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Analysis of a wastewater based low temperature district heating system with booster heat pumps for new and existing residential buildings

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Abstract

District heating networks play a key role in the transition towards sustainable cities, due to their ability to efficiently provide space heating and domestic hot water to buildings located in urban areas. Although an increasing number of buildings is being refurbished, a significant portion of the building stock during next decades will still be made by old buildings with low thermal insulation. The potential of recovering energy from a low temperature heat source and to efficiently supply it to both new and existing residential buildings through a heat pump based district heating system (HPDH) is here investigated on the case study of Abano Terme (Italy), where a large volume of wastewater is discharged to the environment at the temperature range 35-55°C. In particular, an analysis is carried out to compare a district heating system with distributed heat pumps (d-HPDH) to a more conventional one with central heat pump and auxiliary gas boiler (c-HPDH). Simulation of neighborhood heat demand and district heating operation are based on internally developed models in MATLAB/Simulink. A brief description of the models is given here. A real neighborhood consisting of 98 buildings of different age classes has been simulated. Both HPDH systems bring a sharp drop in primary energy consumption with regard to the current situation made of individual gas boilers. The efficiency improvement of the d-HPDH over the c-HPDH is expected to increase with growing number of new and recently constructed buildings. When the latter consume 21% of heat demand, the seasonal coefficient of performance of d-HPDH is 4% higher than c-HPDH.

Keywords – low temperature heat sources; district heating; booster heat pumps

1. Introduction

District heating systems are important infrastructures to efficiently provide space heating and domestic hot water to buildings located in urban areas. The evolution of such systems has gone through four generations, the last one being known as Low Temperature District Heating (LTDH). LTDH networks have reduced supply temperature (55-60°C) in order to limit distribution heat losses and to operate supply plants (Combined Heat Power plants CHP, gas boilers or heat pumps) with higher efficiency compared to traditional DH networks; moreover, reducing supply temperature allows to integrate low grade heat sources such as renewable energy sources and waste heat in the generation mix [1-3]. The step towards 4^{th} generation DH systems has been driven by the reducing trend of heat demand that is expected to continue during next decades due to the progressive refurbishment of existing buildings and to the high energy performance of new buildings prescribed by European Directive 31/2010 [4]. In fact, a reduced heat demand turns into a loss of competitiveness of traditional DH systems compared to autonomous heat supply solutions. LTDH was demonstrated to be economically feasible for both existing and low-energy buildings [2-3].

Although an increasing number of buildings is being refurbished, a significant portion of the building stock during next decades will still be made by old buildings with low thermal insulation [4]. The challenge this work wants to address is therefore to design a DH system that is able to recover heat from low grade heat sources and to efficiently supply heat to low-energy buildings and old poorly-insulated buildings at the same time. To this purpose, thermal energy is transported at very low temperature (below 40°C) and booster heat pumps are used to raise temperature up to the level required by the supplied customers. This solution will be named here d-HPDH, i.e. distributed heat pumps based district heating.

A similar idea was recently proposed by different authors [5-6]. Gudmundsson et al. [5] investigated the economic feasibility of a DH network with supply temperature of 40°C in order to provide space heating to low energy buildings with floor heating systems and to feed booster heat pumps for DHW preparation. The authors called this system ultra-low temperature district heating (U-LTDH). It was concerned that a reduction in supply temperature involved a reduction in network capacity (difference between supply and return temperature) which in turn implied bigger piping and increased investment costs. According to the authors, this additional cost may be compensated by the lower cost of the heat source. Krebs et al. [6] studied the potential of decentralized water to air heat pumps to improve the financial viability of a solar district heating system with thermal energy storage (TES) located in Canada. Heat pumps allow to reduce the network supply temperature, thereby presenting opportunities to reduce the size of the solar collector array and the number of boreholes in the seasonal thermal storage. They concluded the lifecycle cost over 20 years can be reduced by approximately 10% compared to a DH with higher supply temperature that uses air handling units instead of heat pumps. The maximum achievable solar fraction is limited by the heat pumps COP and is in the order of 80% for this study.

