FLEXYNETS – A new district heating network concept for higher renewable and waste heat share

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Abstract

The FLEXYNETS project on low-exergy district heating and cooling systems has been started in summer 2015 in the framework of the European H2020 program. The project aims to develop a new generation of intelligent district heating and cooling networks that reduce energy transportation losses by working at temperature levels lower than 40 °C. Reversible heat pumps and chillers are used at laboratory scale to exchange heat with the DHC network on the demand side. In this way, the same network can provide contemporary heating and cooling. FLEXYNETS solutions integrates effectively multiple generation sources (including high- and low-temperature solar thermal, biomass, cogeneration and waste heat) where they are available along the DHC network. Two network types are considered in simulation: the classic supply-return type and the single-pipe system. This paper describes possible operation strategies and some control aspects related to the second network type.

Keywords: district heating/cooling, low temperature, low exergy, solar thermal feed-in, waste heat

1. Introduction

Traditional District Heating and Cooling (DHC) networks distribute energy from a centralized generation plant to a number of remote customers. As such, actual DHC systems suffer from significant heat losses, highly unexplored integration potential of different available energy sources into the same DHC network and high installation costs. Lowering the network temperature and including multiple distributed sources could reduce these issues. However, a distributed energy generation approach would also introduce issues for heat marketability and management. Hence, a true change of paradigm is needed to move from the “monopolistic” structure (for generation, distribution and trading) implemented in today’s DHC networks, to a structure where multiple actors can play the role of energy providers and where even the final consumers can economically profit from their waste heat rejected to the network.

Centralized/High-level control solutions integrating multiple energy generation sources and sinks within a DH network are today under evaluation in a number of research and demonstration projects (ehub 2016, EnEff:Stadt 2016). However further innovations as the use of very low temperatures within the network loop, exploitation of pipelines storage capacity and bi-directional communication among multiple energy sources and sinks require further research at simulation level.

FLEXYNETS aims to develop a new generation of district heating and cooling networks, which will combine (i) multiple energy sources at different temperature levels, (ii) systems capable of using that heat efficiently (such as Organic Rankine Cycle (ORC) based polygenerative systems, absorption cooling systems) (iii) a low-temperature (<40°C) DH, and (iv) devices able to exploit such low temperature energy in residential buildings, like reversible heat pumps (see fig.1).

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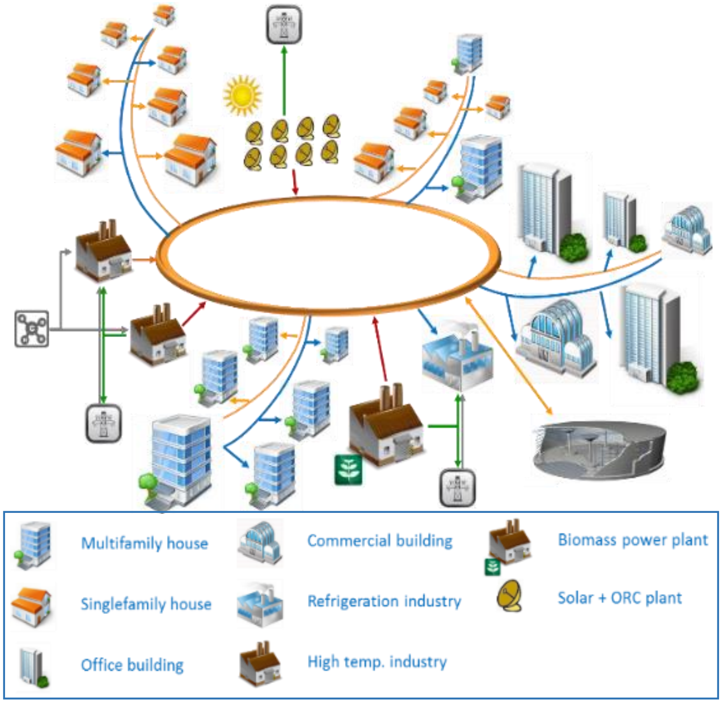

Fig. 1 The FLEXYNETS concept with several prosumers connected to the main loop

Depending on the substation needs, heat is supplied to or removed from the network

The Flexynets concepts considers the low temperature network as infrastructure for storage and heat exchange between geographically dispersed (renewable) prosumers with different sizes. The decentralization of heat and cooling sources as well as the linking of several small networks to independent large systems are topics of high interest. While supplying energy to consumer substations is common in today´s systems, the reverse flow from prosumers into the network remains one of the challenging tasks.

