Influence of system design on heat distribution costs in district heating

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The study introduces an economic analysis for district heating networks from 0.5 MW to 4 MW. The reference case describes a linear network with 1 MW input, 1 km pipeline length, and 2000 annual full-load hours corresponding to a linear heat density of 2 MWh input per year and meter of pipeline. Pipe diameter, connection load, fuel price, electricity price, and insulation class are investigated and the influence of linear and radial connection and the effect of the consumer distribution are evaluated. The reference case for an annuity of 5.1% p.a. and a heat price of 5.0 euro cent per kWh reveals heat distribution costs of 2.16 c/kWh for the optimum pipe diameter. For distributed heat consumers, the costs decrease to 1.99 c/kWh and for a radial network to 1.77 c/kWh. The evaluation reveals that district heating is related to diseconomies of scale for a linear network expansion at constant linear heat density and that the total costs are dominated by the capital costs. Consequently, the main requirement to minimise the heat distribution costs implies the use of the smallest technically feasible pipe diameter which refers to the maximum allowable differential pressure without inadmissible cavitation pitting.

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1. Introduction

District heating enables a comfortable way to use biomass and other renewable energies as well as waste heat for space heating, domestic hot water, and process heat. Although for space heating a reduction of the specific energy consumption (including existing buildings) is of high priority to meet stringent CO₂ targets, a combination of district heating and efficient heat pumps is identified as a most economic approach e.g. for a case study in Denmark which compares different solutions for a 100% renewable energy supply [1]. Consequently, a study on the future energy supply of the EU (European Union) shows, that the scenarios of the European Commission to reduce the primary energy supply and mitigate CO₂ by 2050 without district heating can be improved by a 15% cost reduction, if district heating is additionally considered [2]. Also in Switzerland, district heating is identified as an important measure to meet the energy targets. Its potential is evaluated in the white book by the association on district heating in cooperation with the Swiss Federal Office of Energy which shows that the annual energy consumption for buildings will be reduced from 85 TWh to 45 TWh in 2050 to achieve the energy transition [3]. The potential of district heating for the heat supply of buildings accounts for 17.3 TWh annually which corresponds to 38% of the future heat demand of 45 TWh per year for buildings in Switzerland.

While district heating systems introduced since the 1950’s were mostly based on fossil fuels (including CHP (combined heat and power)) and municipal solid waste incineration, a specific focus on biomass is given in many European countries. In Austria this enabled a relevant increase of energy wood since the 1980’s [4]. In Switzerland, automatic wood combustion plants were widely introduced thanks to funding since the 1990’s, which led to district heating systems mostly in the size range from 500 kW to 10 MW. To guarantee an efficient use of subsidies, the quality management ‘QM Holzheizwerke’ was introduced for the plant planning initially in Switzerland which is now also applied in southern Germany, Austria and other regions [5]. Beside economic issues including requirements for the district heating network, QM considers measures to guarantee low pollutant emissions. In biomass fired district heating plants, this is possible thanks to a fully automated operation and the use of particle precipitation [6]. Consequently, biomass district heating avoids local air pollution by primary and secondary organic aerosols as found in areas with residential wood combustion [7].
On the other hand, district heating causes additional costs for the heat distribution. Beside capital costs, operating costs mainly arise from the heat losses and the electricity consumption for pumping. These additional expenditures can significantly reduce the overall efficiency and the economic performance. Since the network design influences the capital costs and the operating costs, there is a relevant interest to identify the influences of the different design parameters for optimal plant planning. Practical experiences show that several operational factors may entail high heat losses and the non-compliance with the design specification. Beside operational factors in the heating plant, one frequent reason for increased heat losses is a non-ideal operation of the substations with low thermal efficiency and a high terminal temperature difference, i.e. the smallest temperature difference between the hot and the cold medium at the pinch-point [8]. Consequently, the return temperature exceeds the design value, which not only leads to increased heat losses and pumping costs but also reduces the heat distribution capacity due to a reduced temperature difference between the supply and the return flow. To avoid temperature faults in the substations, a quality assurance by monitoring of the temperatures can be applied [9].

The aim of the investigation is to provide a sensitivity analysis of district heating systems that enables the evaluation on the main design and operation parameters on the heat losses and the heat distribution costs. For this purpose, a model network with typical parameters of non-urban district heating systems shall be defined and assessed to determine benchmark values for minimum heat distribution costs and derive an estimation for the optimisation potential in comparison to existing district heating systems.

