PROCEEDINGS OF ECOS 2012 - THE 25TH INTERNATIONAL CONFERENCEON
EFFICIENCY, COST, OPTIMIZATION, SIMULATION AND ENVIRONMENTAL IMPACT OF ENERGY SYSTEMS
JUNE 26-29, 2012, PERUGIA, ITALY

Thermoeconomic approach for the analysis of low temperature district heating systems

Verda Vittorio[a] and Albana Kona[b]

[a] Politecnico di Torino, Torino, Italy, vittorio.verda@polito.it
[b] Politecnico di Torino, Torino, Italy, albana.kona@polito.it

Abstract:

In this paper a thermoeconomic analysis of district heating systems is performed. The analysis aims at comparing possible options to supply heat to the users, using low temperature networks. Thermoeconomic analysis consists a powerful tool to perform such analysis as it allows one to evaluate the possible options in terms of primary energy cost or economic costs. In the first case, the use of exergy as the quantity that is transported along the network makes it possible to properly consider the various qualities of energy that are used to supply heat to the network and to distribute it to the users. In the case of economic cost, the various cost contributions are considered: investment cost, cost of heat supplied to the network, pumping cost. A different cost can be calculated for the various users depending on their position and characteristics of the heating devices. This is a useful information in order to compare possible options for supply them heat.

Keywords:

District heating, low temperature heating, thermoeconomic analysis

1. Introduction

District heating is a rational and reliable way to supply heat to multiple users from a unique or few centralized thermal plants. Heat is mainly produced with systems as combined heat and power plants, biomass boilers and industrial processes heat recovery systems, integrated with high efficiency boilers to cover peak loads. One of the most interesting contributions of district heating networks to future energy systems is the opportunity to integrate heat productions from renewables [1].

The use of renewables in district heating may involve reduction of the operating temperatures. This idea is behind the concept of “low temperature district heating”. Low temperature district heating is typically characterized by supply temperatures between 75°C and 50 °C (even if lower temperatures may be considered) and return temperatures between 40 °C and 20 °C [2,3]. This allows the direct use of renewable energy sources as solar [4] and geothermal [5] or in combination with large-scale heat storages [6]. In addition, there is big potential for utilization of waste heat from cogeneration plants, waste-to-energy plants, heat pumps and industrial processes [7,8]. Low temperature networks allow one to increase the amount of heat recovery from exhausts and also to recover heat from low temperature processes.

The main issue on this kind of systems is referred to investment and operating costs. As any other system it needs to be more convenient than the alternatives. In addition, its energy sustainability should be carefully analyzed in order to ensure that the total primary energy required to supply heat to the users is smaller than possible alternatives.

To build district heating networks several years are usually necessary, with large expenses and discomfort to the community. For this reason, the system must be designed in its final structure, with few possibilities of making changes. In particular it is necessary to determine the possible users to be connected, the topology and the pipe diameter of each branch. Such a problem can be solved as a synthesis problem, i.e. an optimization where the system structure is not defined a priori

[9]. In this way it is possible to define the optimal network that minimize (or maximize) an objective function, such as the minimum cost of heat or the maximum benefit.

This paper deals with the problem of district heating network (DHN) synthesis, i.e the search for the optimal configuration of the network, which consists in the identification of users that should be connected to the network and those to which heat should be supplied through alternative systems. In particular, a low temperature district heating network fed with solar energy is considered. The analysis is conducted considering a supply temperature between 55 °C and 40 °C, while the return temperature is assumed 25 °C or 20 °C. Groundwater heat pumps run with solar photovoltaic are considered as the possible alternative, in order to obtain 100% renewable configurations.

A thermoeconomic approach [10] is applied to a small network by considering both monetary and energy cost as the objective functions in the optimization.

2. Thermoeconomic analysis

The optimal synthesis of energy systems is here approached by starting with a superstructure, which is a DHN involving all of the possible zones and thus all the users. The use of a superstructure is the most common approach to synthesis problems (see for example [11]). Once the superstructure is built, the synthesis problem can be solved as an optimization problem, provided that particular values of the variables associated with the components or with the internal flows correspond to the condition of absence of that component or flow. In the case of DHN when the optimal mass flow rate in a pipe is zero means that the pipe must be eliminated from the structure.