In this paper we briefly go through state-of-the-art concepts for feed-in substations. We comment some weaknesses related to the return-supply feed-in strategy. The Assumption is that in order to facilitate the energy exchange within the system and to increase the share of renewable and waste heat sources, one needs to adapt/optimize the network side. Targets of the adaptation should be high distribution efficiency, high effectiveness of feed-in, less auxiliary energy for better primary energy factors.

In this context we propose the FLEXYNETS concept as an option for new ‘liberalized’ DHC networks where prosumers can easily feed (excess-) heat and enhance the primary energy balance of the whole system. The discussion of the results at the end of the paper is related to district heating and will be extended to cooling networks in the future.

2. Heat feed-in into DH systems

The substation

In accordance to SDH (2012) 0 “distributed” or “decentralized” means that the feed-in plant is not closely located to another major heat generator like a biomass or fossil fuel fired plant. These substations generally make use of the network fluid content instead of providing own storage capacities. Their size is mostly small with regard to the whole district heat demand. Among the feed-in principles described in 0 (2012) and Bucar et al. (2005), two concepts have been realized in the past twenty years: the return-return (RR) and the return-supply (RS) concept as shown in fig. 2.

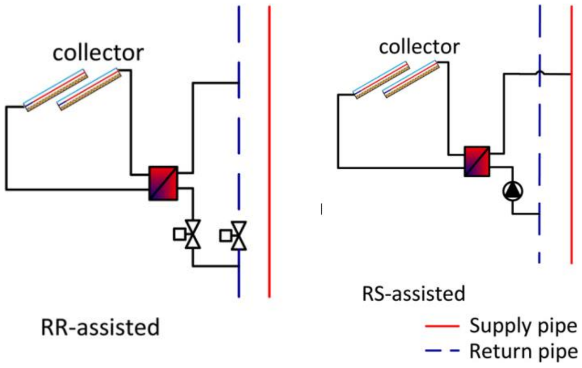

Fig. 2 The most common feed-in layouts

The solar collectors shown in fig. 2 are generally representative for every decentral heat source (waste heat incinerator, heat recovery etc.). The feed-in principles remain the same. In the RS case, the return temperature of the network remains low which is more advantageous/efficient for operating central CHP units. Among the nine European plants assessed in Schlegel (2014), seven are of RS type. In Hamburg Berne (Germany) a combined feed-in substation has been realized (Großmann, 2015) to work in winter and summer mode. In addition to the shortcomings of the RS concept that were discussed in Schlegel (2014), we want to highlight another aspect related to the control.

Due to the dynamic behavior of the network (consumers´ regulating valves, variable speed pumps), the control of RS substation becomes challenging. The pressure difference in two pipe networks changes by more than 30% within short fractions of time. The feed-in substation itself adds through head rise new dynamics to the whole system. The difficulty of regulating the flow under a fluctuating 'resistance' is demonstrated in fig. 3 (Gunnar 2014). The measurements show how the flow changes from no flow to maximum flow in the range of few percent of the pump speed.