2. Method

2.1. Equivalent annual cost

The economic assessment evaluates the specific heat distribution costs consisting of capital and operating costs by means of the EAC (equivalent annual cost) and use of the annuity factor. The investment costs comprise the cost of material and installation including the excavation work for the trench. The operating costs include the fuel costs to cover the heat distribution losses and the electricity costs for the pumping, and the service and maintenance costs. Hence the total specific heat distribution costs $c$ are calculated as follows:

$$ c = c_{cap} + c_{op} \quad (1) $$

$c$ = heat distribution costs in [c/kWh] where one kWh refers to the heat input into the pipeline
$c_{cap}$ = capital costs in [c/kWh]
$c_{op}$ = operating costs in [c/kWh]

The capital costs are found as:

$$ c_{cap} = \frac{I \cdot a}{Q \cdot \tau} \cdot \frac{100c}{\text{euro}} \quad (2) $$

$I$ = investment costs of the distribution network in [euro]
$a$ = annuity factor in [a$^{-1}$] calculated as follows:

for $i = 0$: $a = n^{-1}$, for $i > 0$:

$$ a = \frac{(1 + i)^n}{(1 + i)^n - 1} \quad (3) $$

$i$ = interest rate in [a$^{-1}$]
$n$ = calculation duration in [a]
$Q$ = connection load in [kW]
$\tau$ = annual full-load hours of the heat production in [h/a]

The operating costs are found as:

$$ c_{op} = c_f + c_e + c_m \quad (4) $$

specific fuel costs:

$$ c_f = f \cdot p_f \cdot \eta_a^{-1} \quad (5) $$

$f$ = specific fuel consumption to cover the heat distribution losses in [kWh/kWh]
$p_f$ = fuel price based on heating value in [c/kWh]
$\eta_a$ = annual heat production efficiency in [%]

specific electricity costs:

$$ c_e = e \cdot p_e \quad (6) $$

$e$ = specific electricity consumption for pumping in [kWh/kWh]
$p_e$ = electricity price in [c/kWh]

specific maintenance costs:

$$ c_m = \text{costs for service and maintenance in [c/kWh]} \quad (7) $$

2.2. Operating costs

2.2.1. Heat losses and fuel costs

The costs for fuel needed to cover the heat distribution losses depend on the heat losses and the specific heat production costs at the pipeline input. The heat production costs are determined by the fuel price and the annual efficiency of the heat production (Equation [5]). For the reference case, heat costs of 5.0 euro cents per kWh fed into the network are assumed. This corresponds for instance to the following heat production scenarios:

Scenario 1: Fuel available at a price of 4.15 c/kWh and used in a boiler at an annual efficiency of 83%. This represents typical conditions for automatic wood combustion plants in Switzerland and represents the reference case in the present study.

Scenario 2: Fuel at a price of 5.00 c/kWh used in a boiler at an annual efficiency of 100%. This represents e.g. the use of natural gas in a boiler with flue gas condensation.

Scenario 3: Conversion of electricity at a price of 15.00 c/kWh in a centralised heat pump which achieves an annual coefficient of performance of 3.0. For this scenario, the electricity costs for the heat pump are noted as ‘fuel
The heat distribution losses are determined by the pipeline length, the temperature difference between the soil and the district heating network, the overall heat transfer coefficient $U$ in [W m$^{-2}$ K$^{-1}$], and the annual operation hours of the network. In order to calculate $U$, underground pipes are assumed considering the heat conductivity of the insulation and the soil up to the surface based according to Table 1. The convective heat transfer from the water to the pipe and from the soil to the ambient is far higher than the conductive heat transfer in the insulation and in the soil and thus not considered in the calculation. The insulation class and the temperature of the network are parameters to be varied.

2.2.2. Electricity costs

The power consumption for the pumping is determined by the mass flow, the pressure difference, the annual network operation hours, and the pump efficiency (Tables 1 and 2). For the reference case, an operation of the network during 8760 h per year at nominal mass flow is assumed referring to a pessimistic maximum value of the electricity costs. Thanks to mass flow control, the power consumption can be significantly reduced. Taking into account Bernoulli’s energy equation for inviscid flow, the theoretical pumping work is proportional to the square of the flow velocity. At 50% heat consumption, the heat supply provided by 50% volume flow refers to a theoretical pumping work of 25%. However, the real pumping work depends on the control concept and can therefore deviate from this value e.g. due to the part load efficiency and other effects. Due to experiences, a well operated mass flow controlled network exhibits a power consumption which refers to a pump operation that considers the full-load hours of the heat consumers. Hence for an optimistic pumping scenario, 2000 annual full-load hours (as for the heat production) instead of 8760 annual full-load hours are considered resulting in 22.8% of the pessimistic electricity costs. Although the optimistic pumping is more realistic for nowadays networks, the reference calculations are performed with the pessimistic scenario ascertaining an overestimation of the pumping costs and the minimum pipe diameter.

