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Thermoeconomics as a Tool for the Design and Analysis of Energy Savings Initiatives in Buildings Connected to District Heating Networks

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Abstract

District Heating (DH) is a rational way to supply heat to buildings in urban areas. This is expected to play an important role in future energy scenarios, mainly because of the possibility to recover waste heat and to integrate renewable energy sources. Even if DH is a well known technology, there are open problems to face. Some of these problems are related to tendencies to reduce design and operation temperatures, the improvement of control strategies, connection of new users to existing networks, implementation of energy savings initiatives and the access of multiple heat producers to the same network. This paper aims to show that exergy is an appropriate quantity for the analysis of DH systems and thermoeconomics can be profitably used to improve their design and operation. Three possible applications of thermoeconomic theories are presented: variation of supply temperature along the heating season, opportunities to connect new users, effects of energy savings initiatives in buildings connected with the network.

Keywords: Thermoeconomic analysis; district heating; low temperature networks; network extension; energy savings in buildings.

1. Introduction

District heating (DH) enables whole communities to benefit from low and zero carbon energy sources, including those which cannot easily be installed at the individual building level. DH schemes comprise a network of pipes connecting the buildings in urban areas, so they can be served from centralized plant. This allows any available source of heat to be used, including combined heat and power (CHP), waste to energy, industrial heat surpluses and renewable sources [1]. By providing a way to aggregate a large number of small, inconsistent heating demands, DH provides the key to wide scale primary energy saving and carbon reduction in whole communities [2].

The concept of district heating was quite standardized but has evolved in the last few years, mainly because of new opportunities that the development of renewable energy plants and energy saving techniques have created. Using low-temperature heat from industrial waste heat in DH has proven to be attractive from energy and economic viewpoints [3]. Furthermore an important aspect of new building development is their increasingly high standards of efficiency. In order for DHN to remain an effective solution for such developments, reductions in temperature supply should be achieved. This allows one to use different sources of locally available waste and renewable heat [4] and to reduce the heat losses. The role of DH in future renewable energy systems has been evaluated in Lund et.al [5].

In the case of solar district heating, temperature must be reduced in order to not penalize the efficiency of solar collectors, which depends on the temperature difference between the working fluid and the environment. As an example, the design supply temperature in the Hamburg-Bramfeld solar district heating is 60°C [6]. Another option of energy source for district heating which may involve low temperature distribution networks is geothermal energy. A comprehensive analysis and discussion of geothermal district heating systems and applications has been carried out in Ozgener et al [7].

An important design/operation variable in DH is supply temperature. Lowering this temperature involves reduction in exergy consumption at the end-user and generally causes reduction in temperature difference between supply and return pipe and therefore larger mass flow rates in the pipes. This means that exergy consumption for pumping increases. Trade-off between primary energy required for heat production and pumping can be investigated through the concept of exergy (see for example [8]). Exergy analysis is more significant tool, than energy analysis, for system performance assessment and improvement since it allows true magnitudes of the various losses and degradations. An application of this concept to geothermal district heating has been proposed in Reference [9].

Exergy analysis, pursuing a matching in the quality level of energy supplied and demanded, pinpoints the great necessity of substituting high-quality fossil fuels by other low quality energy flows, such as waste heat. In this paper, steady-state and dynamic energy and exergy analysis of the system are presented and strategies such as lowering supply temperatures from 95 to 57.7 °C increases the final exergy efficiency of the systems from 32% to 39.3%. Similarly, reducing return temperatures to the district heating network from 40.8 to 37.7 ◦C increases the exergy performance in 3.7%. [10].

The exergy analysis and the influence of exergy losses on the heat price in distributed district heating systems provides a thermodynamic fairer basis for the determination of heat price. It also contributes to a lower consumption of the primary energy sources on the consumers' side [11].

Thermoeconomics is a branch of engineering combining exergy and economic principles (Reference [12] provides an introduction to the subject, and references to earlier works.) The thermoeconomic analysis of an energy system allows one to calculate on a thermodynamic and economic base the cost rate of all the fluxes flowing in, out and trough the system, and in particular its products. The cost calculation gives as much information as the representation of the system is detailed. This is more important as the number of products is high, because in those cases the number of components and fluxes, both with physical and productive meaning, are high. Thermoeconomics can be used for costing purpose, design improvement, optimization and the analysis of operating conditions, as illustrated in Reference [13].

The first application of exergy costing to a district heating system was proposed by Keenan in 1932 [14], who suggested that the production costs of a cogeneration plant should be distributed among the products according to their exergy. Various applications of thermoeconomic analysis to DHS have been proposed successively.

