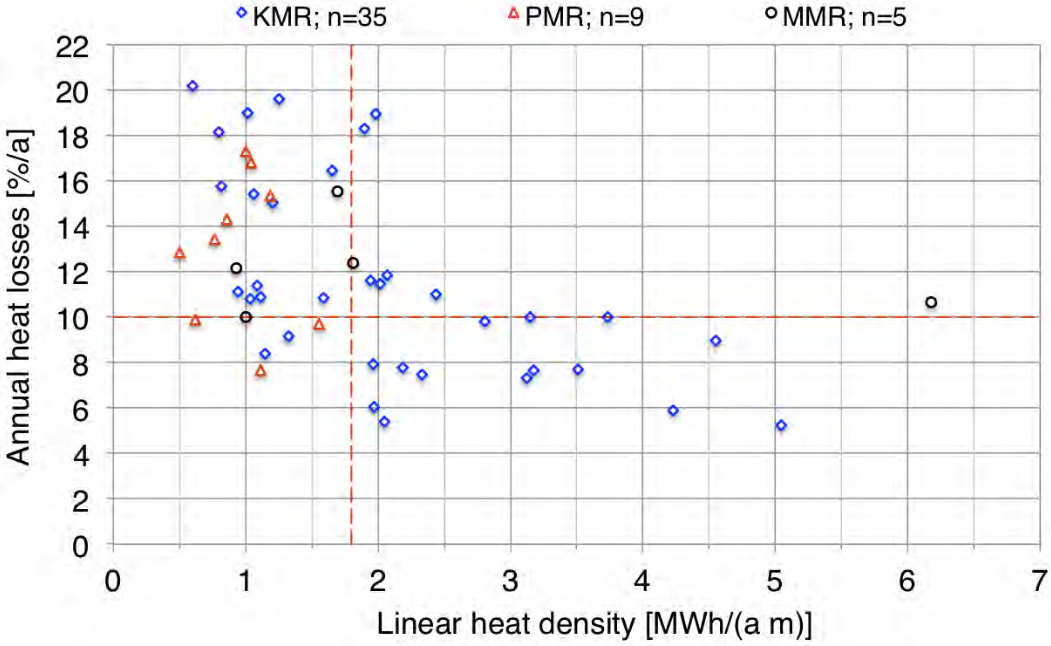

Figure 20 Heat distribution losses as function of the linear heat density classified in the pipe system in use for the main pipeline. Data basis: 49 plants.

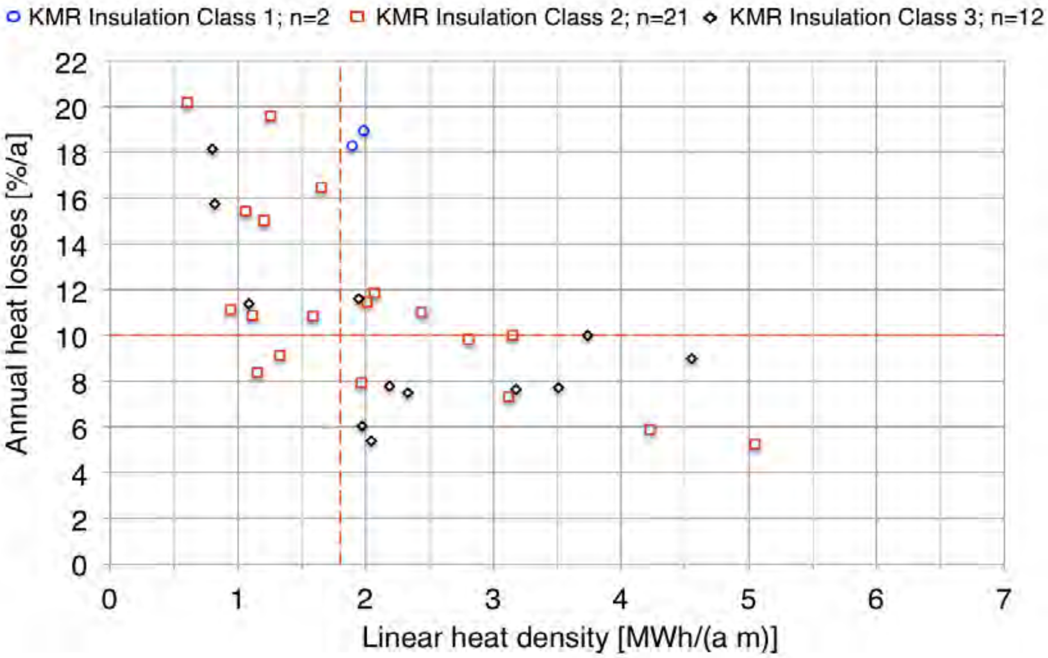

Figure 21 Heat distribution losses as function of the linear heat density classified in insulation classes of the KMR pipes of the main pipeline. Data basis: 35 plants.

Figure 20 displays the influence of the connection load on the heat distribution losses. Among the plants with line heat densities between 2 and 7 MWh/(a m), roughly 75% of the plants fulfil the requirements by QM. In the case of the plants with line heat densities up to 2 MWh/(a m), only 25% fulfil the requirements. Further analyses reveal that neither the number of full-load hours nor the age of the plant seem to influence the heat distribution losses [11].

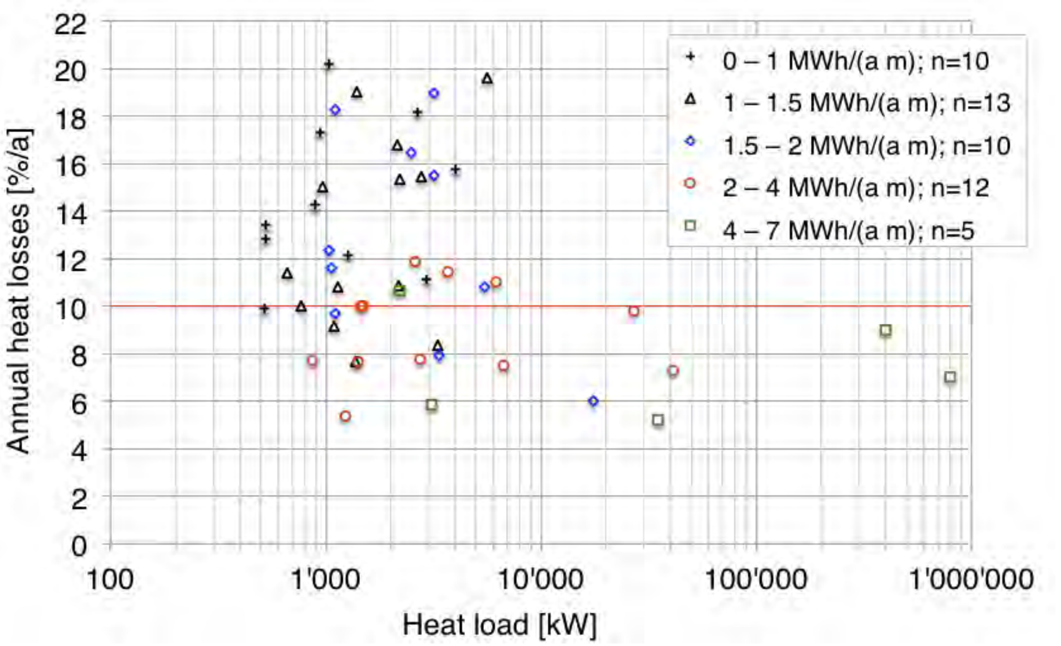

Figure 22 Heat distribution losses as function of the connection load classified in line heat densities [11]. Data basis: 50 plants.

