Potentials of the new design concepts of district heating and cooling toward integration with renewable energy sources

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Abstract

This paper discusses the opportunities of the new design concepts of district heating and cooling towards the integration of renewable energy sources. A comparison between the medium-temperature district heating and the last generation of low-temperature networks is provided. Simulation models and performance evaluations of three different district heating design concepts are carried out. On one hand, the medium-temperature district heating was modeled with combined heat and power generation. On the other hand, the simulation of the low-temperature district heating was carried out including renewable energy sources such as solar energy, geothermal and wind energy . For the three cases analyzed the customer connection to the district network was carried out by using substation types without a local storage tank. The present work aims to investigate the renewable energy utilization in low-temperature district heating which is modeled as a hybrid solar panel and wind turbine assisted geothermal heat pump. We present a case study for a district heating distribution network which supplies heat to 75 apartments. The paper quantifies the performance of different district heating design concepts. The results highlight the potential of the new district heating design concepts towards solutions for sustainable energy planning.

Keywords: District heating, Simulation, Sustainable energy, Wind turbine and solar assisted heat pump

Introduction

The energy sector is central in sustainable development and it affects all aspects of development – social, economic and environmental. In terms of resource exploitation, the sustainability of energy utilization suggests that the satisfaction of present energy consumption should consider the energy requirements of the future. Consequently, a sustainable energy system is usually defined in terms of energy efficiency, reliability and environmental impacts. These two subjects – environmental concerns and fuel supply security – are the main driving factors behind the growth of district heating (DH) in most countries. A district heating system is composed of many elements, building a chain from the heat source to the heated buildings. The introduction of a district heating system provides a fundamental infrastructure for combining heat and power use as well as the integration of renewable energy. In this context simulation tools play an important role for the design and operational optimization of complex DH networks. In terms of technology development, it is considered that district heating is in its fourth generation. The first generation of district heating systems used steam as a heat carrier (steam district heating). These systems were first introduced in the USA in the 1880s. The second generation of systems used pressurized hot water as a heat carrier, with temperatures mostly between 100ºC and 120 ºC (High-temperature district heating). These systems appeared in the 1930s and were the leading systems until the 1970s. The third generation of systems was introduced in the 1970s. Pressurized water is still the heat carrier, but the supply temperatures are between 70ºC and 100ºC -medium-temperature district heating- (Euroheat & Power, 2012).

The fourth generation of district heating technology is being based on lower and more flexible distribution temperatures (supply temperatures lower than 60°C), assembly oriented components, and more flexible materials. The lower and/or more flexible temperatures in the distribution networks will deliver both lower distribution heat losses and higher utilization of available renewable resources such as solar, biomass and geothermal energy. Therefore, the present study deals with the integration of a low temperature district heating system and renewable energy sources. Simulation models, performance evaluations, as well as the comparison between three different district heating design concepts are carried out. Hence, the renewable energy (RE) utilization in low-temperature district heating which is investigated. Therefore, a low-temperature district heating system with a hybrid solar panel and wind turbine assisted geothermal heat pump is modeled. We present a case study for a district heating distribution network which supplies heat to 75 apartments.

Modelling and simulation

Simulation models and performance evaluations of three different design conceptions of district heating were studied. The simulation of the medium-temperature district heating system (MTDH) was carried out considering combined heat and power (CHP) generation. While the simulation of the low-temperature district heating system (LTDH) was carried out including energy production from renewable energy sources (see figure 1). Taking into account that the modeling process is quite similar for all cases analyzed, only a description of the simulation model of the low-temperature district heating system and renewable energy integration (LTDHRE) is presented. First the simulation model of the low-temperature district heating system without consideration of renewable energy sources integration will be presented. Secondly the integration of decentralized solar panels and wind turbine will be considered. Then a summary of the key results of all simulation models will be presented.

