Thermoeconomics as a tool for the design and analysis of energy savings initiatives in buildings connected to district heating networks

Thermoeconomics as a tool for the design and analysis of energy savings initiatives in buildings connected to district heating networks

Vittorio VERDA, Albana KONA

Politecnico di Torino, Energy Department

c.so Duca degli Abruzzi 24, 10129 Turin, Italy

Tel. +390115644449, Fax +390115644499

E-mail: vittorio.verda@polito.it

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 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.

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 approach 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 overall perspective, the best solution will be to combine a gradual expansion of district heating with individual heat pumps in the remaining houses. Such conclusion is valid in the present systems, which are mainly based on fossil fuels, as well as in a potential future system based 100 per cent on renewable energy. New attractive applications for renewable energy heating technologies are combined solar–biomass heating systems, both individual systems as well as in combination with district heating. Biomass is therefore an optimal form of seasonal storage for solar energy and an attractive auxiliary fuel for solar heating systems from renewable energy sources in Faninger et al [6].

Another option of renewable energy source is geothermal energy. A comprehensive analysis and discussion of geothermal district heating systems and applications based on thermodynamic aspects in terms of energy and exergy and performance improvement opportunities of three geothermal district heating systems, installed in Turkey has been carried out in Ozgener et al [7].

As renewable based district heating involves reductions in supply temperature, this generally causes reduction in temperature difference between supply and return pipe and therefore larger mass flow rates in the pipes. This means that energy 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 is proposed in [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. 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 [12]. 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 [13].

An exergoeconomic analysis of a district heating network is conducted in Verda et al [14]. The analysis aims to determine the optimal configuration of the district heating network, i.e. the users that should be connected to the network and those who should be heated through alternative systems. The optimization is performed using a probabilistic approach based on the calculation of exergetic cost of heat associated to each single user connected with the network. It is shown that the disconnection of some small users, which are located far from the thermal plant and the use of local condensing boilers instead allows one to reduce the unit cost of heat for the entire community.

This paper aims to propose a thermoeconomic approach for the analysis of 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 [15] , 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 join together.

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 [16]. 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 [17].

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 solution of the thermoeconomic problem requires to write two groups of equations:

1) the monetary cost balance of every component [18]:

$$\sum_j \Pi_{\mathrm{ji}} + \dot{Z}_i = 0 \tag{1}$$

where Π_{ji} is the cost rate of the jth flow entering (+) or exiting (-) the ith component and $\dot{Z}_{\mathrm{i}}$ the cost rate of the ith component.

If the exergoeconomic unit cost c_{ji} is introduced, defined as ratio between the cost rate of a flow and its exergy flow rate Ψ_{ji}: Using:

$$c_{ji} = \Pi_{\mathrm{ji}}/\Psi_{\mathrm{ji}} \tag{2}$$

equation (1) becomes:

$$\sum_j \Psi_{ji} * c_{ji} + \dot{Z}_i = 0 \tag{3}$$

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 exergoeconomic costs are required;

- the unit cost of the product of components characterized by different products; often this cost is assumed the same for all the products.

This approach is particularly useful in the case of district heating networks, since balance equations can be written in matrix form, using the incidence matrix. This matrix is formulated within the graph theory to express system topology. In the case of fluid networks this matrix can be used to solve the fluid dynamic and thermal problems [19].

The application of thermoeconomics to the combined heat and power (CHP) plants allows to calculate 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 [20].

The internal diameter f 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:

$$\Phi = G\ (h_0 - h_r) \tag{4}$$

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 the users 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 criteria, 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 2.5 m/s is considered. The water mass flow rate G is expressed as:

$$G = \rho\ (\pi D_{int}{}^\wedge 2)/4\ v_{max} \tag{5}$$

The purchase cost of the DHN is calculated by considering the contributions of the insulated pipes constituting the main network (from the thermal plant to each thermal barycenter), 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 (6):

$$L_p = \frac{1}{\eta_p} \int_{year} G \cdot v \cdot \Delta p \cdot dt \tag{6}$$

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 insulated pipes is expressed through a polynomial function, obtained by interpolating available data:

