

Simulation and optimization of the district heating network in Scharnhauser Park

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Abstract

The programme spHeat presented in this paper is designed for the hydraulic and thermal simulation of meshed pipes networks. It calculates the operating parameters of the system with hourly time steps and provides monthly and annual balances of heat load and supply. Entities like supply and return temperature, flow rate, heat losses and pump energy are calculated and compared for different operating scenarios. The biomass ORC power plant efficiency is also evaluated depending on the investigated load situation. Solar energy supply in the network of Scharnhauser Park in the South of Germany is analysed under local climate conditions.

Keywords

District heating (DH) network, solar assisted, graph theory, operation optimization

Introduction

During the last twenty years different approaches for modelling DH networks have been applied and validated. The node method was developed at the Technical university of Denmark [1]. The aggregation methods presented in [2] and [3] have been separately developed in Denmark and Germany. The authors reduced the number of modelled pipes (up to 7% of the initial pipes) without significantly decreasing the accuracy of the model. Based on the graph theory, the programme SMILE [4] developed at the Technical University of Berlin calculates the flow rates and pressure losses in the network. It already has been used for planning and control strategy optimization of a German DH system. Several commercial tools like TERMIS [5], sisHYD [6] and Grades Heating [7] have been upgraded during the last years to simulate both steady and dynamic network behaviour.

This paper presents the programme spHeat developed within the POLYCITY [8] project. The purpose of the work is to establish a tool for modelling DH networks, which can be coupled to building demand simulations and renewable power plants. The DH system in Scharnhauser Park presents the first case study for spHeat. The distribution of the volumetric streams is calculated based on a graph-theoretical approach similar to the method applied in SMILE. A simple algorithm is implemented in MATLAB [9] to dynamically determine the water temperature propagation.

The DH network in Scharnhauser Park

The CHP plant of Scharnhauser Park provides 584 consumers with local heat. Hot water with temperatures between 70°C and 95°C is distributed to consumers through a closed network with multiple-loop topology. The studied part of the network consists of connected underground pipes with the total length of approx. 13.5km. The consumer buildings (grey

blocks in the left side of Figure 1) are indirectly supplied through heat exchangers and are equipped with local flow control systems. The commercial software sisHYD has been used by the operating company SWE (Stadtwerke Esslingen) to model and manage the heat distribution System in Scharnhäuser Park.



Figure 1: The DH network in Scharnhäuser Park (left: real network, right: reduced network)

The Network simulation

The programme structure

In order to limit the simulation time, the modeled network is restricted to 6 main meshes (supply and return sub-network 3 meshes each). The consumers are centralized to 7 load stations as shown in the right side of Figure 1. For high accuracy of the results, the consumer groups were properly chosen using appropriate tools in the geographic information software GeoMedia. The spHeat program consists of 5 sub-programs with appropriate input data like pipe length and diameter, supply temperature and heat load (see Figure 2). The volume flow control is implemented using a simple P-controller. Return temperatures between 50 and 65°C are considered as a set point for the control system.