2.2.3. Service and maintenance

For district heating networks, the service and maintenance costs are considerably lower than the capital and the electricity costs and therefore neglected.

### Table 1

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heat conductivity insulation material</td>
<td>0.026</td>
<td>W/(m K)</td>
</tr>
<tr>
<td>Insulation thickness</td>
<td>30–110</td>
<td>mm</td>
</tr>
<tr>
<td>Soil temperature</td>
<td>10</td>
<td>°C</td>
</tr>
<tr>
<td>Heat conductivity soil</td>
<td>1.2</td>
<td>W/(m K)</td>
</tr>
<tr>
<td>Cover depth of pipes</td>
<td>0.6</td>
<td>m</td>
</tr>
<tr>
<td>Roughness of pipe walls</td>
<td>0.01</td>
<td>mm</td>
</tr>
<tr>
<td>Heat capacity of water at 60 °C</td>
<td>4184</td>
<td>J/(kg K)</td>
</tr>
<tr>
<td>Density of water at 60 °C</td>
<td>983</td>
<td>kg/m$^3$</td>
</tr>
<tr>
<td>Kinematic viscosity of water at 60 °C</td>
<td>4.873 $10^{-7}$</td>
<td>m$^3$/s</td>
</tr>
<tr>
<td>Minimum flow velocity in the pipeline</td>
<td>0.35</td>
<td>m/s</td>
</tr>
<tr>
<td>Pump efficiency</td>
<td>80%</td>
<td>%</td>
</tr>
<tr>
<td>Electric pump drive efficiency</td>
<td>90%</td>
<td>%</td>
</tr>
</tbody>
</table>

2.3. Investment costs and economic parameters

The investment costs for the pipelines depend on pipe type, nominal diameter, and insulation class as well as the pipe-laying costs. In the study, reference values from suppliers confirmed by experiences from existing networks are applied and values for rigid plastic jacket pipes for underground installation in open field as depicted in Table 3 serve as cost base [10]. Pipe-laying in roads results in 23% higher total costs for DN 80 and 18% higher costs for DN 200. The material costs strongly increase with the pipe diameter and dominate the total costs, while the trench costs increase only slightly with the pipe diameter.

2.4. Piping design

The calculations are performed for all nominal diameters between DN 20 and DN 200 based on the actual inner diameters of rigid plastic jacket pipes which differ substantially from the numerical values of the DN labels (Table 2). Since the calculations cover a wide span, the ranges with appropriate flow velocities are considered in the graphs. Within these ranges, the velocities are limited by the maximum technically feasible flow velocities in order to prevent cavitation pitting and unacceptable noise emissions in the district heating pipelines as shown in Table 2 and derived from recommendations from Austria by ÖKL [11]. Instead of specifying maximum flow velocities, recommended values for the specific pressure differences are additionally indicated in Fig. 1 based on [11] and [12]. QM Holzheizwerke recommends a design value of 150–200 Pa/m [5]. Based on practical experience, values of up to 250 Pa/m to cover peak loads during maximally 500 h annually are also recommended [10]. Fig. 1 shows flow velocities for specific pressure differences of 100 Pa/m, 200 Pa/m, and 300 Pa/m determined by the approximation formula for the friction factor in the transition section [13] and assuming pipe friction factors of 0.020 for DN 20, 0.016 for DN 80 and 0.015 for DN 400. The comparison reveals the recommendations by ÖKL to result in a similar design compared to the calculations with maximum pressure difference of slightly less than 300 Pa/m.

2.5. Model district heating system

A district heating network consists of one or several heat production stations, the distribution network, and the heat consumers. According to its size and complexity, the network has one or several heat stations, different network structures (linear, radial, loop, mesh network, etc.) and more or less distributed heat consumers along the pipeline. The structure is determined by urbanistic factors, the network size, and the integration of heat producers. In order to describe the individual influence of each parameter on efficiency and profitability, a simplified system is introduced which consists of one heat station and one pipeline. As base case, all heat consumers are assumed at the final distance of the pipeline. This situation equals the theoretical case of one single consumer and it refers to a worst case assumption with maximum investment costs and maximum heat losses.

As alternative scenario, a relevant number of evenly distributed consumers along the pipeline is calculated. This enables a step-wise reduction of the pipe diameter and can be regarded as an optimistic case for the network structure.