$$PC_{IP} = \left(a_0 + a_1 \cdot D_{int} + a_2 \cdot D_{int}{}^2\right) \cdot L \cdot 2 \tag{7}$$

where Dint is the internal diameter and L the length of the considered trait, 2 accounts for the double pipe. The calculated 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, according with a general function [21]:

$$TC_i = TC_0 \cdot \left(\frac{X_i}{X_0} \right)^{\alpha} \tag{8}$$

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 €/kWe for a CCGT in the range of 50-100MWe output. We is the peak electric power produced by the power plant as a non-cogenerative plant.

$$TC_{chp} = 0.8\, W_{elc} \tag{9}$$

There is a cost in producing heat from a CHP plant, because the electric otput of the plant reduces, when heat is extracted from the turbine. This lost electricity has a value which determines the cost of heat.

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

$$TC_C = TC_{tot} \frac{(1+d)^l}{(1+d)^l - 1} \cdot d \tag{10}$$

in which TC_{tot} is the total capital cost, d is the discount rate and l 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. This cost, which is the result of the contribution of the steam power plant and of the gas turbine plant, linearly decreases as the temperature of the water decreases. The thermal exergy flow provided to the network decreases. 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 [22].

$$c_f * \Psi_F + \dot{Z}_{chp} = c_w * W + c_T * \Psi_T \tag{11}$$

Where $c_f$unit cost of the fuel, c_w e 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 exergoeconomic unit cost of the products is:

$$c_{chp} = (\Psi_F + \dot{Z}_{chp})/(W + \Psi_T) \tag{12}$$

where c_{chp} unit cost of the heat produced by the power plant

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.

$$c_{chp} * \Psi_{DHN} + c_{chp} * \Psi_{pump} + \dot{Z}_{DHN} = c_{heat} * \Psi_{HD} \tag{13}$$

Where Ψpump is the amount exergy due to pumping in the DHN; ΨDHN : the amount of exergy required by the DHN; ΨHD : the amount of exergy required at the users, in the substation; $\dot{Z}_{DHN}$: cost rate of the district heating network.

The exergy efficiency of the DHN is determined as:

$$\psi_{DH} = \Psi_{HD}/\Psi_{DHN} \tag{14}$$

Where $\psi_{DH}$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 is assumed to be constituted by a cogenerative combined cycle and some boilers. Cogeneration is obtained through a steam extraction at about 1.28 bars from the turbine, which feeds a heat exchanger. The remaining requests are covered by means of boilers.

Steady state analysis has been carried out in order to understand the exergetic behavior of the district heating supply. The secondary side operates under given conditions, i.e mass flow rates remains constant while temperature is adjusted as the function of the outdoor temperature. The main variable is the thermal energy input from the primary side. In this analysis seven different outdoor temperatures during the heating period are considered. 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 secondary side.

Three different analyses are performed: 1) change in the control strategy 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

Primary supply temperature is varied for the seven different operating conditions, in order to check the exergoeconomic cost of the heat demands of the users. Tref is the absolute value of the outdoor temperature during the heating period. This should not be assumed as constant in the analysis.

As consequence of the lower temperature of the water is the chance of a larger heat exchange, 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 decreases. The curve corresponding with the last strategy presents lower costs.

