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RESEARCH and EXPERIMENTATION

Low-temperature district heating networks for complete energy needs fulfillment

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ABSTRACT

In order to reduce fossil fuels consumption and pollutant emissions, high contribution is given by district heating. In particular, the integration with renewable energy may lead to a significant increase in energy conversion efficiency and energy saving. Further benefits can be achieved with low temperature networks, reducing the heat dissipations and promoting the exploitation of low enthalpy heat sources.

The aim of the paper is the analysis of the potential related to the conversion of existing district heating networks, to increase the exploitation of renewables and eliminate pollutant emissions in the city area. Further aim, in this context, is the optimization – from both energy production and operation management viewpoints – of a low temperature district heating network for the fulfillment of the connected users' energy needs. To this respect, a traditional network with a fossil fuel driven thermal production plant has been considered and compared with a low temperature district heating scenario, including geothermal heat pumps, photovoltaic panels and absorption chillers. These scenarios have been analyzed and optimized with a developed software, demonstrating the reduction of primary energy consumption and CO_2 pollutant emissions achievable with low temperature networks. In addition, a preliminary economic comparative evaluation on the variable costs has been carried out. Future studies will investigate the economic aspect also from the investment costs viewpoint.

Keywords:

District heating;
Optimization;
Low-temperature networks;
Thermodynamic analysis;
Energy saving;

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1. Introduction

Recently, energy grids became a central issue for the achievement of the standards imposed by international regulations on environmental impact [1]. With this purpose, the integration between renewable generators and traditional production systems has been promoted [2, 3]. Relating to the thermal energy field, District Heating Networks (DHNs) are largely diffused [4, 5], allowing to reduce both pollutant and thermal emissions within the city area, as demonstrated for the case study of Great Copenhagen in [6]. In recent years, efficiency improvement has been reached thanks to the integration of DHN with Renewable Energy Sources (RES) [7] and cogeneration units. In Europe, some instances of integrated thermal grids are present, considering the integration of different technologies with RES for the production of thermal energy [8, 9]. As an example, at the Delft University of Technology the 17% of thermal and cooling needs is currently provided by a system which includes CHP units, geothermal systems and aquifer thermal storage [10], allowing an energy saving equal to the 10%. Particularly, the positive effect of the introduction of heat pumps (HPs) in DHNs has been confirmed [11, 12].

Furthermore, low temperature district heating (DH) has been recently recognized as a viable solution to

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The study provides an original and innovative approach in the research field of low temperature district heating coupled with renewables. The strong novelty stands in the conversion of existing traditional district heating networks into low temperature networks completely avoiding the use of fossil fuels without reducing the energy service to final users. Furthermore, the proposed conversion allows also to fulfill the cooling energy without modifying existing networks. The approach represents a real action in the direction of reducing CO_2 emissions, dependency on fossil fuels and their use in the city area. Finally, this methodology increases the efficiency in the energy sector and represents a strategy to reduce the heating and cooling energy cost for users. All the advantages highlighted in the study are completely in line with the 2030 Agenda for Sustainable Development of European Commission.

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further increase the energy efficiency in the heating sector [13]. The main advantages of low temperature DHNs stand both in the reduction of the heat losses through the network and in the efficiency increase for the production systems. In particular, renewable heat sources, such as HPs, geothermal systems, etc., can achieve important efficiency improvements if the temperature of the network is lowered [14]. As an example, it has been estimated that – with a reduction in DH supply/return temperatures from 80°C/45°C to 55°C/25°C – the coefficient of performance (COP) of industrial waste-based HPs can be increased from 4.2 to 7.1, while the cost of solar thermal can be reduced of about the 30 % [15, 16]. Currently, reductions in the temperature levels down to 10–20°C [17] are investigated in order to further decrease the heat dissipations through the network and exploit very low heat sources.

In this context, the innovative aspects of the study stand in the definition of a low temperature DHN, coupled with renewables, which enables to completely avoid fossil fuel consumption and pollutant emissions at a district/city level, guaranteeing the fulfillment of the whole thermal and cooling users' needs. Considering the will of converting existing DHNs without modifications in the heat emission systems of the final users, this result can be obtained thanks to the introduction of booster HPs: despite a consequent increase in the electricity consumption (partially covered by photovoltaic system), this set-up (low temperature DH + booster HPs) has been proven as a promising solution [18]. Finally, a preliminary economic evaluation on the variable costs has been carried out in this paper, while future studies will deeply investigate also the investment costs.