The procedure starts with the evaluation of the objective function in the initial configuration, corresponding to all the users connected with the network. The network is then reduced, through successive elimination of the users characterized by high costs and the corresponding pipes connecting these users with the rest of the network. The selection of the user to be disconnected to the network is operated using a probabilistic approach. The probability of a user to be disconnected increases with increasing unit cost of heat supplied to that user. As this procedure is not deterministic, it should be repeated several times in order to increase the possibility to find the true optimal configuration. The procedure is stopped when all the users are disconnected.

The details of the selected procedure are shown by considering the average primary energy consumption of heat provided to the users as the objective function to be minimized. This quantity is calculated as the exergetic unit cost of heat. The first step consists then in calculating the productive function:

$$\bar{c} = \frac{C_{tot}}{Q_u} = \frac{C_{net} + c_F \cdot Q_F + c_P \cdot L_P + c_a \cdot Q_a}{Q_u} \qquad (1)$$

The cost of network C_{net} is the amount of primary energy required to produce and install the insulated pipes. Components as heat exchangers, pumps, valves have been neglected in the analysis. Primary energy associated with excavation, installation and paving restoration has been also considered. C_{net} is an annual cost. Year is the best unit time to be used for thermoeconomic analysis of such system due to the production variation depending on the average external temperature and during the day. Cost functions used in this analysis are discussed in the annex.

The energy unit cost of heat has been calculated considering heat production from solar collectors only. The following expression for collector efficiency has been considered [12]:

$$\eta = \eta_0 - a_1 \frac{\Delta T}{I_t} - a_2 \frac{\Delta T^2}{I_t} \qquad (2)$$

ΔT is the difference between the average temperature of the fluid inside the collectors and the air temperature and I_t is the total radiation. Ambient temperature and solar radiation of Turin have been considered (see Table 1).

Table 1. Solar radiation and temperature for Turin

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
I_t(MJ/month/m^2)	155	218.4	378.2	340	607.6	645	728.5	573.5	405	288.3	165	145.7
T (°C)	1.7	5.3	8.5	15.7	19.1	20.5	21.3	24	20.3	13.2	7.7	4.1

In the case of the available collectors: η_0=0.718, a_1=0.974 W/m^{2}K, a_2=0.004 W/m^{2}K^2. Excess heat produced when the heating demand is small is considered to be stored in a seasonal storage system. Efficiency is considered to be linearly dependent on the difference between the internal temperature and ground temperature. Efficiency is assumed 0.9 when the internal temperature is 90 °C and ground temperature is 13 °C [13].

Heat request by the users Q_u and heat supplied by the thermal plant Q_F differ because of heat losses Q_L. Heat losses have been calculated by considering each branch.

$$Q_L = \pi \cdot D \cdot L \cdot k \cdot \left(\overline{T} - T_g\right) \cdot t \qquad (3)$$

where k is the overall heat transfer coefficient and $\overline{T}$ is the average temperature between outgoing an return network, T_g is the ground temperature an t is time period (a year).

Last term on numerator of equation (1) accounts for the primary energy association with electricity required for pumping, being c_P the exergetic unit cost of electricity and L_p is the annual electricity consumption, calculated as:

$$L_p = \frac{1}{\eta_p} \int_{year} G \cdot v \cdot \Delta p \cdot dt \qquad (4)$$

where η_p is the average pump efficiency, G is the water mass flow rate, v is the water specific volume (constant) and Δp the total pressure losses due to pipe friction and localized resistances.

The last term on the right hand side of equation (1) is the cost of heat supplied to the users fed with alternative systems. This is obtained as the product of the exergetic unit cost of the heat produced with these systems (c_a) times the annual heat supplied to the users not connected with the district heating (Q_a). In the initial network configuration this term is zero.