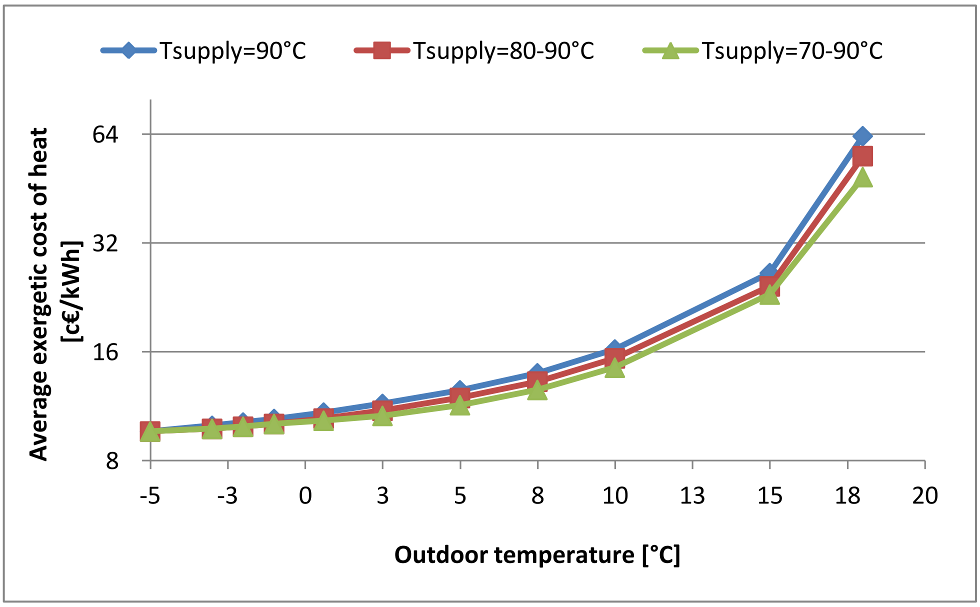

Figure 1. Average exergetic cost of heat with different supply temperature

To explain such behavior, Fig. 2. shows the process formation of the average cost of heat supplied to the users for supply temperatures of DHN of 70°C, varying the outdoor conditions. The average cost of heat increases as the outdoor temperature decreases mainly because of the increase in the component due to the heat production. The reason is that the component related to heat losses remains almost constant, while the amount of heat supplied to the users decreases significantly (because of the reduction in the heat request). In the case of higher temperatures (i.e. the other control strategies) 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.

Exergy losses which occurs during the transport of thermal energy to the users indicate that this loss is large and primarily dependent on the temperature of the hot water. Therefore it is worth to decrease the operating temperature when possible.

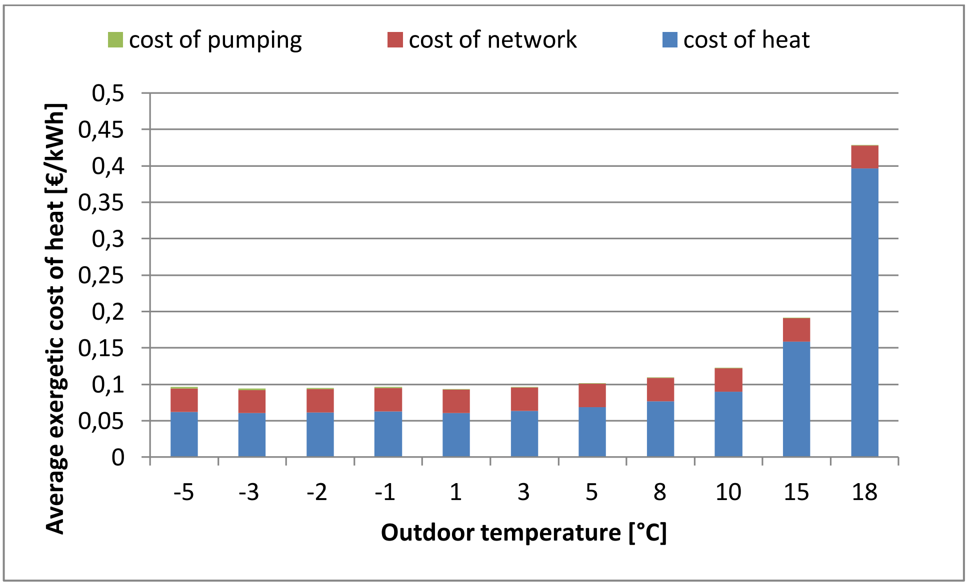

Figure 2. The process formation of the average cost of heat

These aspects can be analyzed considering the exergy efficiency of the network, calculated within the equation (14). This parameter decreases as the outdoor temperature increases, as it can be seen in the 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.