The present work investigates the performance of a d-HPDH system compared to a district heating system supplied by a central heat pump unit with auxiliary gas boiler (called here c-HPDH) for a real residential neighborhood located in Abano Terme (Italy). Here, hotels and thermal spas extract almost 8 million cubic meters thermal groundwater per year at 60-87°C [7] and then discharge it to the environment at a temperature in the range 35-55°C. Numerical models have been developed to simulate the use of this geothermal wastewater as a heat source for the neighborhood (made by both low energy buildings and existing ones) through a district heating network, according to the two different design strategies (c-HPDH and d-HPDH). d-HPDH is expected to bring with some energy saving with respect to the c-HPDH, because the closer the heat pump to the customer, the closer the supply temperature to the customer need. If the heat pump serves one building only, the supply temperature will actually follow the building requirement in terms of supply temperature. If the heat pump serves a set of buildings, the supply temperature must be high enough to provide thermal comfort to all of them.

2. Methods

2.1 Heat demand model for a residential neighbourhood

The energy demand during the heating season is predicted through a simplified dynamic model of the district. The tool, written in MATLAB/Simulink environment, uses a limited number of reference envelopes, each corresponding to the construction criteria prescribed by national legislation in force at time of construction. This is a widely used method also known as the archetype method; this method is present in literature among the top-down engineering-based building stock models [8]. Moreover, the archetypes used by our model take advantage of a previous study that analyses the reference envelopes present in the Veneto region, divided by age classes [9].

In this method, each building of the district is given a reference envelope according to its age of construction and the dimensions and orientation of external walls are imported from the GIS software ArcGIS®. The other inputs are weather data (external air temperature and solar radiation) and building occupancy profiles. A MATLAB script elaborates all these features and gives them as input parameters to a Simulink model that calculates the energy need at each hour according to the 5R1C model of EN ISO 13790 [10]. All calculations are performed in matrix form to reduce the computation time. The implementation of the model follows the overall structure proposed by Lauster [11]. The mathematical representation of the 5R1C model is in state-space form, as suggested by Michalak [12]. The model has been validated on a single building by comparing the monthly energy need with that produced by the commercial software TRNSYS [13] in three different climatic regions. Moreover, the model is not yet capable of reproducing patterns of presence of occupants in buildings, that would be very important in order to account for simultaneity of internal heat gains, domestic hot water demand and other variables that depend on users behaviour rather than on physical quantities [14]. This upgrade of the model will be done as a later step of this research.

The simulated neighborhood consists of 98 buildings, 35 of which were built after the implementation of L.10/1991 (see Fig. 1). The latter drove a significant improvement in the energy performance of buildings. Moreover, among these buildings, 8 are recently constructed (or still in construction) low-energy buildings. Table 1 summarizes the composition of the considered neighborhood of Abano Terme, including the calculated specific heat consumption.

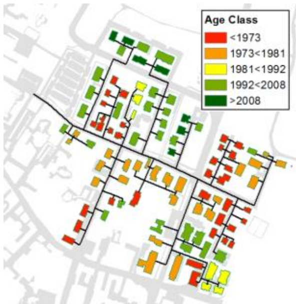

Fig. 1 Residential neighbourhood in Abano Terme with district heating network.

Table 1. Composition of neighborhood building stock.

Age of construction	Buildings [-]	Gross heated volume [m^3]	Reference regulation	Specific consumption [kWh/(m^{2}y)]	Floor heating systems [-]
<1973	32	54910	-	125-240	0
1973<1981	23	61865			0
1981<1992	8	15165	L. 373/76	115-180	0
1992<2008	27	57470	L. 10/91	65-95	9
>2008	8	15260	DPR 59/09	40-55	8
TOTAL	98	204670	-	-	17

Supply temperature has been considered as function of external air temperature. For each age class, the supply temperature was selected in order to be as low as possible throughout the heating season but high enough to provide thermal comfort to the occupants. These simulations were performed with TRNSYS; a similar approach was used by Brand et al. [3].