4.2.2 Power consumption

Information on the power consumption of the networks is available for 9 DH networks (Figure 23). QM indicates a target value between 0.5% and 1.0% of the heat supplied to the network [8]. 7 of the 9 district heating networks exhibit annual power consumption below 0.5% which may be understood as a sign for oversizing of the DH pipelines. One network exhibits a power consumption of slightly more than 0.5% and the remaining one slightly more than 1%.

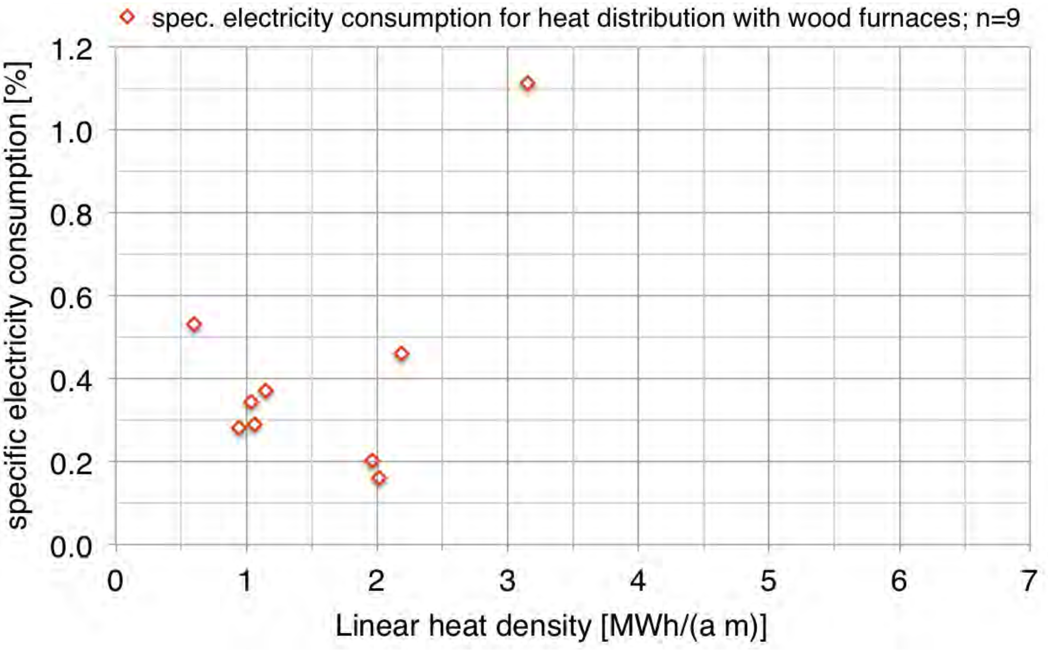

Figure 23 Specific electricity consumption of the heat distribution of district heating networks with wood firings (excluding CHP) [11]. Data basis: 9 plants.

4.3 Cost and connection conditions

4.3.1 Investment cost

The investment cost of the heat distribution includes the material and construction costs for the network, equipment (e.g. pump, heat exchanger) and the transfer station. Since the cost for the house substation and the transfer station could not be differentiated, the data are presented partially including and partially excluding the house substation. The substation includes the transfer station and the house heat exchanger and links the DH network to the house installation. The transfer station generally belongs to the system operator, whereas the house substation is typically owned by the heat costumer.

The evaluation reveals that the specific investment costs of the network tend to decrease with increasing linear heat density as displayed in Figure 24. The costs of the evaluated systems however exhibit a large range of values with some networks revealing costs well above the expected values by QM Holzheizwerke [19].

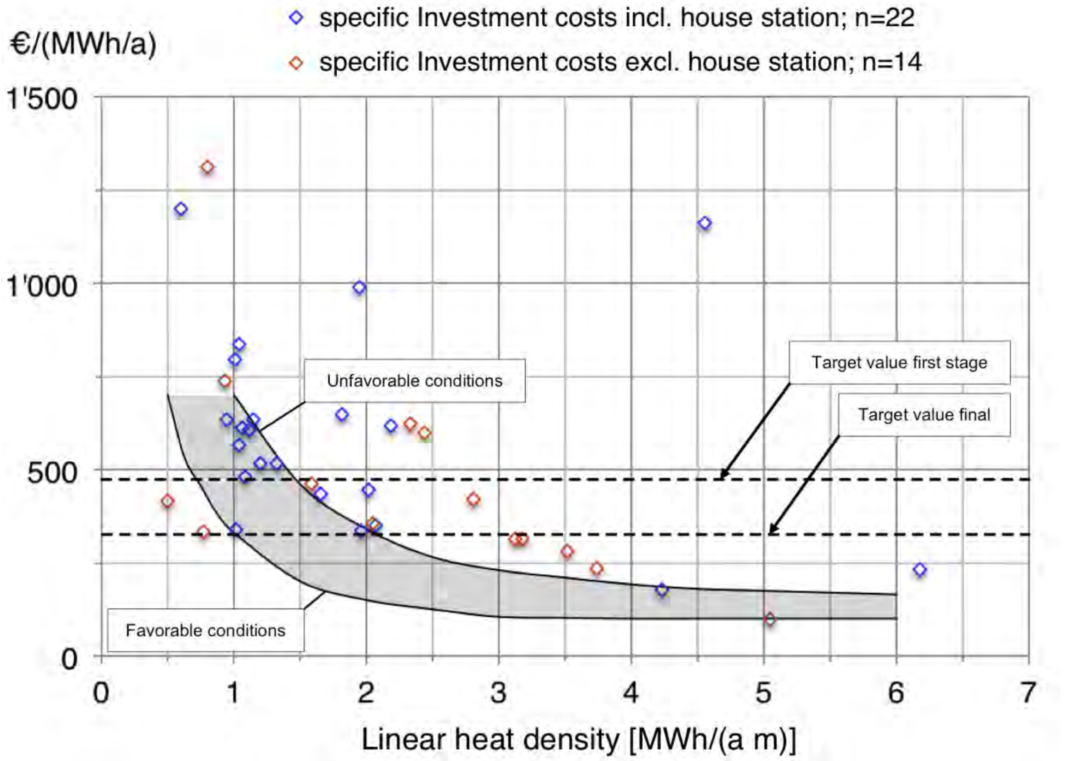

Figure 24 Specific investment cost of the district heating networks related to the sold heat as function to the linear heat density. The expected range and target values by QM Holzheizwerke are added [19]. The expected range is based on data of plants in Switzerland (as of 2004) and Austria (as of 2010).