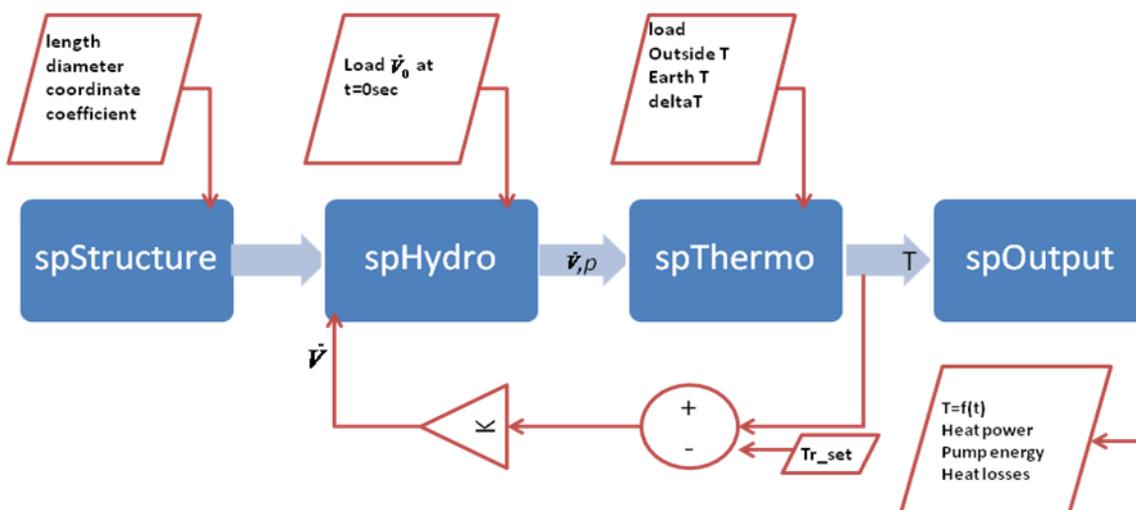


Figure 2: the spHeat programme structure

The model is based on a quasi-dynamic approach, where the flow and pressure are calculated using a static flow model in spHydro. The temperature is calculated dynamically in spThermo depending on the flow velocity and several boundary conditions like earth and outside temperature. The backward-difference method is implemented to solve the differential equations of heat transfer along the pipes. The following assumptions are made during the calculation:

- High flow resistance in the node area is neglected
- The fluid pipe flow is one-dimensional
- Turbulent fluctuations are not considered
- The network is free of leakage
- The fluid characteristics like density and heat capacity are constant

The hydraulic calculation

The network description is based on the graph theory [10], [11]. The DH system in Figure 3 is considered as a collection of nodes connected by directed edges (pipes): the network graph. The studied graph consists of 11 nodes, 13 edges and 3 circuits (a path which ends at the node it begins). Each circuit contains at least one link: an edge that belongs only to this circuit.

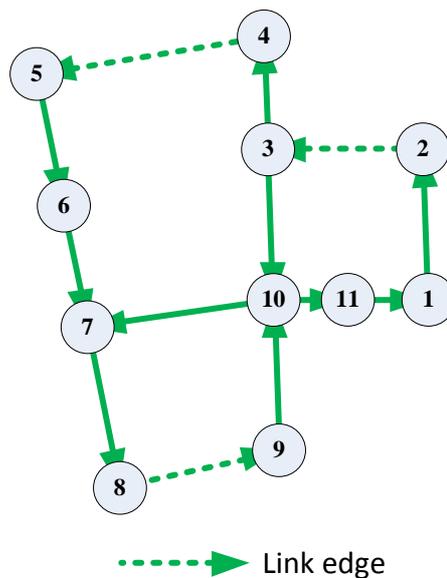


Figure 3: The network graph

The sub-programme spStructure stores the network graph in a matrix data structure containing the incidence matrices $A = (a_{i,j})$ and $B = (b_{i,j})$:

$$A = \begin{pmatrix} 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & -1 & 0 & 0 \\ -1 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & -1 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & -1 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & -1 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & -1 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & -1 & 1 & 0 & 0 & 0 & 0 & 0 & -1 \\ 0 & 0 & 0 & 0 & 0 & 0 & -1 & 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & -1 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & -1 & 1 & 0 & -1 & 1 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & -1 & 1 & 0 & 0 \end{pmatrix}$$

$$B = \begin{pmatrix} 1 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 1 & 1 & 0 \\ 0 & 0 & 1 & 1 & 1 & 1 & 0 & 0 & 0 & 0 & 0 & -1 & -1 \\ 0 & 0 & 0 & 0 & 0 & 0 & 1 & 1 & 1 & 0 & 0 & 0 & 1 \end{pmatrix}$$

The 11-by-13 matrix A associates each edge with its pair of nodes. The 3-by-13 matrix B describes the orientation of the edges in each circuit. In analogy to the Kirchhoff's circuit laws for calculating the current and the voltage in electric circuits, we build the equations describing the flow rates and pressure losses in the network:

- The law of conservation of mass: the total amount of flow into one node is equal to the total amount of flow out of it:

$$A\dot{V} = 0$$

With the flow vector $\dot{V} = \{\dot{V}_1, \dot{V}_2, \dots, \dot{V}_{11}\}$

- The law of conservation of energy: the sum of all pressure differences along the edges of one circuit is equal 0:

$$B\Delta p = 0,$$

With the pressure difference vector $\Delta p = \{\Delta p_1, \Delta p_2, \dots, \Delta p_{11}\}$

