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Abstract:
This paper aims at showing the capabilities of thermoeconomic analysis for solving cost assessments in district heating systems both at user and producer sides. In the near future it is expected that multiple producers are allowed to supply heat to the same district heating network, 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, and also the pumping power that is requested to supply a unity of thermal energy to the end-users. Moreover, buildings equipped with low temperature heating system allow better use of the thermal energy vector, thus allowing larger efficiency of thermal plants.
In the present work, the use of thermoeconomics for the analysis of these aspects is proposed. The approach allows one performing cost assessment in district heating, taking into account the effects of investment and operating costs and thermodynamic irreversibilities in the cost formation of heat from its production in the plants to its use in the buildings. Simple examples are analyzed in order to provide a quantitative evaluation of the various cost terms, depending on the operating conditions, topology and characteristics of the users/producers.

Keywords:
District heating; Low temperature; Thermoeconomic analysis; Exergy analysis; Third-party access

1. Introduction

Despite the concept of district heating is known since long time, it has significantly evolved in the last few years, mainly because of new opportunities that the development of renewable energy plants and energy saving techniques have created. The use of low-temperature heat from industrial waste heat in district heating has proven to be attractive from energy and economic viewpoints [1]. Furthermore, an important aspect of new building development is their increasingly high standard of efficiency. In order for district heating networks to remain an effective option for such developments, reductions in temperature supply should be achieved. This allows one to use different sources of locally available waste and renewable heat [2] and to reduce heat losses.

The role of district heating in future renewable energy systems has been evaluated in Lund et al. [3]. More specifically, district heating is expected to supply heat to the buildings located in more densely populated areas, primarily taking advantage of thermal energy sources that are recovered from industries or produced by Waste-to-Energy plants, cogeneration systems and renewable energy plants. Areas with lower population density are more suitable for heating through alternative technologies such as geothermal heat pumps.

District heating networks involve the use of at least two forms of energy: mechanical and thermal energies. In fact, the network distributes heat that is produced in one or more plants, to the users, while power is required for the fluid flow. These energy forms are somehow competing, since a reduction in the quality of heat generally allows one increasing the performance of the thermal plants, but may involve larger amount of power for pumping, due to the increase in the water mass flow rate circulating in the network. Moreover, there are links between the design/operation conditions of the network and the performance of the thermal plant and thus the production cost of heat.

Thermoeconomic approaches have proven to be suitable for the design of this kind of systems since they allow one to account for the effects that the characteristics of the various users (mainly their position and their thermal needs) have on the cost of heat supplied and on the total primary energy requirements. Thermoeconomics is a branch of engineering combining exergy and economic principles [4][1]. 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 through 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 [5].

For these reasons, thermoeconomics has been used for the design of optimal district heating networks, for the optimization of the supply temperature during operation and the analysis of possible network expansions.

The first application of exergy costing to a district heating system was proposed by Keenan in 1932 [6], 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 of District Heating Systems (DHSs) have been proposed successively.

Adamo et al. [7] have used a thermoeconomic approach for the optimal choice of pipe diameters in a district heating network. Verda et al. [8] 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 [9]. 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 district heating 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 [10] presented an application of an exergoeconomic model, which included both exergy and cost accounting analyses for a geothermal district heating system.

In [11], a thermoeconomic approach for the analysis of other possible improvements of existing district heating networks is proposed. 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.

Other problems are still open in district heating that can be solved through a thermoeconomic approach. In particular, the link between quality of heat and its price should be considered in the analysis of both the producers and the users. In the near future it is expected that multiple producers are allowed to supply heat to the same district heating network, 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 floors are installed, a lower temperature can be obtained at the outlet section of the heat exchanger on the primary network. Therefore, the temperature difference between supply and return piping can be increased

[1] Reference [4] provides an introduction to the subject, and references to earlier works.

significantly, which means that a smaller mass flow rate is requested per unit heat flux with respect to heating devices operating at a higher temperature (e.g. radiators). As an alternative, these buildings may be directly connected with the return piping network. This means that water extracted from the return network (which is at a low temperature) enters the heat exchanger in the buildings and it is further cooled before being returned to the return pipeline (i.e. the same pipeline where it is extracted but downstream). This means that low grade heating is used. In both cases there are generally significant benefits 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.