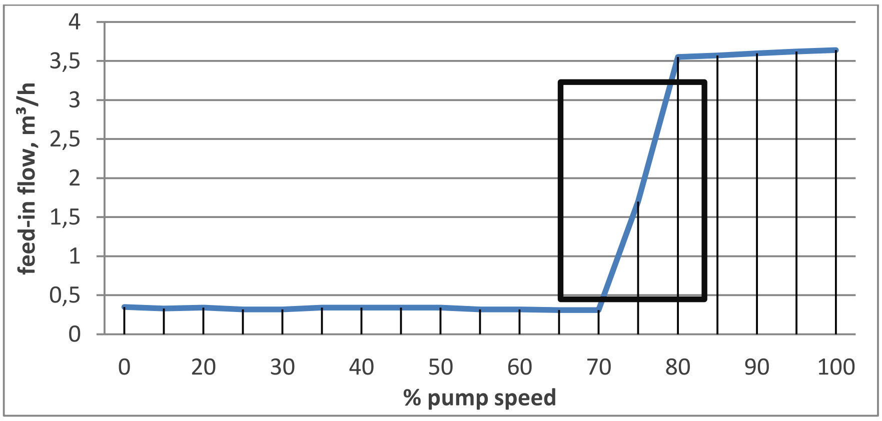

Fig. 3 Example of feed-in flow dependency on pump speed from a Swedish network

The problem is more relevant for small feed-in substations because they are generally equipped with (relatively) small feed-in pumps that are not able to cope with the network dynamics, at least not as able as high pressure/high flow pump stations which are common for large supply units. In substations without storages, supply interruptions due to too low or too high temperatures are common (Gunnar (2014), Eicker et al (2012)). Bucar (2005) reported about longer feed-in outages in Austrian networks due to too high pressure differences in the network.

This –among other reasons- may explain the decline of the reported solar gains in small size installations which is plotted in fig. 4.

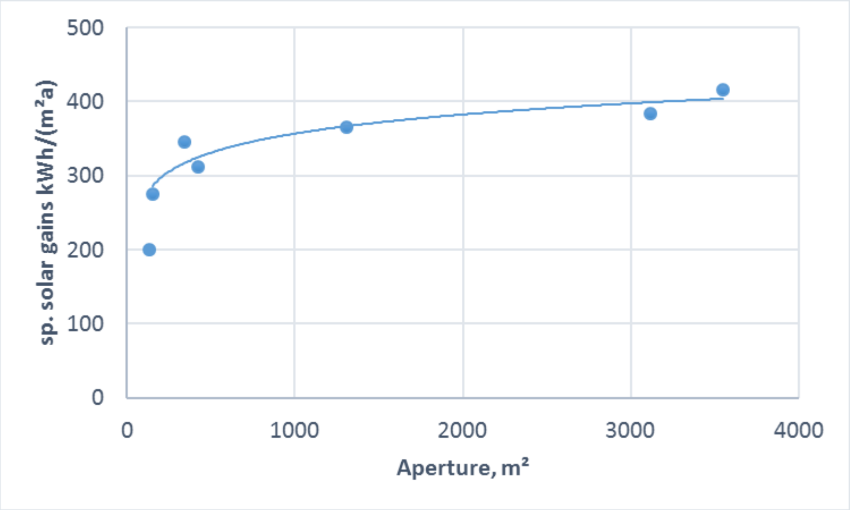

Fig. 4 Specific solar gains of seven European installations from Schlegel (2014)

The network

In conventional 2-pipe networks, the pump illustrated in fig. 2 needs to overcome the pressure difference between return and supply lines. This makes the feed pump power and rate depend on two factors: the governing network head and the substation location. Fig. 5 shows how much power is needed to supply approx. 200 kW of heat into a 6.3 km long DH network under different governing pressure differences. Fig 6 presents the pressure difference in a 13.5 km long network in the south of Germany. Halmdienst et al (2014) expect that substations which are closer to the main supplier need more power to provide the same heat amount to the network than those outside. However, we recognized in recent investigations within the FLEXYNETS project that the dimensions of the existing pipes as well as the flow direction (opposite or inline with main flow) are affecting.