Adamo et al. [15] have used a thermoeconomic approach for the optimal choice of diameters in a district heating network. Verda et al. [16a] have proposed the design optimization of a district heating system using a thermoeconomic approach. The relation between exergy based parameters of the network and the unit cost of heat supplied to the users is also investigated. A procedure for the search of the optimal configuration of district heating networks is proposed in Reference [17]. The optimization was performed using a probabilistic approach based on the calculation of thermoeconomic cost of heat associated to each single user connected with the network. It was shown that the minimum cost for the entire community is obtained by disconnecting from the network some small buildings, which are located far from the thermal plant, and providing them heat with local boilers. Oktay and Dincer [18] presented an application of an exergoeconomic model, which included both exergy and cost accounting analyses for a geothermal district heating system.

The present paper aims to propose a thermoeconomic approach for the analysis of other possible improvements of existing district heating networks. These are related to changes in the operating strategies, connection of new users and application of energy savings initiatives in buildings connected to the network.

2. Thermoeconomic analysis of a DHN

The theoretical considerations are applied to a network, whose possible users are constituted by the buildings located close to the area at the moment actually connected with the district heating network (DHN). The thermal plant is considered to be in the center of this area.

The topological model of such a system is usually made by using graph theory [19] , which is based on the use of two kinds of elements: branches and nodes. Branches represent components that transport the working fluid and where the thermodynamic processes take place (pipes, heat exchangers, pumps, valves). Nodes represent the elements where the branches are connected.

The approach to the thermoeconomic problem that is used in this paper requires the definition of a productive structure. The physical structure, where each component is characterized by entering and exiting mass and energy flows, is substituted by a different structure, where every component is represented in terms of fuels and products [20]. Fuel is a flow expressing the amount of resources needed by the component to carry out its function; product is a flow expressing the function itself. The products of each component are fuels of other components or overall plant products. In modern thermoeconomics both fuels and products are exergy flows, eventually separated into mechanical, thermal and chemical components [21].

Thermoeconomic theories allow one to determine the costs of the productive flows (fuels and products of all the components), which can be expressed in thermodynamic and monetary units. The exergetic cost [22] expresses the amount of exergy associated to the natural resources required to produce a product. The thermoeconomic cost expresses the amount of money required to produce a product.

The solution of the thermoeconomic problem requires writing two groups of equations:

1) the cost balance of every component

$$\sum_j \Psi^*{}_{\mathrm{ji}} = 0 \qquad (1)$$

in thermodynamic units and

$$\sum_j \Pi_{\mathrm{ji}} + \dot{Z}_i = 0 \qquad (2)$$

in monetary units. $\Psi^*{}_{\mathrm{ji}}$ is the exergetic cost of the jth flow entering (+) or exiting (-) the ith component, Π_{ji} its thermoeconomic cost, and $\dot{Z}_{\mathrm{i}}$ the moneraty cost rate of owning the ith component. Note that in equation (1) there is no exergetic cost of components, even if it is possible to consider this term, as discussed in Reference [22].

Unit costs can be also introduced. The exergetic unit cost k^*_{ji} is defined as the ratio between the exergetic cost $\Psi^*{}_{\mathrm{ji}}$ of a flow and its exergy Ψ_{ji}. Similarly the thermoeconomic unit cost c_{ji} is the ratio between the thermoeconomic cost of a flow Π_{ji} and its exergy. Using these concepts, equations (1) and (2) become

$$\sum_j \Psi_{ji} \cdot k^*{}_{ji} + \dot{Z}_i = 0 \qquad (3)$$

$$\sum_j \Psi_{ji} \cdot c_{ji} + \dot{Z}_i = 0 \qquad (4)$$

2) auxiliary equations, obtained by evaluating the cost of some flows, in particular:

- the unit cost of the overall plant resources, equal to 1 if the exergetic costs are required or equal to the prices of exergy if the monetary costs are required;

- in the case of multi-product components, the same unit cost is assumed for all the products.

In the approach proposed in Reference [22] equations are written in matrix form. In particular, the incidence matrix allows one to express the balance equations (1) and (2) for all the components. This matrix was introduced within the graph theory to express system topology. In the case of fluid networks the incidence matrix can be used to solve the fluid dynamic and thermal problems [23].

The application of thermoeconomics to the combined heat and power (CHP) plants allows calculation of the unit costs of electricity (c_w) and thermal flow provided to the DHN (c_T). Those costs depend on the production processes. Moreover, the thermoeconomic analysis of the DHN allows one to determine the unit cost of the thermal energy flows provided to the end users [24].

The internal diameter of the various 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 from that branch:

$$\Phi = G\,(h_s - h_r) \tag{5}$$

where Φ is the thermal flow provided to the users (the maximum load is considered in design), G the water mass flow rate, h_s and h_r the enthalpies of fluid feeding the users and returning from the users. The diameter is determined by imposing the maximum velocity v_{max} allowed in the pipes. The optimal velocity from economic viewpoint is obtained as the trade-off between pumping cost, which depends on the square of velocity, and investment cost, which increases with increasing diameter and thus with decreasing velocity. The optimal velocity varies with the mass flow rate flowing in each pipe and depends on the current cost of electricity. In this analysis a reasonable value of 2.5 m/s is taken for sake of simplicity, instead of considering it as an additional design variable. Water mass flow rate G is expressed as:

$$G = \rho\,(\pi D_{int}\hat{}2)/4\;v_{max} \tag{6}$$

The purchase cost of the DHN is calculated by considering the contributions of the pre-insulated pipes constituting the main distribution network, the pumps, the special components, such as valves and junctions between pipes, the heat exchangers in the buildings and in the thermal plant and the costs for installation and special components as well.

