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Optimization of the thermal load profile in district heating networks through "virtual storage" at building level

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Abstract

Thermal storage is of extreme importance in modern district heating networks in order to increase the share of waste heat and heat produced through renewable sources and cogeneration. Nevertheless, installation of large storage volumes is not always feasible, especially in dense urban areas. A possible option consists in virtual storage, which is obtained through variation of the thermal request profiles of some of the connected buildings with the goal of producing an effect similar to that obtained using storage. To perform such approach there are three crucial elements: 1) an advanced ICT solution able provide real time information about the thermal request of the buildings and the thermodynamic conditions at the thermal substations; 2) a detailed thermo fluid-dynamic model of the district heating network able to simulate the temperature evolution along the network as the function of time; 3) a compact model of the buildings in the district able to check the acceptability of the internal temperatures following the modified strategies.

The model produces changes in the start-up time of the buildings connected with the network as well as possible pauses during the day. These changes in the request profiles usually involve a slightly larger heat load. Nevertheless, peak shaving is accompanied by a reduction in heat generation of boilers and an increase in the thermal production of efficient systems, such as cogeneration units. This results in a significant reduction in the primary energy consumption.

An application to the Turin district heating network, which is the largest network in Italy, is presented. In particular, a subnetwork connecting the main transport network to about 100 buildings located in the central area of the town is considered. The analysis if performed in selected days where the optimization was conducted the day before on the basis of weather forecasts and then applied to the network. Despite the changes in the request profiles could be applied only to a limited number of buildings, the analysis show that the peak request can be reduced. Simulations performed considering the application of changes to a larger number of buildings show that reduction in the primary energy consumptions of the order of 5% can be obtained.

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1. Main text

District Heating (DH) is a very widespread technology because it allows to reduce the primary energy cost for domestic heating in urban areas, trough the integration of industrial waste heat, high efficiency cogeneration plants and renewable energy plants [1]. In fact not only combined cycle but also heat recovered from industrial processes and sustainable energy plants can be used to produce the heat distributed to the users trough a DH network [2,3,4]. An important aims related to district heating systems technology regards the maximization of the cogeneration exploitation with the aim of increasing the overall system performances and consequently reduce primary energy consumption. In fact the simultaneous production of thermal energy and electricity significantly decreases the primary energy consumption for house heating with a consequent reduction of carbon emissions. For instance the Turin district heating network, that is the largest network in Italy and it is primarily fed by cogeneration power plants, allows a reduction of primary energy consumption to about 50% with respect to the use of condensing boilers [5]. In order to increase the fraction of heat produced through cogeneration it is necessary to shave the thermal request peaks. The presence of a morning thermal peak is a typical problem in the Mediterranean areas, where during the night building heating are typically switched off and early in the morning the thermal request is very high. Therefore it is worth investigating possible opportunities for thermal peak shaving, among them, the variation in the thermal request profiles for some of the connected buildings and the installation of local storage systems.

Also many recent works in literature demonstrate the increasing interest for increasing exploitation of cogeneration, renewable sources and storage technologies. In [6] the use of storage systems charged during the night and used during the start-up transient are examined in order to reduce the morning peak. This is shown to be a very effective measure for reducing the boiler utilization and enhance cogeneration use. In [7], a model for optimizing integration of boilers, heat pumps and cogeneration is carried out. The possibility of using a dynamic simulation tool with the aim of studying interactions of CHP/DHN, with a particular emphasis on the network to heat storage capacity, is examined in [8]. In [9] and [10] models are used in order to study the opportunities to modify the thermal request profile of some users for maximizing the heat production from cogeneration or renewable plants. Due to the large range of possibilities and the complexity of the DH systems, the improvements of technical and managements aspects can be obtained using simulation tools. This is the reason why district heating system modelling have been largely applied in both design and management stages [11,12].