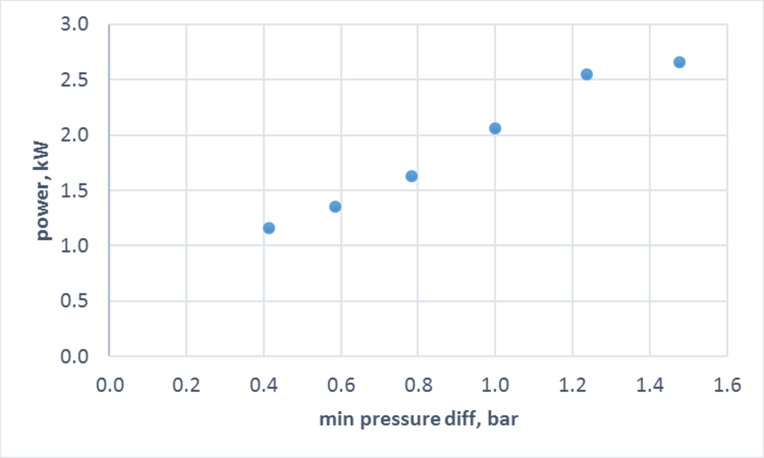

Fig. 5 Power requirements as function of lowest pressure difference

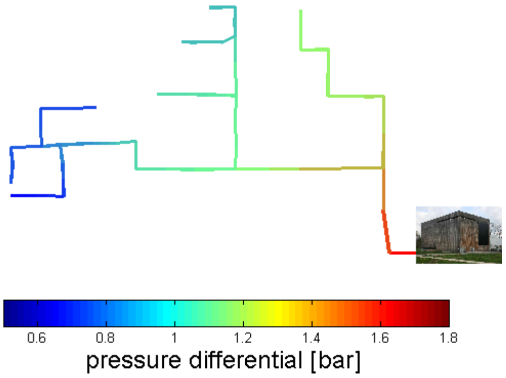

Fig. 6 Pressure profile in a tree-type network

3. The case study

With regard to the difficulties encountered in regulating feed-in substations, the following question arises: can the network be adapted/designed to facilitate (excess-) heat supply from decentralized prosumers with limited capacities? Keeping the auxiliary energy consumption low while assuring stability of supply is of course of high interest.

In the context of the FLEXYNETS project, two new network topologies were proposed as alternative to an existing 2-pipe system in the city of Aarhus in Denmark. The network contains -as part of the city DH system- more than 500 consumer substations and was aggregated to 23 nodes for the current study. The systems are simulated afterwards in TRNSYS and compared using some performance indicators.

The system aggregation

The map of the Aarhus south west area is shown in the left hand side of fig. 7. In order to aggregate the demands to 23 nodes, an affiliation function in the software program Termis is used. Termis is a hydraulic modeling tool that simulates the behavior of flow directions, pressure, and thermal conditions in a DH or Cooling network. The network from the geographic information system (GIS) tool and the demand points from the Heat Atlas is loaded in Termis as shape files. To affiliate the demand, the nodes are placed on different locations in the network chosen strategically for the affiliation of demand to be dependent on typology type. The nodes are placed manually by the best individual ability and evaluation in each case. The purpose of this process is to estimate the sum of the capacity of the collected demands in each of the chosen nodes for further analysis in TRNSYS.

In this way, the demands from the reference towns can be used in the analysis. The demands from Heat Atlas is an expression of actual demands for each building from these reference towns, in this case Aarhus. The Heat Atlas is developed by Aalborg University. It is designed to explore the possibility of development and application of a detailed mapping of the buildings' heating needs in Denmark. The Heat Atlas is developed for use in GIS software with the purpose to extract building data from the Building and Housing Register (BBR) and a number of heat consumption specifications that are developed by the Danish Building Research Institute (SBi). The Heat Atlas includes data such as construction year, building area and heat demand for each building.

The Danish reference towns are divided in areas according to the FLEXYNETS typologies, as seen in the figure. A GIS software is used as tool to establish the town or city boundary and the boundaries for the different typologies. For this purpose, municipality planning and the Heat Atlas is used. In Denmark, the data from the Heat Atlas, local planning and municipality planning is available for all towns and cities. Each reference town is divided into the different typologies based on the specific use category in the municipality planning.