The annual electricity consumption Lp is calculated through the equation (7):

$$L_p = \frac{1}{\eta_p}\int_{year} G\cdot v\cdot \Delta p\cdot dt \tag{7}$$

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

The purchase cost of the pre-insulated pipes is expressed through a polynomial function, obtained by interpolating available data:

$$PC_{IP} = \left(a_0 + a_1\cdot D_{int} + a_2\cdot D_{int}^{\;2}\right)\cdot L\cdot 2 \tag{8}$$

where D_{int} is the internal diameter and L the length of the considered pipe, 2 accounts for the double pipe, supply and return. The values of polynomial coefficients are: a_0=28.14 €/m, a_1=0.297 €/(mm·m), and a_2 =5.01·10-4 €/(mm^2·m).

The total cost of the substations (including heat exchangers, pumps, an installation at the users) has been calculated as the function of the heat transfer area, using a general function [25]:

$$TC_i = TC_0\cdot\left(\frac{X_i}{X_0}\right)^{\alpha} \tag{9}$$

where TC_0 is the known cost of the device at a specific size, X is a variable selected for expressing the component size, X_i is its value for the device whose cost is calculated and X_0 its reference value. For heat exchangers the variable expressing the component size is the heat power. Reference values TC_0 and X_0 are respectively assumed to be 8782 € and 150 kW, while α=0.7306.

The total cost of the CHP plant is very dependent on the size. Published prices indicate a basic cost of 800 €/kW for a CCGT in the range of 50-100 MW electric power:

$$TC_{chp} = 0.8\,W_{elc} \tag{10}$$

where W_{elc} is the peak electric power produced by the power plant when operating in non-cogenerative mode.

Both capital and operational costs have been amortized. For the first ones a discount rate of 5% has been considered. The equivalent annual cost A has been computed as:

$$A = TC\,\frac{d\cdot(1+d)^n}{(1+d)^n-1} \tag{11}$$

in which TC is the total capital cost, d is the discount rate and n is the life of the network, expressed in years.(30 years)

Thermoeconomics applied to the system allows one to calculate the total cost rate of the thermal flow supplied to the network. The influence of the production of thermal exergy on the costs can be examined in a simple way considering the plant as a black box and applying the cost balance equation to the system, keeping constant the fuel and varying the thermal request [26].

$$c_f * \Psi_F + \dot{Z}_{chp} = c_w * W + c_T * \Psi_T \tag{12}$$

Where c_f is the unit cost of the fuel, c_w and c_T are the unit costs of electric power and thermal exergy; $\dot{Z}_{chp}$ is the cost rate of the CHP plant, Ψ_F : exergy of the fuel; Ψ_T is the amount of the thermal exergy produced by the CHP plant; W is the electric power produced by the CHP plant.

The average value of the thermoeconomic unit cost of the products is:

$$c_{chp} = (\Psi_F + \dot{Z}_{chp})/(W + \Psi_T) \tag{13}$$

where c_{chp} is the unit cost of the thermal exergy produced by the power plant (0.062 €/kWh in the present work). The exergy content of heat reduces with the supply temperature, therefore the unit cost of heat reduces at constant exergetic cost. As an example, assuming the external temperature -5 °C and a fixed difference between supply and return temperatures of 25 °C, the cost of heat is 0.0177 €/kWh at 90 °C, 0.0165 €/kWh at 80 °C and 0.0152 €/kWh at 70°C. The ratio between heat and exergy content of heat at these temperatures is 3.86, 4.18 and 4.59, respectively. In the calculations performed here, costs are calculated for each scenario, depending on the supply temperature and the outdoor temperature. The returning temperature is not a design variable, since it depends on the heat exchanger behavior.

The influence of the production of thermal exergy on the costs can be examined in a simple way considering the district heating network as a black box and applying the cost balance equation to the system, varying the thermal request of the district heating network, the pumping and the thermal exergy required by the users.

$$c_{chp} * \Psi_{DHN} + c_{chp} * \Psi_{pump} + \dot{Z}_{DHN} = c_{heat} * \Psi_U \quad (14)$$

where Ψ_{DHN} is the amount of thermal exergy required by the DHN (i.e. thermal exergy required by the users and thermal exergy losses), Ψ_{pump} is the amount of mechanical exergy due to pumping, Ψ_U is the amount of thermal exergy required by the users and $\dot{Z}_{DHN}$ is cost rate of the district heating network.