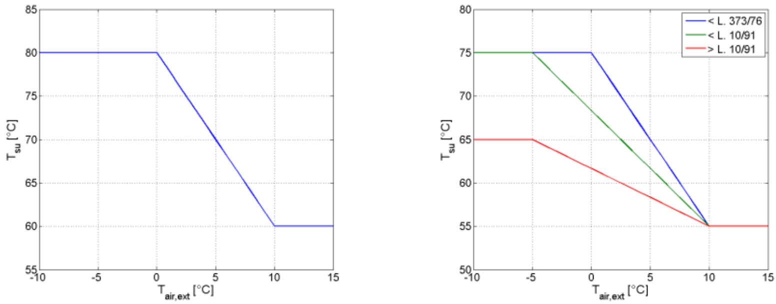

Fig. 2 Supply temperature curves of central heat pump (left) and of distributed heat pumps (right).

2.2 District heating network model

A district heating network is a thermodynamic system made by a set of interconnected pipes that brings a hot fluid from the heat source to the final users. Simulating systems with a heat carrier covering large distances requires to account for variations in both time and space. Spatial variability is particularly challenging when it comes to networks, i.e. systems with complex topology. To overcome this difficulty in the modelling, many models proposed in literature rely on graph theory [15-16]. Basically, the network is described as a set of nodes and branches and all the information about their interconnections are stored in a matrix A, called incidence matrix.

The system is solved when all mass flow rates and temperatures of the network are determined. If the heat-carrier is an uncompressible fluid, three equations are sufficient to solve the system: continuity equation (conservation of mass), momentum equation (conservation of momentum) and energy balance (conservation of energy). The first two equations allow to determine the distribution of pressures and velocities in the network and in turn of all mass flow rates (fluid-dynamic problem), while the third allows to calculate the distribution of temperatures (thermal problem). In forced convection, the two problems can be solved separately, since velocities do not depend on the temperature. Once all mass flow rates are determined by the fluid dynamic equations, they become input variables for the energy equation.

The model consists of a MATLAB code that runs four consecutive routines. First, a pre-processing block loads dimensions and topology of the network and heat demand profile of the users. Then the fluid-dynamic block solves the coupled equations of mass and momentum conservation by using the SIMPLE algorithm [17]. The computed mass flow rates serve as inputs for the thermal block, that solves the equation of energy conservation with the upwind scheme [18]. Finally, a post-processing routine is utilized to analyse and visualize results. The model follows the one proposed by Politecnico of Torino [16-17]. Yet, our model does not account for the storage of heat in the water volume. Thus, it is a steady-state model where all time steps can be run independently.

2.3 High temperature heat pumps for district heating

Recently there has been a growing attention for integration of heat pumps into district heating systems [19-21]. This may be due to different reasons. From a thermodynamic perspective, using heat pumps allow exploiting heat sources at a temperature lower than that required to feed traditional heat emitters or to prepare domestic hot water (i.e. 50°C). Moreover, it allows seasonal thermal energy storage (STES) systems to be designed at low temperature, thereby reducing their heat losses [6]. From an economic point of view, heat pump based district heating systems (HPDH) was found to be cost-effective in systems with high penetration of RE power sources [19-20]. Indeed, the "electrification" of end-uses such as heating and mobility -that were traditionally met by other energy carriers- reduces the need for energy storage capacity [19].

The most conventional water to water heat pumps for space heating are GSHPs that work at undisturbed ground temperature on the heat source side and at usually about 40°C on the heat sink side. As a consequence, low temperature heat emitters such as fan coils or radiant surfaces are required. As reported above, Abano Terme is an area with geothermal anomaly and the groundwater is available at 35-55°C after being processed in thermal baths. Thus heat pump can produce hot water at 60-75°C without affecting its COP.