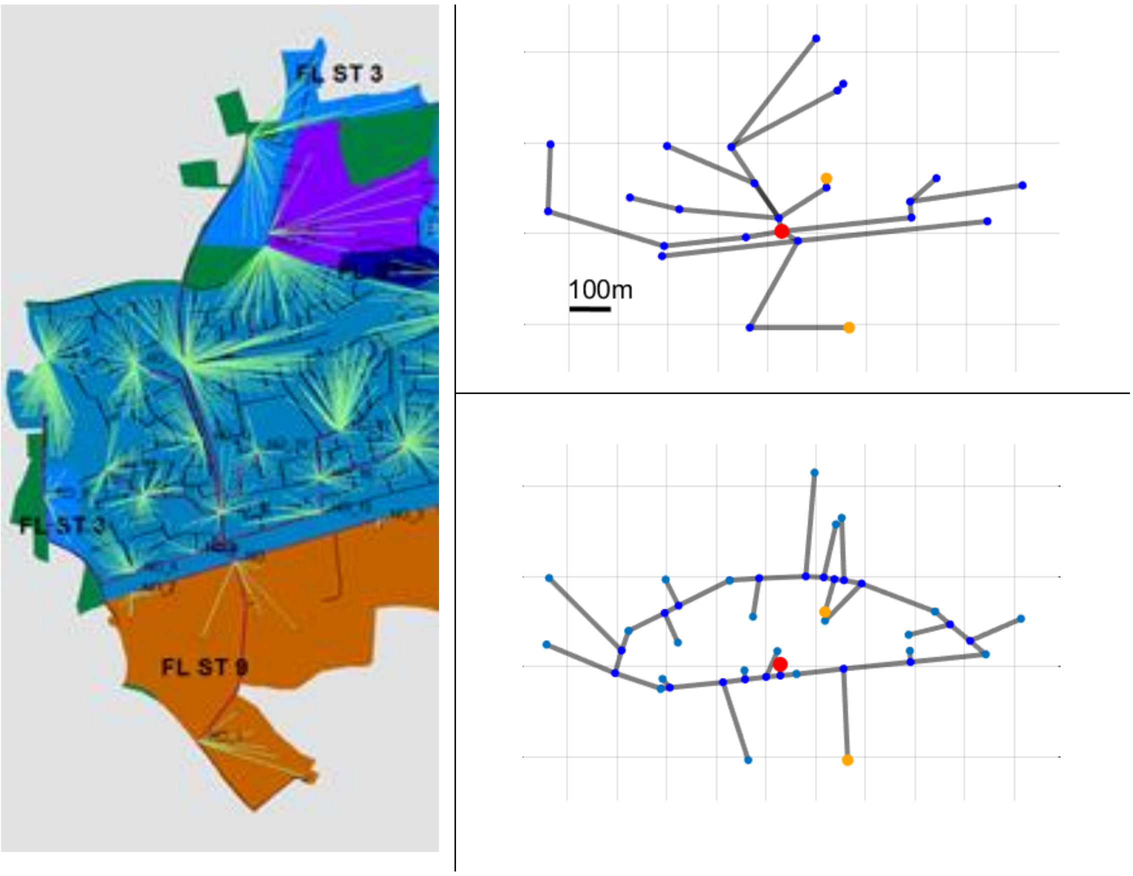

Fig. 7 Map of Aarhus SW (left), tree-type and loop-type network (right)

The network types

Additionally to the tree-type network of the south west of Aarhus (fig. 7), two additional models have been designed out of the loop-type system presented in the same figure. As can be seen in fig 8, the first model incorporates two loops (each for low and higher temperature) that are connected through a stratified storage tank. The system is called low-pressure type due to the low head difference between supply and return line. Storage inlets and outlets generally cause minor head losses in the range of <10 mbar. Feed-in substations inject hot water into the supply loop. In case of low demand, the injected heat can be stored in the central tank. The energy balance of the whole system is performed in the storage level, where heat can be removed or added via heat exchangers.

The operation of the feed-in pump is favorized by the fact, that other consumer substations circulate water in the same direction of flow. However, in real installations two aspects should be taken into account: a) the formation of small loops between two neighboring substations (one consumer and one producer) which may result in too low supply temperatures. b) the overflow of the feed-in pump due to high pressure rise in the consumer substations.