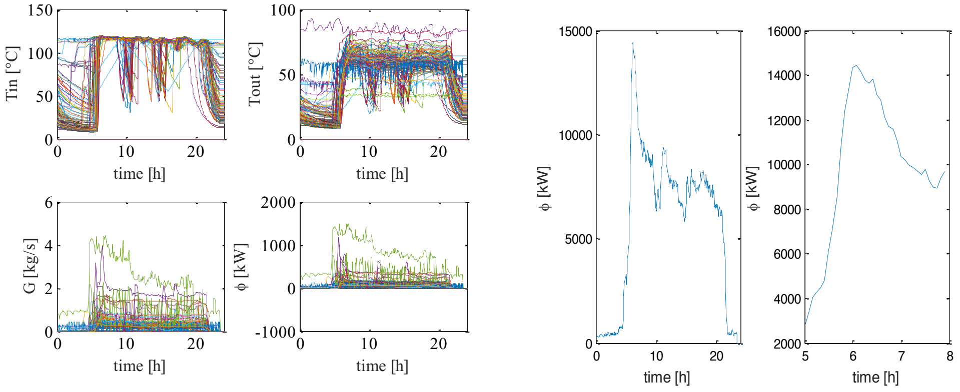
In this paper a physical based optimization tool is discussed with the aims of analyzing the possibilities for peak shaving trough changes in user thermal requests. In particular changes in the start-up time of heating systems, for a different number of users located in the same distribution network, have been studied. The optimization tool allows to evaluate the best set of anticipation of the heating system start-up time in order to minimize the energy fraction produced trough boilers. Furthermore in order to evaluate the maximum value of anticipation allowed to preserve the internal comfort, a compact model of the building has been performed. The effects of the heating system start-up time changes on the total distribution network request evolution have been obtained through the physical model. A physical model is used because of the long distances involved in the network that cause a temperature evolution at the barycentre significantly different than that at the users.

Nomenclature

c	Thermal Capacity
M	Mass
T	Temperature
U_{vol}	Thermal losses coefficient
V	Volume
Φ	Heat Power

2. Data collection system

In order to obtain the optimal set of the switching on times of the users heating systems, it is necessary to estimate the expected thermal profile of each building. For this reason, a system for monitoring the thermal request of the buildings has been implemented over the past years. Temperature sensors collect temperature at the inlet and at the outlet sections of the heat exchangers and mass flow meters gather the flowing mass flow rate. These data can be used in order to evaluate the evolution of heat request to the monitored user, with different external temperatures. It is therefore possible to estimate the heat load profile at the user for different level of external temperature. In Fig. 1 the data collected in the BCT_414 are shown for an external average temperature of 0 °C.



(a) (b)

Fig. 1. Data gathered. a) Data at the heat exchangers of users in the BCT_414 b) Total thermal request

Fig. 1a reports the evolution of the temperature at the inlet section, the temperature at the outlet section, the mass flow rate and the heat flux requested. On the basis of the inlet temperature evolution, it is clear that most of the heating systems are switched off during the night and are switched on between 5 am and 6 am. Only few users are never switched off and their inlet temperatures are about constant. When the systems are switched on, the inlet temperature values are between 118 °C and 113 °C. The difference of these values is due to the different distances from the barycentre, i.e the link between the distribution network and the main transport network. In fact, the larger the distance between the user and the thermal barycentre, the larger the thermal losses and the lower the inlet temperature at the heat exchanger. The temperature in the outlet section of the heat exchanger depends on the inlet temperature, the mass flow rate and the heat flux exchanged. Most recorded values are between 45 °C and 65 °C.

Mass flow rate and heat power evolutions present various peaks during the day. The larger peaks take place at early morning. This is confirmed also from Fig. 1b, which reports the sum of the power request to all the users (in the left part) and a detail of the peak time (in the right part). In particular, the time period considered for the peak analysis and minimization, as reported in Fig. 1b, is 5.30 am - 8.30 am.