Two types of heat pumps are considered depending on the DH system configuration. High capacity heat pumps (2-10 MW) require a centrifugal compressor instead of a usual scroll compressor and shell-and-tube heat exchangers instead of brazed plate heat exchangers. Thus, different performance curves are used to correlate COP to water supply temperature and to part load ratio. For the big size unit, the correlation found in literature [22] (Eq. 1) was adapted to the heat source temperature of in this case study.

$$COP_{pl,c} = \left(0.558\,\frac{T_{cd,out} + 273.15 + 4}{(T_{cd,out} + 4) - (T_{ev,out} - 4)} + 1.168\right)(0.393\,x + 0.612) \qquad (1)$$

For the decentralized unit, full load COP values have been obtained by measurements on a real machine with a thermal capacity of 30 kW developed in the labs of a manufacturer (Eq. 2). Partial load COP was then obtained by using the procedure of EN 14825 (Eq. 3) [23]:

$$COP_{fl,d} = 0.000366\,T_{cd,out}^{3} - 0.0723\,T_{cd,out}^{2} + 4.6046\,T_{cd,out} - 89.477 \qquad (2)$$

$$COP_{pl,d} = COP_{fl,d} \frac{x}{0.1 + 0.9\,x} \quad (3)$$

2.4 District heating network design

The same tree-shaped network has been adopted for both systems (c-HPDH and d-HPDH). All 98 buildings are assumed to be connected to the DH system. Each building/substation was given a nominal capacity and a number of equivalent apartments. The substation nominal capacities are higher than the peak loads for space heating obtained by the district heat demand model because the latter does not account for DHW demand yet. The design mass flow rate for DHW production was obtained by following the Italian standard UNI 9182 [24] and the design heat load for each substation adds part of the nominal load for DHW to the nominal load for space heating as suggested by [25]. The design heat flow rate for each branch of the network was determined by applying simultaneity factors [26] to the number of equivalent apartments supplied.

As mentioned above, d-HPDH is expected to be more efficient than c-HPDH due to the lower water temperature in the network. This on the one hand reduces heat losses from the heat distribution network, and on the other hand allows heat pumps to deliver water to the temperature required by the supplied customer, thus achieving a higher COP than with a central unit. Moreover, the use of heat pumps can be avoided for those buildings that have radiant surfaces or other low temperature heat emitters. Since in d-HPDH the network supplies the evaporator of the decentralized heat pumps, the substation design heat flow rate must be reduced by the following factor:

$$f_{red} = \left(1 - \frac{1}{COP_{nom}}\right) \quad (4)$$

This might lead to the conclusion that pipe diameters in the d-HPDH system can be reduced compared to those of c-HPDH. Nonetheless, this does not occur because working with a high network capacity (difference between design supply and return temperature) would reduce the COP of heat pumps. In our case, the network capacity has been set to 15 K for c-HPDH system and to 10 K for d-HPDH system.

3. Results

3.1 Heat demand of the residential neighbourhood

The heat demand model outputs the hourly heat demand profile of each building throughout the year. The net energy need of the district is approximately 5.54 GWh with a peak demand of approximately 2.7 MW. Fig. 3 outlines the energy required by the buildings by age class. Although old buildings (built before any regulation on building energy performance) account for 57% of total built volume, they are responsible for 71% of heat demand. Buildings built after L.10/91 account for 35% of built volume but their heat consumption is only 21%. The wide range of specific heat consumption for old buildings (Table 1) may be explained by the significant variation in the buildings shape ratios, as shown in Fig. 4. This stresses the importance of having accurate geospatial data as input for the model.

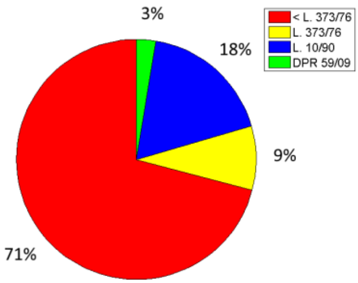

Fig. 3 Energy consumption of the neighbourhood by age class

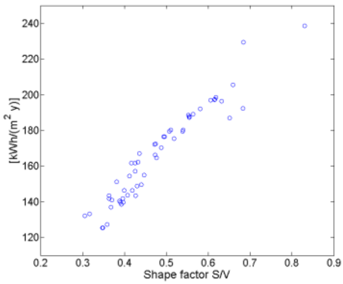

Fig. 4 Specific heat consumption vs shape factor for old buildings (< L. 373/76)