In the present work, the use of thermoeconomics for the analysis of these aspects is proposed. The main advantage of thermoeconomics is that relies on the concept of exergy, therefore costs reflect not only the quantity of energy transferred and used but also its quality. This is very important in district heating in order to properly account for the use of both thermal and mechanical energies as well as their possible relations when temperatures at the production or at the users are modified.

The use of thermoeconomic analysis in district heating networks is discussed in the next section.Two scenarios based on simple examples are analyzed in the subsequent sections in order to highlight the feature of this methodology while providing a quantitative evaluation of the various cost terms as the function of the operating conditions, topology and characteristics of the users/producers.

2. Thermoeconomic Analysis of District Heating Networks

Thermoeconomic analysis is based on cost balance equations that are written for all components. This balance can be written for the ith component as

$$\sum_j \Pi_{\mathrm{ji}} + \dot{Z}_i = 0 \qquad (1)$$

where Π_{ji} is its thermoeconomic cost rate associated with a general exergy flow exchanged between components j and i and $\dot{\mathrm{Z}}_{\mathrm{i}}$ the moneraty cost rate of owning the ith component. Physical flows can be composed together in order to define resources (F) and products (P) of the components, as discussed for instance in [12]. Equation (1) can be thus rewritten as

$$\Pi_{\mathrm{Fi}} + \dot{Z}_i = \Pi_{\mathrm{Pi}} \qquad (2)$$

where the term Π_{Fi} represents the total resource of the ith component, which may be constituted by a single resource or multiple resources, and the term Π_{Pi} represents the total product.

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

$$\sum_j \Psi_{ji} \cdot c_{ji} + \dot{Z}_i = 0 \qquad (3)$$

$$\Psi_{Fi} \cdot c_{Fi} + \dot{Z}_i = \Psi_{Pi} \cdot c_{Pi} \qquad (4)$$

Equation (4) can be rearranged introducing the relation between resources and products, when these quantities are expressed in terms of exergy flows

$$\Psi_{Fi} = \Psi_{Pi} + I \qquad (5)$$

where I is the irreversibility. The unit cost of the product is expressed as:

$$c_{Pi} = c_{Fi} + c_{Fi} \cdot \frac{I}{\Psi_{Pi}} + \frac{\dot{Z}_i}{\Psi_{Pi}} \qquad (6)$$

In a network, each single pipe can be considered as a component, which goal consists in transporting the inlet exergy flow to the outlet section. The inlet flow can be considered as the resource while the outlet flow as the product. This concept can be applied to the entire system. In this case the unit cost of exergy supplied to the users depends on the unit cost of resource (i.e. the heat flux supplied by the thermal plants to the network), the irreversibilities occurring in the network (heat losses, pressure drops, mixing of streams at different temperature) and the investment cost. In addition, it should be considered that "users need energy not exergy". This means that the final product that is supplied to the users is a heat flux at the indoor temperature, no matter the operating temperature of the system, therefore the comparison between district heating and alternative systems or between different district heating configuration or operating conditions should be performed on the basis of a product evaluated in energy basis:

$$c_\Phi = c_P \cdot \frac{\Psi_P}{\Phi} \qquad (7)$$

where c_Φ is the unit cost of heat (i.e. the cost of a unit of thermal energy calculated using exergy accounting) and Φ is the heat flux supplied to the users.

The same type of analysis can be performed at component level, which brings to a different unit cost for the various users. This cost depends on the characteristics of the user, particularly its heat request and the position of the user with respect to the other users and the thermal plants. Its position affects the irreversibilities and the investment cost of the portion of network required to reach it. This concept is the basis for using thermoeconomics in optimal planning of district heating networks (see for example [9]).