In detail, the structure of the manuscript is organized as it follows. In Section 2 the methodology applied for the analysis is discussed, highlighting the users' energy needs, the considered scenarios and assumptions and describing the developed software used for the analysis. Instead, in Section 3 the results are presented and discussed, while in Section 4 the concluding remarks are highlighted.

2. Methodology

To evaluate the possibility of converting existing DHNs into low temperature DHNs for electrical, thermal and cooling energy fulfillment, a network composed by a centralized thermal production and three users of different typology has been considered. The hourly based energy needs profiles for each user has been evaluated for three typical days separately. Then, the Reference Case has been set, representative of a traditional network operation: the heat is produced by natural gas (NG) boilers and provided to the users via DH with temperature levels of 90°C/60°C (respectively for the supply and the return of the network), while the electrical and cooling needs are fulfilled by electricity purchase. The Reference Case has been compared with a low temperature DHN, in which the network is operated with temperature levels of 20°C/10°C, with a centralized geothermal system and providing heat to fulfill both the users' thermal and cooling needs, via HPs and absorption chillers respectively. In addition, photovoltaic (PV) panels are considered as decentralized production system. The optimization has been carried out with a developed software and preliminary economic evaluations have been assessed. In the following paragraphs, the methodology will be discussed.

2.1. Energy needs profiles

The electrical, thermal and cooling needs hourly profiles for the three typical days representative of winter, middle season and summer are shown in Figure 1 as