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

Table 1. The exergy efficiency of the DHN

The overall benefit of the three strategies can be analyzed considering the frequency of each operating condition during the heating season. The average annual exergetic cost of heat would be 0.123 €/kWh in the case of constant operating temperature, 0.118 €/kWh in the case of the possible reduction up 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. while in the night hours the network operates without supplying heat to the users. As thermal losses occur also during night operation, a reduction of the operating temperature would be even more profitable.

3.2 Connection of additional users

The marginal cost is often defined as the cost to produce the last unit of product. In energy systems with several production plants, the plant with the highest operational cost is the one that produces the last unit of DH [23]. 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 [24-25]. 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-range 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 [26]. We can also split total cost into fixed cost and variable cost as follows:

$$C(q) = FC + VC(q) \tag{15}$$

In the short-run, 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. In our case the quantity is represented by the exergy request from the users.

$$ATC = TC/q = (FC + VC(q))/q \tag{16}$$

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.

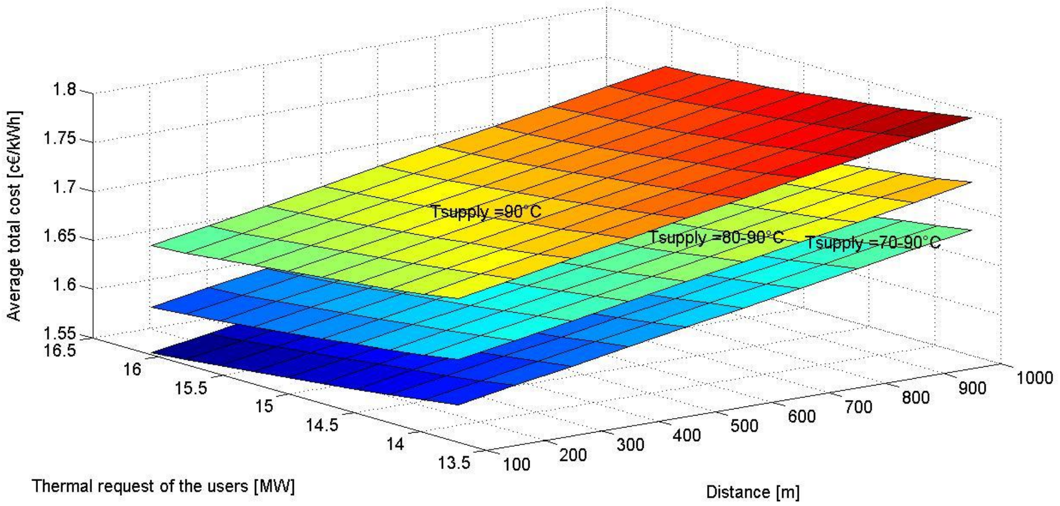

Figure 3. The average total cost as a function of thermal request and the delta distance variation from the existing DHN configuration

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

$$MC = dVC(q)/q \tag{17}$$

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

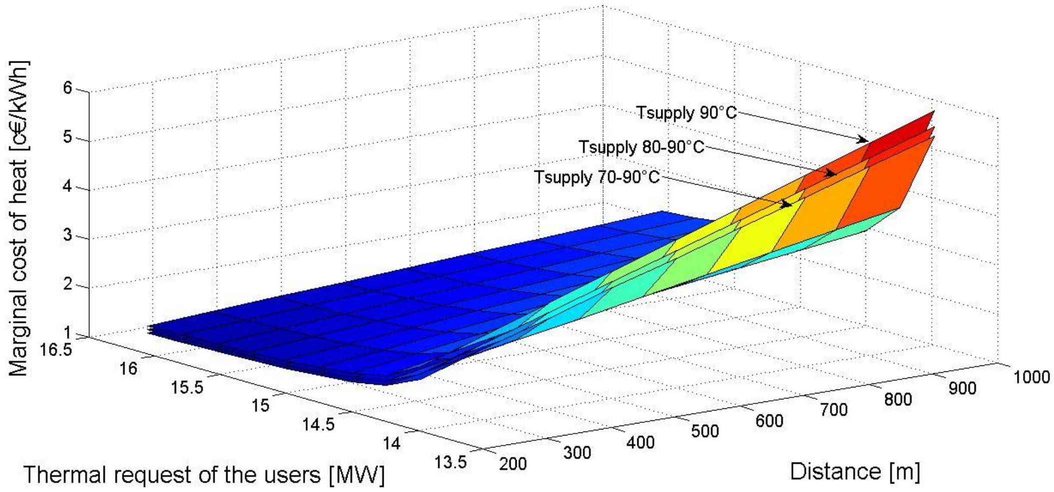

Figure 4. Marginal costs as a function of thermal request of the users and the delta distance from existing configuration DHN.