Among the available techniques that have been proposed in the literature for thermoeconomic analysis, the one proposed by Valero and co-workers in the 1980's [12, 13] is particularly suitable for the analysis of district heating network. One of its main characteristics is the matrix based approach, in particular the use of incidence matrix for expressing the equation of cost conservation. In district heating networks the same matrix can be applied to the formulation of thermo-fluid dynamic model [14].

The incidence matrix (see for example [15]) was formulated within the graph theory [16], which is widely adopted for the topology definition as well as the fluid dynamic and thermal calculation of distribution networks [17]. The incidence matrix **A** is characterised by as many rows as the number of components (*m*) and as many columns as the number of nodes (*n*). The general element A_{ij} is equal to +1 or –1, respectively if the branch *j* is entering or exiting the node *i* and 0 in the other cases. The use of the incidence matrix allows one to express the balance equation of the flow of the general extensive quantity G_x (exergy flows, cost flows, etc.) as:

$$\mathbf{A} \cdot \mathbf{G}_x + \mathbf{G}_{x_d} = \mathbf{0} \qquad (8)$$

where $\mathbf{G}_x$ is the vector containing the values assumed by the quantity G_x in the n nodes and $\mathbf{G}_{xd}$ is the vector that allows to account for the amount generated/destructed in the m components, if non null. In thermoeconomics, equation (8) allows one writing the cost balance (2) simultaneously for all the components:

$$\mathbf{A} \cdot \mathbf{\Pi} + \mathbf{Z} = \mathbf{0} \qquad (9)$$

where $\mathbf{\Pi}$ is the vector containing the cost of all the flows exchanged between the m components at the interconnection nodes, while **Z** contains the total investment cost rate of the components, which is thus a source (generated) term. The calculation of all the costs requires the formulation of n-m auxiliary equations, which are obtained through definition of resources and products of each component, expressed in terms of exergy flows [18]. The auxiliary equations were formulated as four propositions [12], whose first (P1) is the conservation of cost, expressed by equation (9). The other propositions are: (P2) in absence of a different evaluation the economic unit cost of an exergy flow entering the system from the environment can be assumed equal to its price; (P3) in absence of a different evaluation, the unit cost of a lost exergy flow is the same; (P4a) if the fuel of a component is defined as the difference between two exergy flows, the unit cost of these flows is equal; (P4b) if the product of a component is defined as the summation of two or more flows, the unit cost of these flows is the same.

In the case of a district heating network, the only auxiliary equations to be applied is the assignment of the same unit cost to the flow exiting each bifurcation and the assignment of unit costs to the flows entering the system from outside, i.e. the unit cost of thermal exergy supplied in the plants and the unit cost of electricity required for pumping [19].

3. Third Party Access to District Heating Networks

In 1996, when the European electricity market opened up for competition, the earlier regulated district heating market was de-regulated in the sense that the companies now could set their own prices. The earlier directive that the district heating companies should not make any profit was removed, and any firm (not only municipal) could enter the market [20].

However, the lack of attention and targeted policies, the absence of a European directive that takes care of the particular case of district energy led to a situation in which district heating sector becomes substantially an example of market failure, because, in the absence of regulation authorities and measures, economic operators in free market have not been able to solve the main problem related to district heating systems: natural monopoly, third party access and effective competition, increasing prices due to unbalances in the market concentration.

This situation entails costs and inefficiencies for consumers and communities, for this reason in the current years many voices were raised in favor of a new regulation of the sector according to its new free market configuration, both on the academic side [20-22] and on the consumers side [23]. Some National Competition Authorities, for instance Sweden, have urged the need for adjustment in district energy system free market. The The Italian Competition Authority, in January 2012, launched a survey on the level of prices, constraints on choice for consumers of whether or not to connect to the district heating network and procedures for service management.

According to Becchis et al. [22], an absence of regulation in the district energy markets exposes consumers to possible exploitations by a monopolist willing to maximise his profit. Considering the strong pressure against District Heating and Cooling (DHC) projects coming from conflicting market interest and the relevant transaction and regulatory costs, a bit of regulation of the costs and tariffs might improve the penetration capacity of the technology and should be welcomed by DHC true supporters.