We also have three independent link edge flows belonging to three different circuits. All other volume flows can be calculated as a linear combination of them. Since the columns of B describe which link edge stream flows in which pipe, we obtain:

$$\dot{V} = B^T \dot{V}_M$$

With the link flow vector $\dot{V}_M = \{\dot{V}_1, \dot{V}_2, \dot{V}_3\}$. This equation reduces the number of unknown entities to three. We consider each pipe as a flow resistance whose pressure loss is proportional to the square of its flow rate [4]. That means in general:

$$\Delta p = R_r \dot{V}^2$$

R_r depends on the pipe's coefficient of friction, the fluid density and both length and diameter of the considered pipe. If we develop this relationship for all pipes, the equation of conservation of energy becomes:

$$B \cdot f(\vec{V}) = \vec{0} \quad ; f : \mathfrak{R}^n \rightarrow \mathfrak{R}^n$$

With the nonlinear vector function f . We substitute \vec{V} to obtain:

$$B \cdot f(B^T \cdot \vec{V}_M) = F(\vec{V}_M) = \vec{0}$$

Using the vector function $F = f * B^T$

We solve this nonlinear equation system by means of a Newton algorithm [12]:

- We set an initial value for \vec{V}_M
- We calculate $F(\vec{V}_M)$
- We calculate the Jacobian matrix JF of F using $JF = B \cdot \text{diag}(f') \cdot B^T$ and $f'_i = \frac{\partial f_i}{\partial \dot{V}_i}$
- We solve the linear equation system $JF \cdot \Delta \vec{V}_M = -F(\vec{V}_M)$
- We calculate $\vec{V}_M = \vec{V}_M + \Delta \vec{V}_M$
- We repeat the last four procedures until $\Delta \vec{V}_M$ becomes too small. The flow rates can be subsequently calculated using $\dot{V} = B^T \dot{V}_M$

The thermal calculation

Once the flow rates are determined for all pipes, spThermo calculates the propagation of heated water in the network. First the propagation within one pipe is introduced in this chapter. Then the complete algorithm for the network will be presented.

Each pipe contains a finite number of elements with the section A and length dx (Figure 4)

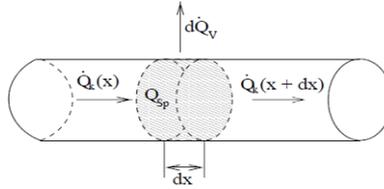


Figure 4: the pipe element

\dot{Q}_k and $d\dot{Q}_v$ describe the convective heat flow and heat loss flow respectively. We consider the following notation: m for the element mass, c_p for the specific heat capacitance, h for the specific enthalpy, k for the linear heat transmission coefficient, T for the water temperature and T_{sarth} for the pipe surrounding temperature. If we apply the first law of thermodynamic for one element:

$$\frac{\partial(mh)}{\partial t} = \dot{Q}_k(x) - \dot{Q}_k(x+dx) - d\dot{Q}_v$$

An approximation of $\dot{Q}_k(x+dx)$ with 1.st order Taylor series leads to:

$$\dot{Q}_k(x+dx) = \dot{Q}_k(x) + \frac{\partial \dot{Q}_k(x)}{\partial x} \cdot dx$$

Applied in the first equation, we get

$$\frac{\partial(mh)}{\partial t} = -\frac{\partial \dot{Q}_k(x)}{\partial x} \cdot dx - d\dot{Q}_v$$

Assuming the following two equations:

$$\dot{Q}_k(x) = \dot{m}_x h = \dot{m}_x c_p T$$

and

$$d\dot{Q}_v = k \cdot dx \cdot (T - T_{sarth})$$

We obtain:

$$m c_p \frac{\partial T}{\partial t} = -\dot{m}_x c_p \frac{\partial T}{\partial x} \cdot dx - k \cdot dx \cdot (T - T_{sarth})$$

$$\frac{\partial T}{\partial t} = -\frac{\dot{m}_x}{\rho A} \cdot \frac{\partial T}{\partial x} - \frac{k}{\rho A c_p} \cdot (T - T_{sarth})$$

This PDE describes the temperature propagation in the small element. We apply then the finite difference method to approximate $\frac{\partial T}{\partial t}$ and $\frac{\partial T}{\partial x}$ and iteratively solve the PDE:

$$\frac{\partial T(x,t)}{\partial x} = \frac{f(x,t) - f(x-dx,t)}{dx}$$

$$\frac{\partial T(x,t)}{\partial t} = \frac{f(x,t) - f(x,t-dt)}{dt}$$

Solving this PDE for an element series enables the determination of the temperature profile along the pipe after dt sec:

- The discretization of the pipe length into finite elements with the length dx each.
- The approximation of $\frac{\partial T}{\partial t}$ and $\frac{\partial T}{\partial x}$ according to the equations above
- The calculation of $\frac{\partial T}{\partial t}$ and $\frac{\partial T}{\partial x}$ using the previous temperature profile as initial condition and the pipe input temperature as boundary condition.
- The calculation of the new temperature profile based on the values $\frac{\partial T}{\partial t}$ and $\frac{\partial T}{\partial x}$

The pipe output temperature varies after each time step dt . In other words, new boundary conditions are available for the next pipe. This new condition (node temperature) results after the mixture of all streams flowing into this node [4]. For example if pipe 1 receives hot water from pipe 2 and 3, then:

$$T_1 = \frac{\sum \dot{m}_i T_{out,i}}{\sum \dot{m}_i} = \frac{\dot{m}_2 T_{out,2} + \dot{m}_3 T_{out,3}}{\dot{m}_2 + \dot{m}_3}$$

To determine the network temperature profile at the end of the simulation time t_s , spThermo runs the following steps:

- The definition of the initial temperature in the different nodes of the network
- The calculation of the temperature propagation in each pipe after dt sec using the finite difference method
- The calculation of the new node temperature using the rule of mixture
- The repetition of the last two steps until the end of the simulation time t_s

The simulation results

Dynamic simulations were run with the introduced programme to predict the heat propagation in the DH network in Scharnhäuser Park. To validate the model, three parameters were used: the return temperature, the flow rate and the heat loss percentage. Figure 5 and Figure 6 show a good agreement between calculated and measured data. The recorded supply temperature profile of Figure 6 was used as input value for this simulation. The calculated data show high fluctuations in both diagrams. They are mainly caused by sudden variations in the consumer load and high k-factor in the implemented P-controller. The low measured temperature values in Figure 6 are due to previous measurement error.