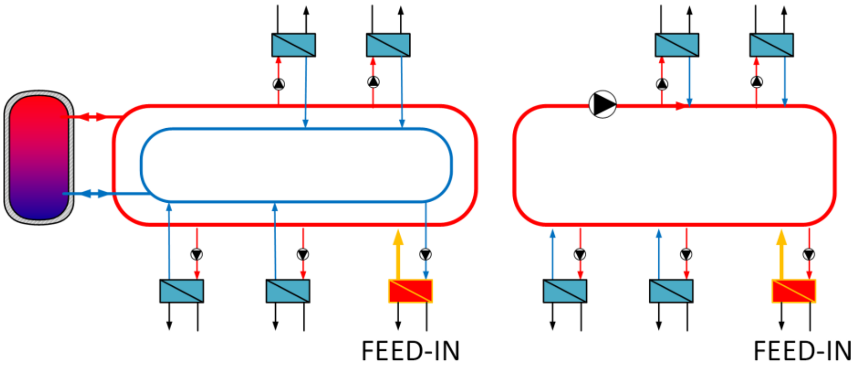

Fig. 8 Simple layouts of the loop-type networks

The second loop-type network contains a single circuit for both removal and feed of heat. At least one substation is needed to balance the network. The main loop pump recirculates water at high flow rates to e.g. compensate for the water cooling after each substation (in case of heat consumers). The feed-in concept is similar to the RR layout of fig. 2 where a part of the circulating volume is heated up and reinjected in the loop. Large differences between the inlet temperatures of the different substations are expected. If the consumers are equipped with heat pumps, their coefficients of performance (COP) will vary. The pump power requirements of the individual substations are assumed to be very low: the major head losses are due to the heat exchanger and service pipe friction.

General design and operational aspects

The modification from a conventional 2-pipe network to the proposed systems has some advantages for the operation of feed-in substations. Not only the power consumption of the decentral pump decreases, but also the flow control is expected to be more stable. This can be deduced from the open-loop behavior of the system. In fig. 9 the heat demand of the considered network is varied from full to partial by keeping both main and feed-in pumps at constant speed. If only 1/3 of the consumers are supplied, the decentral feed-in flow drops by 24% in the tree network compared to 11% in the low-pressure one. The same tendency is seen in the case of small variations. The single loop system exhibits the most robust behavior towards these variations. The substations are almost ‘decoupled’ from each other.

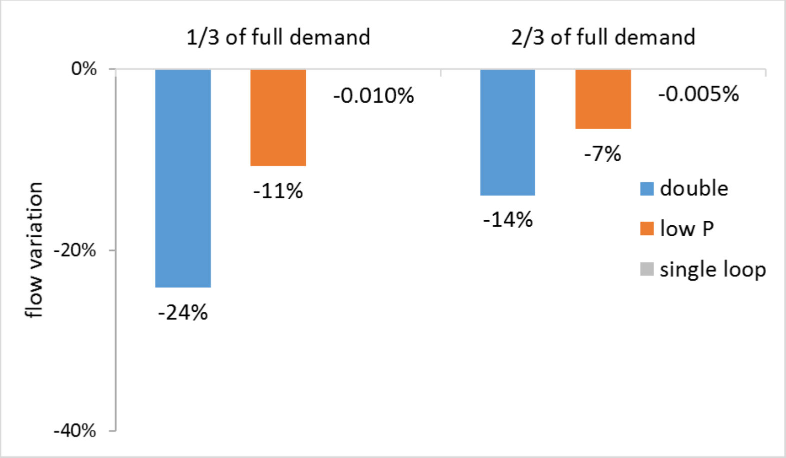

Fig. 9 Feed flow variation depending on demand decline

We also calculated the power needed to feed 32kW of heat into the three network types at different nodes. Head losses associated with mountings like heat meters and gate valves or pipe connections are not considered in this paper. The power requirements in the 2-pipe network are higher by a factor of five to ten than in the other two loop-based systems (see fig. 10). Also in the 2-pipe case, no clear dependency between the pumping power and the distance to the main supply node can be recognized. The power requirements logically depend on the distance to the consumers to be served, which can be variable depending on the current flow/demand situation. In the loop-based systems, the power consumption depends on the distance to the main loop. In other words, pipe friction in the service pipes presents the major head loss independent on the flow situation.