The main causes of market inefficiencies that require regulation are:

- situations leading to high prices, such as situations of economies of scale or scope, anticompetitive behaviour, network externalities, government limits to competition (patents, for instance);
- externalities leading to inappropriate prices;
- information problems that might lead to market breakdown, for example quality;

Regulation deals with the considered situation, explicitly controlling prices, profits and quality. Regulation specifies precise details of what companies can and cannot do (ex-ante intervention).

The aim of regulation is fundamentally to reach economic efficiency, that is, prices equal to marginal costs, taking into account the externalities, assuring entry of most efficient companies (productive efficiency), dynamic efficiency. Moreover, it has also re-distributional concerns between consumers and shareholders and between poor and rich consumers.

Third Party Access (TPA), i.e., separation between generation and retailing of district heating in order to open up the network for more competitors, is one suggestion that has been addressed in order to increase the competition in the market. Generally TPA implies that a third party can access the district heating network in a non-discriminatory way, in order to supply its heat, but there exist different forms of TPA that all are compatible with the above definition:

1) Regulated TPA refers to a situation of full access to the district heating networks, where the network owner has a legal obligation to allow access to the network. The network operations are

regulated ex ante, i.e., the conditions for access to the network (e.g., fees, etc.) are determined in advance.

2) Negotiated TPA implies that the district heating network owners are required to negotiate about access to the network with the producers of heat. The main difference between regulated and negotiated TPA is thus that the latter form implies that the network operations are determined ex post. The specific conditions for network access are negotiated between the network owner and the third party.

3) Finally, a so-called single-buyer solution means that all potential consumers in the network have the right to negotiate contracts with all eligible suppliers to the network. The single-buyer is obliged to purchase the contracted volume from this supplier and resell it to the customer at a price equal to the contract price plus distribution or system costs.

In this paper, the third party access is analyzed from technical and economic viewpoints. This analysis aims at showing that these aspects can be correctly captured using a thermoeconomic approach for costing purpose. A simple example, shown in Figure 1, is considered. This consists of a district heating network with two thermal plants that can supply heat to the users. The two plants are characterized by a different position, which involves a different contribution due to pumping. The quality of heat that is supplied to the network by the two plants is considered as different, which means that water is heated by the two plants at different temperature.

For sake of simplicity some assumptions are considered. Pressure drops Δp_i in the i-th pipe are assumed as proportional to the square of the mass flow rate G_i:

$$\Delta p_i = \beta_i \cdot G_i^{\ 2} \qquad (10)$$

Pipes in the present analysis are considered as perfectly insulated. The following quantities are assumed:

1) thermal request of the users in design conditions, Φ=20 MW;

2) pressure loss coefficient in pipe b_1, β_1=10 (corresponding with a straight pipe of about 200 m length and diameter 0.3 m);

3) supply temperature from the thermal plant TP1, T_{b1}=100 °C;

4) supply and return temperatures on the secondary circuit of the users, T_s=80 °C and T_r=60 °C;

5) return temperature on the main temperature of the district heating network, T_{b4}=65 °C;

6) cost of thermal exergy produced by the thermal plant TP1, c_{TP1}=0.16 €/kWh.

The latter has been considered as constant in all operating conditions. This is a good approximation of the behavior of combined cycles operating in cogeneration mode, if the effect of ambient temperature is not considered. In fact these kind of plants are characterized by an almost constant exergetic efficiency when steam extraction is varied from zero to the maximum value.

Only operating costs have been considered in the analysis, since the district heating network has been considered as existing, therefore the contribution of the investment cost is the same in all the examined scenarios.

A first case that can be considered in the analysis corresponds to the thermal plant TP2 producing heat at lower temperature than TP1. TP2 is considered as located closer to the users in comparison to TP1. The pressure loss coefficient in the pipe b2 is assumed as 10% of that in b1, the supply temperature from thermal plant TP2 is assumed as 90 °C. The analysis has been conducted by varying the percentage of heat supplied by TP2, the unit cost of thermal exergy supplied by the thermal plant TP2 and the heat requested by the users.