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.

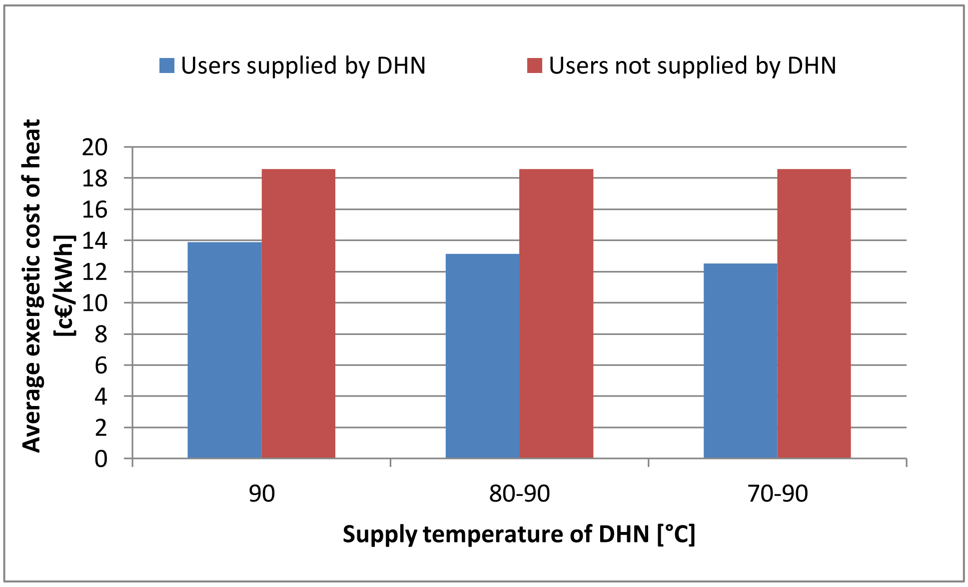

Figure 5. Weighted average cost of heat

Figure 6. shows that introducing energy savings in the buildings, the weighted average cost of heat (weighted for the frequency of the outdoor temperature during the heating season) decreases as the ratio of the energy savings increases. At the same ratio of energy savings in the buildings, the weighted average cost of heat decreases as the supply temperature at the primary side of heat exchangers at the users decreases.

