District Heating and Cooling Networks Based on Decentralized Heat Pumps: Energy Efficiency and Reversibility at Affordable Costs

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District heating and cooling networks based on decentralized reversible heat pumps offer the possibility of balancing heating and cooling demands and exploiting low-temperature waste heat sources. This enhanced "energy recycling" can bring significant environmental benefits. On the economic side, however, the energy savings are offset by higher investment costs. This article shows how it is possible to identify realistic scenarios where economic figures for this technology are similar to or even better than those of traditional solutions, while greatly reducing carbon dioxide emissions.

Introduction

The residential heating and cooling sector is the subject of continuous research in the field of energy efficiency. Significant attention is being focused on district solutions, where heating or cooling is supplied to a large number of buildings through a piping network. Several studies (e.g., Ref. [1]) address this technology as one of the most promising for a significant impact on the future energy system. Traditional district heating and cooling (DHC) systems, however, also involve a few drawbacks which can limit their application in certain cases. For example, they are run at temperatures relatively far from the ambient temperature (e.g., a supply temperature of 90 °C for heating), giving rise to non-negligible thermal losses. Moreover, the concept of district heating relies on the availability of some "convenient" centralized energy source (the same condition, but with reversed energy flow, is required for district cooling). This convenience may be either economic or environmental in nature. Typical examples of convenient sources include cogeneration units, industrial waste heat and incinerators, where heat is a by-product generated by other applications. However, such sources are not always available. In their absence, traditional district heating networks can be less sustainable than decentralized individual solutions.

The urban environment actually offers several other options of waste heat, though at lower temperatures. A simple example is refrigeration units in shopping malls. In principle, these systems could also be connected to a high-temperature network through a high-temperature heat pump. However, this type of source alone typically does not justify the installation of a traditional district heating network. An alternative option to consider is a low-temperature network, with average operating temperatures of around 20 °C.

The concept of a low-temperature network coupled to decentralized HPs is the subject of the FLEXYNETS project, supported by the Horizon 2020 European research programme. This approach, with some preliminary economic estimates, is described in Ref. [2]. Its main advantages are the decrease in thermal losses (and/or the possibility of using cheaper pipes), the reversibility of the network and the possibility of directly recovering low-temperature waste heat. On the other hand, two main criticalities are present: electricity needed by HPs comes at a higher cost (and has a higher primary energy factor) than thermal energy, and investment costs for substations based on HPs are higher than for traditional systems. These effects are exemplified below by a few simple scenarios.

Considered scenarios

We provide an estimate of the feasibility of a FLEXYNETS network, comparing five different scenarios. To include in our evidence the role played by the reversibility of the system, we consider a case with significant cooling needs – as expected for typical Southern European climates.

We start from a reference scenario with individual heating and cooling, and contrast this with scenarios based on traditional district heating or FLEXYNETS. The general conditions, valid for all scenarios, comprise a typical Southern European climate (namely that of Rome) and a city zone with 500 small multifamily houses of 500 m^2 each, with an overall land area of 1 km^2. This corresponds to a plot ratio (ratio between floor area and land area) of 0.25 – not a very demanding value in terms of building density. We assume the availability of various amounts of low-temperature waste heat in the area. This could be provided by the refrigeration units of a medium-sized shopping mall. Both the presence of such a facility and the chosen plot ratio are compatible with common city outskirts.

For the scenario based on individual systems, we assume that all the buildings are equipped with gas boilers and electric cooling units. While cooling systems are currently not always present in buildings, their spread is a constantly growing trend. Increasing demand for building comfort and increasing outdoor temperatures suggest that full penetration of cooling systems could be realistic in the near future. The main costs of this "Individual" scenario are the investment costs for individual