Figure 2 shows the unit cost of heat supplied to the users as the function of the percent heat load supplied by the thermal plant TP2, for three different values of the unit cost of thermal exergy. If this cost is considered equal to that for TP1, the unit cost of heat supplied to the users decreases with increasing contribution of the thermal plant TP2. This means that, despites the reduced temperature of the water flow exiting TP2, the smaller friction losses associated with b2 allow one to reduce the cost of heat supplied to the users. Similar results are obtained by increasing the unit cost of thermal exergy produced by TP2 up to 4%. If this unit cost is increased to 8% (i.e. about 0.173 €/kWh) the minimum cost is obtained by using the plant TP1 only. This means that the beneficial effects of a reduced pumping cost is always lower than the effects due to the smaller unit cost of thermal exergy produced by TP1 and the larger specific exergy.

In the case of costs of thermal exergy produced by TP2 between 4% and 8% larger than the cost of TP1, the optimal cost of heat is obtained by supplying heat from the two plants. At partial load, the unit cost of heat reduces, because of the reduction in pumping costs as well as the reduction in the temperatures on the secondary circuit. The latter causes a reduction in the returning temperature of the district heating network, which means that the exergy content associated to the enthalpy flux supplied by the thermal plant to the network reduces and so the corresponding unit cost of heat.

Figure 3 shows the unit cost of heat supplied to the users as the function of the percentage of heat supplied by the thermal plant TP2. The curves refer to three different percentage of the total heat request and are obtained considering a cost for the thermal exergy produced by TP2 6% higher than that produced by TP1. In the case of design load, there is a minimum when 45% of heat is produced by TP2. When a smaller heat load is considered, the curves is flattened and the minimum shifts towards lower percentage of contribution by TP2. In the case of heat load reduced to 75% of the design value, the minimum is obtained when about 40% of heat is produced by TP2. In this case, the minimum cost is 5% lower than the minimum cost at design load. When the heat load is reduced to 50%, the minimum is obtained when heat is entirely produced by TP1, but the cost is almost constant. The unit cost of heat is about 11% lower than at design load.

Similarly, when lower costs of thermal exergy supplied by TP2 are considered, the unit cost of heat is reduced as the heat load reduces. The curves are flattened and keep a similar slope as the one shown in Figure 2. Analogous behavior is observed when the unit cost of thermal exergy produced by TP2 is increased.

4. Buildings Equipped with Low Temperature Heating System

A further aspect that deserves to be considered refers to buildings equipped with low temperature heating systems, such as radiant floor. This kind of systems has positive impact on the efficiency of district heating systems, since the operating temperature of the network can be reduced. Similar effect is achieved in existing buildings, where energy savings initiatives (e.g. wall, roof or window insulation) are introduced. In such a case, the existing heating system becomes oversized and its operating temperatures can be reduced.

Buildings with these characteristics can be connected on the supply network as the other buildings. In this case the temperature difference between supply and return values can be significantly increased. In fact the return temperature has a lower bound imposed by the return temperature on the secondary circuit. If the latter is lowered, the return temperature can be lowered as well. The positive effect is particularly important in the case of small networks, which are designed with small difference between the supply and return temperature. An alternative configuration is also possible. Buildings with low temperature heating system can be theoretically connected to the return pipeline. The inlet temperature on the hot side of the heat exchanger is therefore equal to the return temperature of the district heating network. Water is then rejected, at lower temperature, on the same pipe.

Figure 4 shows the unit cost of heat supplied to a user connected with the supply network as the function of the operating temperature on the secondary circuit. The analysis is performed considering two values of the supply temperature on the main circuit.

The figure shows that unit cost of heat decreases with decreasing operating temperature on the secondary circuit, in the case a fixed value of the supply temperature of the district heating network is considered. A reduction in the network temperature also allows on to reduce the unit cost of heat.