4.3.2 Specific cost per kilowatt hour delivered heat

The price of a house connection line depends on the heat supplier. It is common to charge a one-time connection fee, annual base fee and the heat price. Some DH networks however dispense with the connection and/or the annual base fee.

To compare the different networks, the cost for one house connection with a load of 50 kW is converted in specific cost of heat consumed in cents per kilowatt hour delivered heat. The calculation is carried out using the equivalent annual cost (EAC) method assuming an interest rate of 3% p.a. and a calculation period of 30 years for a heat demand of 2000 full-load hours per year.

Figure 25 shows the cost of heat consumed evaluated as function of the linear heat density of 39 plants which provided information. The values vary between roughly 8.0 c/kWh and 22.0 c/kWh with an average of 13.5 c/kWh. The investment costs of the network with capital costs determined using the EAC method is also displayed for comparison. The capital cost of the heat distribution amounts in average to 2.51 c/kWh for networks including the house substation corresponding to 19% of the average cost of heat consumed. The capital costs for networks excluding the house substation amount in average to 1.93 c/kWh corresponding to 14% of the average cost of heat consumed. By comparison, a 1 MW model DH network excluding the house station induces capital costs of 1.34 c/kWh at optimal design.

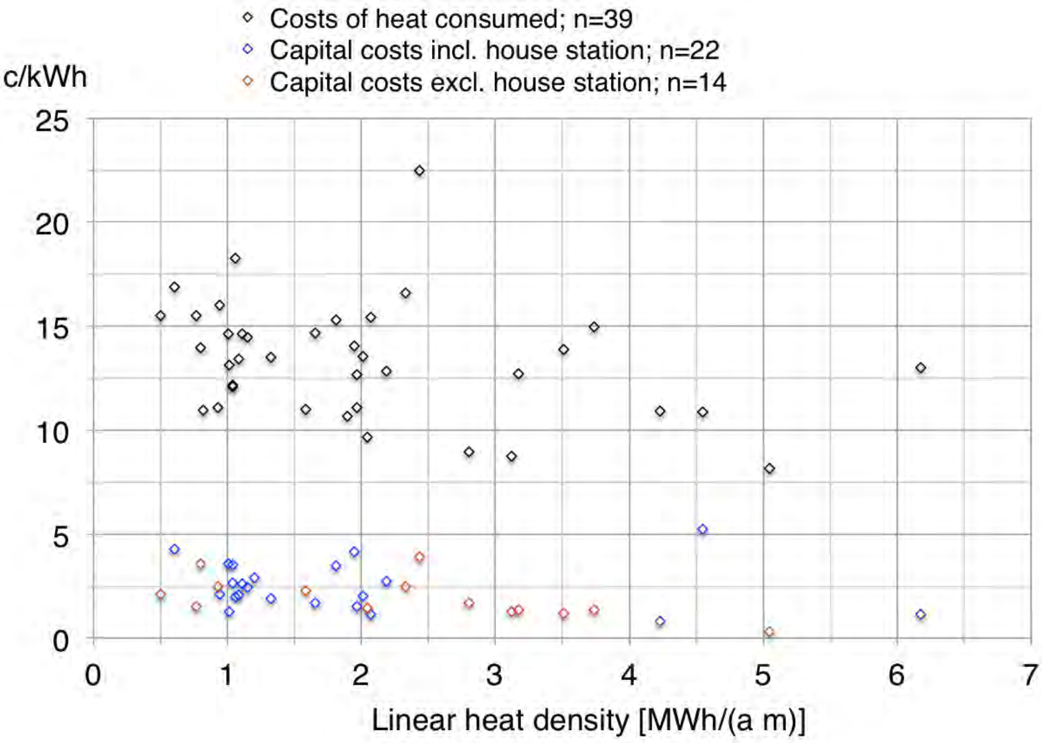

Figure 25 Specific costs of heat consumed and investment costs as function of the linear heat density.

In Figure 26 are displayed the individual parts of the costs of heat consumed for one house connection. In the case of a connection fee or an annual base fee, they amount in average to 1.18 c/kWh and 4.24 c/kWh, respectively. The heat price accounts in average to 8.90 c/kWh and displays a slight decreasing tendency with increasing connection load. Even though the heat price depending on the heat consumption mostly accounts for the major part, the networks also exhibit high fixed charges.

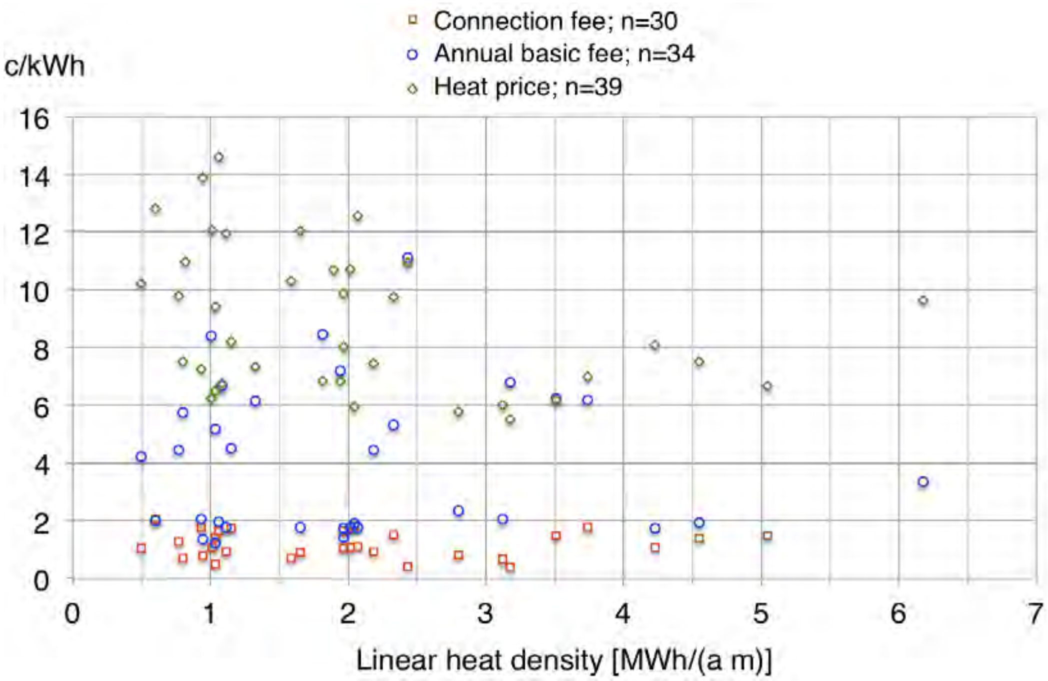

Figure 26 Connection fee, annual base fee and heat price for a 50 kW house connection as function of the linear heat density [11].

5 Influence of optimum pipe dimensioning

5.1 Methodology

The following results are based on the calculation procedure for a model DH system with one heat costumer as described in [10] and expanded to real DH networks in [11] in order to investigate the profitability and the optimisation and expansion potential thanks to network plans and data. In the simulated network, the most important parameters are varied in order to determine a theoretical cost minimum used as basis of comparison. Therefrom optimisation measures are derived that are only meaningful in theoretical evaluations and cease to be useful upon variation of the nominal diameter in the case of existing networks. The evaluation provides a basis for the quantification of the optimisation potential that missed to be exploited upon design. The importance of the network dimensioning during the design phase is hence illustrated, and the reasons for the large spread of heat distribution losses at equal line heat densities is explained (Figure 5).