The exergy efficiency of the DHN is determined as:

$$\varepsilon_{DH} = \Psi_U/\Psi_{DHN} \quad (15)$$

Where ε_{DH} is the exergy efficiency of the network.

3. Results and discussion

The DHN considered as the application of thermoeconomic analysis is located in a small town in Piedmont, Italy. The end users are residential and public buildings, up to a total of about 26 MW of thermal power. The extension of the network is about 20 km. The analysis has been carried on by using different conditions during the heating season. The water temperature in the supplying network is about 90°C, while in the return pipes is about 60°C. Load variations are mainly controlled by operating on the water mass flow rate. A heat exchanger located in each building operates the connection between the main network and the building distribution system. Water circulation through the network is obtained by means of pumps located at the thermal plant.

The thermal plant considered in the present application consists of a cogenerative combined cycle and auxiliary boilers. Cogeneration is obtained through a steam extraction from the turbine at about 1.28 bars, which is condensed in a heat exchanger. The peak thermal request is covered by the auxiliary boilers.

The district heating operation along the heating season has been modeled. Steady state conditions have been considered. The thermal request has been assumed as proportional to the difference between the design temperature in the buildings (20 °C) and the average outside daily temperature. In this analysis, the thermal season has been simulated by considering seven different ranges of the outdoor temperatures from -5°C to 18 °C. Each range is represented by a crisp value, e.g. -3°C is assumed as the crisp value for the range between -4°C and -2°C. For each value, its frequency in the heating season is obtained from a weather database. The building substation operated at constant mass flow rate while the supply temperature is adjusted as a function of the outdoor temperature. As the outdoor temperature increases, the power delivered in the heat exchanger at the user substation decreases, as well as the supply and return temperature at the building substation.

Three different analyses are performed in order to show some possible applications of the thermoeconomic theories to district heating networks: 1) analysis of control strategies involving variable supply temperature; 2) analysis of additional potential users that may be connected to the district heating network in order to consider what it the effect of their characteristics on the economic cost of heat; 3) effects of energy savings initiatives applied to users.

3.1 Low temperature supply

The supply temperature is varied for the seven different operating conditions, in order to check the thermoeconomic cost of the heat demands of the users. The outdoor temperature during the heating period (T_{ref}) should not be assumed as constant in the analysis.

A consequence of the lower temperature of the water is larger heat exchangers (as the difference in the pinch point temperature is assumed constant). In this way the steam turbine has to supply a thermal energy flow to the network lower than in design conditions, so the amount of electric power produced by the system increases.

Fig. 1. shows the cost rate of the thermal energy flow supplied to the users for different supply temperatures of DHN, varying the outdoor conditions. Three control strategies are considered: constant supply temperature (90 °C), which is the reference strategy; variable supply temperature in the range between 80 °C and 90 °C; variable supply temperature in the range between 70 °C and 90 °C. Variable temperature means that when the outdoor temperature increases, the supply temperature can be decreased. As expected, the curve corresponding with the last strategy presents lower costs.