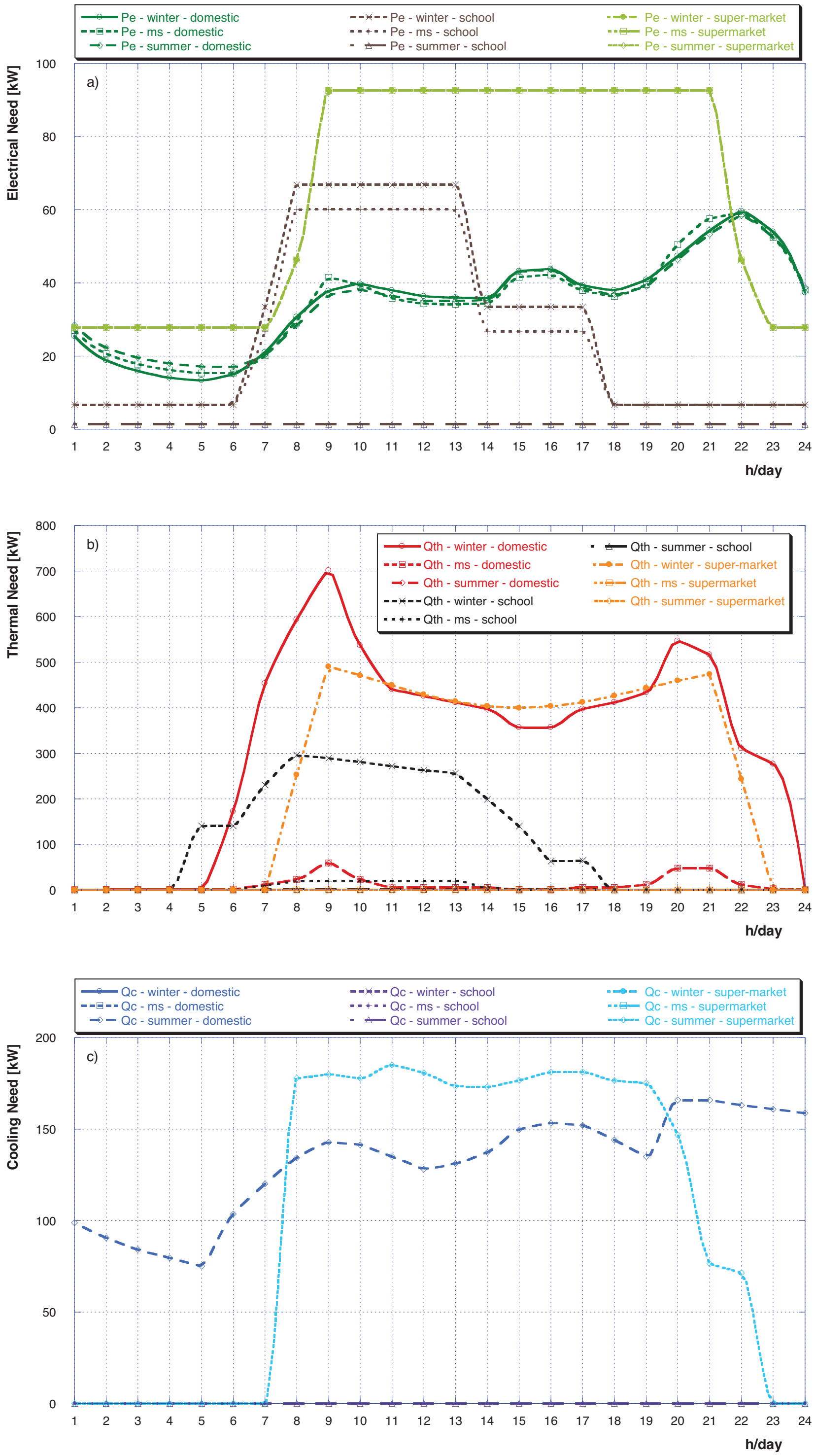

Figure 1: Users' needs as function of the user typology and of the considered typical day (winter, middle season – ms and summertime): a) electrical needs, b) thermal needs and c) cooling needs

function of the considered user typology (domestic user, school or supermarket). These curves has been determined on the basis of literature [19–24] and considering the following assumptions:

– domestic user: building composed by 83 apartments, each one with (*i*) a peak of electrical need equal to 0.65 kW_e, (*ii*) a peak of thermal need of 7.7 kW_{th} for space heating and

0.7 kW_{th} for hot water and (*iii*) a peak of cooling need of 2 kW_c. In addition, a peak of 12 kWe has been considered for the lightening of the common areas of the building;

- school: peaks equal to 67 kW_e (for the electrical need) and equal to 276 kW_{th} and to 20 kW_{th} (for the thermal needs, space heating and hot water respectively). No cooling needs have been considered for the school, due to the summer closure;
- supermarket: peaks equal to 93 kW_e (electrical need), equal to 490 kW_{th} (thermal need, space heating only) and equal to 185 kW_c (cooling need).

In detail, Figure 1a shows the electrical needs profiles: the domestic user electrical need presents three peaks, while the lower request is registered during the night. Furthermore, for domestic users a slight increase in the electrical needs can be seen in middle season and summer with respect to winter season. As it regards the supermarket, instead, the same electrical need profile is registered for the three typical days, with a maximum constant request during the opening hours equal to around 93 kWe. Finally, the electrical needs for the school present similar trends during winter and middle season, while a minimum constant request is considered during the summer closure for the maintenance of the installed appliances.

Relating to the thermal needs, for domestic users and school hot water and space heating needs are considered during winter, while only hot water is required during middle season and summer. On the other hand, for the supermarket only space heating needs are provided via DHN; consequently, no thermal needs are registered during middle season and summer.

Finally, for the domestic user and the supermarket, the cooling needs are present only during summertime, while no cooling need is considered for the school, due to summer closure.

2.2. Reference Case

As shown in the schematic of Figure 2a, to define a Reference Case, a traditional DHN has been considered for the fulfillment of the previously mentioned three users of different typology. Space heating and hot water needs are provided via DH, while each user provides by itself for electrical and cooling needs by electricity purchase. The heat production occurs by means of NG boilers installed at the centralized thermal power station, characterized by a rated efficiency equal to 90 % and by a total rated thermal power equal to 1600 kW. The off-design behavior of the NG boilers has been modeled as presented in [25]. Furthermore, the network temperature levels have been assumed equal to 90°C and 60°C, respectively for the supply and the return lines.

As it regards the cooling needs, compression chillers installed at each user have been considered, with an Energy Efficiency Ratio (EER) equal to 4.

2.3. Low temperature DHN case

The proposed low temperature DHN scenario (Figure 2b) considers the presence of a geothermal source at the centralized thermal power station, which provides heat to the network allowing to reduce the temperature levels – with respect to the Reference Case – down to 20°C and 10°C, respectively for the supply and return pipes of the network.