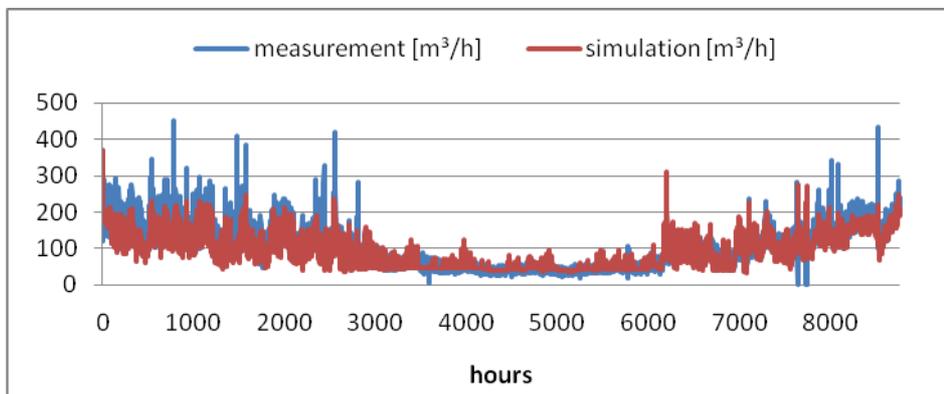


Figure 5: The flow rate in the DH network

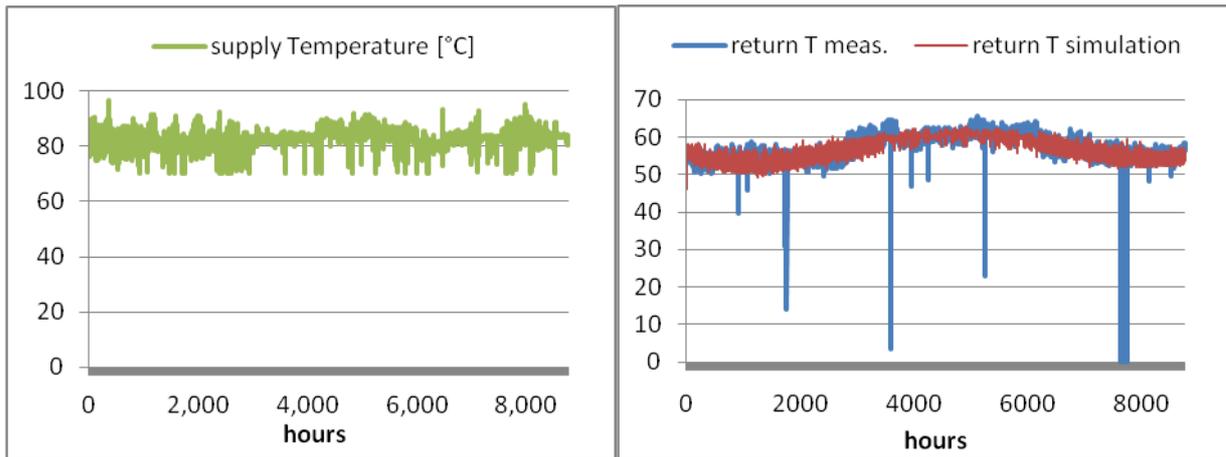


Figure 6: The supply and return temperature of the DH network

The calculated heat loss amounts to 8.5% and characterises the energy transmitted through the pipe cover to the earth. It is smaller than the real value of about 15%. The difference between the calculated and the measured percentage may be explained as follow:

The modelled network has a total pipe length of 11.16 km. An approximation for the remaining (unconsidered) pipe length is calculated acc. to the equation below:

$$Q_{l,r} = \int_{1.Jan.}^{31.Dec.} \{k \cdot L_r \cdot (T_{pipe} - T_{earth})\} dt$$

With:

$Q_{l,r}$ The heat losses in the remaining pipe length $L_r = 2.34\text{km}$

k The average heat transmission coefficient of the pipes

T_{pipe} The water temperature (in both supply and return pipes)

T_{earth} The earth temperature

The heat loss amounts to 9.6% including these extra losses. Further incertitude is due to:

- The neglecting of water leakage (approx. 1m³/day)
- The reduction of the number of heat transfer stations from 584 to only 7 which decreases the calculated heat losses within the building installations.
- The heat transmission coefficient may be higher than its nominal value in the pipe connection areas.

The Optimization

The operating pressure control

The control variables of the district heating in Scharnhauser Park are the supply temperature and the pump pressure. The temperature set point of the heated water depends on the ambient temperature according to the following relationship for winter mode:

$$T_{supply} = -1.316 \cdot T_{amb} + 85.26 \text{ [}^\circ\text{C]}$$

For ambient temperatures above 4°C, the supply temperature is fixed to 80°C. The static pump control is based on a constant pressure difference value between supply and return subsystem, which considers the pressure losses along the pipes in the worst case (i.e. in the case of maximal flow rate). The advantage of a dynamic pressure control is to decrease the pressure between the supply and return pipes to the minimum necessary level for given operating conditions. Higher pressure values during the summer are avoided and the pump operating costs can be minimized.

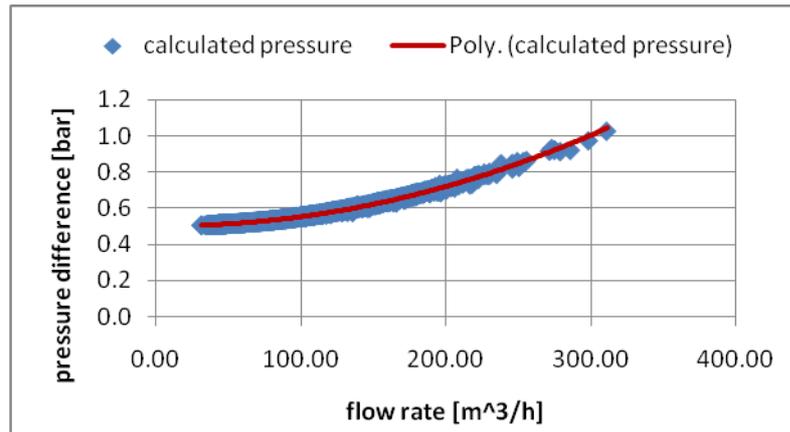


Figure 7: Fitting curve for dynamic pressure control

Figure 7 shows the necessary pressure difference that should be applied by the plant pumps depending on the total volume flow, indicated in the x-axis. Applying the approximated red curve as a control function $\Delta p = f(\dot{V})$ instead of a fixed set value (1bar) decreases the electrical pump energy by about 40% from 35.6MWh to 21MWh yearly. A pump efficiency of 65% was assumed in this calculation.

The consumer distribution

The impact of load distribution on the system performance has been investigated with spHeat. The following questions are important especially during the network layout phase: Is there a relationship between the average consumer distance from power plant and the heat losses? Can we supply the same number of consumers with the same load profile and with lower pump energy?