Terms in equation (1) depend on the thermal load supplied by the network and on its extension. The possible area to be heated by the thermal plant must be chosen. This area can be divided into zones, each including one or more buildings. The number of zones should be selected as trade-off between result accuracy (large number of zones) and time required for design and calculation (small number of zones). For each zone, the total volume of buildings is determined. The thermal barycentre can be easily located in the area by considering the position of buildings and their respective volume (the geometric barycentre can be used as well, especially when the building structure is sufficiently regular). At this point, the network connecting the thermal plant with TBs can be traced.

The annual heat load of each single zone Q_z is calculated by considering, for the whole heating season, the daily difference between the internal temperature (20 °C) and the external temperature, the average thermal transmittance of buildings (through walls, windows, floor, etc.), the number of daily heating hours (hh). The thermal transmittance of building can be multiplied for a shape factor defined as the ratio of external surface and building volume; this quantity, here indicated as r, expresses the volumetric heat losses per unit temperature difference. This value has been measured for several buildings; an average value of 0.9 W/(m^{3}K) can be assumed. The annual heat load for a zone, in kWh, is then calculated as

$$Q_z = \frac{r \cdot DTD \cdot hh \cdot V_z}{1000} \qquad (5)$$

where V_z is the total volume of buildings in the zone and DTD is the summation of daily difference between internal and external temperature, calculated for the whole heating season (degree day). The number of daily heating hours is considered to be the same as for buildings with individual heating system, which is established by law, depending on DTD. In the specific case analyzed in this paper, this quantity is about 2730 °C, being the heating season from the middle of October to the middle of April, while the number of heating hours is 12 per day.

The total heat load is calculated as summation of the contributions of all zones. The network operates for longer time than specified, mainly due to four causes: 1) non contemporary request by the users, 2) presence of particular users, like hospitals, that requires heat for more than 14 hours per day and for an extended period, 3) domestic water demand, 4) presence of users that requires heat in summer for air conditioning through absorption chillers. For all these reason, the total load calculated through equation (5) has been considered as spread on 18 hours per day in the seasonal heating, moreover the thermal flow outside this period has been assumed non null, but calculated on the basis of the thermal losses.

The cost of the network is calculated by considering each single branch and depends on its diameter. Internal diameter of pipes is calculated by first determining the mass flow rate in each branch. The mass flow rate is imposed by the thermal requirement of each user downstream that branch:

$$\Phi = G \cdot \left(h_o - h_r\right) \qquad (6)$$

where Φ is the thermal flow provided to the users (the maximum load is considered in design), G the water mass flow rate, h_0 and h_r the enthalpies of fluid feeding and returning from the users. The diameter is determined by imposing the maximum velocity v_{max} allowed in the pipes. This value is mainly defined on the basis of economic criterion, since friction losses and thus pumping cost depend on the square of velocity. On the other hand, a too low velocity would determine a large pipe diameter, thus high investment costs. In this analysis a value of 1.5 m/s is considered. The water mass flow rate G is expressed as:

$$G = \rho \frac{\pi D_{\text{int}}^{2}}{4} v_{\max} \qquad (7)$$

A thermoeconomic analysis is then implemented for the designed network, where all the possible users are connected. In particular, a useful approach that can be adopted for this purpose is that proposed by Valero and co-workers in the eighties [14, 15]. One of its main characteristics is the matrix based approach, in particular the use of incidence matrix for expressing the equation of cost conservation. The only auxiliary equation to be applied is the assignment of the same unit cost to the flow exiting each bifurcation [16].

The unit cost of a flow *c* can then be calculated, by dividing the costs for the corresponding exergy flow:

$$c = \frac{B}{\Psi} \cdot 3600 \qquad (8)$$

Where B is the exergetic cost of a general flow and Ψ its exergy.

At this point, the unit cost for each user, can be calculated. This cost is not the same for all of them because of the different exergy destruction (mainly due to friction) and the pipe cost associated to the different paths joining the thermal plant with the users.