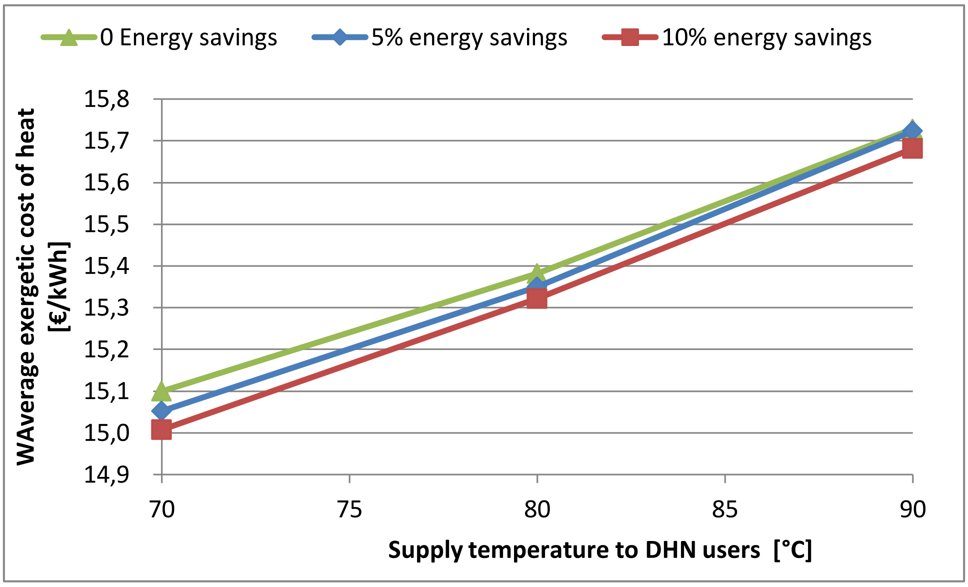

Figure 6. Weighted average cost of heat

The implementation of energy savings initiatives allows one to connect more users to the district heating network, which is a good design options in urban areas with existing saturated networks, i.e. networks which have already reached the maximum capacity (at least in some areas).

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.

In the calculation of marginal costs, a basic presupposition here is that, optimal prices from a societal point of view should equal short-range marginal costs (SRMC) of DH generation. In a such complex thermoeconomic analysis, measures for the exergy loss reduction should also play a role. They can thus be taken as a point of departure when determining the district-heating tariff. Rather, prices can be set to reflect marginal costs, and a fixed charge can be set to cover investment costs. The utilities also has a fixed price element in the tariff. Using these prices based on SRMC and a fixed charge should be able to bring about a close to optimal resource-allocation.

Finally this paper shows that there are potential advantages in introducing energy savings initiatives in buildings connected to district heating networks, mainly related to the possible reduction in operating temperatures and the possibility of connecting new users to the DHN, which is a cost effective solution for the community.

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, similar to what happens with electricity producers in the case of the electric grid. Not only the amount of heat they may produce is important, but also its quality. Exergy is an effective way to measure quality. Moreover, users characterized by local heating systems working 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, users with radiant panels may be theoretically connected to the return network and use low grade heating. This is generally a big benefit for the energy system, since the returning temperature decreases and a more effective heat recovery is obtained in the thermal plant.

It should be possible to encourage a more rational use of heat by implementing a fairer pricing policy, which would take into account not only the quantity but also the quality of this heat. Such a pricing would be based on the exergy losses. This factor allows us to determine a heat price, which takes into account the heat exergy value or the quality of the heat.

Nomeclature

DHN: District heating network

Φ: is the thermal energy flow

G: the water mass flow rate

h : enthalpy of the water

D_{int}: internal diameter of the pipe

v_{max} : max velocity of the mass flow rate in the pipes

ρ: density of the water

η_p: is the average pump efficiency

ν: is the water specific volume (assumed constant)

Δp the total pressure losses due to pipe friction and localized resistances.

TC_{tot}: is the total capital cost

d: is the discount rate

l: is the life of the network, expressed in years

c: average unit cost of heat

Ψ_F : is the thermal exergy flow ;

$\dot{Z}_{chp}$: cost rate of the CHP plant

$\dot{Z}_{DHN}$: cost rate of the district heating network

ψ_{DH}: Exergy efficiency of the network

T_{ref} : is the absolute value of the average outdoor temperature during the heating period 5°C

C(q): function cost of the quantity q

TC: Total cost, wich includes investments and operational cost

FC: fixed cost, investments costs

VC: variable cost

ATC: average total cost

MC: marginal cost

SRMC : short run marginal cost

T_{supply}: flow temperature supply in the primary side at the user's substation heat exchanger

References

[1] Rezaie B, Rosen MA. District heating and cooling: Review of technology and potential enhancements. Article in press. Applied Energy (2011), doi: 10.1016/j.apenergy.2011.04.020

[2] Wiltshire R, J. Williams, S. Werner. European DHC research issues. The 11th International Symposium on District Heating and Cooling, August 31 to September 2, 2008, Reykjavik, ICELAND

[3] Woods P., Gunning R., Snoek C., Onno T., Yang L., Ahonen M., Wiltshire R. Optimization of operating temperatures and an appraisal of the benefits of low temperature district heating. Report IEA district heating 1999. www.iea-dhc.org