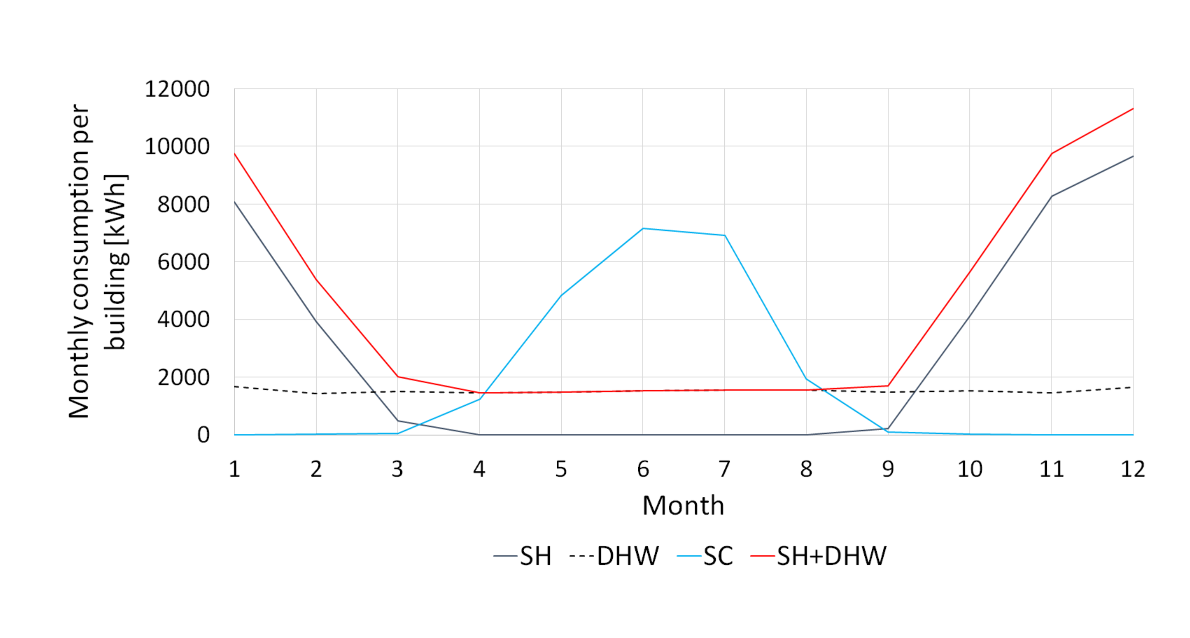

Fig. 1: Typical monthly consumption profiles for a single building of 500 m². The different curves correspond to space heating (SH), domestic hot water (DHW), total heating (SH+DHW) and space cooling (SC).

boilers and chillers, plus corresponding gas and electricity costs. Residential prices must be applied in this case.

As a first variation from this scenario, we consider the substitution of individual boilers with traditional district heating (DH) while keeping individual cooling units. Hence cost changes apply only to the heating element. Investment costs for individual boilers are replaced by investment costs for the network, substations and a centralized boiler (as no other high-temperature sources are assumed). Gas costs now have to be evaluated as for industrial customers. The traditional network is assumed to operate with a supply temperature of 80 °C and a supply-return temperature difference of 30 K.

Finally, we consider three FLEXYNETS scenarios (FL), where the network replaces both individual heating and cooling systems. The three different scenarios include, respectively, 0 % of waste heat, 35 % of waste heat, and finally 60 % of waste heat (referring to the share of the network heat supply). This could also be seen as representing the progressive integration of new waste heat sources. The network supply temperature is set at 30 °C, with a supply-return temperature difference of 10 K. Industrial prices are assumed for both gas and electricity.

The modelling approach

Each of the above scenarios is analysed in terms of costs and emissions using a simplified model. The model takes into account yearly profiles with a time slicing approach: a characteristic daily profile is coupled with monthly energy consumption to simulate an entire year. The monthly profiles considered for a single building are reported in Figure 1. The corresponding specific annual consumption is 70 kWh/(m²·year) for space heating, 37 kWh/(m²·year) for domestic hot water, and 45 kWh/(m²·year) for space cooling. The total yearly consumption (i.e., for the 500 buildings) for each scenario is 27 GWh/year for heating and 11 GWh/year for cooling. The overall performance, including estimates for network thermal losses and pumping costs where applicable, is then estimated with energy balances in an Excel model. For the scenarios where a district network is considered, the model includes sizing rules to estimate pipe lengths, diameters, and capacities of centralized units.

For the waste heat availability, a constant profile is assumed. For large shares, this implies a surplus of heat during summer. Two waste heat penetration cases are considered: one with an availability of 15 GWh/year, where 8 GWh/year can be exploited (yielding a 35 % share of the network supply), and another with an availability of 28 GWh/year, with an exploitation of 13 GWh/year (60 % share).

For economic calculations , the investment costs and the operating and maintenance costs for equipment and piping are based on values provided by the Danish Energy Agency – a valuable reference for DH data. Comparisons of individual costs with Italian values do not show critical differences. Energy prices representative of the Italian case are chosen: a residential gas price of €80/MWh, an industrial gas price of €35/MWh, a residential electricity price of €200/MWh, and an industrial electricity price of €100/MWh. Costs of low-temperature waste heat are considered only for FLEXYNETS scenarios. A simple business model is assumed: all the available heat is absorbed by the network, for a price of €10/MWh, excess heat being dissipated by a centralized cooling tower. All investment costs are converted into annualized costs using the annuity method, with an interest rate of 3 % and lifetime values depending on the equipment chosen.