The network is then optimized using a probabilistic approach similar to simulated annealing [17]. The probability of users to be disconnected to the district heating network is assumed to be dependent on their unit cost. In the optimization procedure, users are progressively disconnected from the network. Each iteration the user to be disconnected is randomly selected from an ensemble where the number of samples for each user is proportional to its probability. The users disconnected with the network are considered to be heated through the alternative system, which is, in this case a solar photovoltaic driven groundwater heat pump. The average COP of the heat pump is assumed equal to 4 in the case of unperturbed groundwater temperature. In the case of multiple installations, possible interferences between heat pumps are considered, as discussed in [18]. A simplified expression for the effects of the distance d between an upstream installation on a downstream installation is assumed:

$$COP = COP_0 \cdot (0.9 + 0.0108 \cdot \ln(d)) \qquad (9)$$

Since a probabilistic approach has been considered, the complete optimization procedure has been repeated several times in order to increase the probability to find the true optimum.

The entire procedure is similar in the case of economic costs, the only difference is that unit costs are expressed in monetary units. Costs of insulated pipes have been considered as in [10], while the cost of solar collectors and storage system have been taken from [13]. No incentives have been considered for solar energy.

In the cases where minimum primary energy and minimum economic cost are competing, the optimization has been performed by imposing a variable constraint on the maximum acceptable cost of heat (i.e. the economic objective function), so that the problem can be treated as single objective optimization. Once an optimal point is found, the optimization is repeated by modifying the maximum acceptable cost of heat.

3. Application

Figure 1 shows a schematic of the district heating network that has been considered as the case study. It is a network located in a small town in the north west part of Italy. The maximum thermal request is about 7 MW [19]. Heat to this network is supplied by an internal combustion engine (about 3 MW) and gas boilers. This case study is considered since it is a reasonable size of network that can be fed with renewable energy and because there is availability of groundwater to feed groundwater heat pumps, that can be considered as potential alternatives to the district heating network.

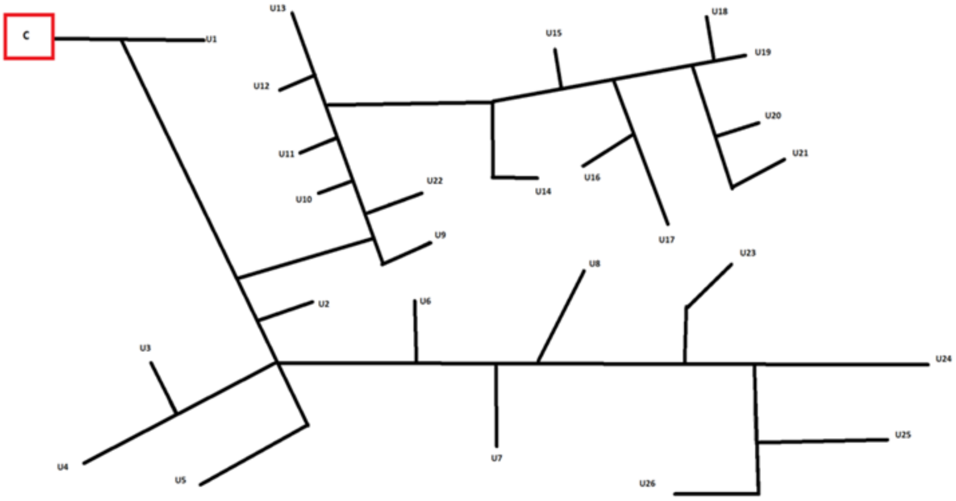

Fig. 1. Schematic of the District Heating Network.

The network shown in the figure corresponds to all the users connected to the district heating system. This superstructure is progressively simplified in order to discover the optimal configuration. The analysis is conducted by considering various combinations of the supply temperature and return temperature, which are here assumed as parameters in the analysis instead of design variables. Therefore, several optimal curves are obtained for each couple of these parameters. These results are shown in figure 2 for the following cases: 40-20 °C, 45-20 °C, 50-20 °C, 55-20 °C and 55-25 °C.

