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Influence of system design on heat distribution costs in district heating

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ABSTRACT

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 CO_2 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 CO_2 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 a 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].

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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 losses in the network, the electricity costs for the pumping, and the service and maintenance costs. Hence the total specific heat distribution costs c are calculated as follows:

$$c = c_{cap} + c_{op} \tag{1}$$

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:

$$c_{cap} = \frac{I \cdot a}{\dot{Q} \cdot \tau}(100c/€) \tag{2}$$

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

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

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

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

The operating costs are found as:

$$c_{op} = c_f + c_e + c_m \tag{4}$$

specific fuel costs:

$$c_f = f \ p_f \ \eta_a^{-1} \tag{5}$$

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

specific electricity costs:

$$c_e = e \ p_e \tag{6}$$

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

specific maintenance costs:

c_m = costs for service and maintenance in [c/kWh]

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 denoted as ‘fuel

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