The illustration implies the availability of detailed information on the network including the nominal diameters of each subsection. The analysis is also primarily interesting for the planed final completion. On the following pages, the results of five selected DH networks with connection loads between roughly 1.1 MW and 2.8 MW are described (Table 4). All networks use wood for the base load coverage and all but one are operated year-round. The start-up occurred between the years 2000 and 2012 and all networks but one have completed final construction. An evaluation tool carried out the following calculations for each plant:

1. The current situation (**IST**) provides the basis for further calculations and for comparison with the information in the questionnaire and hence to check the plausibility. Based on the current situation, the nominal diameter, temperature spread, and insulation thickness are varied and their optimum values are determined.

2. The optimisation of the nominal diameter (**OPT DN**) induces that each subsection has the smallest possible nominal diameter limited by the maximally admissible flow velocity as required by the ÖKL-Merkblatt 67 [20]. These values correspond to pressure drops of approximately 300 Pa/m and hence slightly higher pressure drops as defined by QM Holzheizwerke (150 Pa/m up to 200 Pa/m [19]) and as required by practical experience (200 Pa/m and 250 Pa/m at peak load [21]) [10].

3. In a further step, the temperature spread is increased by 10 K (**OPT DN-dT**) to simulate a decrease in return temperature.

4. In order to examine the effect of the insulation thickness, the maximum insulation class is applied in a further step (**OPT Dämm**).

Table 4 shows the comparison of the data in the questionnaire with the data determined by the evaluation tool (IST). Deviations between the questionnaire and the determined values are low. The information on connection load, pipeline length and hence also on linear heat density are therefore in accordance in most cases (< 4% deviation) with only one plant depicting a deviation of 9.2%. Contrarily, three networks exhibit heat distribution losses increased by 20% to 40% in practice compared to the theoretical evaluation. These deviations may be attributed to the fact that the calculation is done statically for constant temperature spreads corresponding to the winter situation and omits non-insulated fittings and other components. For plant number 052, it is important to consider that its construction is not yet completed.

Table 4 Comparison of the data in the questionnaire with the data determined by the evaluation tool based on the current situation. [1] No information on the pipeline length: determined by means of the evaluation tool. [2] Estimate by the design engineer (no heat meter).

	Questionnaire				**IST** (calculated)				**Deviation**			
Plant	**Connection load**	**Pipeline length**	**Linear heat density**	**Heat distribution losses**	**Connection load**	**Pipeline length**	**Linear heat density**	**Heat distribution losses**	**Connection load**	**Pipeline length**	**Linear heat density**	**Heat distribution losses**
	MW	m	MWh/(a m)	%	MW	m	MWh/(a m)	%	%	%	%	%
8	2.135	3403	1.04	16.8	2.188	3364	1.08	13.8	2.4	-1.2	3.7	-21.7
11	1.093	1200	1.33	9.1	1.073	1213	1.29	8.8	-1.9	1.1	-3.1	-3.4
37	1.108	1130	1.89	18.3	1.108	1142	1.88	14.1	0.0	1.1	-0.5	-29.8
42	2.759	3300	1.06	15.4	2.566	3318	0.98	16.9	-7.5	0.5	-8.2	8.9
52	1.388	2026[1]	1.01	19[2]	1.388	2026[1]	1.01	13.3	0.0	0.0	0.0	-42.9

5.2 Results

Figure 27 illustrates the decrease in heat losses thanks to the three above mentioned scenarios. The optimisation of the nominal diameter decreases the heat losses in average by 11%. With an additional increase in the temperature spread, the savings amount to 21%. The choice of the maximum insulation class reduces the heat losses in average by 13%.

The repartition of the costs is displayed in Figure 28. Even though the heat distribution losses of the five networks exhibit large differences with values between 1.5 c/kWh and 4.4 c/kWh [11], the capital costs are the dominant factor in all cases with a mean share of 64%.

The potential for reduction of the total costs is illustrated in Figure 29. By optimising the pipe diameter, the costs can in average be reduced by 13%. The values are however distributed over a large range. With a simultaneous reduction of the return temperature, the savings increase to 21%. A maximum insulation may in comparison only lead to mean savings of 3.3%. It is hence confirmed that the choice of the smallest possible nominal diameter is essential [10].

In Figure 30 is displayed the specific pressure drop of the decisive line, i.e. the line leading from the heat generation plant to the most distant customer. This value represents an additional reference for the sizing of the pipe diameter. QM Holzheizwerke recommends a target value of 150 to 200 Pa per line meter. Only one of the five networks complies with this target value in the current situation, whereas the mean value only amounts to 78 Pa/m. The optimal sizing of the pipe diameter (OPT DN / OPT DN-DT) however results in specific pressure drops in the required spread or even above.

The heat distribution losses of the different scenarios applied to two plants are illustrated in Figure 31. Plant 8 (left) may be considered as well designed DH network, since 72% of the subsections have an optimum nominal diameter. The theoretical optimisation potential of the costs and hence the actual expansion potential are low. Plant 37 represents a DH network where the nominal diameters of all subsection could be decreased by one to four sizes thus reducing the heat distribution losses by 20.5% and the costs by 28.0%. Maximum insulation could reduce the heat distribution losses by even 28.5%. This case would economically be more profitable than the current situation but still less profitable than the sole reduction of the pipe diameter. In the case of this plant, the exhaustion of all possible optimisations (diameter, lower return temperature, better insulation) would result in cost reductions by 40.0%.

The comparison illustrates the large spread of heat distribution losses in the case of identical line heat densities that can be reduced thanks to the optimisation measures. The sporadic highly increased heat losses at identical linear heat density can hence be attributed to a great extent to the oversizing of the pipe diameters and the corresponding high heat losses.

Overall, it is shown that all five plants exhibit room for improvement which may be identified and quantified by the presented method. Though, the differences in cost savings in the heat distribution are large and expand from roughly 5% to more than 30%. It was evaluated that in 73% of the subsections only 50% or less of the possible transfer capacity are actually used [11]. Contrarily, the oversizing may also be understood as reserve capacity for future network expansions. They are however not possible in all cases and the energetic renovation of existing heat costumers may even lead to a reduction in connection load. In the case of an expansion, the pressure reserves of the single subsections need to be considered [11].

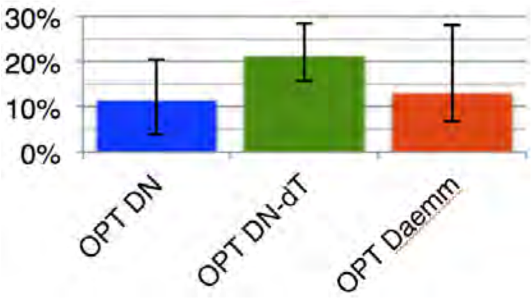

Figure 27 Reduction of the heat losses by the scenarios OPT DN, OPT DN-dT and OPT Dämm.