As described in Table 4, the reference network exhibits a linear heat density of 2 MWh pipeline input per year and meter of pipeline. Since the linear heat density is usually referred to one unit of heat supplied to the consumers, while here, the pipeline input is used as basis, the heat distribution losses need to be considered to compare the linear heat density presented here with other data. In

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case of 10% losses, the linear heat density of the reference case then refers to 1.8 MWh/(a m). This value is recommended as target value by Ref. [5] to enable an economic network operation at heat distribution losses of less than 10%.

For the reference case, a constant supply temperature of 80 °C and a constant temperature difference between supply and return of 30 K are assumed. This corresponds to a return temperature of 50 °C and an average network temperature of 65 °C as illustrated in Fig. 2. The temperature changes along the pipeline due to heat losses are neglected. The soil temperature, which is responsible for the heat losses of the network to the ambient, is assumed to be 10 °C thus resulting in a temperature difference between the network and the ambient of 55 °C. With these assumptions, a mass flow of water in the pipeline of 28 m3/h is needed for the reference network with 1 MW heat input into the pipeline as shown in Fig. 3. Since the mass flow is inversely proportional to the temperature difference between supply and return, it increases with decreasing temperature difference between supply and return as illustrated in Fig. 3. Consequently, a higher return temperature than the design value e.g. due to fouling in the substations leads to a higher demand of the mass flow. This causes an increased pumping work or a reduced heat distribution capacity of the pipeline. If the temperature difference is reduced from 30 K to 15 K, the mass flow needs to be doubled to 56 m3/h which causes an increase of the pumping work in the order of a factor of 4 for a given pipe diameter, if a doubling of the flow velocity is possible.

### 3. Results for a linear network

This chapter describes the sensitivity analysis for a linear network with one single consumer in the final distance. This refers to a theoretical network structure, which is unfavourable with respect to economy. The influence of the network structure is discussed in chapter 4.

#### 3.1. Heat distribution losses

Prior to calculate the operating costs, the heat distribution losses and the pressure difference are evaluated for each investigated case. Figures on the influence of the parameters on the heat losses are presented in Ref. [10] and show that the reference case with insulation class Series 2 and minimum diameter yields heat distribution losses of 10.5%. Series 1 result in an increase to 13.0%, while Series 3 enable a reduction to 9.0%. The target value of 10% as proposed by Ref. [5] is achieved with the maximum insulation class if the minimum or one nominal diameter larger is applied.
3.2. Capital costs and operating costs

Fig. 4 shows the specific capital costs, the fuel costs to cover the heat losses, and the electricity costs for pumping as function of the nominal diameter DN for the reference case. For the resulting total heat distribution costs, the available nominal diameters are indicated with a marker in the graph and the technically feasible pipe diameters are illustrated with filled markers. While the electricity costs decrease with increasing pipe diameter due to a decreasing pressure difference, the capital costs and the fuel costs increase due to increasing investments and heat losses, respectively. The heat distribution costs therefore exhibit a minimum which for the reference case appears at a nominal diameter DN 80 and refers to 2.16 c/kWh. Since smaller diameters exhibit inadmissibly high flow velocities, the economically ideal diameter corresponds to the smallest technically feasible one.

In the reference case, the dominant contribution to the heat distribution costs results from the capital costs with 1.34 c/kWh corresponding to a share of 62%. The fuel costs contribute 0.52 c/kWh or 24%, while the electricity costs account for 0.30 c/kWh or 14% for the pessimistic pumping assumptions. For well operated networks with mass flow control and a heat production with 2000 annual full-load hours, the electricity consumption is reduced to

Table 4
Input parameters (variables) and derived parameters (determined by variables) for the reference case.