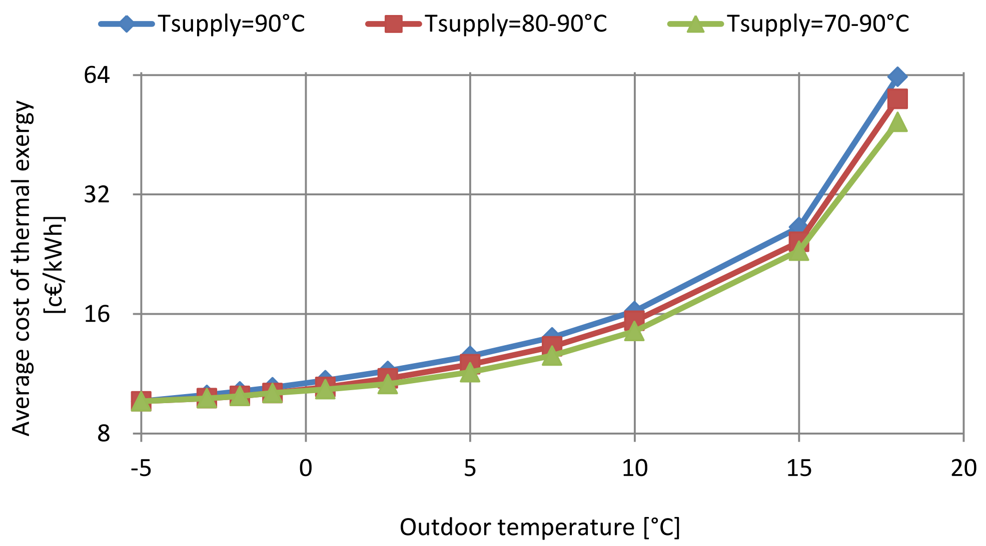

Figure 1. Average exergetic cost of heat with different supply temperature

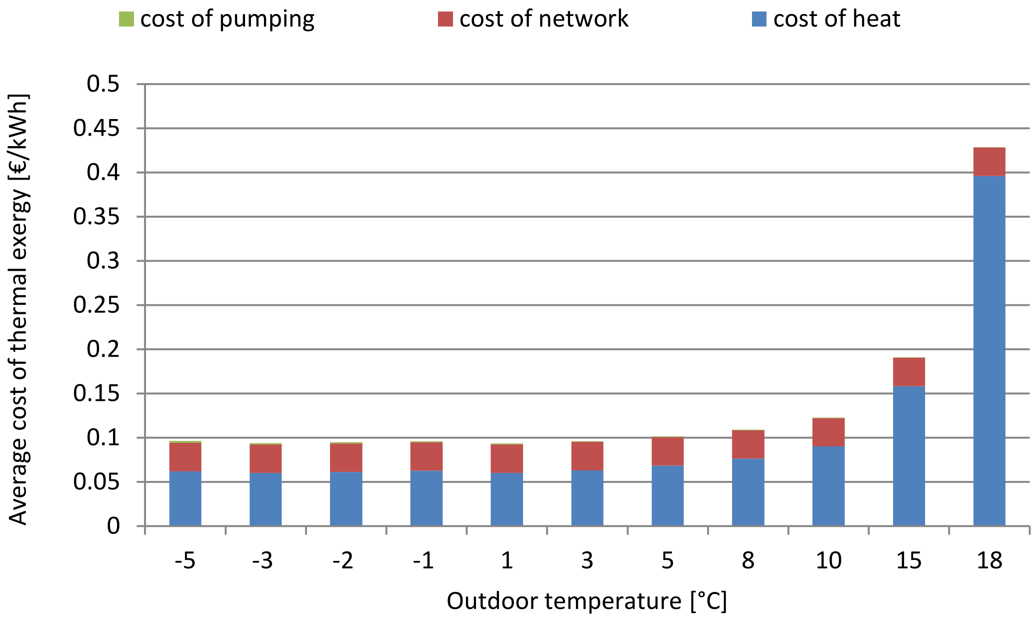

Figure 2. The process formation of the average cost of heat

To explain such behavior, Fig. 2. shows the process formation of the average cost of heat supplied to the users for variable supply temperature in the range between 70°C and 90 °C, varying the outdoor conditions. The average cost of heat increases as the outdoor temperature decreases. The reason is that the heat losses from piping slightly reduce, while the amount of heat supplied to the users decreases significantly. In fact, thermal losses primarily depend on the supply and return temperatures, while the heat request depends on the outdoor temperature.

In the case of higher supply temperatures (i.e. control strategies 1 and 2) the effect of heat losses is clearly much larger. In contrast, the contribution due to pumping is very small, which suggests that an increase in water mass flow rate flowing in the network does not affect the cost significantly (note that strategies involving reduction in the supply temperature cause increases in the water mass flow rate because of the reduction in the difference between supply and return temperatures). Therefore it is worth to decrease the supply temperature when possible.

The low pumping cost also indicates that smaller pipe sizes would improve the overall economics. Flow velocity could be considered as an additional free variable in the optimization instead of assuming it as fixed, as already discussed. Nevertheless, velocity cannot be increased too much because of vibrations and possible failures.

These aspects can be analyzed considering the exergy efficiency of the network, calculated using equation (15). This parameter decreases as the outdoor temperature increases, as shown in Table (1). The energy efficiency of the DHN remains constant as the supply temperature decreases, but the exergy efficiency increases as the supply temperature in the primary side at the heat exchanger at the users substations decreases.

The overall benefit of the three strategies can be analyzed considering the frequency of each operating condition during the heating season. The annual average cost of thermal exergy would be 0.123 €/kWh in the case of constant operating temperature, 0.118 €/kWh in the case of the possible reduction to 80 °C and 0.115 €/kWh in the case of possible reduction up to 70 °C. This is a conservative evaluation, since the heat demand has been considered on the 24 hours per day. In DH networks, the heat demand is typically between 6 a.m. to 10 p.m. As thermal losses occur also during night operation, a reduction of the operating temperature would be even more profitable.

Table 1. The exergy efficiency of the DHN.

Outdoor temperature [°C]	Frequency of temperature [%]	Exergy efficency Tsupply =90°C	Exergy efficency Tsupply =80°C	Exergy efficency Tsupply =70°C
-5	4%	0,71	0,71	0,71
-3	6%	0,68	0,72	0,72
-2	5%	0,66	0,70	0,70
-1	8%	0,64	0,68	0,68
0,6	14%	0,61	0,65	0,70
2,5	7%	0,57	0,61	0,66
5	22%	0,51	0,55	0,59
7,5	5%	0,45	0,48	0,52
10	17%	0,38	0,41	0,45
15	10%	0,23	0,25	0,26
18	1%	0,08	0,09	0,11

The annual exergetic efficiency of the DHN is 50.1% in the case of strategy 1 (i.e. fixed supply temperature of 90°C). The primary energy savings with respect to onsite boilers is 48.8%, assuming boiler efficiency of 95%. In the case of strategy 2 (supply temperature variable between 80 °C and 90 °C), the annual exergetic efficiency is 54% and the primary energy savings is 49.2%. In the case of strategy 3 (supply temperature variable between 70 °C and 90 °C), the annual exergetic efficiency is 57% and the primary energy savings is 49.5%.