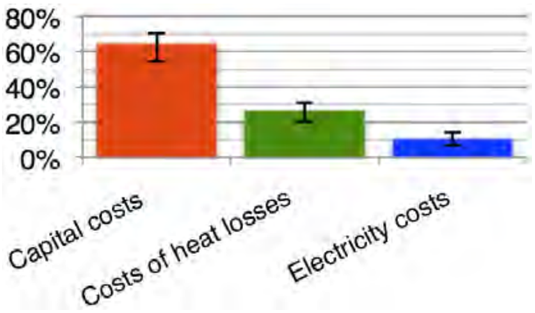

Figure 28 Shares of the capital, heat loss and pump cost in the heat distribution cost (mean values and min/max of five plants).

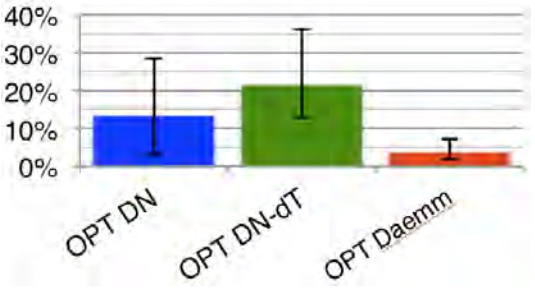

Figure 29 Reduction of the total cost by the scenarios OPT DN, OPT DN-dT and OPT Dämm.

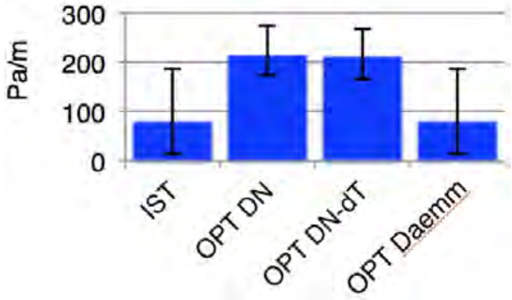

Figure 30 Specific pressure drop in the decisive pipelines of the network.

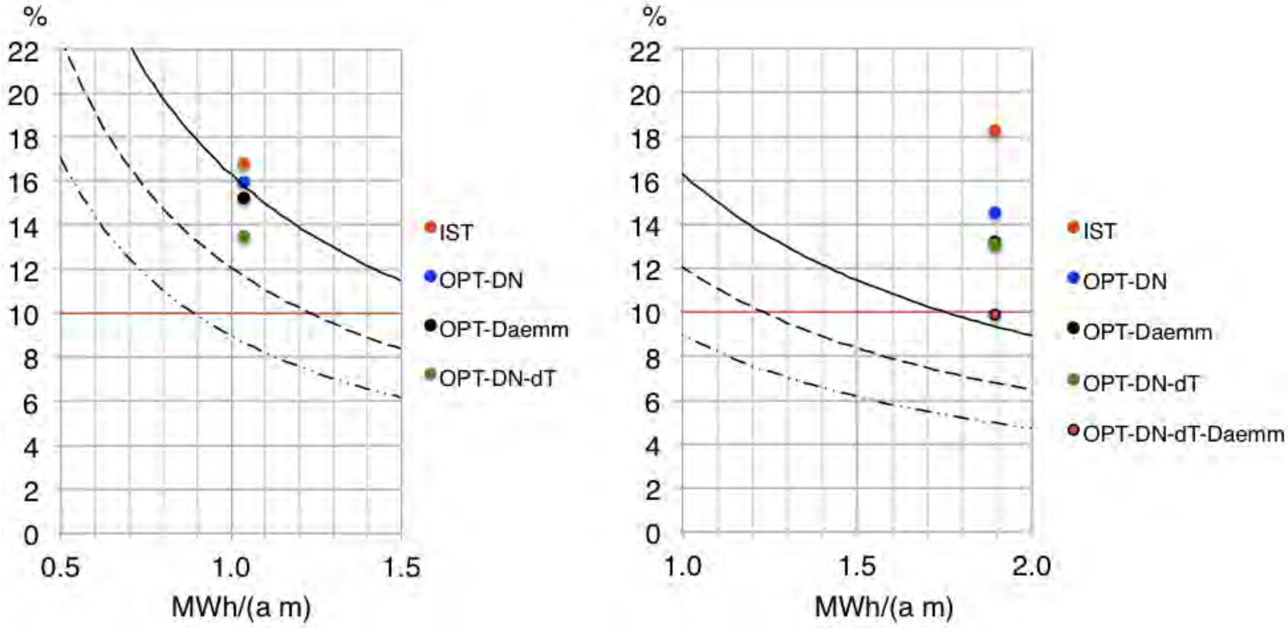

Figure 31 Heat distribution losses as function of the linear heat density for different scenarios. Left side: plant 8 which is a plant with an almost optimal design. Right side: Plant 37 as example of a highly oversized plant and the corresponding large potential for savings.

6 Characterisation of network layout

6.1 Methodology

The linear heat density is indeed an important parameter of district heating networks but shows no indication concerning the network structure which is also essential for the profitability. For this reason, a graphic illustration is introduced enabling a qualitative comparison of different network structures as well as identifying for instance the influence of different location of the heat plant. The dimensionless pipeline length of the customer is thus introduced and opposed to the dimensionless connection loads [11]. For explanatory reasons, an example of a fictitious network with a heat generation plant and two heat customers is displayed in Figure 32.

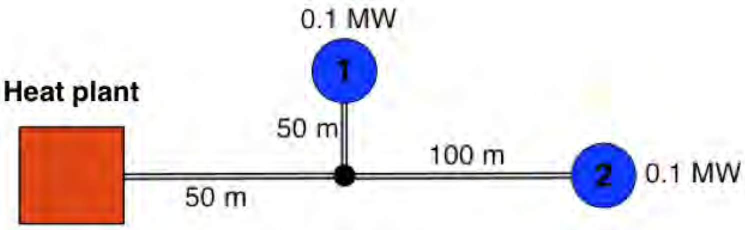

Figure 32 Structure of the exemplary district heating network.

In order to depict the characteristic curves, the x and y values are needed that correspond to each corner point. As summarised in Table 5, five corner points appear in this example that represent the following features of the characteristic line for the dimensionless pipeline length X_i (Figure 33 upper left corner, black line):

Point 1:	Point 1 corresponds to the heat generation plant.
Point 1 to point 2:	The heat is transported from the heat plant to the first consumer as depicted by the connection between point 1 and point 2. In the example, a distance of 100 m is between the first consumer and the heat plant. With a total length of 200 m, this results in the dimensionless pipeline length $X_i = 0.5$.
Point 2 to point 3:	The heat required by the first consumer is delivered. In the example, the first consumer demands 50% of the total heat. The dimensionless connection load hence amounts to $Y_{i\_Q} = 0.5$ and needs to be subtracted from the initial value $Y = 1$. Point 3 corresponds to consumer 1.
Point 3 to point 4:	The remaining heat is transported to the next consumer. In the example, the second consumer is also the last one with the dimensionless pipeline length $X_i = 150\ \text{m}/200\ \text{m} = 0.75$.
Point 4 to point 5:	The heat required by the second consumer is delivered. In the example, the second consumer also demands 50% of the total heat. Therefore, $Y_{i\_Q} = 0.5$ is subtracted from the initial value of point 4 in order to reach point 5 corresponding to consumer 2.
Point 5:	Point 5 corresponds to the most distant consumer.