In particular when the optimization for the future day (DATE1) is required, the expected external temperature for that day is selected through the weather forecast. Also the day type of DATE1 is selected that affects the energy consumption evolution. In fact if the day selected is Saturday, some of the offices are closed therefore the heat demand is lower than in the working days, while if it is Sunday most offices are closed and the request is even smaller than in Saturday. If it is Monday the heat request is larger respect to the other days of the week because of the need of re-heat the buildings that switch off the heating system during the weekend. The other days, between Tuesday and Friday, are considered to have a similar temperature request at a given external temperature. Secondly a past day (DATE2) with an external temperature that is similar to the one of DATE1 and the same day of the week (Saturday, Sunday, Monday or Other days), is selected. The data collected through the gathering system for the DATE2 are used as the expected thermal request for the day DATE1.

For technical and management reasons not all the considered distribution networks can be included in the anticipation evaluation. Therefore different tests have been carried out with a different number of variable users.

3. Model

3.1 Thermal fluid dynamic network model

The network model is used in order to take into account the long distances involved in the network; in fact the water exiting the users heat exchangers flows on the return distribution network and mixes with the various streams coming from the users located in the other areas. The various streams are at different temperatures, because of the different distances of the users respect to the connection with the transportation network (this node is called barycentre). Therefore in the end temperature evolution at the barycentre is significantly different than that obtained as the temperature evolution obtained as the weighted average at the users. A one dimensional model has been used to study the thermo fluid-dynamic behaviour of the distribution network. The topology of the network has been treated with a graph approach [13]. Each pipe of the network was considered as branch that starts from a node, the inlet section, and ends in another node, the outlet section. In order to to express the connections between nodes and branches incidence matrix has been used. The general element a_{ij} is equal to 1 or -1 if the branch j enters or exits the node i and 0 otherwise. The fluid-dynamic model considers the mass conservation equation applied to all the nodes (eq. 1) and the momentum conservation equation applied to all the branches(eq. 2) . Further details on the method are available in [14].

3.2 Compact User Model

A user model has been carried out for the selection of a maximum anticipation value. The user model includes both the building and the substation. A schematic of the heating system considered to model the users is shown in Fig. 2.

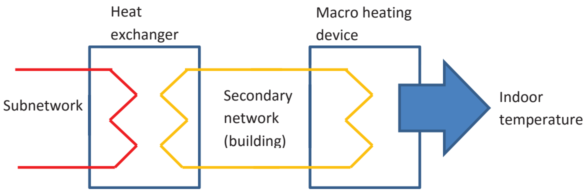


Fig. 2. Schematic of the heating system in the buildings

As regards the substation the heating system of each building has been modeled considering two heat exchangers. The first heat exchanger is the one in the substation where the water of the district heating network flows at the primary side and the water of the building heating system flows at the secondary side. The second heat exchanger simulates the heating devices in the building as a single component exchanging heat with the indoor environments. The heat exchangers are modeled using a effectiveness-NTU method.The temperatures on the secondary network have been calculated at each time step, since these values vary during operation. As regards the mass flow rate on the secondary network, it is constant when the heating system is operating, since typically no variable speed pumps are installed in the buildings. The mass flow rate on the secondary network is zero when the heating system is not operating.

As regards the building the model it is essentially an energy balance including the unsteady term, the heat provided to the heating system and the losses with the environment, as shown in (eq. 1).

$$\Phi_{syst} + \Phi_{losses} = Mc\frac{dT}{dt} \tag{1}$$

where the losses can be expressed trough the global dispersion coefficient per unit volume U_{vol}:

$$\Phi_{losses} = U_{vol}V(T - T_{outside}) \tag{2}$$

Both the coefficients Mc and $U_{vol}V$ have been evaluated trough the analysis of experimental data.
The term $U_{vol}V$ is evaluated trough the data collected when in the system no effective temperature changes occur, because the system reaches a stationary condition where the heat flux provided to the heating system is the heat flux

lost towards the environment. This condition usually occurs during the afternoon. In this time period the unsteady term can be considered as constant and therefore the term UV can be evaluated through (eq. 3).