In a first step the yearly heat consumption of the Scharnhäuser Park was redistributed among the 7 consumers in order to get 3 different load repartitions (in addition to the real one). Figure 8 gives the average consumer distance to power plant weighted by load for all 4 cases.

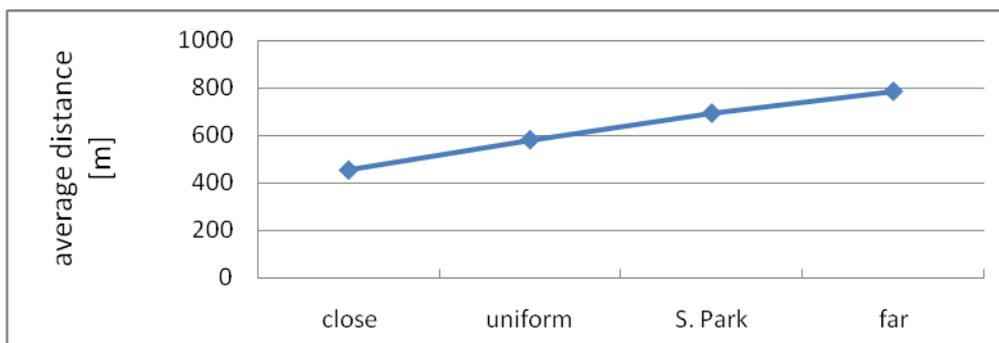


Figure 8: The average consumer distance

Second, dynamic simulations were run for each case. The total heating energy consumption was set to 24077 MWh/a and the measured supply temperatures of 2008 were used as input for the yearly simulation. In all cases a dynamic pressure control was applied. As shown in Figure 9, the yearly heat losses and the electric pump energy increase with increasing consumer distance from heat source. Although the curve in Figure 8 is quasi linear, the Scharnhäuser Park has an approximately uniform behaviour in Figure 9. In fact, Figure 8 illustrates the straight line distance to the power plant, without taking into account the real pipe length needed by the

heated water to reach the consumer. In a meshed network, this pipe length strongly depends on the water streams in the different pipes.

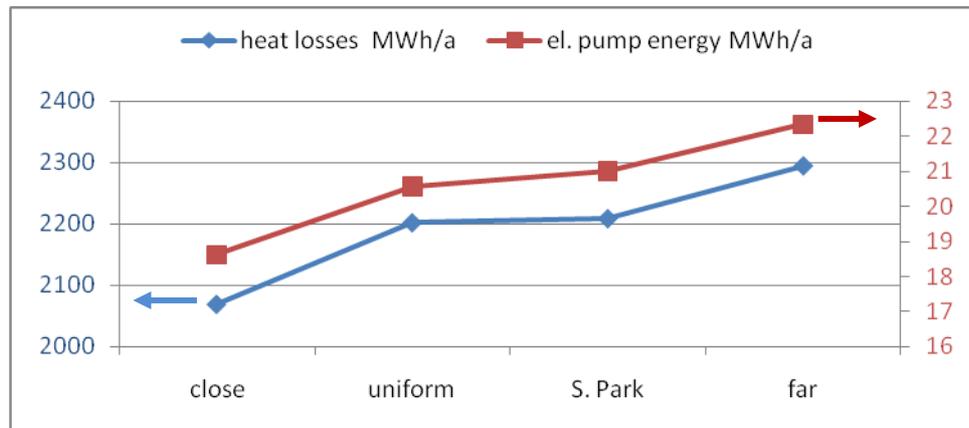


Figure 9: Heat losses and electric pump energy

Figure 9 demonstrates that we can deliver the same heat energy in a more efficient way. If the main consumers are closer to the power plant, the global temperature and flow rate levels of the network is lower. That leads to smaller heat and pressure losses along the pipes. However larger temperature differences between the consumer nodes are calculated for the close case. Far consumers (node 5 and node 8) would be supplied with slightly lower water temperatures (see Figure 10) especially in the winter season.