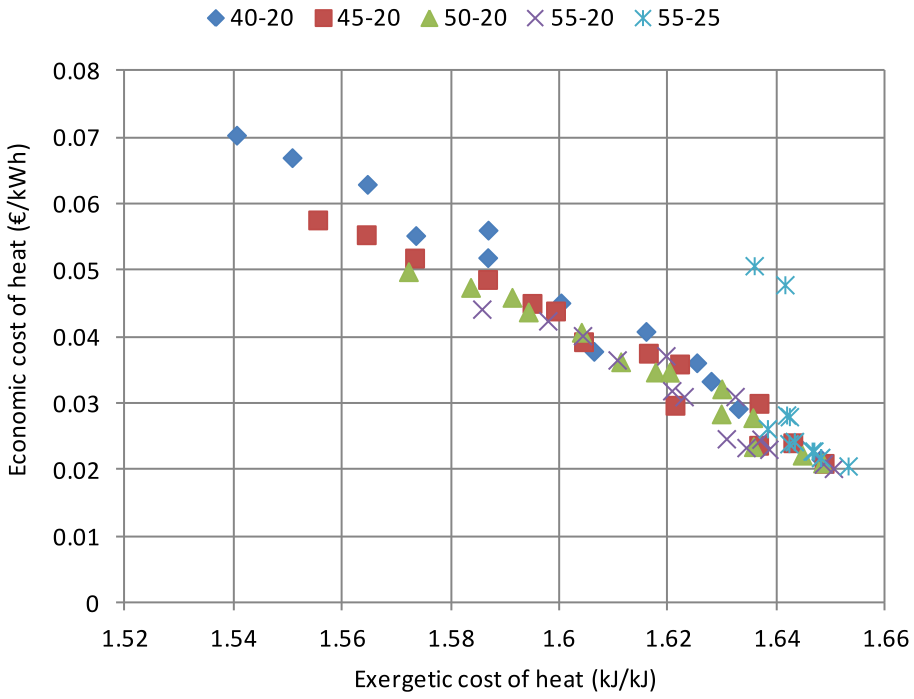

Fig. 2. Optimization results.

Results show that the two objective functions are competing for the values of the supply and return temperatures here considered. The lowest exergetic unit cost of heat is obtained in the case of smallest supply and return temperature. This also corresponds to the highest economic cost. This configuration corresponds to 54% of the users connected to the district heating network. This percentage refers to the annual heat demand with respect to the total heat demand of the users in the urban area. Increasing the supply temperature, the number of users connected to the district heating network in this condition (i.e. minimum exergetic cost of heat) increases. It becomes 67% in the case of supply temperature of 45 °C, 80% in the case of supply temperature of 50 °C and 93% in the case of supply temperature of 55 °C. The reason of such behaviour can be analyzed by considering the diagram in figure 3.

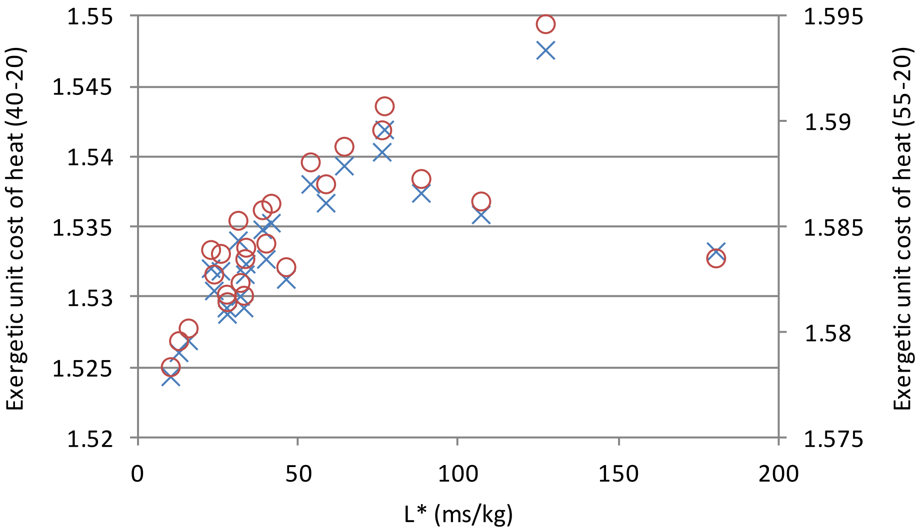

Fig. 3. Effect of weighted distance from the thermal plant to the unit cost of heat in (kWh/kWh).