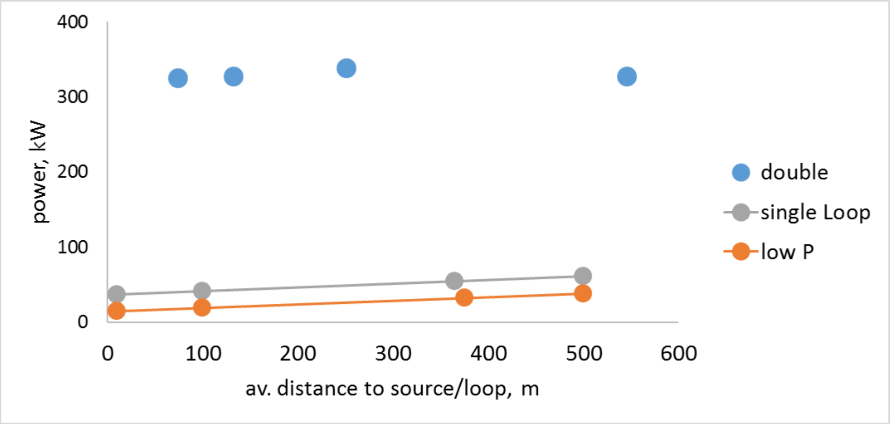

Fig. 10 Power requirements of feed-in pump at different nodes

The fluctuating (wavy) temperature profile in the case of single loop system made the control of the substations unstable. The heat pump model used was valid for a certain temperature range on the evaporator side. Many heat pumps would not be able to run adequately in case of too low temperatures. The study was therefore limited to the 2-pipe and low-pressure systems. The pipes were designed to a maximum velocity of 0.65m/s. The following table summarizes the obtained network sizes:

Table 1 Network dimensions

	2-pipe system	**Low-pressure system**
Length of pipes, m	6365.5	7313.5
Av. size of pipes	DN 150	DN 200
Total volume, m³	129.7	289.8

4. The simulation results

The system setup

The systems simulated in TRNSYS are the district heating networks of fig. 7. They distribute heat at low temperature (in a range between 20 °C and 30 °C) to decentralized heat pumps, which have to fulfil the heat demand of the buildings in the given area. The yearly heat demand is approximately 20.7 GWh with a peak load of approximately 6.0 MW. The network manager NM of the considered system is responsible for balancing the energy flows and owns the central supply station of the district heating grid that consists of a 2.2 MW gas-fired reciprocating engine that produces combined heat and power (CHP) and a 2.3 MW auxiliary gas boiler (GB) assumed here to have a constant efficiency of 80%. The NM is placed at the red dot of fig. 7. A 330 m³ central storage tank is used to buffer the heat supply by the CHP unit- Figure 11 shows the layout of the central heat supply station. In the low-pressure case, the central storage CS is directly connected to the network without any pump. The flow direction on the network side can be from top to bottom or reversed depending on the amount of feed-in. The CHP unit covers the base load whereas the gas boiler GB is operated during peak phases.

Two decentral substations supply heat to the network, that is gained out of two solar collector fields of different sizes (200 and 2000m² aperture). The solar pump is run in high flow mode (30l/hm²) and the feed-in temperature is regulated to 5K above the network temperature. The corresponding integration nodes are colored in orange in fig. 7.

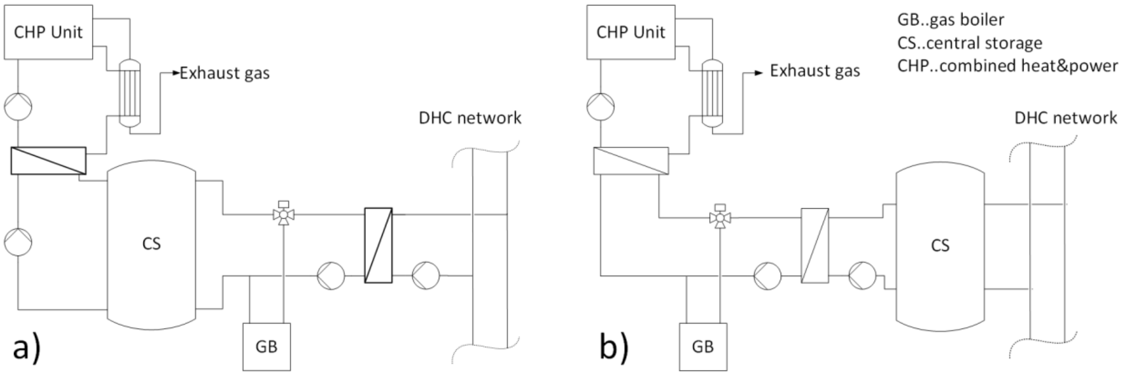

Fig. 11 Layout of main heat supply station in a) 2-pipe and b) low-pressure system