As a consequence, due to the need of increasing the temperature level at the final users, for a correct operation of the current heating systems and to satisfy the hot water needs, the installation of HPs at each user has been considered. With this assumption, the temperature levels required by the user side circuit can be guaranteed. Furthermore, a COP equal to 3 has been assumed: indeed, even if geothermal HPs commonly achieve higher COP values [26], this assumption has been made as a mere precaution due to the high difference between the temperature levels of the condenser and of the evaporator of the HP. Instead, as it concerns the cooling needs, absorption chillers have been considered, fed by the outlet stream of the HP and assuming an EER equal to 0.67. Finally, the installation of PV panels at the final users is accounted: the peak power has been evaluated based on the solar irradiation data for the considered location (Bologna, North of Italy [27]) and on the available rooftop surface [27], considering (*i*) an occupancy factor of the 70 % (to allow installation and maintenance), (*ii*) a conversion efficiency equal to the 10 %, (*iii*) a tilt angle of 30° and (*iv*) an exposition to South. The electrical energy produced by the PV panels can be used to move the HP and/or to fulfill the electrical needs of

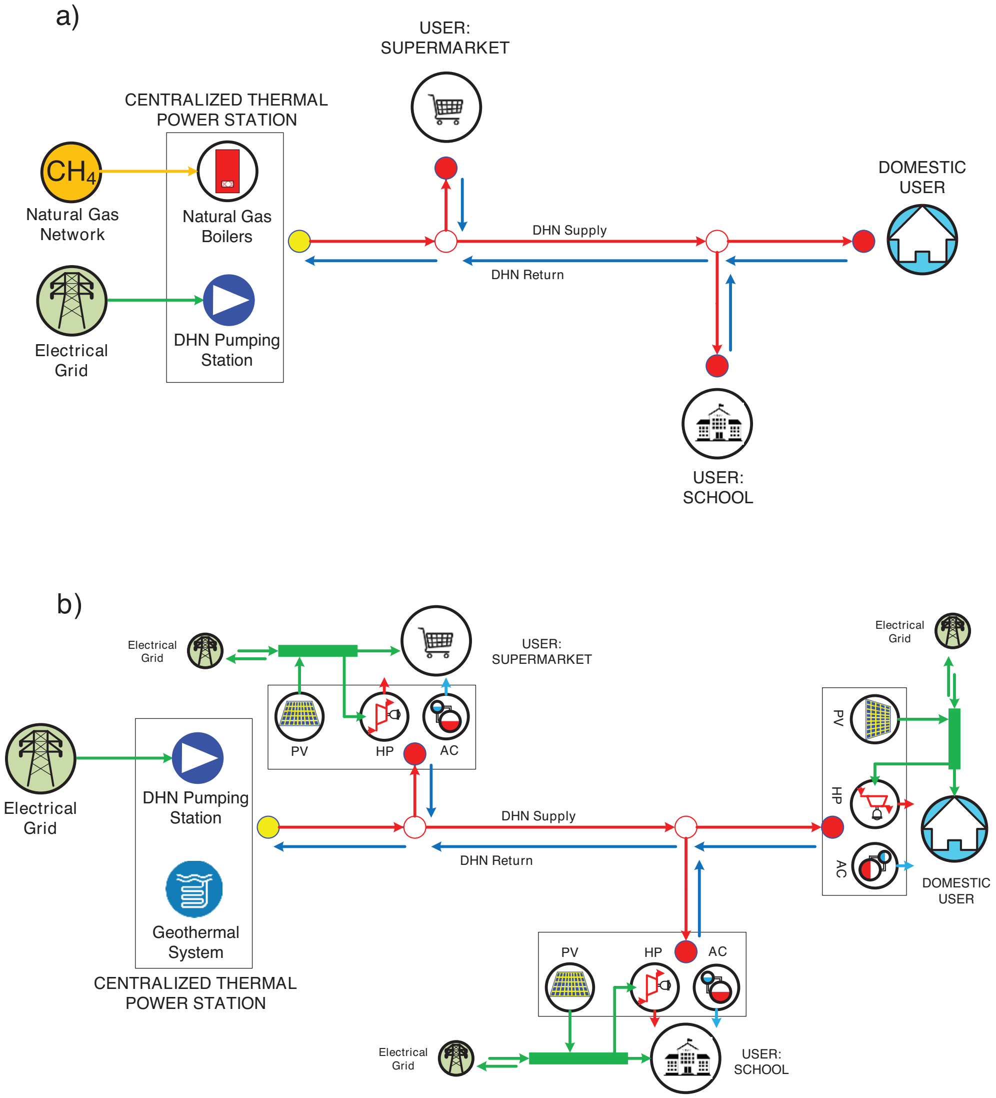

Figure 2: Schematic of the analyzed scenarios: a) Reference Case and b) Low temperature DHN case

the users. A connection with the national electric grid is obviously maintained.