3.2 Connection of additional users

The marginal cost is often defined as the cost to produce the last unit of product. In district heating systems, when several plants are available, the one with the highest operational cost is that producing the last unit of heat [27]. Marginal costs are used in thermoeconomics for the optimization of energy systems. Major contributions in this field came from the work developed by prof. El Sayed [28-29]. Here the concept of marginal cost is used to examine potential effects on an existing network obtained by connecting additional users. Two quantities are considered to characterize an additional user: the distance from the main network and the design thermal power required by the user.

The calculated marginal costs can be viewed as short-term (i.e., sunk capital for 'main' equipment) marginal costs. A cost function C(q) is a function of the amount of produced quantities q, which tells us what is the cost for producing q units of output [30]. We can also split total cost into fixed cost and variable cost as follows:

$$\mathrm{C(q) = FC + VC(q)} \quad (16)$$

In the short-term, with no change in investment capital, that is to say, FC =const.

The average total cost can be written as a function of total cost divided by the quantity where, in our case, the quantity is represented by the exergy request from the users.

$$\mathrm{ATC = TC/q = (FC + VC(q))/q} \quad (17)$$

As it can be seen in the Figure (3), the average total cost decreases as the thermal request of the users increases, and it increases as the distance of the users from the main DHN pipe increases.

The marginal cost can be written as the derivative of variable costs:

$$\mathrm{MC} = \partial \mathrm{VC(q)}/\partial \mathrm{q} \quad (18)$$

Marginal costs related to the connection of an additional user are shown in figure (4). As the distance from the main network increases, at constant thermal request of the additional user, the marginal costs increases for all the flow temperature supply. This is due to the exergy losses associated with friction and the investment cost, which is particularly evident when the thermal request of the additional user is small. The high costs are due to the effect of the user on the water pressure, which must be increased for the entire water mass flow rate exiting the thermal plant. If these costs are comparable with the investment cost of a pump, the installation of an additional pump should be considered. The additional pump allows one to fractionate the pressure losses, so that it is not necessary to pump the entire mass flow rate to the maximum pressure.

At lower supply temperature (70-90°C), the marginal cost curve presents lower values in comparison to the other temperature supply.

3.3 Energy savings

Last analysis refers to the implementation of energy savings initiatives. In this case an area of buildings with a total thermal request of about 42 MW has been considered. A ratio of 62% of the users are connected with the DHN, and the remaining users has an alternative heating supply system (gas boilers). Figure 5 shows the average exergetic cost of heat for the whole area, i.e. users connected with the network and those who are not connected. This is examined for the three control strategies previously considered.

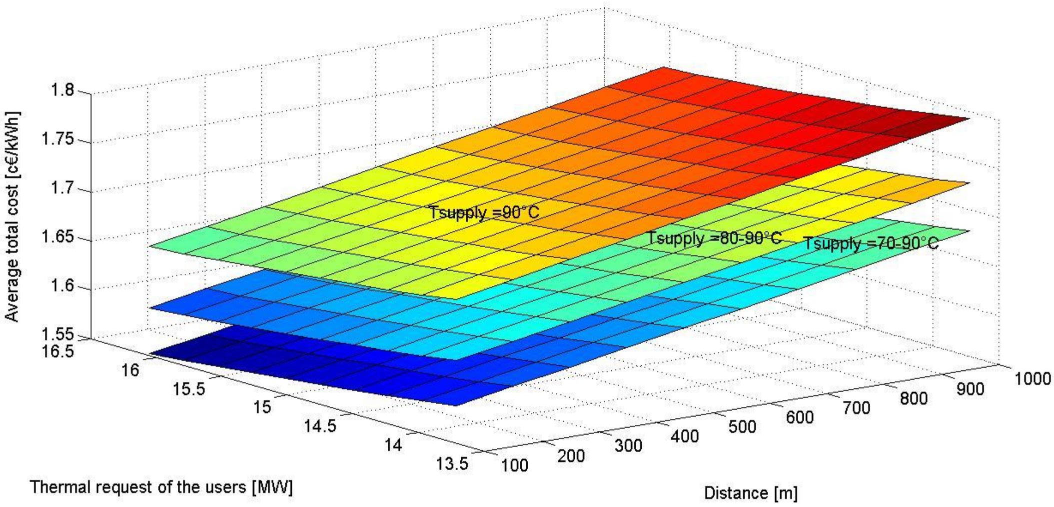

Figure 3. The average total cost as a function of thermal request and the delta distance variation from the existing DHN configuration (Figure is in color in the on-line version of the paper).