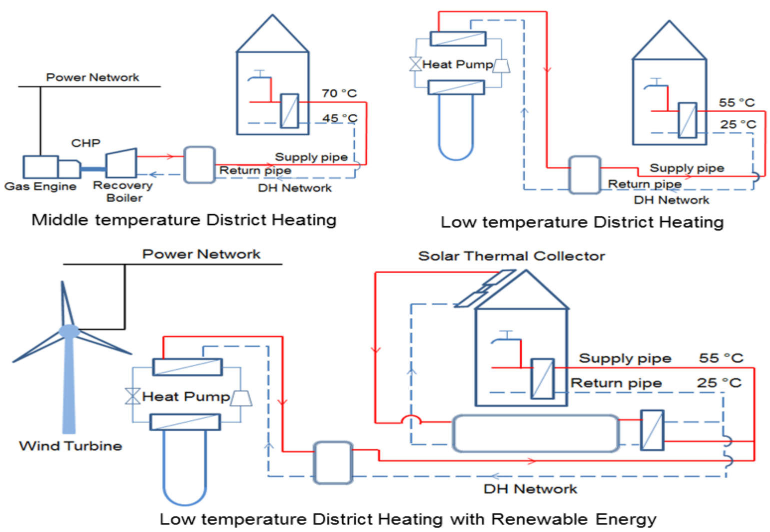

Figure 1 District heating systems representation

For the purpose of dynamic simulations, energy demand profiles for space heating (SH) and domestic hot water (DHW) were developed. Based on the case of a low-energy apartment in which the heat losses through transmission and ventilation are *1.9 kW* when the outside winter design temperature is *-8°C*, a space heating demand equation as a function of the outdoor temperature was derived. For the dynamic simulations, the space heating control was designed according to typical low-energy house from the Belgium standard regulation. Hourly outside temperatures were selected for Belgium. Three domestic hot water profiles (low, normal and heavy) were developed. The case study is composed of three multi-family buildings of 25 apartments that are placed in front of each other. The distribution networks of the buildings are connected to each other and to a central heat generation plant through buried twin pipes. The one-way network length is *475 m*. The heating plant consists of a heat pump coupled with a central storage tank that is connected to the network distribution system. Consumer substations connect and separate the collective part of the district heating system and the parts within the individual dwellings. The direct substation is equipped with one heat exchanger for transferring heat from the collective heating network to the tap water. For space heating, hot water from the collective network is introduced into the dwelling space heating distribution grid.

Based on the state of the art of solar assisted district heating system a reference system was defined. The system was built based on several German systems such as the one in Friedichshafen and Hamburg, that were reported by Raab et al. (2003). Each building has a solar system with an insulated storage tank that is connected to the district heating network. The solar circuit is separated by a heat exchanger from the storage circuit since it uses a water-glycol-mixture (60/40 %) to protect the collector field (flat plate collectors, *250* m^2) from frost damage. A heat exchanger, which separates the solar circuit from the district heating network, is installed to heat the return flow of the building when the temperature of the storage tank reaches the required conditions. Figure 2 displays the simulation with the main components of the low-temperature district heating system and renewable energy integration.