To estimate CO_2 emissions, specific values are assumed to be 0.250 t/MWh for gas and 0.377 t/MWh for electricity, compatible with recent Italian grid values.

Results

The overall costs of the five scenarios considered are shown in Figure 2. We can see the significant role played by cooling costs. The lower cost of district solutions compared with individual ones is also apparent. It should be noted, however, that district costs do not include personnel costs and indirect costs, or other company revenues.

A few major effects can be observed. When moving from individual heating to DH, a substantial reduction in gas costs is achieved due to the significant difference between residential and industrial gas prices. Moreover, investment costs for centralized boilers are significantly lower than for individual boilers. On the other hand, district solutions involve network costs. These costs are similar for all district scenarios: indeed, the cost variations due to the larger diameters and lower insulation levels required in FLEXYNETS are opposite to each other, and basically balance out. For FLEXYNETS scenarios, the largest cost item is heat pump investment costs – here taken from the Danish Energy Agency data for individual installations. Alternative market investigations and the possibility of exploiting economies of scale suggest that these costs could be roughly halved, with the significant impact shown in the figure. Finally, we can see that the introduction of waste barely affects economic performance. This is due to two main aspects: the mismatch between waste heat and heating profiles, and the chosen business model. Under such conditions, in order to raise the waste heat share, one also has to increase the amount of excess heat to be bought and dissipated – almost balancing out gas savings and additional costs.

Environmental performance is reported in Figure 3. Here the outcomes are quite different. When moving from individual heating to traditional DH, emissions increase. Indeed, in the absence of particularly efficient sources, DH only introduces higher thermal losses. In contrast, by moving to FLEXYNETS scenarios higher and higher emission savings can be achieved. This highlights the advantage of having a reversible network – with some balancing between heating and cooling demands – and of including waste heat.

Conclusions

Summarizing, five different scenarios related to a Southern European climate and a city zone with 500 small multifamily houses were analysed. The FLEXYNETS approach was compared to traditional individual and district systems, under the assumption of no "convenient" high-temperature sources in the surroundings. Different shares of low-temperature waste heat were instead considered.