[4] Wiltshire R, Low temperature district energy systems. 16th„ Building Services, Mechanical and Building Industry Days". International conference, 14-15 october 2011, Debrecen, Hungary

[5] Lund H., Möller B., Mathiesen B.V., Dyrelund A,. The role of district heating in future renewable energy systems. Energy, Vol 35, Issue 3, March 2010, Pages 1381-1390

[6] Faninger G. Combined solar biomass district heating in Austria. Solar Energy 2000; 69:425–35

[7] Ozgener L., Hepbasli A., Dincer I., A key review on performance improvement aspects of geothermal district heating systems and applications. Renewable and Sustainable Energy Reviews, Vol 11, Issue 8, October 2007, Pages 1675-1697

[8] M.J. Moran, H.N. Shapiro, Fundamentals of Engineering Thermodynamics, 3rd edition, John Wiley & Sons, New York, USA, 1998.

[9] Ozenger L, Hepbasli A, Dincer I. Energy and Exergy analysis of geothermal district heating system: an application. Build Environ 2005;40(10):1309–22.

[10] Helena Torio, Dietrich Schmidt. Development of system concepts for improving performance of waste heat district heating network with exergy analysis.

[11] Poredoš A., Kitanovski A. Exergy loss as a basis for the price of thermal energy. Energy Conversion and Management 43 (2002) 2163–2173

[12] R. A. Gaggioli, W. J. Wepfer, Exergy Economics, Energy, Vol. 5, pp. 823-837 (1980).

[13] Y.M. El Sayed (2003). The Thermoeconomics of Energy Conversions. Elsevier.

[14] V. Verda, S. Fausone. Exergoeconomic Analysis of district heating systems. Proceedings of ES2009 2009 ASME 3RD International Conference on Energy Sustainability San Francisco, California, July 19-23, 2009 ES2009-90351.

[15] F. Harary, *Graph Theory*, Narosa Publishing House, New Delhi (1995).

[16] G. Tsatsaronis, M. Winhold, Exergoeconomic Analysis and Evaluation of energy-conversion. Plants – I. A new general Theory. Energy, Vol.10. N.1, pp. 69-80 (1985).

[17] C. A. Frangopoulos. Thermoeconomic Functional Analysis; a method for the optimal design or improvement of complex thermal systems. Ph. D. Thesis, Georgia Institute of Technology. (1983).

[18] M.A. Lozano, A. Valero (1993). Theory of the Exergetic Cost. Energy, Vol. 18 No. 9, pp. 939-960.

[19] M. Calì, R. Borchiellini (2002). District Heating Network Calculation and Optimization. Encyclopedia of Life Support Systems, UNESCO (paper 3.19.3.8).

[20] V. Verda. Thermoeconomic Diagnosis of an Urban District Heating System Based on Cogenerative Steam and Gas Turbines, Ph.D. Thesis, Polytechnic of Turin and University of Zaragoza (2001).

[21] A. Bejan, G. Tsatsaronis, M. Moran., Thermal design and Optimization. Wiley. New York (1996).

[22] Verda V.; Borchiellini R.; Calì Quaglia M. (2001). A thermoeconomic approach for the analysis of district heating systems. In: International Journal of Applied Thermodynamics. vol. 4, pp. 183-190. - ISSN 1301-9724

[23] Difs K., Trygg L., Pricing district heating by marginal cost. Energy Policy 37 (2009) 606–616

[24] Y.M. El-Sayed, R.B. Evans (1970). Thermoeconomics and the Design of Heat Systems. Journal of Engineering for Power. 27-35

[25] Y.M. El-Sayed, R.A. Gaggioli (1987). The Integration of Synthesis and Optimization for the Conceptual Designs of Energy Systems. 4th International Symposium on Second Law Analysis of Thermal Systems. Rome. May 25-29.

[26] Chia-Hui Chen, course materials for 14.01 Principles of Microeconomics, Fall 2007. MIT OpenCourseWare (http://ocw.mit.edu), Massachusetts Institute of Technology. Downloaded on February / 2012.