$$U_{vol}V = \frac{\Phi_{syst}}{(T - T_{outside})} \tag{3}$$

The term c has been evaluated considering the transient after the heating system switching off. In fact when the temperature of water exiting the heat exchanger at the secondary side of the heating system is at low temperature, its decrease in a similar way of the indoor environments temperature. Therefore, data collected during the last stage of the water cooling can be used to evaluate the c value. Temperatures of the water exiting the DHS heat exchangers at the secondary side ,T_{out_sec} , and heat flow exchange at the users ,Φ_{syst} , are evaluated using the substation model.

$$Mc = U_{vol}V(T - T_{outside}) \cdot \frac{dt}{dT} \tag{4}$$

3.3 Optimizer

The optimization model aims at finding the best set of heating systems start-up time anticipations **x** that allows to maximize the peak reduction. The set of optimal value **x** guarantees the minimum fraction of heat produced through boilers, maximizing the cogeneration exploitation. Currently not all the 103 user thermal profiles can be changed, therefore only a fraction of the buildings is considered in the optimization, while the others are not modified. Due to this reason the total number of independent variables, with the control system used nowadays, is 30. However tests with a different number of variable users have been performed in order to quantify the possible future primary energy saving. The variable vector **x** is therefore a vector n_{Var} x1 where n_{Var} is the number of users with an adjustable thermal load. The **x** variable can assume only discrete values since the time demand modification is performed considering slots of 10 minute multiples. This assumption is related with the structure of the ICT system which commands the rescheduling. The changing in temperature profiles are selected through the use of the user model in order guarantee an indoor temperature sufficiently high for the comfort conditions. A genetic algorithm, set for integer-value, has been used to perform the minimization.
The objective function that has to be minimized is the integral of the thermal power over the time when the thermal power exceeds the cogeneration maximum heat power.

$$\mathrm{Q_{Non\_cog}} = \int_{\mathrm{t_a}}^{\mathrm{t_b}} \Phi_{\mathrm{BCT_{414}}}(\mathrm{t}) - \Phi_{\mathrm{maxCog}}(\mathrm{t_b} - \mathrm{t_a}) \tag{5}$$

$$\Phi_{\mathrm{BCT_{414}}}(\mathrm{t}) = \mathrm{G_{TOT\_BCT_{414}}}(\mathrm{t})\ \mathrm{c_p}\ (\mathrm{T_{supply}} - \mathrm{T_{ret\_nodeBCT_{414}}}(\mathrm{t})) \tag{6}$$

where t_a is the time when the heat request exceed the maximum cogeneration power and t_b the time when the system starts requiring only cogeneration power. Φ_{BCT_414} is the thermal power request to the barycentre 414.

4. Selected network description

The Turin district heating network is the largest network in Italy and one of the largest in Europe. It currently connects about 55000 buildings. The maximum thermal power is about 1.3 GW. The water supply temperature is constant and its value is almost 120°C while the return temperature varies with mass flow rate circulating in the network and thus with the thermal load.The complete network can be considered as composed of two main parts hydraulically connected: a transport network and the distribution networks. The transport network, consists in large diameter pipes, and connects the thermal plants to the thermal barycentres. The distribution networks connect the transport pipeline to the users. The point that links the transport network each distribution network is called barycentre. In the Turin network there are 182 barycentres.
For the aims of this paper only one of the distribution network has been considered. The network selected is called BCT 414 and includes 103 users. This is 4.7 km long and links the transport network to 103 buildings. The

BCT_414 has been selected because of the large number of users linked to this network that are monitored using a data gathering system and because some analysis conducted on buildings volume, utilization and consumption, demonstrated that it can be considered as representative of a typical distribution network of the Turin DHS.

5. Results

5.1 Anticipation Selection

The capability of the user model of simulating the indoor temperature evolution was tested trough the comparison with some experimental data. Results in terms of indoor temperature evolution are reported in [15]

The model has been used to test the effect of thermal request anticipation on the internal temperature. In particular the differences between the internal temperature obtained through the normal strategy and the anticipated strategy has been analyzed. The result obtained with 10 and 20 minutes anticipation are reported in Fig. 3.