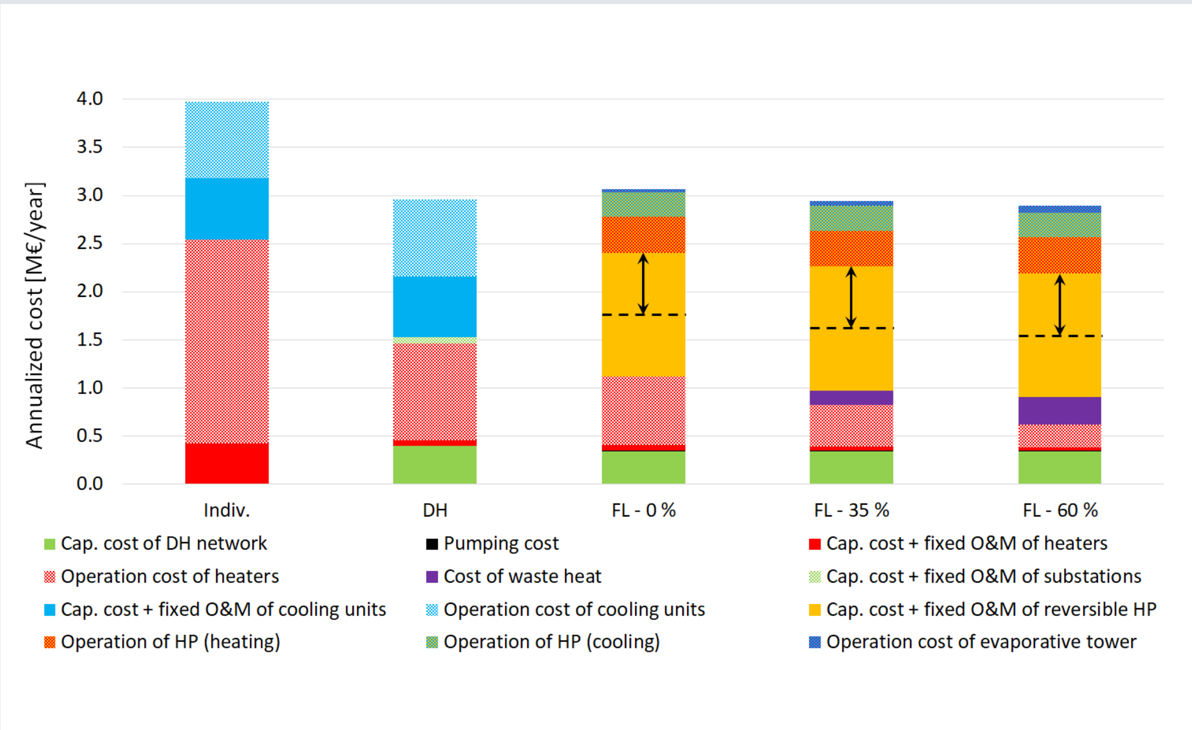

Fig. 2: Annualized costs for the different scenarios. Investment, operation and maintenance, as well as energy costs are fully included. Personnel and additional company revenues for the district scenarios are instead not considered. Investment costs for HPs are taken from reference values for single installations. Black arrows indicate the expected potential decrease of HP investment costs on the basis of alternative market investigations and economies of scale.

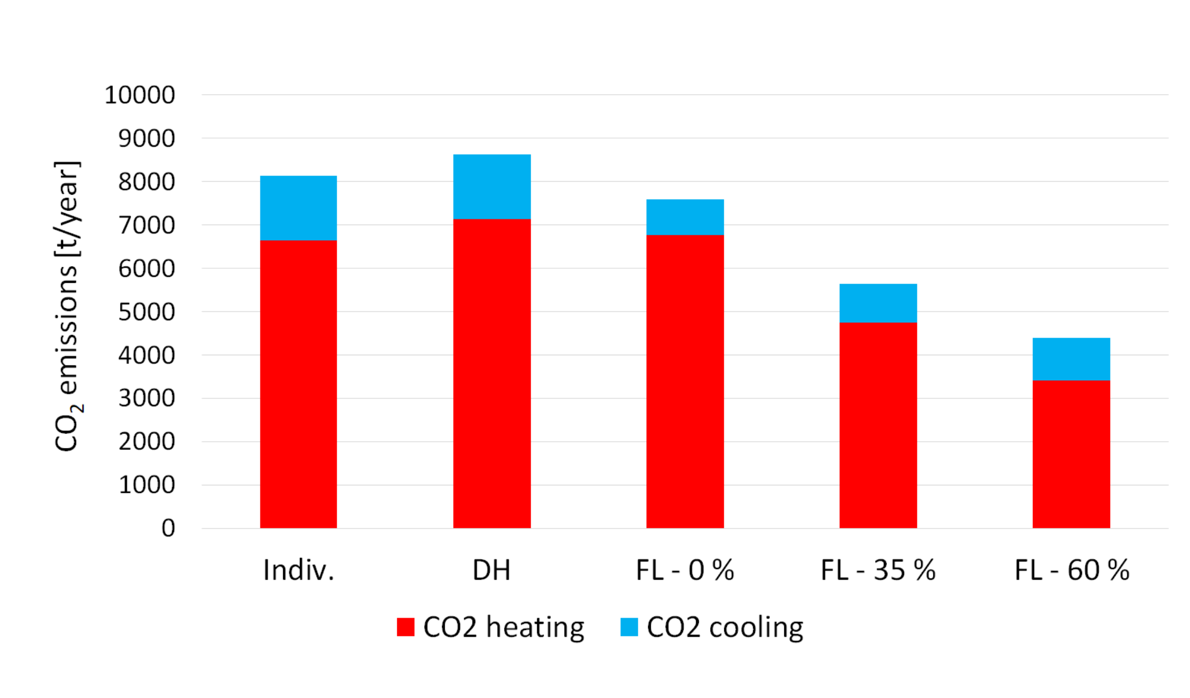

Fig. 3: Carbon dioxide emissions for the different considered scenarios. Emissions for heating and cooling needs are shown separately.

The main evidence is that, in spite of the high costs for HPs, a FLEXYNETS system can be economically feasible without great cost differences from traditional approaches. On the other hand, it can greatly improve environmental sustainability. It must be emphasized that different geographical conditions could change this picture: a non-negligible cooling demand is indeed an important requirement for exploiting the potential of reversible systems. Nevertheless, these general estimates show that investigating this option further is of interest.

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