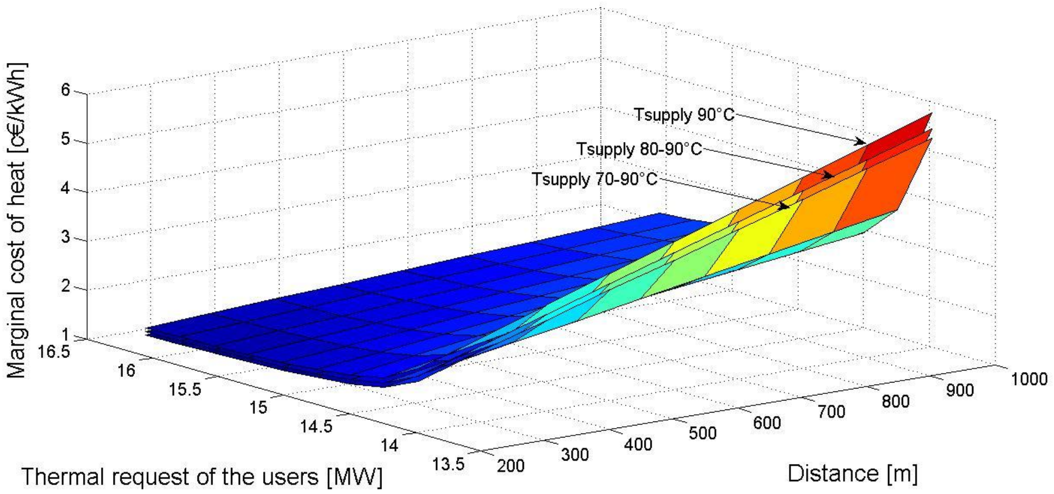

Figure 4. Marginal costs as a function of thermal request of the users and the distance from existing configuration DHN (Figure is in color in the on-line version of the paper).

Figure 6 shows the annual average cost of thermal exergy supplied to the users as the function of the supply temperature, with and without introducing energy savings in the buildings. Results show that the reduction in the unit cost of thermal exergy is larger when energy savings initiatives are implemented. The reason is that, when energy savings is considered, the heat request of the buildings reduces. The thermal substations become oversized with respect to the design conditions, it is therefore possible to reduce the supply and return temperatures at constant water mass flow rate, thus reducing the thermal exergy losses.

As an alternative, it is possible to reduce the water mass flow rate at constant supply temperature. Water mass flow rate can be increased up to the design value, in the case new users are interested to be connected with the network. The implementation of energy savings initiatives is a good design options in urban areas where existing networks are saturated, i.e. the maximum thermal load has been reached, but not all the potential users have been connected.

4. Conclusions

The use of thermoeconomics for the analysis of district heating systems allows one to obtain some useful information for the plant design and management. In this paper these aspects have been examined, considering three possible uses of thermoeconomics.

The temperature of water flow feeding the network has been assumed as an operating parameter. It has been shown how this parameter influences the whole system operation conditions, as the products, electricity and heat supplied to the users depend on it. Heat losses need to be reduced and this can be achieved by means of lower temperature supply, which also extends the scope for using different sources of locally available waste and renewable heat.

Marginal thermoeconomic costs are calculated in order to analyze the effects that would be produced by connecting additional users to the network. Depending on their position with respect to the thermal plant and their heat request, it is possible to evaluate whether it is economically convenient to connect these users or not and if one or more additional pumps should be installed in the network.

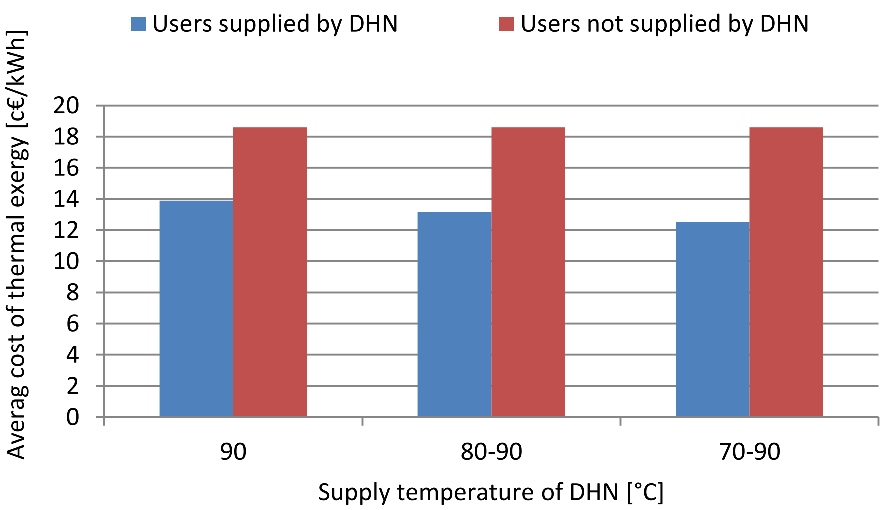

Figure 5. Annual average cost of thermal exergy in the case of the examined control strategies.