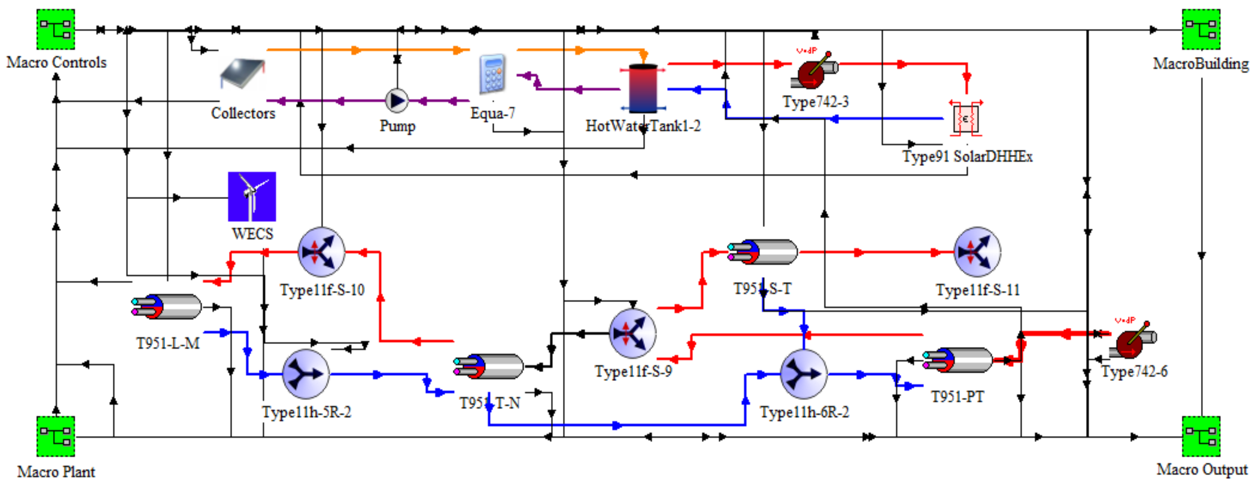

Figure 2 Simulation of Low temperature district heating with renewable energy integration

In the mathematical user guide of TRNsys a detailed description of the components model can be found (TRANSSOLAR,2010). Thermal stratification in the storage tank is modeled by assuming that the tank consists of a number of fully-mixed equal volume segments. The TRNsys component models the thermal behavior of the pipe by splitting the pipe in a number of fluid segments at different temperatures. Buried twin pipes are another important modeling component. In the case of twin pipes (two media pipes in the same casing), the two single pipes are considered identical, placed horizontally and in the same depth from the ground surface. The heat transfer equations for the ground buried pipe for stationary conditions are based on analytic equations presented by Wallenten (1991). In this study the system constants are reduced to two, $U_{11} = U_{22}$ and $U_{12} = U_{21}$, and the total heat loss, q_{tot}, in (*W/m*), is calculated:

$$q_{tot} = 2(U_{11} - U_{12})\left[\frac{t_1+t_2}{2} + t_0\right] \quad (1)$$

With *Uij* is the heat loss coefficient (*W/mK*), t_1 supply temperature (°*C*), t_2 return temperature (°*C*) and t_0 ground temperature(°*C*).

The flat-plate collector component assumes that the efficiency vs. $\Delta T/I_T$ curve can be modeled as a quadratic equation. Thus the collector efficiency is given by the following expression:

$$\eta = \frac{Q_u}{AI_T} = F_R(\tau\alpha)_n - F_R U_L \frac{(T_i - T_a)}{I_T} - F_R U_{L/T} \frac{(T_i - T_a)^2}{I_T} \quad (2)$$

With F_R the overall collector heat removal efficiency factor, U_L overall thermal loss coefficient of the collector per unit area (*kJ/hm²K*), $U_{L/T}$ is the thermal loss coefficient dependency on T (*kJ/hm²K²*), T_i inlet temperature of fluid to collector (°*C*), T_a ambient temperature (°*C*), I_T global radiation incident on the solar collector (kJ/h-m²), α short-wave absorptance of the absorber plate and τ short-wave transmittance of the collector cover. Correction factors derived for linear efficiency curves and additional analytical corrections are applied to the collector parameters for: operation at flow rates other than the value at test conditions, identical collectors mounted in series and non-normal solar incidence. These modifications are outlined in (Duffie and Beckman, 1991). Solar assisted district heating with short-term and seasonal storage have been introduced, principally in Denmark and Germany. As was aforementioned seasonal heat storage has been used, since in Europe, the energy density of solar insolation is low and insolation is maximum in summer while, on the other hand, heat is mainly needed in winter.