2.4. Software 3-CENTO and preliminary economic analysis

The software 3-CENTO (electrical, thermal/cooling and fuel – Complex Energy Network Tool Optimizer) has been developed to optimize the design and operation of complex energy networks, including – eventually in smart configuration – electrical grids, DHNs and district cooling networks (DCNs). The software (see the flowchart of Figure 3), on the basis of several inputs – related to networks topology, users loads, energy systems typology and characteristics, economic tariffs, etc. – allows to optimize both the networks operation and the scheduling of the energy systems by the application of specific objective functions. In detail, the calculation core consists of two calculation models based on the Todini-Pilati [28] and genetic algorithms [29], for DHN/DCN operation and energy systems' scheduling optimization respectively.

In particular, once the calculation has been carried-out, for the DHNs the developed software evaluates:

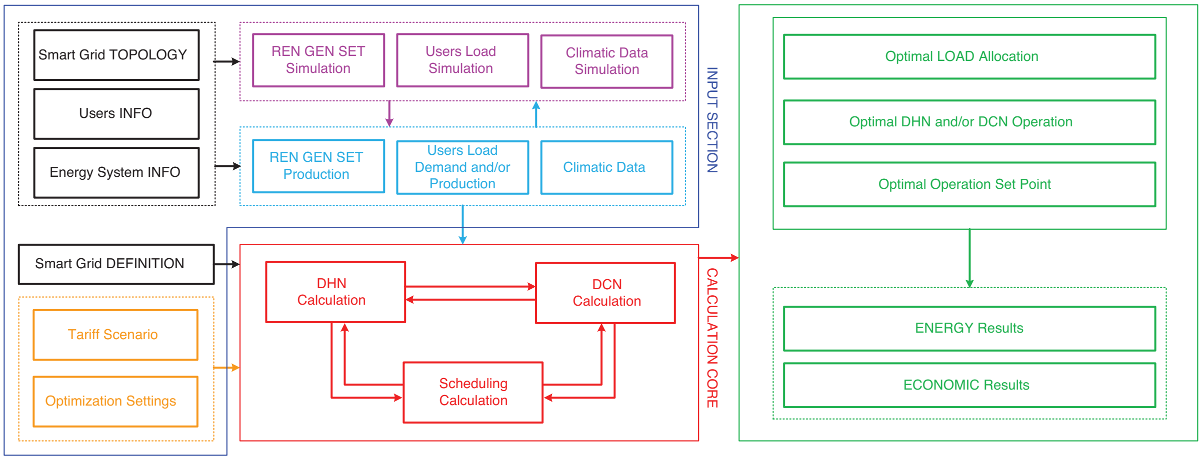

Figure 3: General schematic of the 3-CENTO software

- thermal energy to be produced at the centralized production plant;
- inlet and outlet temperature and pressure, mass flow rate, velocity and pressure drop for each pipe;
- electric power for the pumping station;
- pressure drops of the primary circuit of each users;
- heat losses through the network.

Furthermore, as a result of the software application, the energy systems optimal scheduling and design is calculated.

Based on the energy results obtained from the software, a preliminary economic analysis has been carried out for the evaluation of the annual cash flow (CF_i) related to the two compared scenarios, accounting for the costs of fuel and electricity purchase, as well as for the operation and maintenance costs of the energy systems:

$$CF_i = E_{fuel} \cdot c_{fuel} + E_e \cdot c_e + E_{th,B} \cdot c_{M,B} + E_{c,CC} \cdot c_{M,CC} + E_{th,HP} \cdot c_{M,HP} + E_{C,AC} \cdot c_{M,AC} \quad [€]$$

being:

- E_{fuel} yearly fuel consumption of the plant [kWh/y];
- c_{fuel} specific cost of the fuel (NG);
- E_e yearly electricity purchase [kWh/y];
- c_e specific cost of electricity;
- $E_{th,B}$ thermal energy yearly produced by the NG boilers [kWh/y];
- $c_{M,B}$ maintenance specific cost of NG boilers, assumed equal to 0.005 €/kWh [30];
- $E_{c,CC}$ cooling energy yearly produced by the compression chillers [kWh/y];
- $c_{M,CC}$ maintenance specific cost of compression chillers, assumed equal to 0.006 €/kWh [30];
- $E_{th,HP}$ thermal energy yearly produced by the HPs [kWh/y];
- $c_{M,HP}$ maintenance specific cost of HPs, assumed equal to 0.010 €/kWh [30];
- $E_{C,AC}$ cooling energy yearly produced by the absorption chillers [kWh/y];
- $c_{M,AC}$ maintenance specific cost of absorption chillers, assumed equal to 0.002 €/kWh [30].

Since c_{fuel} and c_e strongly depend from the considered Country, three different hypothesis in terms of c_{fuel}/c_e ratio have been accounted: 0.5 (corresponding to the Italian values, 0.087 €/kWh for the NG and 0.180 €/kWh for the electricity), 0.3 and 0.7.

3. Results and discussion

The yearly energy results obtained for the proposed scenarios are presented in Figure 4 and in Figure 5. In detail, both for the Reference Case and for the Low temperature DHN case, two off-design operation strategies have been considered and evaluated, respectively maintaining constant (at the design value) the mass flow rate through the network or the temperature difference between the supply and the return of the network. In Figure 4 the yearly fuel consumption and electricity purchase of the proposed scenarios are shown. As it can be seen, for the Reference Case a yearly fuel consumption equal to around 3900 MWh/y and to about 3700 MWh/y is registered, respectively in case of constant mass flow rate and in case of constant temperature difference off-design management strategies. On the

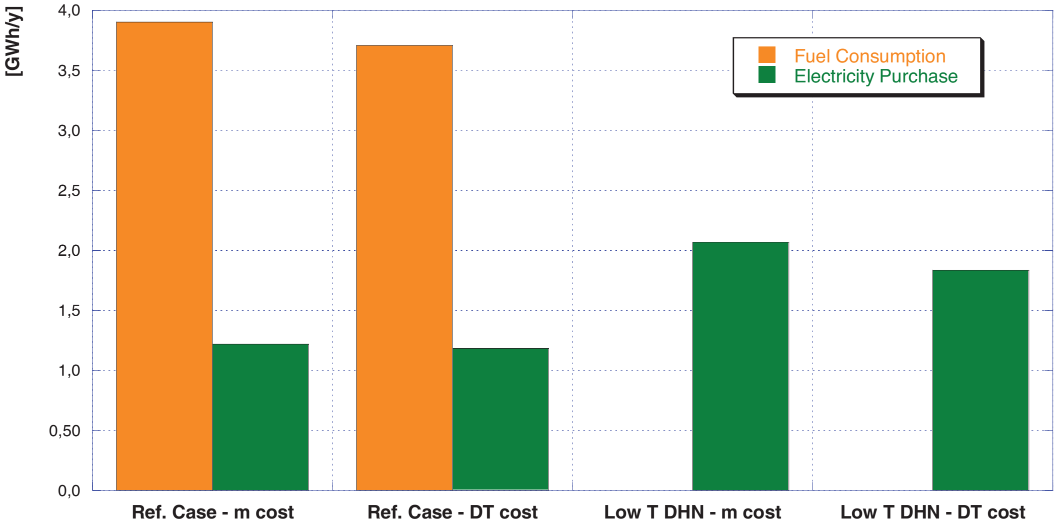

Figure 4: Annual fuel consumption and electricity purchase for the proposed scenarios (Ref. Case, Low temperature DHN) and for the evaluated off-design management strategies (constant mass flow rate or temperature difference)