Figure 3 shows the exergetic cost of heat associated to the users when they are all connected to the network. In the figure this is represented as the function of L*, which is the ratio between the distance of the user from the thermal plant and the mass flow rate required by the user. The graph shows that when the users are far from the plant, the efficient use of primary energy decreases. The only exception is represented by very small users (i.e. small mass flow rate required to satisfy the thermal request) located quite close to the thermal plant.

When the supply temperature is increased from 40 °C (crosses) to 55 °C (circles), the behaviour remains the same, but the exergetic costs increases of about 3%. This is due to the increase in the term due to heat production, which is basically associated to the efficiency of solar collectors, which decreases (of about 4.5%) because of the larger operating temperature.

Starting from the points in figure 2 corresponding with all users connected with the network (for each series, these are the points on the left part of the diagram), it is possible to reduce the economic unit cost of heat by disconnecting some users from the network (those characterized with larger economic unit cost of heat) and supplying them heat with groundwater heat pumps.

This can be observed by analyzing the exergetic and economic unit costs of heat as the users are disconnected to the network. This is analyzed in figure 4 in the case of supply temperature of 55 °C and return temperature of 20 °C.

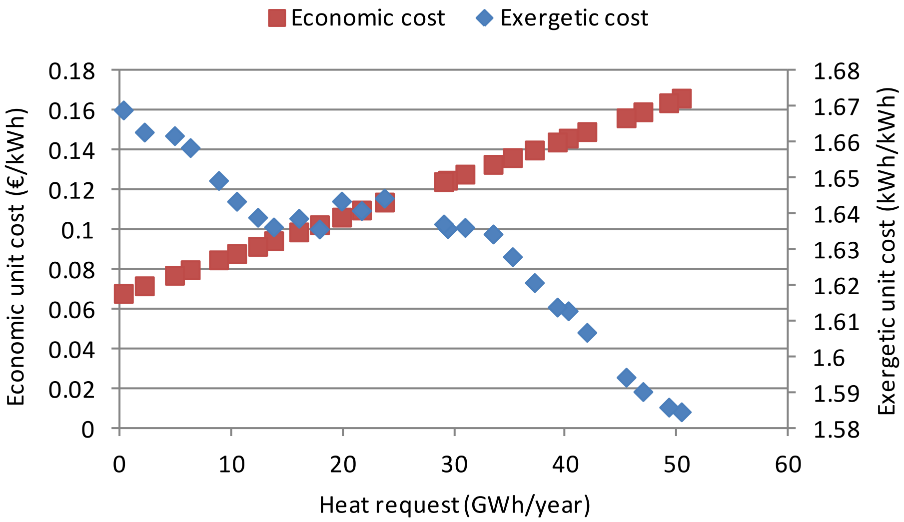

Fig. 4. Trends of exergetic and economic unit costs during a iterative network simplification.

The reasons why the exergetic unit cost tends to increase as the users are disconnected is that solar district heating is more efficient than the alternative. In addition, there are interactions between the various heat pump installations that affect their efficiency, as discussed above. In contrast, the economic cost tends to decrease. The minimum economic cost is obtained with few users still connected with the district heating system (about 6-10% of the annual heat, depending on the combination of temperatures). This is due to the interferences between heat pumps, that cause a reduction in the COP of downstream installation and thus an increase in the primary energy consumption.

Also, it is interesting to compare the unit costs corresponding to a fixed amount of heat supplied to users connected with the district heating network, for the various supply temperatures and fixed return temperature (20 °C). The amount of heat supplied through district heating network is considered to be 55% of the total annual request. Figure 5 shows that an increase in the supply temperature causes an increase in the exergetic unit cost but a decrease in the economic unit cost.