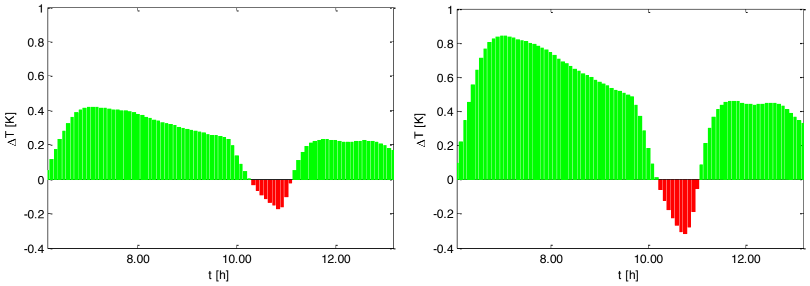


Fig. 3. Indoor temperature variation a) 10 minutes b) 20 minutes

The indoor temperature obtained using the modified strategy is always higher respect to the one with the current strategy, except the period between 10.15 am and 11.15 am. When a 10 minutes anticipation is applied a maximum temperature reduction of 0.2 °C occurs, with an average values lower than 0.1°C. As regards the use of 20 minutes anticipation, a maximum temperature reduction of 0.3 °C occurs, with an average values lower than 0.2°C. Because of the low average temperature differences and low maximum temperature differences, both the cases can be considered acceptable. The selected ranges for the users anticipation are therefore 0, 10 minutes, 20 minutes.

5.2 Optimizer results

In this section the results of the optimization are described. Three cases, with different variable users number have been considered: CASE 1 with 30 variable users, CASE 2 with 60 variable users and CASE 3 with 95 variable users. CASE1 correspond to the currently situation, while the other two days are considered in order to quantify the potential for future developments. Fig. 4 depicts the thermal request evolution of all the users (black line), the variable users (green line) and the non variable users (red line), for the three considered cases.

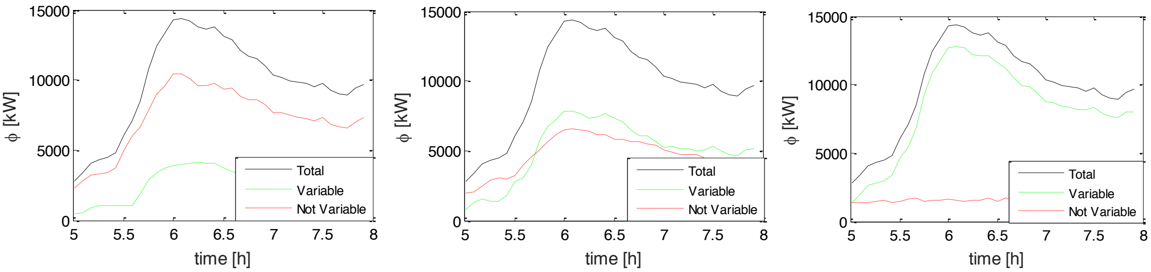


Fig. 4. Variable thermal request considered

It is clear from the figure that in the CASE 1 most of the thermal power request can't be modified trough the switching time rescheduling, in CASE 2 two, about an half of the users can be modified while in CASE 3 most of the thermal power request can be modified.Fig. 5 depicts the required thermal power obtained through the genetic algorithm optimization, compared to the current ones, for the three selected cases. In all the considered cases the curve obtained with the modified strategies is shifted to the left because of the heating systems switching on anticipation. In the CASE 1it is slightly shifted while in the other cases the shifting is remarkable. The green dashed line represents the maximum cogeneration power. The integral over this value represents the energy produced through boilers, the quantity that has been minimized. From Fig. 5 is evident that in all the selected cases the integral in the part over the green dashed line is reduced respect to the one obtained with the current strategy. Furthermore the maximum value of the thermal peak always presents a decrease; it is a very important point regarding the possibility of connecting other users to the network. The total energy request, instead, increases in all the three considered cases; in fact it is clear from Fig. 5 that the value of the overall integral obtained with the modified strategy is always higher respect to the current strategy.