Table 5 Corner points of the characteristic curve of the dimensionless pipeline length X_i of the i^{th} line related to the total pipeline length (black line) and to the most distant consumer (red).

Point	Lower X axis X_i	Upper X axis X_{i_max}	Y axis Y_{i_Q}	Comments
1	0	0	1	Heat generation plant
2	0.5	0.55	1	Heat transport to consumer 1
3	0.5	0.55	0.5	Consumer 1
4	0.75	1	0.5	Heat transport to consumer 2
5	0.75	1	0	Consumer 2

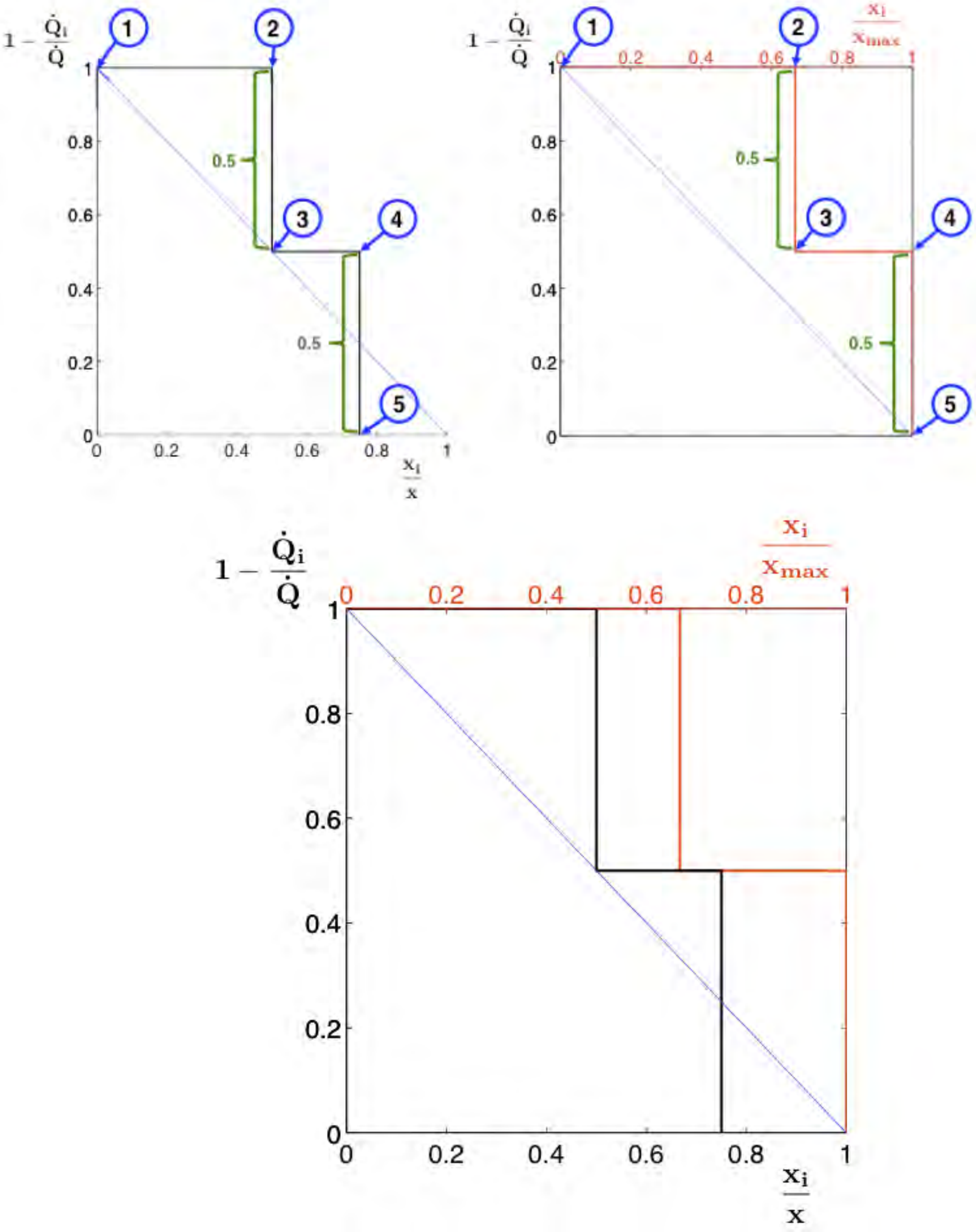

Figure 33 Characteristic curves for the analysis of the network structure on the basis of the present example. Upper left corner: corner points of the dimensionless pipeline length X_i of the i^{th} line related to the total pipeline length (black line) with the lower X axis being x_i/x. Upper right corner: corner points of the dimensionless pipeline length X_{i_max} of the i^{th} line related to the most distant consumer (red line) with the upper X axis being x_i/x_{max}. Lower diagram: Both step diagrams combined.

The step-line diagram enables the qualitative comparison of different networks and provides a characterisation of the network structure by the area ratio A* between area A_1 below the red characteristic line and area A_2 below the diagonal (Figure 32):

$$A^* = \frac{A_1}{A_2} \quad [–]\text{ , where } 0 \leq A^* \leq 2$$

The area ratio provides an indication of the structure of a network:

- A network with an area ratio close to 1 (i.e. with a characteristic curve similar to the diagonal) features homogenously distributed heat consumers which is advantageous concerning losses and cost. An area ratio close to 1 is an indication of a well-situated heat generation plant and a spatially well-configured network structure.
- An area ratio much higher than 1 appears for instance when the heat generation plant is at great distance to a large heat consumer. The network structure could be improved by the displacement of the heat plant.
- An area ratio significantly below 1 appears for instance when the most distant consumers require small connection loads and are at great distance from the second last consumer. Such a network can be improved by omitting the connection to the last consumer.