One of the main advantages in the reduction of the operating temperatures consists in the larger plant efficiency [24, 25]. An additional advantage that is obtained by lowering the return temperature consists in the reduction of the mass flow rate flowing in the district heating network, which allows one to reduce the pumping cost. The effect of secondary temperature on the specific mass flow rate (i.e. the mass flow rate per unit heat flux) flowing in the network is shown in Figure 5.

The curves show that there is a significant reduction, especially in the case of network operating with smaller supply temperature. An additional potential advantage in lowering the mass flow rate is registered in the case of existing network in areas where there are possible urban expansions. In this case, new users may be connected to the network even in the case of a "saturated" network, i.e. when the thermal request of the user causes water velocity in portions of the system close to the upper limit. A reduction in the mass flow rate that is requested to supply the connected users with their thermal request allows one to connect new users.

It is finally worth considering the analysis of unit cost of heat as the function of the temperature on the district heating network, for fixed operating temperatures on the secondary circuit. These have been fixed equal to 40 °C (supply) and 30 °C (return).

Figure 6 shows that unit cost decreases with decreasing temperature, which means that a configuration with the building connected on the returning pipe would allow a cost reduction, therefore the price of heat for this user should be lower than a user connected on the supply network. In addition, the figure shows that a reduction in the source temperature causes a significant increase in the mass flow rate, about 4 to 6 times larger than usual connection, depending on the supply temperature. Therefore this kind of configurations is possible only in portion of the network where the number of users is large enough, so that the mass flow rate flowing in the pipes is sufficient.

5. Conclusions

Future district heating systems are expected to be flexible in the operation, based on renewable energy sources and open to various producers. In principle, the users can also become producers, thus implementing a sort of "peer-to-peer" energy exchange system. Additional aspects related to this new vision of district heating networks are related with the possibility of also supply cooling to the users through thermally driven chillers, or the possibility to distribute heat produced by heat pumps that are fed with excess productions of electricity (e.g. from wind farms).

The present paper represents a first attempt to tackle particular aspects that can occur in the operation of advanced district heating systems. This is performed through proper application of Thermoeconomics, which is an exergy based costing approach. This allows one to account for the various thermodynamic and economic aspects that are involved in the process of cost formation from heat generation in the plants, through heat transport in the network, to heat use in the buildings. The analysis is conducted by examining two simple applications: third-party access of multiple producers and the connection of buildings equipped with low temperature heating systems to the district heating network.

In the case of multiple heat producers, the analysis requires the evaluation of various aspects: unit cost of heat supplied to the network, quality of heat (i.e. supply temperature) and pressure required for correct operation. An additional aspect that should be considered refers to the use of thermal storage devices, which operation (charge and discharge) may be decided on the basis of the cost of heat, total heat request, supply temperature of the network. In thermoeconomics, all these aspects are included in the costing analysis thanks to the use of an exergy evaluation of energy flows.

In the case of low temperature heating systems, thermoeconomics allows one to properly account for the quality of heat request by the users and the corresponding impact on the primary energy associated with heat generation and transport.

Both applications show how the use of different energy forms, their quality and cost can affect the cost of the product supplied to the users. These pieces of information can be used for operational purposes, since costing is performed considering the entire process from generation to the final use. These can be also applied in the design phase of both existing and not-existing networks, for instance evaluating the cost of connection of additional areas to the networks, the connection of industrial plants with availability of waste heat, the installation of storage units on the network or at the users.

Nomenclature

A Incidence matrix
c Thermoeconomic unit cost (€/kJ)
G Mass flow rate (kg/s)
G_x General flow
I Rate of irreversibilities (kW)
p pressure (bar)
$\dot{Z}$ Total investment cost rate (€/s)

Subscripts
d Destruction term
F Resource
P Product

Greek
β Pressure drop coefficient (bar·s^2/kg^2)
Φ Heat flux (kW)
Ψ Exergy flow (kW)
Π Thermoeconomic cost rate (€/s)