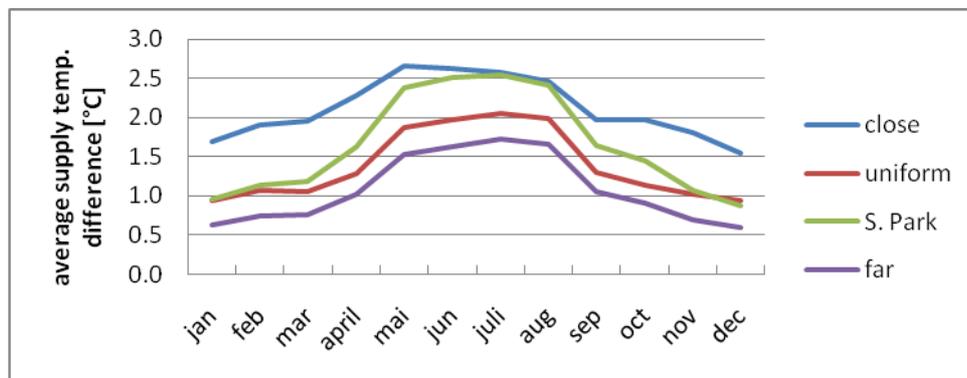


Figure 10: The supply temperature difference between consumers

The average temperature decrease in the winter can be neglected compared to the savings made in the pump energy and heat distribution. With approximately 1°C lower supply temperature for far nodes, the total heat needed for the Scharnhäuser Park can be delivered more efficiently (up to 11% lower heat losses).

The solar assisted network

This section presents the results of the solar assisted district heating network. The integration of 200m² preinstalled flat plate collectors into the supply pipes sub-network of the Scharnhäuser Park is investigated and the heat balances are calculated. A direct integration without heat storage unit is implemented in this case: water flows from the supply pipe into the collector heat exchanger circuit. It is heated proportionally to solar radiation and finally re-fed into the pipe. Depending on the selected location of heat injection, the mean supply temperature in the appropriate consumer side increases. Solar heat supply is used in this case to increase the operational temperature of distant consumers with lower supply temperatures. Supplying pipe 4 or 8, respectively connected to consumers 5 and 8, is therefore most efficient (see. Figure 11).

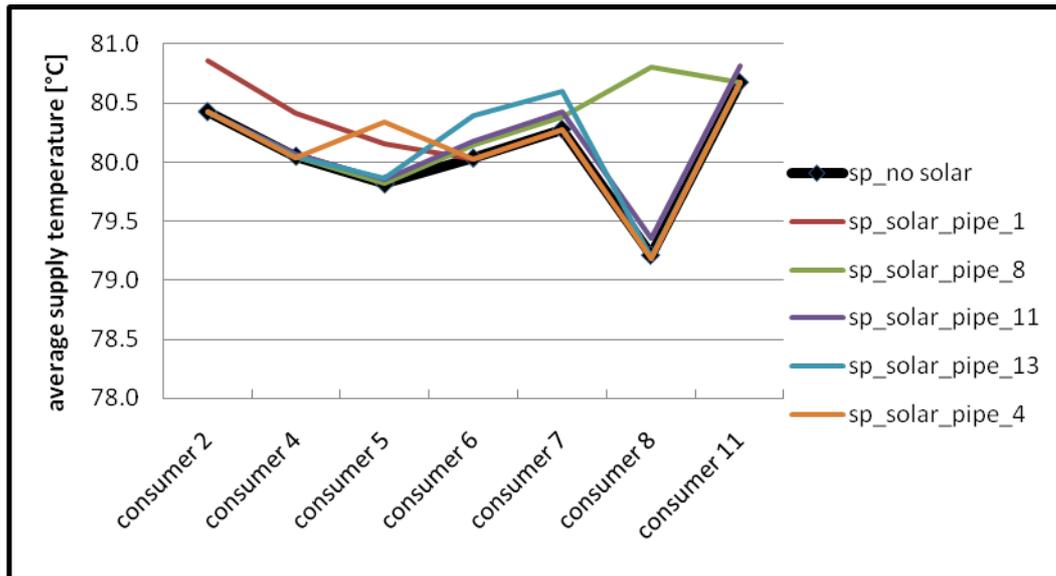


Figure 11: The average consumer supply temperature in 2008

Supplying for example pipe 8 with additional solar heat decreases the temperature difference range from around 1.5°C to 1°C over all consumers. A significant improvement is logically calculated in the summer. A DH network with solar assisted distant pipes and the main consumers concentrated around the heat source is a good alternative to the current system: higher efficiency and well-balanced temperature profile.

Another supply scenario consists of reducing the plant supply temperature and subsequently heating the water through the solar heat exchanger to maintain the initial operation temperature level. The energy savings for this case are presented in Figure 12 depending on the collector size. Using collectors with the aperture area of 200m² results in 0.2% solar fraction over the year with a specific solar gain of 248kWh/m²a. The high temperature level in the supply pipes limits the thermal collector efficiency and leads to relative low solar gain values.