<table>
<thead>
<tr>
<th>Group</th>
<th>Parameter</th>
<th>Unit</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Input parameters</td>
<td>Connection load</td>
<td>MW</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>Pipeline length</td>
<td>m</td>
<td>1000</td>
</tr>
<tr>
<td></td>
<td>Full-load hours heat production</td>
<td>h/a</td>
<td>2000</td>
</tr>
<tr>
<td></td>
<td>Network operation hours</td>
<td>h/a</td>
<td>8760</td>
</tr>
<tr>
<td></td>
<td>Supply temperature</td>
<td>°C</td>
<td>80</td>
</tr>
<tr>
<td></td>
<td>Temperature difference between supply and return</td>
<td>K</td>
<td>30</td>
</tr>
<tr>
<td></td>
<td>Soil temperature</td>
<td>°C</td>
<td>10</td>
</tr>
<tr>
<td></td>
<td>Insulation class (Series)</td>
<td></td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>Electricity price</td>
<td>c/kWh</td>
<td>16.5</td>
</tr>
<tr>
<td></td>
<td>Fuel price</td>
<td>c/kWh</td>
<td>4.15</td>
</tr>
<tr>
<td></td>
<td>Capital interest rate</td>
<td>%/a</td>
<td>3.0</td>
</tr>
<tr>
<td></td>
<td>Calculation duration</td>
<td>a</td>
<td>30</td>
</tr>
<tr>
<td>Derived parameters</td>
<td>Linear heat density</td>
<td>MWh/(a m)</td>
<td>2.0</td>
</tr>
<tr>
<td></td>
<td>Return temperature</td>
<td>°C</td>
<td>50</td>
</tr>
<tr>
<td></td>
<td>Average network temperature</td>
<td>°C</td>
<td>65</td>
</tr>
<tr>
<td></td>
<td>Temperature difference between network and soil (ambient)</td>
<td>°C</td>
<td>55</td>
</tr>
<tr>
<td></td>
<td>Annuity factor</td>
<td>%/a</td>
<td>5.10</td>
</tr>
<tr>
<td></td>
<td>Heat production costs</td>
<td>c/kWh</td>
<td>5.0</td>
</tr>
</tbody>
</table>

3.2. Capital costs and operating costs

Fig. 4 shows the specific capital costs, the fuel costs to cover the heat losses, and the electricity costs for pumping as function of the nominal diameter DN for the reference case. For the resulting total heat distribution costs, the available nominal diameters are indicated with a marker in the graph and the technically feasible pipe diameters are illustrated with filled markers. While the electricity costs decrease with increasing pipe diameter due to a decreasing pressure difference, the capital costs and the fuel costs increase due to increasing investments and heat losses, respectively. The heat distribution costs therefore exhibit a minimum which for the reference case appears at a nominal diameter DN 80 and refers to 2.16 c/kWh. Since smaller diameters exhibit inadmissibly high flow velocities, the economically ideal diameter corresponds to the smallest technically feasible one.

In the reference case, the dominant contribution to the heat distribution costs results from the capital costs with 1.34 c/kWh corresponding to a share of 62%. The fuel costs contribute 0.52 c/kWh or 24%, while the electricity costs account for 0.30 c/kWh or 14% for the pessimistic pumping assumptions. For well operated networks with mass flow control and a heat production with 2000 annual full-load hours, the electricity consumption is reduced to
0.07 c/kWh or less than 4% of the then resulting total of 1.99 c/kWh. The advantage of the smallest feasible pipe diameter then becomes even more emphasized.

Different boundary conditions, such as lower electricity prices and/or higher annuity can imply situations where the economically optimal diameter refers to unfeasible flow velocities. In this case, the smallest admissible nominal diameter needs to be chosen. Contrarily, higher electricity prices and/or reduced annuity can theoretically cause situations where the economically optimal diameter is larger than the smallest feasible one. The analysis however shows that this is not expected for networks with reasonable pumping at nowadays or even nearly doubled electricity prices [10]. The economic advantage of small pipe diameters confirms findings from a case study where even higher pressure differences of more than 300 Pa/m are considered [14].

3.3. Influence of pipe diameter

The pipe diameter exhibits a relevant influence on the heat distribution costs. A network with an increased diameter by one nominal size results in 5% higher heat distribution costs compared to 2.16 c/kWh (Fig. 4). A two sizes larger nominal diameter causes an increase in heat distribution costs by 30%.

3.4. Influence of interest rate

Since the capital costs represent the main cost factor, the interest rate exhibits a considerable influence on the total costs. Doubling the interest rate from 3% to 6% p.a. for a calculation period of 30 years results in an increase of the heat distribution costs for the reference case at 2.16 c/kWh by 20%, whereas interest-free capital decreases the costs by 20% [10].

3.5. Influence of electricity price

The pumping costs increase proportionally to the electricity price. Hence for the smallest diameter, doubling the electricity price increases the pumping costs of 14% for the pessimistic and of 4% for the optimistic scenario. In the case of a network with one nominal diameter larger than necessary, the electricity costs are reduced by roughly a factor of four and the impact of the electricity costs is becoming accordingly less important.

3.6. Influence of fuel price

Based on heat production costs of 5 c/kWh, halving the fuel price results in a decrease of the total costs by 14%. In the case of cost-free fuel, the reduction amounts to 26%, while doubling the fuel costs results in an increase of the total costs by 26% [10].

3.7. Influence of insulation class

Compared to the influence of the fuel price, the insulation class exhibits a minor impact on the costs. While the heat losses can be reduced by more than 10% for Series 3 instead of Series 2 class, the higher capital costs are not fully compensated by the fuel savings thus leading to slight increase in the heat distribution costs of less than 2%.