The water-to-water heat pumps use R407c as refrigerant and provide water to the buildings at 55-65°C. The performance of the heat pumps is affected by the temperature of the water supplied by the DH network. A higher network temperature increases the COP of the heat pumps, which turns into a lower power consumption of the compressors for a given heat demand of the buildings. As long as the power consumption is reduced, a higher amount of heat is extracted from the DH network.

Results

The two systems composed of the network, the main supply station, the consumer heat pumps and the solar feed-in substations were simulated over one year with a time step of 15 minutes. Due to the fact that the time constant of the hydraulic system is much lower than the simulation time step, continuous control of the feed-in pumps would be time intensive. We decided to run the pumps with an offset value that allow them to overcome the pressure difference at any time. The simulation study lead to the results of table 2.

The network pipe losses of the low-pressure system were higher than those obtained in the 2-pipe one. This can be explained by the larger size of pipes used as indicated in table 1. The main loop pipe with DN300 causes the major part of the losses. The average network temperature is slightly lower, which is reflected in the average COP of the heat pumps. The CHP unit produces more electric energy and enhances the primary energy balance of the system (lower PER). The solar gains of both small (200 m²) and large (2000m²) collector fields are comparable in the low pressure network. In the pressurized case, the larger installation feeds less heat than the smaller one. Further investigations are needed to find out if the feed-in flow is at nominal level in the 2000 m² installation.

Table 2 Simulation result summary

	2-pipe system	**Low-pressure system**
Users´ end energy, GWh	20.77	20.77
Net delivered energy, GWh	16.52	16.33
CHP thermal energy, GWh	13.74	13.42
CHP electric yield, GWh	13.48	13.22
Network heat losses, MWh	17.02	458.8
Average COP	4.88	4.67
Solar irrad., kWh/m²	1204	1204
Solar gains small, kWh/m²	446.16	462.56
Solar gains large, kWh/m²	427.61	460.28
Network pump consumption, MWh_{el}	71.98	24.45
Feed-in pump consumption, kWh_{el}	2519.8	288.1
Primary energy factor PER	0.638	0.648

When coming to the electric pump consumption, the low-pressure system is more advantageous and requires around one third of the energy needed in the other case. At feed-in substation level, the power requirements are much lower (1/9th) which confirms the results presented in fig. 10. Here we need to repeat that only the heat exchanger and the pipe friction are considered to calculate the pressure drop. In reality, other substation mountings and pipe connection will lead to higher electric consumption.

5. Conclusion and outlook

The paper focuses on feed-in substations as measure to enhance the share of renewable and waste heat in DH networks. The weaknesses related to the flow stability in conventional 2-pipe systems are shortly discussed. In the context of the FLEXYNETS project, two alternative (loop type) topologies were suggested out of which the low-pressure one was considered in simulation.

The simulation results of the low-pressure system show some advantages related to the pump power demand. Considering the open loop response, the low-pressure system is expected to operate with higher stability and to reach higher feed-in rates over the whole year. This can be assessed by testing the dynamic flow behavior under real conditions and with discrete controllers. The Energy Exchange lab established by the project partner EURAC in Italy will allow to perform this kind of investigations. The lab recreates on a small scale the various stages involved during the operation of district heating and cooling systems, from heat generation and distribution to consumption by end customers. This enables it to investigate the best network management solutions as well as the supply of heat from several sources. The flexible lab infrastructure allows various configurations as well as hardware and control software to be tested.

Higher heat losses were calculated in the low-pressure system and were explained by the larger pipe size. It is planned to redesign the main loop taking the head losses (and not the flow velocity) into account and to check if the system can be optimized in both investment and operational costs.

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