However, the produced electric power of the modelled heat source (the biomass ORC power plant) decreases with reduced heat production and increasing supply temperatures. The electric energy illustrated in Figure 12 has been calculated in relationship to the produced thermal power P_{th} [kW] and supply temperature T [°C] using an empiric approximation based on measurement data fits:

$$P_e [kVA] = \frac{830,4}{0,97 * \left(\frac{5147,6}{P_{th}} \right) \frac{18,7 * T + \frac{9942,7}{1378,3 - 16,3 * T}}{0,3 * P_{th}}}$$

The heating energy savings are accompanied with lower electric energy values (Figure 12). Total savings about 2275€/a can be reached with 200m² collector surface (2385€/a saved through solar supply minus 110€/a electric energy sales). The electric consumption of the collector pumps is not considered.

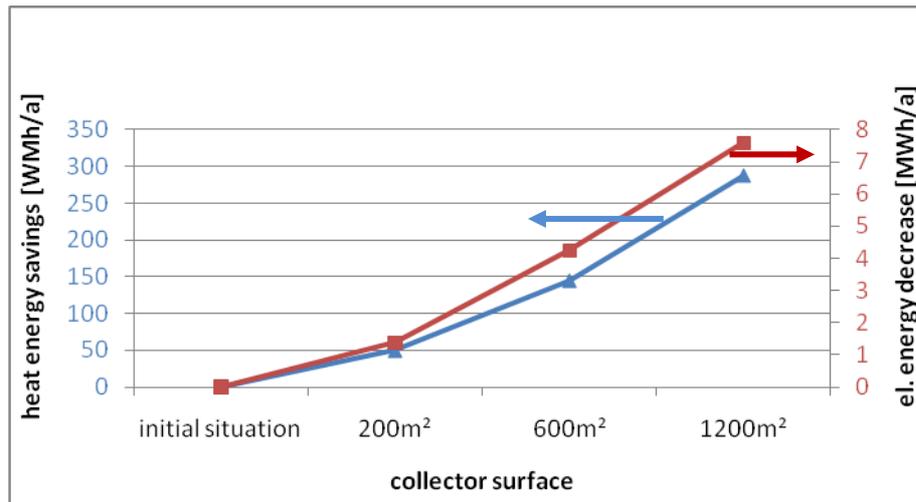


Figure 12: The energy balances of the solar-assisted system

Under local climate conditions, direct solar assistance with 200m² collector aperture does not have a significant economic benefit in the case of Scharnhäuser Park. A larger aperture surface has to be installed to increase the solar fraction. Supplying the return sub-network with solar energy may be more attractive due to the lower operating temperature. Further solar supply scenarios are investigated and will be published in the future.

Further improvements

Substituting the consumers in Scharnhäuser Park through 7 load groups significantly limits the calculated heat losses. The model validity should be improved using more detailed consumer classes.

Furthermore, the supply and return pipe sub-networks are hydraulically considered as separate systems. An intensive analysis of the hydraulic behaviour of house stations should be done to know more about the interactions between both network levels. A model for the whole system can be then developed.

Other solar supply scenarios with heat storage integration should be also evaluated.

Conclusions

In the paper a network model was introduced and used to simulate the DH system in Scharnhäuser Park. The programme structure in MATLAB was described and the obtained results were compared to the measured data. Applying a dynamic pressure control in the simulation reduces the pump energy costs by 40%. The influence of consumer distribution on heat losses was also investigated. The calculated solar fraction of the assisted system is very low under local climate conditions (0.2%). Other solar energy supply strategies have to be simulated and compared.

Acknowledgements

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Nomenclature

- T : Temperature [K]
- \dot{V} : Water flow [m³/s]
- Δp : Pressure loss [Pa]
- A : Element section [m²]

dx :	Element length [m]
dt :	Time interval [s]
\dot{Q}_k :	Convective heat flow [W]
$d\dot{Q}_V$:	Heat loss flow [W]
m :	Element mass [kg]
c_p :	Specific heat capacitance [J/kgK]
h :	Specific enthalpy [J/kg]
k :	Linear heat transmission coefficient [W/mK]
T_{earth} :	Earth temperature [K]
ρ :	Density [kg/m ³]
\dot{m} :	Mass flow [kg/s]
t_s :	Simulation time [s]

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