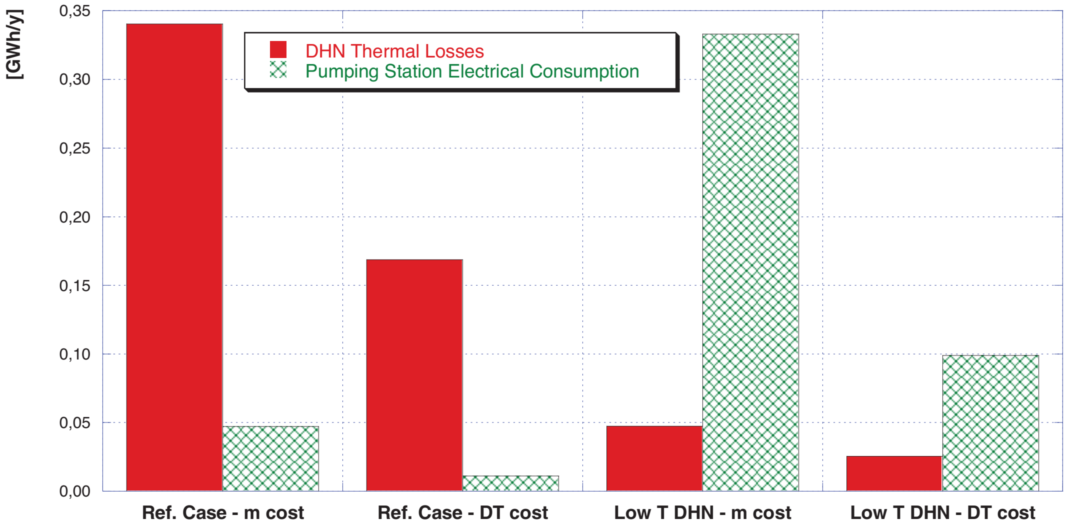

Figure 5: Annual thermal losses through the network and electricity consumption of the pumping station for the proposed scenarios (Ref. Case, Low temperature DHN) and for the evaluated off-design management strategies (constant mass flow rate or temperature difference)

contrary, the proposed low temperature scenario – by the exploitation of a geothermal source – allows to completely avoid the fossil fuel consumption at the district area, with the consequent elimination of the related pollutant emissions. In particular, considering an emission factor equal to 0.198 $kgCO_2/kWh_{CH4}$ for the NG, a total emission ranging from 735 to 773 $tonCO_2/y$ (depending on the off-design strategy) can be locally avoided during a year. This result is particularly interesting to promote environmental sustainability and to increase the life quality at the city areas. On the other hand, evidently, an increase in the electricity purchase is registered during the year for the low temperature case (see Figure 4), mainly due to the introduction of the HPs employed to provide both the thermal needs of the users and the heat required by the absorption chillers. However, this increase is limited thanks to the PV panels installation, which allow a production of around 600 MWh/y of electric energy. In more detail, the PV production covers the 22 % and the 24 % of the annual total request of electricity respectively for the case with constant mass flow rate and with constant temperature difference off-design management strategies. Furthermore, the comparative evaluation, between the Reference Case and the Low temperature case, of the total annual fuel consumption – composed by a contribution attributable to the centralized production plant (*i.e.* the annual fuel consumption shown in Figure 4) and by the amount of fuel consumed to generate the electrical energy purchased from the national electrical grid – confirms a reduction ranging from the 26 % to the 34 %, obtainable for the Low temperature scenario. To this respect, in order to evaluate the fuel amount for the electricity production, the mean efficiency value for the Italian power generation plants has been considered (40.2 %) [31]. As a consequence, an overall reduction in the CO2 equivalent emissions ranging from 355 to 414 tonCO_2/y (depending on the off-design considered strategy).

As it regards the DHN operation, Figure 5 shows the yearly thermal losses through the network and the annual electrical consumption of the pumping station. As it can be seen, the thermal losses are importantly reduced by the decrease of the network temperature levels: being equal for the two cases the off-design strategy, indeed, a thermal losses reduction of around the 85 % can be achieved with the Low Temperature DHN scenario. On the other hand, the reduction in the temperature difference between the supply and the return of the network leads to an increase in the mass flow rate through the network, from a value of around 12 kg/s (Reference Case) to a value equal to about 24 kg/s (Low Temperature DHN scenario). As a consequence, the electrical consumption of the pumping station results importantly increased (see Figure 5) especially when the constant mass flow rate strategy is adopted for the off-design operation. In addition, an increase in the network supply pressure is required for the Low Temperature DHN scenario with respect to the Reference Case. In particular, the 3-CENTO software has enabled to evaluate the optimal supply pressure for the correct network operation, which allows to guarantee a minimum pressure drop equal to 0.5 bar in correspondence of the user located at the end of the critical path (*i.e.* the path from the centralized production plant to the user with the highest pressure losses). The resulting optimal supply pressures are equal to 8 bar for the Reference Case and to 18.5 bar for the Low Temperature DHN scenario.