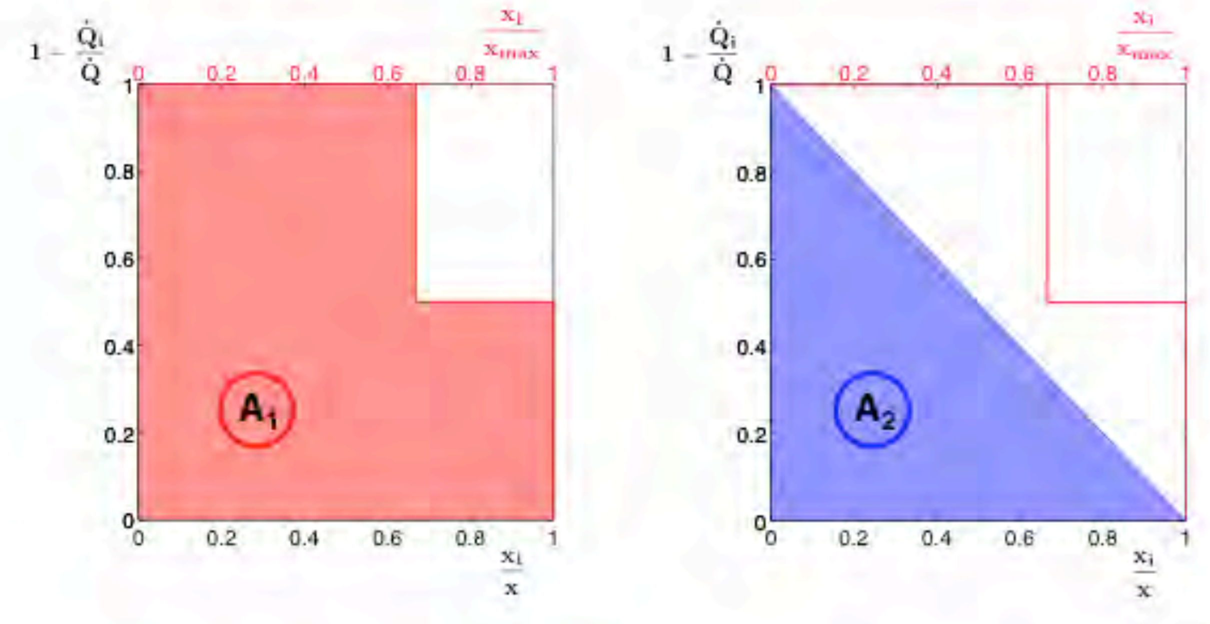

Figure 34 Area ratio. Left side: Area A_1 below the red characteristic line for the dimensionless pipeline lengths X_{i_max}. Right side: Area A_2 below the diagonal.

Another characteristic value is the compactness ratio (CR) defined by the ratio between the pipeline length of the consumer at maximum distance x_{max} and the total pipeline length x (including house connection lines):

$$CR = \frac{x_{max}}{x} = \frac{X_i}{X_{i\_max}} \quad [–]\text{ , where } 0 \leq CR \leq 1$$

CR can also be understood as the ratio between the dimensionless pipeline lengths. For networks with equal connection loads, CR gives an indication on the compactness of the network.

CR = 1 corresponds to a network with one single heat consumer and hence an absurd case except if the heat plant has high self-consumption. The case of CR = 1 is not considered, since the heat generator could directly be shifted to the large consumer. A network with further consumers with short house connection lines results in a CR slightly smaller than 1. A compactness ratio CR =1 or slightly below 1 hence gives evidence that the network structure can be significantly improved by shifting the heat generation plant. Contrarily, a small CR gives indication for a compact (dense) network with little potential for profitability improvement by shifting the heat plant or changing the pipeline structure.

The method hence exhibits the following application spectra:

- Existing district heating networks may be compared with respect to the compactness of the network structure giving rise to a qualitative evaluation of the structure as a complement to the linear heat density.
- For the design of new and the expansion of already existing DH networks, the method may serve for the comparison of different configurations and the optimisation of the network structure. Thereby, two scenarios may arise:
  a) In the case of a predefined location of the heat plant, the network structure can be optimally designed for the given heat consumers. The graphical assessment of different network configurations enables the fast comparison of alternatives and the segregation of energetically and economically unattractive consumers.
  b) In the case of predefined consumer structure, the optimum location of the heat plant can be determined by iterative investigation.

6.2 Examples of network structures of evaluated plants

Plant 8 is a DH network with 56 consumers and one heat generation plant with two equally sized sub-networks (two main lines from the plant) and annual operation (Figure 35). Single consumers require year-long process heat. On the basis of the characteristic curves, the area ratio A* = 1.04 and the compactness ratio CR = 0.209, it is obvious that this network has a well-balanced structure. The relatively high heat losses of the network may be attributed to the use of plastic pipelines and the partly oversized nominal diameters of the subsections. The characteristic curve illustrates that the network structure could presumably be improved by relocation of the heat plant close to the biggest heat consumer. Even though the location selection is generally limited, the graphic illustration may help to oppose and compare eligible alternatives.

Plant 37 has one heat plant and seven heat consumers supplied year-round via the main line (Figure 36). The plant was expanded some years ago to the last consumer thus doubling the the connection load. The analysis reveals that the diameter of the main line is still oversized by four nominal diameters even at the present configuration. This leads in combination with low insulation to high heat losses. Based on the step-line diagram, the area ratio A* = 1.37

and the compactness ratio CR = 0.926, a reconstruction would be designed very differently. The location selection of the heat generator plant and the pipeline configuration exhibit high potential for improvement.