In order to contribute to the electricity demand of the heat pump, a wind turbine (*600 kW*) was considered as a part of the district heating plant. For wind turbines, the rotor is a homogeneous disk which removes energy from the moving fluid. In the simulation the actuator disk approach to the momentum theory analysis of wind turbines is used. The simulation approach does not include turbulent mixing between the air in the stream tube and the air in the balance of the control volume. However the model is appropriate for analysis of axial mass, momentum, and energy balances. Combining the expression of thrust derived from Bernouilli's equation with one derived from the momentum theory. The power output of a wind turbine can then be written as the product of the thrust times velocity. Considering that the wind speed at the rotor is the average of the upstream and downstream wind speeds it is then possible define:

$$P = \frac{1}{2}\rho A_R v_0^3 4a(1-a)^2 = C_P \rho A_R v_0^3 \quad (3)$$

Where ρ is density of the air *(kg/m₃)*, v_0 is velocity in the free stream *(m/s)* and A_R is area through the rotor (*m²*). The term *a* is defined as the *axial induction factor* (or the *retardation factor*) and is a measure of the influence of the rotor on the wind. The power coefficient for a wind turbine, C_P, is defined as the power of the turbine divided by the power in the wind. The value of *59.3%* as a maximum power coefficient was first derived by Betz in 1919, and has since been called Betz's limit. The value of the coefficient is that, when multiplied by the area of the rotor and power in the wind, it describes the power output of the wind turbine.

Results and discussion

In this section the results of the simulations are described. The main study was to compare a system without renewable energy with the most promising systems including renewable energy, and investigate the primary energy savings for the different systems. The performance of the district heating system is assessed by three performance indicators: the heat loss (in the distribution system), the total energy consumption and the fuel energy saving ratio. A characteristic parameter for defining the performance of the DH networks is the heat loss in the distribution system. The heat loss does not depend only on the overall heat transfer coefficient, which characterizes the efficiency of the pipe insulation, it also depends on the specific surface area of the distribution pipes, the level of water distribution temperature relative to the annual average of the outdoor temperature, and other parameters. The total energy consumption (in *MWh*), takes into account the power consumption of all water pumps of the network and the power consumption of the heat pump. This output parameter is an extra indicator to evaluate the performance of the district heating. A further operational criterion is the fuel energy saving ratio which characterizes the impact of different district heating systems with a similar base of analysis. The fuel energy saving ratio (FESR), also called Percent of Fuel Saving measures the extent of fuel savings directly. It is given by the following expression:

$$FESR = 1 - \frac{F_I}{F_{SHP}} \qquad (4)$$

Where F_I is the total amount of fuel consumed at a given system (in *MWh*) and F_{SHP} (in *MWh*) is the total amount of fuel consumed by a system that cover similar energy demand by mean of a separate production of heat and power using non-renewable energy. In the present work the reference system produces a similar amount of electricity than those in the medium-temperature district heating since the value of this system represents the largest electricity production of the three systems. In figure 3 and figure 4, a summary of the simulation results is displayed. The monthly heat supply, the heat losses, the energy consumption, and the energy production are drawn. The heat supply, the energy production and the energy consumption are strongly conditioned by the ambient temperature, while the curve of the heat losses is more flattened. This behavior of the heat losses take place due to the use of a modern district heating design approach (pre-insulated pipes, buried twin pipes, low supply and return temperatures).