The latter is due to the reduction of the investment costs associated with heat storage and pipe network. Nevertheless the economic advantage obtained increasing the supply temperature tends to decrease with increasing temperature, in fact the distance between points at fixed increase in the supply temperature tends to reduce.

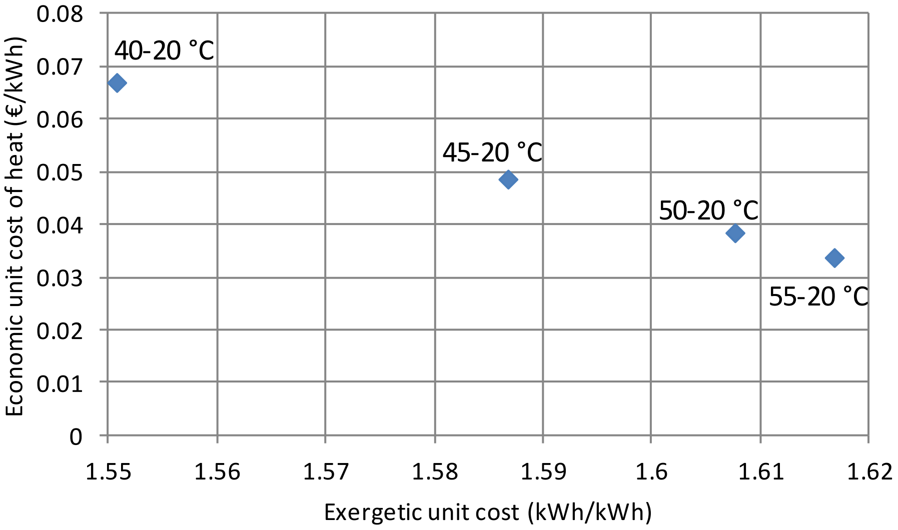

Fig. 5. Unit costs for fixed users connected to the network as the function of supply temperature.

In the case of higher return temperature (e.g. 25 °C), the Pareto front presents sudden increase in the economic unit cost of heat with decreasing exergetic cost. It should be also mentioned that in the case of high temperatures (65-40 °C, 70-35 °C, 75-30 °C...) no Pareto front takes place and the optimal system is obtained with most users heated through groundwater heat pumps.

4. Conclusions

In this paper the energy and economic optimization of a district heating network is conducted using a thermoeconomic based probabilistic procedure. The procedure is applied to a small low temperature district heating network. Groundwater heat pumps are considered as the possible alternative systems to supply heat to the users not connected to the district heating network.

A multi-objective optimization is performed for various combinations of the supply and return temperatures. The analysis shows that supply and return temperatures play a crucial role in the optimal configuration. In particular a reduction of both temperatures allows one to achieve smaller cost of heat in terms of required primary energy, but causes an increase in the economic costs. An increase in the return temperature causes an increase in both costs, which conducts to non competing objective functions.

The most important terms that affect to optimal configuration are the efficiency of solar collectors and the possible thermal interferences between heat pump, and, from the economic viewpoint only, the investment cost due to the seasonal thermal storage and the pipe network.

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Appendix: cost calculation

Purchase cost for pre-insulated pipes has been calculated through the following equation [20]:

$$C_{pipe} = (a_0 + a_1 \cdot D + a_2 \cdot D^2) \cdot 1.25 \cdot 2 \cdot L$$

where D is the internal diameter and L the length of the pipe, 1.25 is a corrective factor used to include the cost of special components also determined through available data and 2 accounts for the double pipe. The values of polynomial coefficients have been updated with respect to those available in [20]: a_0=11.7 €/m, a_1=133.7 €/m^2, 1575 €/m^3.

Installation costs include the excavation (5.2 €/m^3) and pavement restoring (10.3 €/m^2).

Concerning heat generation, the following specific equipment costs are considered: solar collectors 250 €/m^2, photovoltaic panels 2500 €/kW, heat pumps 500 €/kW [21], seasonal storage tank 80 €/m^3 [13]. Linear cost functions have been considered for these components.