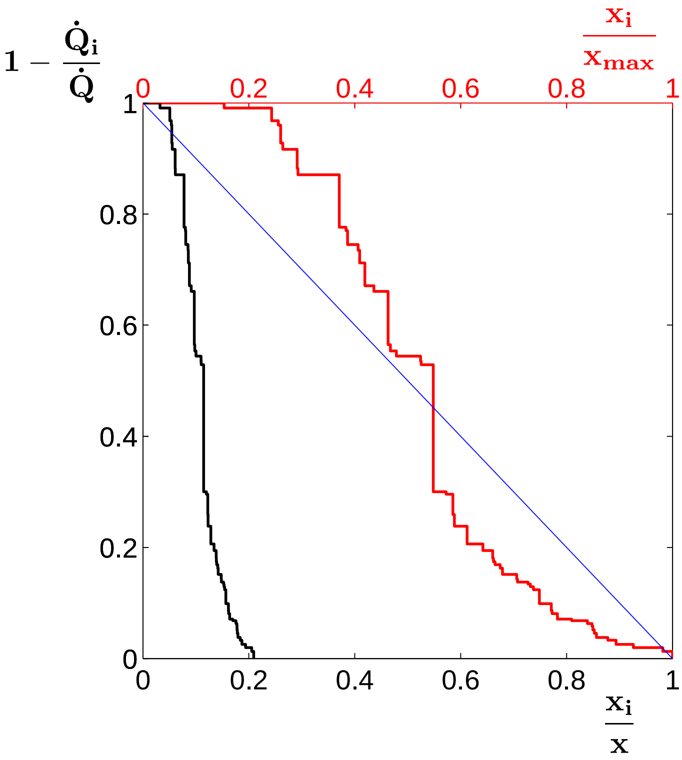

Figure 35 Visualisation of the network structure of plant 8. A*=1.04; CR=0.209

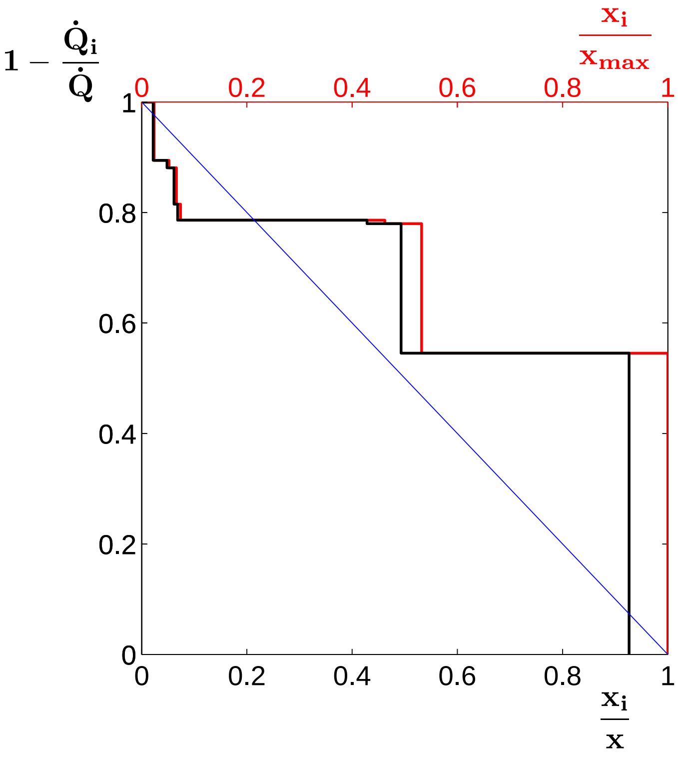

Figure 36 Visualisation of the network structure of plant 37. A*=1.37; CR=0.926.

7 Conclusions

7.1 Comparison of district heating systems in IEA countries

The evaluation of the reported data from slightly more than 800 district heating systems in Austria, Denmark, Finland, Germany, and Switzerland reveals a strong dependence of the heat losses on the linear heat density. Thus the recommendation of a minimum linear heat density is confirmed. For the minimum value of 1.8 MWh/(a m) as proposed by QM Holzheizwerke in Switzerland, Germany, and Austria, mean heat losses of 13% are reported compared to the target value of 10% by QM.

The reported heat losses however are distributed over a broad range. A number of systems claim to have less than 5% heat losses even at small line heat densities which is questionable due to thermodynamic limitations. Data is reported for a relevant number of district heating systems mainly in Denmark and Germany with considerably low line heat densities of less than 0.5 MWh/(a m) and annual heat losses of more than 40%.

Upon comparison of data from different countries, relevant differences for typical connection loads appear. While district heating at connection loads of 0.5 MW to 5.0 MW is most common in Switzerland with a small number of bigger systems, the majority of DH systems in Finland and Denmark exhibit connection loads larger than 10 MW and sometimes even exceeding 1 GW.

Although the linear heat density is confirmed to be an important parameter, the survey also shows that the heat losses have a high dispersion of more than a factor of three at a given linear heat density. Consequently, additional parameters also influence the heat distribution losses according to the following trends:

- The pipe diameter strongly affects the capital cost and the heat distribution losses. Application of pipes with significantly larger diameters than necessary to avoid cavitation pitting leads to highly increased capital cost and heat distribution losses.

- Additional parameters like the network layout, the temperature spread, the temperature level, the insulation thickness, the ratio between the operation hours of the heat production and the full-load hours of heat demand also affect the heat losses and costs.

- While the heat production plants exhibit a strong economy of scale, heat distribution has diseconomy of scale which is not reflected in the linear heat density. Consequently, large district heating systems as, e.g. in Denmark, are economically feasible thanks to the economy of scale in the CHP, however related to higher distribution losses when compared to smaller systems as, e.g. common in Switzerland.

7.2 Effect on economy for the case study Switzerland

The detailed analysis of 52 district heating systems in Switzerland exhibits the following cost factors and how they are influenced by the main design and operation parameters:

- The analysis reveals the capital costs for networks including the house station to amount in average to 2.51 euro cent per kWh purchased heat. For networks without house substations, they amount to 1.93 c/kWh (Figure 25). A 50 kW house connection induces mean total heat supply costs of roughly 13.5 c/kWh including connection fee, annual base fee and heat price. The capital costs of heat distribution hence correspond in average to roughly 14% (excluding the house station) and 19% (including the house station) of the cost borne by the heat consumers.

- In comparison with the mean capital costs excluding the house station of 1.93 c/kWh, the model DH network exhibits with 1.34 c/kWh roughly 32% lower capital costs at optimal design [10]. Even though the specific boundary conditions of the network are thereby not considered, the values can still provide an indication for possible saving potentials.

- Since the heat distribution losses and the specific cost reduce with increasing linear heat density at elsewise identical boundary conditions, high line heat densities should generally be sought. This is confirmed by the analysis of 52 district heating networks (Figure 5 and Figure 24). However, it also illustrates that the heat distribution losses exhibit a spread of more than a factor three at identical linear heat density.

- Even though the linear heat density is proven to be a characteristic parameter of district heating networks, the evaluation also points out the fact that additional factors are essential for the profitability such as the network structure which is not covered by the linear heat density. The hereby-presented method to illustrate DH networks in a dimensionless way enables a qualitative characterisation of the network structure including the assessment of the compactness and the location selection of the heat generation.

- The analysis of all nominal diameters of five selected networks depicts that only in 20% of the subsections (main- and branch-pipeline) the smallest technically feasible nominal diameter is in use. Roughly 73% of the subsections employ less than 50% of their capacity. Even though in single cases this may be used as reserve for later network expansions, it is assumed that the majority of the lines are oversized. This oversizing by mostly one or two, sporadically also by up to four nominal diameters is an essential factor of increased losses and cost. A theoretical comparison between the real designs with a pipeline at minimum diameters in each section exhibits a potential to reduce the heat distribution losses of up to 20% and the heat distribution costs of up to 30 %.

- The oversizing of the pipeline diameters or the potential reserve capacity is confirmed by the fact that only one of the 5 evaluated plants exhibits a pressure drop in the range recommended by QM and verified by practical experience, whereas the pressure drops reach in average less than 50% of the recommended target values.

- Insofar as the purpose of reserve capacity can be excluded, the theoretical optimisation of the pipeline diameter reveals a relevant saving potential. The heat losses can thereby be reduced in average by 11% (Figure 27) and mean savings in total costs of 13% with a range of 5% up to 30% may be achieved (Figure 29).

- The analysis also reveals that the capital costs represent the main share of the heat distribution cost with 64% followed by the heat loss costs with a share of 26% and electricity costs for the pumping of 11% (Figure 28).
- While heat generators take profit of the economy of scale, this is not the case for district heating networks.

7.3 Characterisation of the network layout

Since the network layout is not reflected in the linear heat density but also highly relevant for the total cost, a method is introduced enabling the qualitative assessment of the local distribution of the heat consumers and an evaluation of potential locations for the heat production site. The heat distribution is thereby illustrated as function of the dimensionless network distance from the heat production site. Furthermore, a dimensionless number showing the compactness of a network (the compactness ratio) is defined.

Based on these factors, the layout of existing networks can be qualitatively characterised. In particular, non-idealities with respect to economy and efficiency are revealed. On the one hand, individual heat consumers that significantly reduce the linear heat density are immediately identified in the graph. On the other hand, the location of the heat production site is specified enabling the evaluation of the suitability of different potential locations in the planning phase and to identify the best alternatives.

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