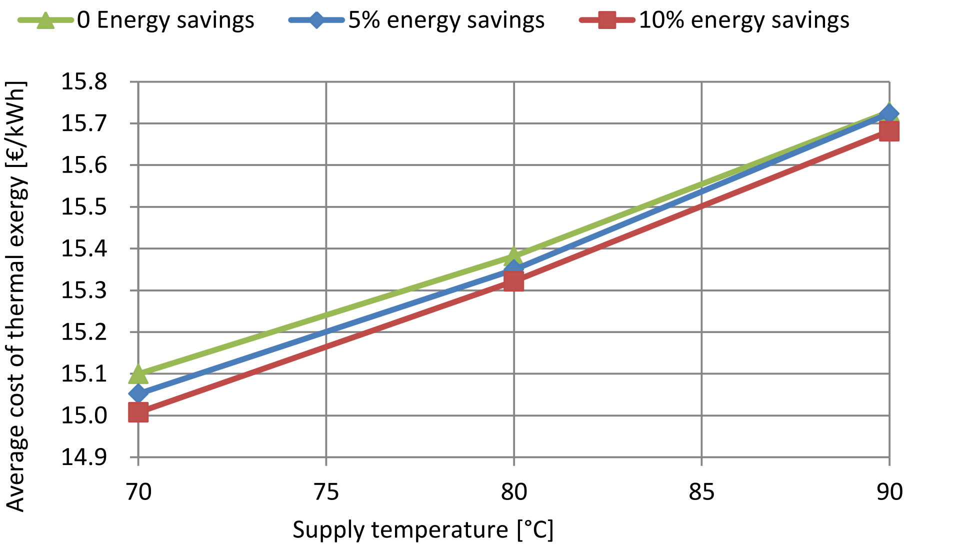

Figure 6. Annual average cost of thermal exergy in the case of energy savings implementation.

Finally this paper shows that there are potential economic advantages in introducing energy savings initiatives in buildings connected to district heating networks. This is a new paradigm since the economic convenience of district heating increases with increasing heat request of the users. A first advantage is related to the possible reduction in the supply and return temperatures, which allows one larger heat recovery from cogeneration or renewable plants. An additional advantage is the possibility to connect new users to the DHN in the case of saturated networks, i.e. when it is not possible to increase the water mass flow rate flowing in the pipes.

Other problems are still open in district heating. In particular, the link between quality of heat and its price should be considered in order to properly consider the characteristics of the producers and users. In the near future it is expected that multiple producers are allowed to supply heat to district heating networks, similarly to what happens in the case of the electric grid. Not only the amount of heat they may produce should be properly accounted, but also its quality. Exergy is an effective way to evaluate both quantity and quality of energy flows. Moreover, users characterized by a heating system able to operate at lower temperatures should be considered in a different way than users requiring the same amount of heat, but at higher temperature. As an example, in buildings where radiant panels are installed, the temperature difference between supply and return piping can be increased significantly. As an alternative, these buildings may be theoretically connected directly with the return piping network (i.e. water supplied to the buildings comes from the main return piping instead of the supply piping network), thus using low grade heating. In both cases there is generally a big benefit for the overall energy system, since the returning temperature decreases and a more effective heat recovery is obtained in the thermal plant. In all cases, low temperature heating systems use less exergy than conventional heating systems.

It should be possible to encourage a more rational use of heat by implementing a pricing policy accounting not only for the quantity of heat but also for its quality. Such a pricing would be based on exergy instead of energy.

Nomenclature

A	equivalent annual cost (€/year)
ATC	average total cost
c	average unit cost of heat (€/kJ)
CHP	Combined heat and power
C(q)	cost function
d	discount rate
DHN	District heating network
D_{int}	internal diameter of the pipe (m)
FC	fixed investment cost (€)
G	mass flow rate (kg/s)
h	specific enthalpy (kJ/kg)
k^*	exergetic unit cost (kJ/kJ)
L	pipe length (m)
MC	marginal cost
n	lifetime (years)
q	general independent variable in cost function
TC	Total cost (€)
T	temperature (°C)
T_{ref}	average outdoor temperature (°C)
VC	variable cost
v_{max}	maximum velocity of water in the pipes (m/s)
W	power (kW)
W_{elc}	peak electric power (MW)
X	general variable expressing component size
$\dot{Z}$	cost rate (€/s)

Greek

ε_{DH}	exergy efficiency of the network
Φ	heat flux (kW)
Ψ	exergy flow (kW)
Ψ^*	exergetic cost rate (kW)
Π	thermoeconomic cost of a flow (€/s)
ρ	density (kg/m^3)
η_p	pump efficiency
ν	specific volume (m^3/kg)
Δp	total pressure losses (Pa)

Subscripts

F	fuel
r	return
s	supply

T	thermal
U	user
w	power

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