3.2 District heating network: central vs distributed solution

As reported in Section 1, this study aims at comparing the energy performance of two different heat pump based district heating systems (HPDH) that supply thermal energy for space heating to a residential neighborhood in Abano Terme. The heat source is geothermal wastewater assumed to be at constant temperature of 41°C during the year. The amount of available wastewater exceeds the amount needed to feed the DH system. Table 2 summarizes results for the central and distributed district heating configurations. The comparison is carried out through the seasonal COP that does not account for the electrical consumption of circulation pumps.

Table 2. Comparison between c-HPDH and d-HPDH.

	HP condenser(s) load [MWh]	Gas boiler load [MWh]	SCOP [-]
c-HPDH	5289	683	4.64
d-HPDH	5541	-	4.82 (on-off) 5.00 (inverter)

The seasonal COP (SCOP) for the c-HPDH system is the ratio between the heat load of the central heat pump (on the condenser side) and the electrical load of the compressor. The sum of gas boiler and heat pump load is higher for the c-HPDH system compared to the d-HPDH due to distribution heat losses that amount to about 6.3%. Note that in the d-HPDH system there are 17 buildings with radiant floor (Table 1) that are directly coupled to the low temperature network. Thus SCOP of the d-HPDH system is calculated as the ratio between the sum of the heat load of all the buildings (including those without heat pump) and the electrical consumption of the distributed heat pumps. In the d-HPDH system, the use of variable speed compressors (i.e. compressors with inverter) involves an increase of about 4% of SCOP.

Figures 5 and 6 show the primary energy consumption and the CO_2 emissions of the proposed HPDH systems compared to the current situation (assuming all the buildings are supplied by individual gas boilers with mean energy efficiency equal to 0.9). Coefficients for primary energy consumption and CO_2 emission are taken from a study of ISPRA [27].

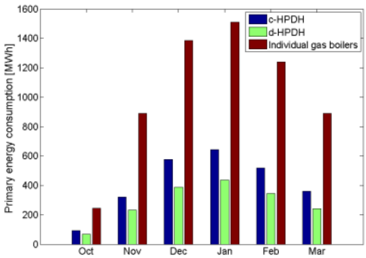

Fig.5 Primary energy consumption of c-HPDH, d-HPDH and current situation.

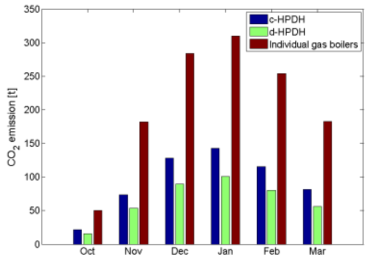

Fig. 6 Carbon dioxide emissions of c-HPDH, d-HPDH and current situation.

4. Conclusions

This work investigated the use of heat pumps in district heating systems for the exploitation of low grade heat sources. In particular, geothermal wastewater at about 40°C was considered as heat source for two different DH system configurations. The latter (c-HPDH) was supplied by a central heat pump with auxiliary gas boiler while the former (d-HPDH) transported heat at low temperature (slightly less than 40°C) and then utilized booster heat pumps to raise temperature up to the level required by customers.

Both HPDH systems bring a sharp drop in primary energy consumption with regard to the current situation made of individual gas boilers (-60 to -72%). System d-HPDH appears to be more energy efficient in terms of SCOP (+4%), primary energy consumption (-30%) and CO_2 emissions (-30%). Moreover, a further improvement could be brought with by the d-HPDH system through a better control on the heat load at building level. Finally, the convenience of the d-HPDH system is supposed to increase compared to the c-HPDH system by increasing the share of new low energy buildings in the building stock.

Further research steps include the economic analysis of the proposed solutions, the integration of renewable power sources (PV and/or biomass combined heat and power plants) and smart control for network operation.

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