3.8. Influence of temperature difference between supply and return

The temperature difference between supply and return plays a crucial role for the network design and economy, as it primarily affects the necessary pipe diameter and it additionally influences the heat losses. A decrease in the temperature difference from 30 K to 15 K results in a theoretical increase of the losses from 10.5% to 13.0% in the reference case with the smallest diameter [10]. In order to operate the network at halved temperature difference, it is however necessary to increase the nominal diameter by one step due to the doubled mass flow rate. This results not only in higher investment costs but also in an additional increase of the losses to 13.5%. The losses contrarily decrease with increasing temperature difference and enable the use of smaller pipe diameters. As illustrated in Fig. 5, an increase by 15 K enables to reduce the nominal diameter by one size, while a reduction by 15 K has the opposite effect. At the optimum nominal diameters, the costs are thus reduced from 2.16 c/kWh to 1.82 c/kWh or by 15% upon increase of the temperature difference from 30 K to 45 K. 15 K instead of 30 K contrarily induces a cost increase to 2.94 c/kWh or by 36%.

3.9. Influence of full-load hours and linear heat density

In the reference case, 2000 annual full-load hours are assumed for the heat production while the district heating network is operated during 8760 h annually. Doubling the full-load hours of the heat production to 4000 h/a cuts the specific heat distribution losses in half since the absolute losses are constant at doubled heat supply [10]. Halving the full-load hours correspondingly results in doubling the specific losses.

The linear heat density is proportional to the full-load hours of the heat production if all other parameters remain constant. In the case of a year-round operated network, the doubling of the full-load hours (and consequently the doubling of the linear heat density) results in the halving of the specific heat distribution costs since the heat supply is doubled at equal expenditures. The specific costs are hence inversely proportional to the full-load hours or the linear heat density as depicted in Fig. 6 for the district heating network with a connection load of 1 MW and a pipeline length of 1000 m.

Varying the full-load hours of the heat production at constant pipeline length and connection load shifts the linear heat density in a directly proportional way. The influence of the full-load hours may therefore also be described by the linear heat density which is introduced as parameter in Figs. 6–8.

3.10. Influence of network length and connection load

Doubling the connection load of the given network from 1 MW to 2 MW yields in the doubling of the linear heat density from 2 to 4 MWh/(a m). In order to distribute the increased heat load, an increase in pipe diameter by one nominal size is necessary. The heat distribution losses would however be halved at the same diameter.

Fig. 5. Heat distribution costs as function of the nominal diameter for different temperature differences. Reference case: 30 K.
As shown by the contribution of the individual cost factors in or by 32% if in both cases the smallest possible diameter is chosen. The increase in heat distribution costs from 2.16 c/kWh to 2.86 c/kWh reference case in Fig. 6 reveals that the 2 MW network yields an increase in heat distribution costs from 10.5% to 11.0% as summarised in Table 5. Due to the shift to a larger diameter, the actual specific losses amount to slightly more than half. Doubling the connection load from 1 MW to 2 MW at constant linear heat density of 2 MWh/(a m) refers to a doubled pipeline length of 2000 m. To distribute 2 MW, an increase in pipe diameter from DN 80 to DN 100 is needed resulting in an increase of the heat distribution losses from 10.5% to 11.0% as summarised in Table 5 and Fig. 7. The diagram describes the heat distribution costs for the 2 MW network and illustrates the need of DN 100. The comparison with the reference case in Fig. 6 reveals that the 2 MW network yields an increase in heat distribution costs from 2.16 c/kWh to 2.86 c/kWh or by 32% if in both cases the smallest possible diameter is chosen. As shown by the contribution of the individual cost factors in Table 5, the main increase results from higher capital costs followed by an increase of the pumping costs, while the additional fuel costs are of minor importance. 

Fig. 8 shows the case of a network with halved pipeline length and connection load. The inverse effects thereby appear with a reduction of the heat distribution costs from 2.16 c/kWh to 1.77 c/ kWh or by 18%.

4. Influence of network structure

The sensitivity analysis in chapter 3 describes an unfavourable scenario of a linear network with one single consumer in the final distance. Since real network structures reveal a broad variety which enables a separate evaluation of the influence of one single parameter, two additional characteristics are introduced to describe the influence of the network structure:

1. For the basic network structure a radial connection can be assumed as best case while a linear connection describes the worst case.
2. For the pipeline structure, all consumers (or one theoretical consumer respectively) are assumed at the final distance of the pipeline describing the worst case. As more favourable scenario, the consumers are assumed to be evenly distributed along the pipeline.