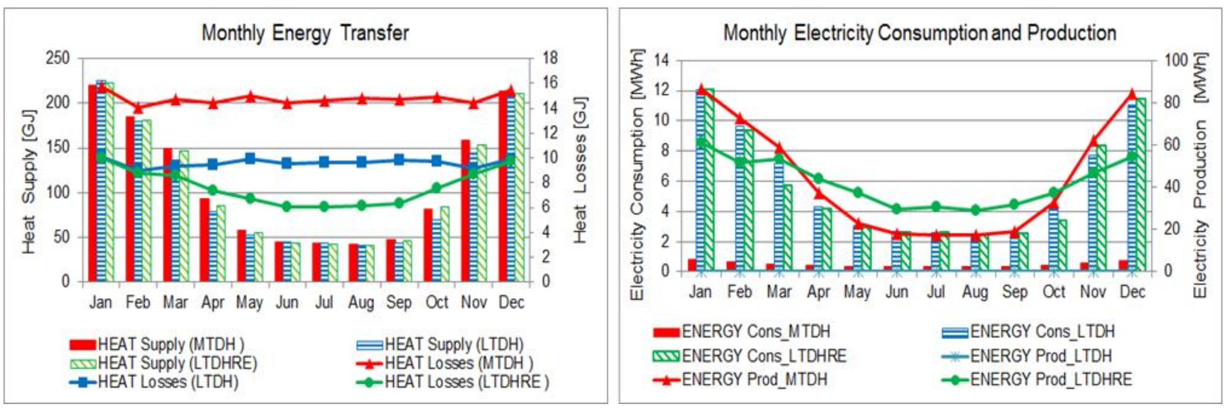

Figure 3 Monthly energy transfer of the systems

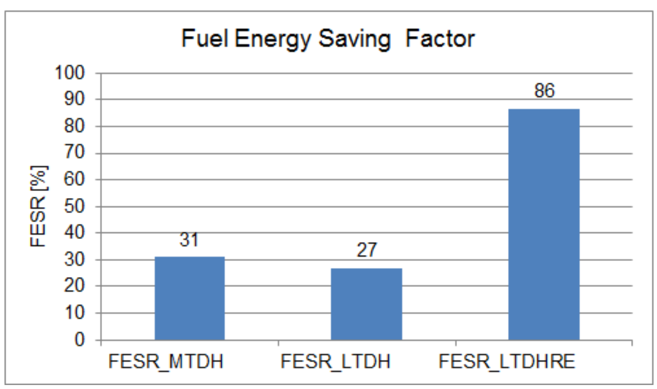

Figure 4 Fuel energy saving factor

The graphs in figure 3 shows a significant reduction of the heat losses of both low temperature district heating systems without and with the use of renewable energy, with respect to the medium-temperature district heating system. This result is in accordance with the reduction of the supply temperature in those systems. Additionally, in the low temperature district heating system with renewable energy (LTDHRE), during summer, an important decrease in the heat losses is achieved, since during this period the heat demand is mainly covered by mean of the solar system. In the case of the energy consumption, the electricity consumption in the medium-temperature district heating is negligible in comparison with the other system analysed. The increase of the electricity consumption in both low temperature district heating systems, (without and with RE integration) is due to the use of heat pump. Note that the *FESR* of the MTDH is larger than the *FESR* of the LTDH. This result denotes that a DH system with CHP plant is more interesting than DH system with a heat pump in the heating production plant. However, when the contribution of the renewable energy use on the LTDH is taken into account the results reflect a significant improvement. Figure 4 displays a comparison of the fuel energy saving ratio between the three system analyzed. In the case of the low temperature system up to *86* percent of energy is saved as a result of the use of wind turbine in combination with solar panel collector.

Conclusion

This paper discusses the opportunities of the new district heating design concepts towards the integration with renewable energy sources. A case study for a district heating network which supplies heat to 75 apartments was presented. A comparison between the medium-temperature district heating and the low-temperature networks was provided. Simulation models and performance evaluations of three different district heating design concepts were carried out. A low-temperature district heating system with a hybrid solar panel and wind turbine assisted geothermal heat pump was studied. The results show a significant reduction of the heat losses of both low temperature district heating systems without and with the use of renewable energy, with respect to the medium-temperature district heating system. This behavior of the heat losses take place due to the use of a modern district heating design approach (pre-insulated pipes, buried twin pipes, low supply and return temperatures). In addition, when renewable energy is used in a low-temperature systems, an important reduction of the heat losses during summer is achieved because the heat demand, during this period, is mainly covered by the solar system.

It should be noted that the electricity consumption in the medium-temperature district heating is negligible in comparison with the other systems analyzed. The increase of the electricity consumption in both cases with low supply temperature is due to the use of heat pumps. The *FESR* of the MTDH is larger than the *FESR* of the LTDH. Thus a district heating system with CHP plant is more interesting than a district heating system with a heat pump in the heating production plant. Nevertheless, when the contribution of the renewable energy use is taken into account the results reflect a significant improvement. In the case of the low temperature district heating system up to *86* percent of non-renewable energy is saved as a result of the use of wind turbine in combination with solar panel collector. Concluding, the paper quantifies the performance of different district heating design concepts. The results highlight the potential of the new district heating design concepts towards solutions for sustainable energy planning.

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