Finally, the results of the preliminary economic analysis are presented in Figure 6 in terms of annual cash flow, as function of the ratio c_{fuel}/c_e. As it can be seen, the Low Temperature scenario always allows to reduce the annual costs to be sustained for the energy production and network's operation and maintenance. In detail, the annual costs reduction ranges from the 5 % to the 47 % (depending on the ratio c_{fuel}/c_e). To this respect, it should be highlighted that the investment costs for the conversion of a traditional DHN into a low temperature network are quite high. As a consequence, even if the environmental advantages have been demonstrated in this study, incentives for the installation of renewable

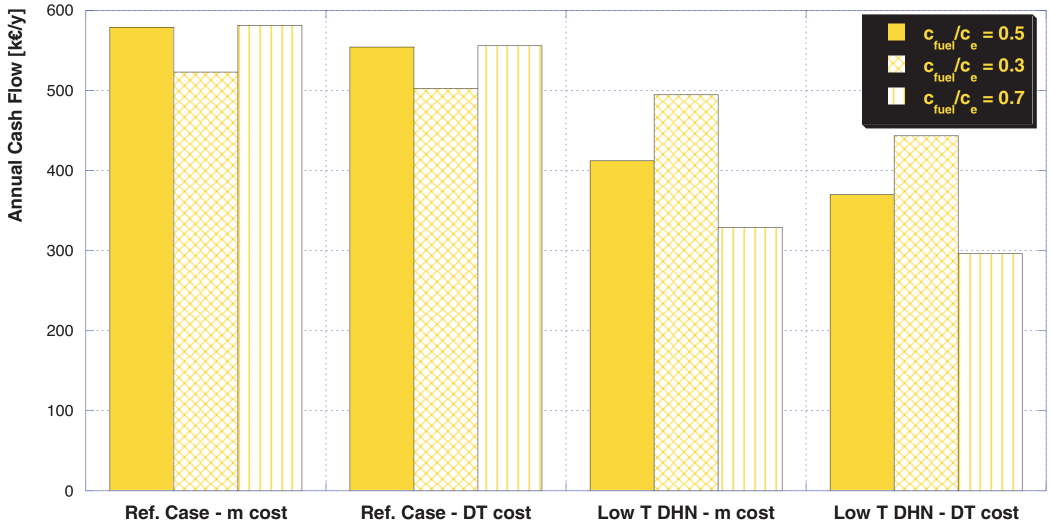

Figure 6: Annual cash flow (costs sustained for energy production and network's operation and maintenance) for the proposed scenarios and for the evaluated off-design management strategies as function of the ratio c_{fuel}/c_e.

generators and carbon taxes related to the pollutant emissions should be considered, to make the proposed solution economically viable. Furthermore, the economic convenience is strongly affected by the ratio between the costs of the NG and of the electricity. To this respect, a greater convenience can be achieved in a perspective in which – thanks to the increase in the RES penetration for electricity production – the price of NG is expected to increase while the price for electricity purchase is supposed to decrease.

4. Concluding remarks

To promote primary energy saving and pollutant emissions reduction, in this study a low temperature DHN scenario has been proposed for the fulfillment of the connected users' energy needs. The low temperature DHN operates with supply and return temperatures equal to 20°C and 10°C respectively and includes RES (geothermal and photovoltaic), HPs and absorption chillers. This scenario has been compared – in terms of primary energy consumption, network's thermal losses and pumping consumption, annual cash flows – with a traditional DHN with NG boilers as energy production systems, operating at 90°C/60°C. The results show that the proposed low temperature scenario allows to completely avoid the fossil fuel consumption at the district area, with the consequent elimination of the related pollutant emissions. In addition, even if the yearly electricity purchase is increased due to the HPs installation, the total annual fuel consumption – calculated as the sum of the fuel locally consumed and the amount of fuel consumed to generate the electrical energy purchased from the national electrical grid – results decreased by a value ranging from the 26 % to the 34 %. Further advantages can be achieved for the network operation, since the low temperature DHN scenario enables to importantly reduce (85 %) the heat losses through the network. Finally, the low temperature scenario allows to reduce the annual costs to be sustained for the energy production and network's operation and maintenance (29-33 % of reduction). Evidently, due to the quite high investment costs related to the DHN conversion, incentives for the installation of renewable generators and carbon taxes related to the pollutant emissions should be considered.

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