To investigate the influence of radial and linear connection as well as the consumer distribution, a virtual network module of 0.5 MW and 500 m is introduced in Fig. 9. To enable a comparison with the sensitivity analysis, 2000 annual full-load hours referring to a linear heat density of 2 MWh/(a m) are assumed as for the reference case in chapter 3. As described in Fig. 8 the 0.5 MW module then exhibits total heat distribution costs of 1.77 c/kWh. As evidence from Fig. 9, doubling the connection load of the module to 1 MW and the pipeline length to 1000 m by application of two identical modules in a radial network does not affect the economic situation and thus results in identical heat distribution costs as illustrated in Table 6 and Fig. 10. This remains true for the implementation of any additional module in a radial connection illustrated by doubling once more to 2 MW and 2000 m. However, the opportunities to increase the connection load by radial expansion is physically limited in real applications.

Doubling the connection load of the module by a linear expansion of the pipeline with one consumer at the final distance results in the reference case with 1 MW and 1000 m pipeline discussed so far and refers to heat distribution costs of 2.16 c/kWh introduced in Table 6 and Fig. 10. The implementation of four evenly distributed consumers along the pipeline enables a step-wise reduction of the pipe diameter which results in reduced capital, fuel, and pumping costs. This enables a cost reduction from 2.16 c/ kWh to 1.99 c/kWh. Doubling once again by linear expansion results in the pre-described case of 2 MW and 2000 m with heat distribution costs of 2.86 c/kWh. For this case, evenly distributed consumers enable a cost reduction to 2.45 c/kWh or by 14%. A linear expansion to 4 MW and 4000 m leads to heat distribution costs of 3.78 c/kWh or 3.33 c/kWh respectively.

Since a radial expansion to more than four branches is not considered realistic for the investigated size range, the radial expansion to 4 MW is assumed to be performed by linear expansion of the four introduced pipes. Since this case denoted as 'radial and linear' consists of four radial branches of 1 MW linear connection each, it exhibits identical heat distribution costs as the 1 MW linear connection, hence 1.99 c/kWh in case of distributed consumers as displayed in Table 6 and Fig. 10.
Table 5
Influence of the connection load on heat losses and heat distribution costs. Comparison of a district heating system with 1 MW and 1000 m (reference case) with a linearly doubled network with 2 MW and 2000 m operated at 2000 annual full-load hours. Both cases thus refer to a linear heat density of 2 MWh/(a m) [10].

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Unit</th>
<th>1 MW 1000 m</th>
<th>2 MW 2000 m</th>
<th>Δ</th>
</tr>
</thead>
<tbody>
<tr>
<td>Optimum nominal pipe diameter</td>
<td>–</td>
<td>DN 80</td>
<td>DN 100</td>
<td>+1 DN</td>
</tr>
<tr>
<td>Annual heat losses</td>
<td>%</td>
<td>10.5%</td>
<td>11.0%</td>
<td>+0.5%</td>
</tr>
<tr>
<td>Heat distribution costs</td>
<td>c/kWh</td>
<td>0.30</td>
<td>0.59</td>
<td>+0.29</td>
</tr>
<tr>
<td>electricity</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>capital costs</td>
<td>c/kWh</td>
<td>1.34</td>
<td>1.73</td>
<td>+0.39</td>
</tr>
<tr>
<td>heat losses</td>
<td>c/kWh</td>
<td>0.52</td>
<td>0.54</td>
<td>+0.02</td>
</tr>
<tr>
<td>Total</td>
<td>c/kWh</td>
<td>2.16</td>
<td>2.86</td>
<td>+0.70</td>
</tr>
</tbody>
</table>

Fig. 9. Definition of different network expansions from 0.5 MW introduced as an initial module to 4 MW by radial and linear expansion and for one single consumer and for distributed consumers.

5. Conclusions

A sensitivity analysis to investigate the heat distribution costs of district heating networks with a connection load between 0.5 MW and 4 MW is performed. The reference case exhibits a connection load of 1 MW, a pipeline length of 1 km in open-field conditions, and a network operation with 2000 full-load hours per year corresponding to a linear heat density of 2 MWh per year and meter of pipeline length. In addition, pessimistic electricity costs with a pump operation at nominal load during 8760 h per year are assumed as reference case and compared to an optimistic (and however more realistic) scenario with 2000 h operated at nominal load thanks to mass flow control. For a network supply with heat costs of 5.0 c/kWh, an electricity price of 16.5 c/kWh, and capital at

Table 6
Heat distribution costs for different network expansions from 0.5 MW to 1 MW, 2 MW, and 4 MW, a linear heat density of 2 MWh/(a m) and a heat production with 2000 annual full-load hours.