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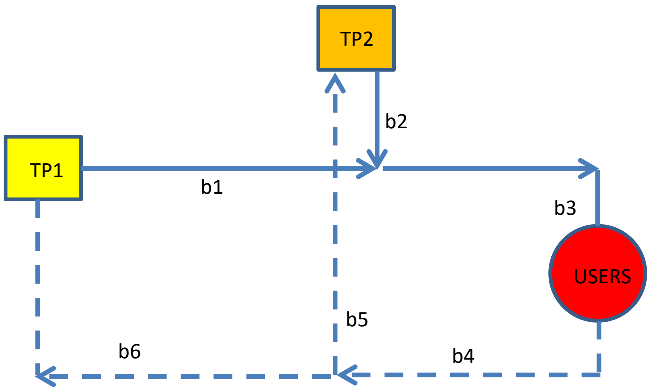

Figure 1. Schematic of a district heating network with two heating plants

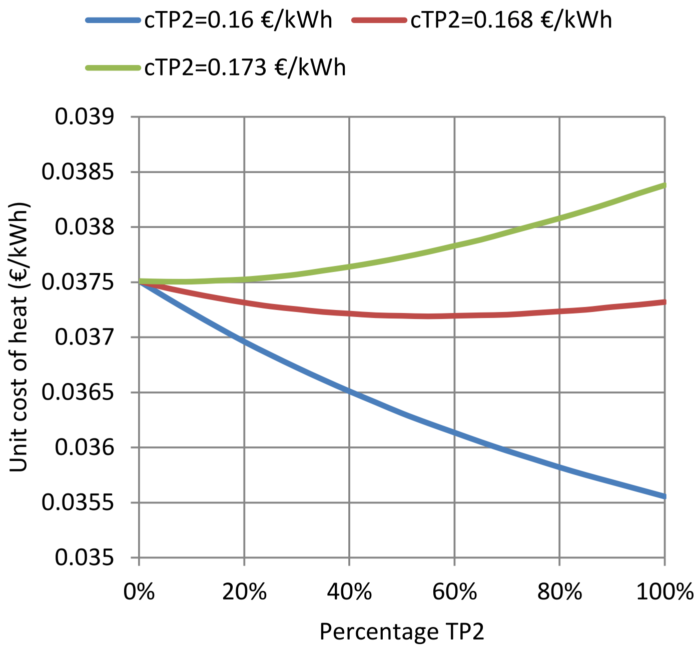

Figure 2. Unit cost of heat as the function of the percent thermal supply from TP2 at design load.

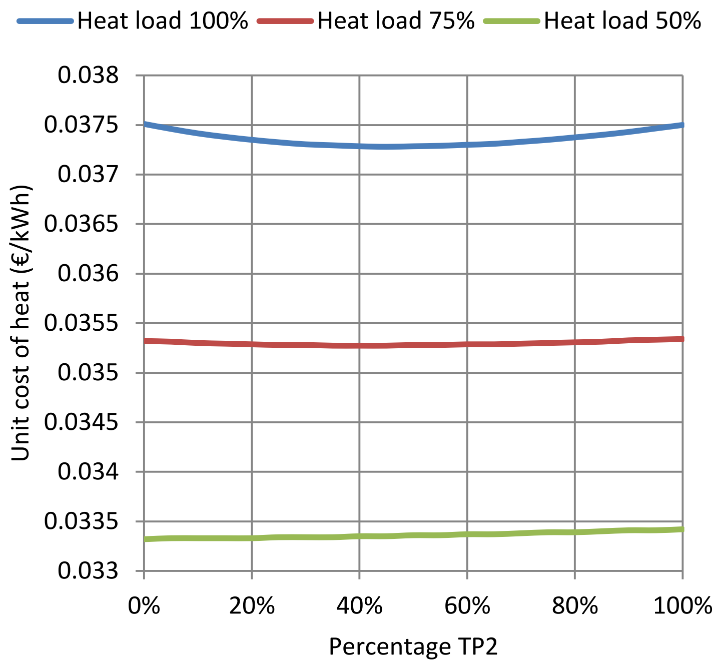

Figure 3. Unit cost of heat as the function of the percent thermal supply from TP2 per various thermal loads, at fixed cost of thermal exergy.