<table>
<thead>
<tr>
<th>Connection load/Pipeline length</th>
<th>Radial connection [c/kWh]</th>
<th>Linear connection</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.5 MW/500 m (mod)</td>
<td>1.77</td>
<td>1.77</td>
</tr>
<tr>
<td>1 MW/1000 m</td>
<td>1.77&lt;sup&gt;a&lt;/sup&gt;</td>
<td>2.16</td>
</tr>
<tr>
<td>2 MW/2000 m</td>
<td>1.77&lt;sup&gt;b&lt;/sup&gt;</td>
<td>2.86</td>
</tr>
<tr>
<td>4 MW/4000 m</td>
<td>1.99&lt;sup&gt;c&lt;/sup&gt; (radial and linear)</td>
<td>3.78</td>
</tr>
</tbody>
</table>

<sup>a</sup> The radial connection with 1 MW corresponds to 2 modules at identical costs as 1 module.

<sup>b</sup> The radial connection with 2 MW corresponds to 4 modules at identical costs as 1 module.

<sup>c</sup> The 4 MW case “radial and linear” consists of four radial connections of 1 MW systems with linear connections of distributed consumers. Consequently these two cases exhibit identical costs of 1.99 c/kW.
an annuity of 5.1% p.a. (3% p.a. for 30 years), heat distribution costs of 2.16 cents per kWh heat input to the pipeline are obtained for the optimum pipe diameter. With a share of 62% the capital costs clearly dominate the total costs, while the fuel costs to cover the heat losses amount to 24% and the electricity costs to 14% for the pessimistic pumping scenario. In case of street conditions for the excavation, the capital costs and their contribution to the total costs further increase. For optimised pumping and else constant reference conditions, the electricity consumption decreases enabling heat distribution costs of 1.93 c/kWh with a contribution of the electricity of 4%.

With respect to the network structure, the reference scenario refers to the worst case of all heat consumers or one single consumer being located at the final distance of the pipeline. For evenly distributed heat consumers along the pipeline, the heat distribution costs are reduced from 2.16 c/kWh to 1.99 c/kWh or by 8% due to a step-wise reduction of the pipe diameter. On the other hand, the presented heat distribution costs are based on the heat input to the pipeline, while the tradeable heat output from the network is reduced by the heat losses, which account to 9% of the heat input in case of the best insulation class for the reference case [10]. Hence the distribution costs based on tradeable heat are 10% higher than the presented heat distribution costs. The breakdown of the investment costs shows that the capital costs are the dominating effect of the capital costs, the economically optimal nominal diameter is never larger than the smallest technically feasible one required for avoiding cavitation pitting and noise emissions for the reference network. A sensitivity analysis reveals, that this remains valid even if the fuel price, the interest rate, and the electricity price change in a relevant range as follows [10]:

a) The smallest pipe diameter remains the most economic one for a fuel price of zero, which reduces the effect of the heat losses that decrease with decreasing pipe diameter.

b) For a decreasing interest rate, the smallest pipe diameter remains the most economic one down to an interest rate of zero.

c) Doubling the electricity price to 33 c/kWh leads to an increase of the heat distribution costs by 4% in the optimistic and by 14% in the pessimistic pumping scenario. For the pessimistic pumping, the heat distribution costs for the smallest and the second smallest pipe diameter then become equal, while for the optimistic scenario, the smallest diameter remains most economic. Hence for reasonable pumping technology, the smallest pipe diameter remains most economic for more than doubled electricity prices.

In order to achieve an economic optimisation, a network design at the smallest possible nominal diameter is therefore decisive. This requirement is already true for pessimistic pumping costs and fortified for optimised pumping. For the reference case, one nominal size larger than the smallest necessary one increases the heat distribution costs by 9%, two nominal sizes larger by 30%. The breakdown of the investment costs shows that the capital costs are for their part dominated by pipe costs. The excavation costs only marginally depend on the pipe diameter and have a minor influence on the total costs in open-field conditions.

Besides the design at the smallest pipe diameter, a large temperature difference between supply and return is decisive. Furthermore, low capital costs and low specific heat losses can be achieved due to a high linear heat density, which for a given network is determined by the annual full-load hours and the connection load. In addition, low return temperatures positively contribute to the efficiency of the heat production. The insulation class however has only a minor influence on the profitability since the increase in capital costs is in the same magnitude as the cost reduction due to fuel savings. Nevertheless, maximum insulation is recommended because it is energetically worthwhile and represents an asset in the case of increasing energy prices.

**Acknowledgements**

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References