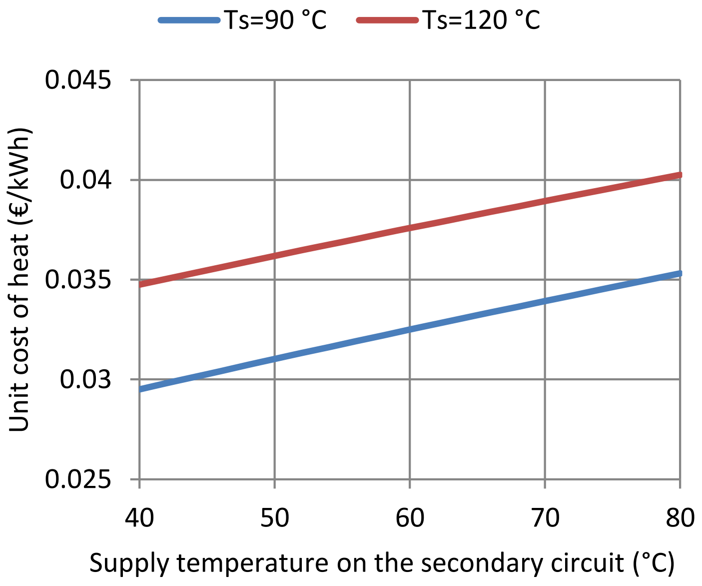

Figure 4. Unit cost of heat as the function of the supply temperature on the secondary circuit.

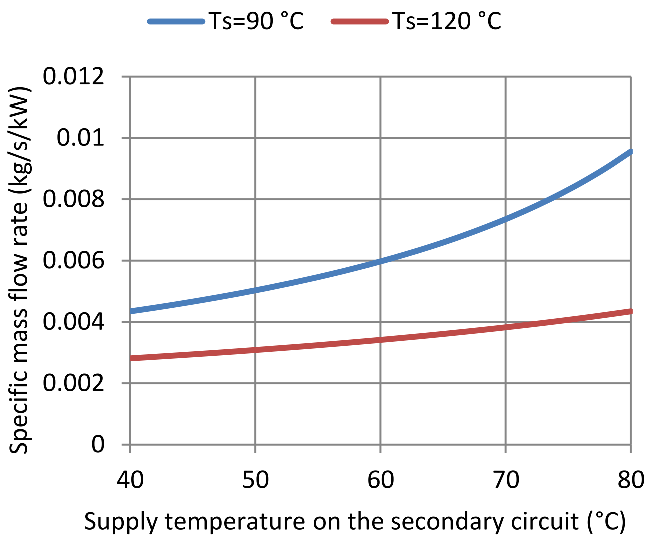

Figure 5. Specific mass flow rate in the district heating network as the function of the supply temperature on the secondary circuit.

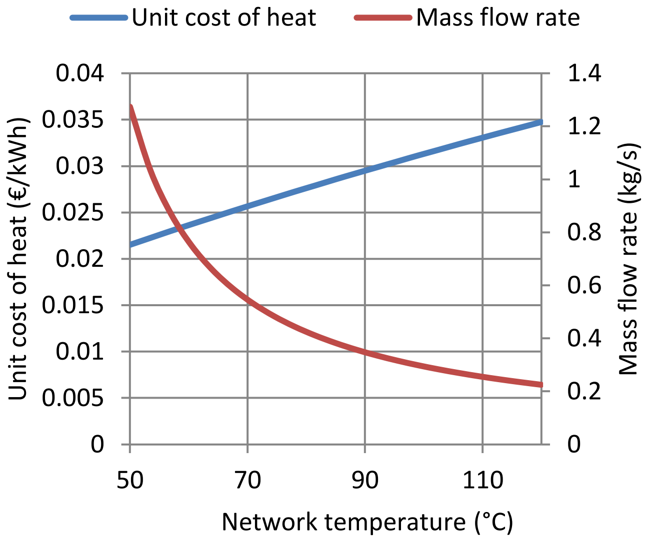

Figure 6. Unit cost of heat as the function of the network temperature.