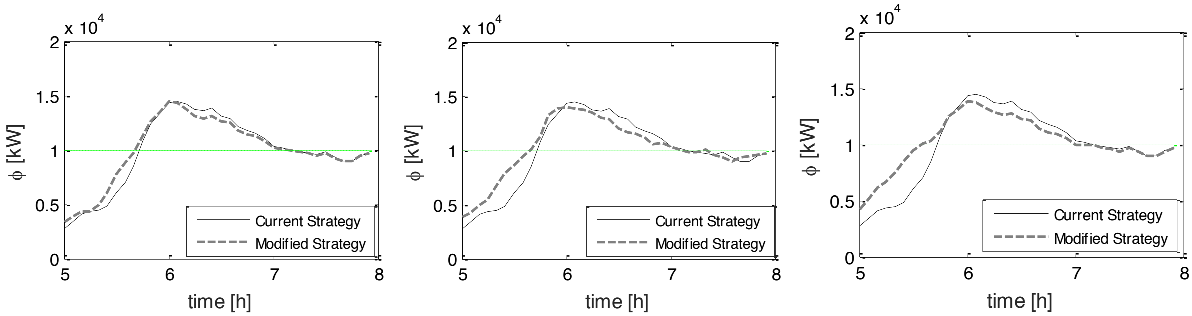


Fig. 5. Current ant modified strategies for the three considered cases

Fig. 6 reports the results in terms of primary energy savings in the different cases. The ratio between primary energy consumption and heat produced is considered 1.11 for the boilers and 0.36 for the cogeneration system. In all the considered cases, even if the total energy request increases, the overall primary energy consumption decreases because of the higher performances of cogeneration with respect to the boilers.

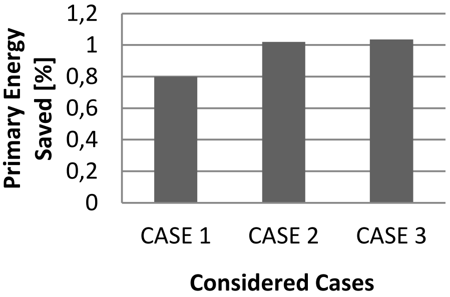


Fig. 6. Primary Energy savings a) for the three considered cases

The energy savings obtained with the best set of anticipation is the 0.8% of the total primary energy consumption for the distribution network in the CASE 1. As regards CASE 2 and 3, an increase of the primary energy consumption is verified. The main difference occurs when more than a half of the users can be changed, respect that only the 25% (between CASE 1 and CASE2). Instead, a small difference occurs when the percentage of variable users almost reaches the 100%, respect to the 60% (difference between CASE 2 and CASE 3) Therefore the possibility of varying about an half of the users is sufficient in order to obtain a satisfactory primary energy reduction and a further increase of the number of variable users does not strongly affect the primary energy savings.

6. Conclusions

In this work a physical tool able to evaluate the request of the whole distribution network has been used for the morning peak shaving. In fact the peak request, typical of Mediterranean areas, do not allow a major cogeneration utilization. The physical model used is based on mass, momentum and energy conservation equation applied to a distribution network of the Turin DHS.

Furthermore a user physical model, including both the building and the substation behaviour has been carried out with the aim of testing the effect of the thermal request anticipation on the indoor temperature. Trough this model it is possible to select the maximum anticipation value that allows to obtain acceptable comfort conditions inside the buildings. The user model has been tested on the experimental data in order to prove its capability on describing the indoor temperature.

The optimizer has been used to simulate different cases; each case has a different numbers users with variable switch on time. Results show that the proposed physical optimizer tool allow to reduce the heat flux provided using boiler systems. The primary energy consumption reduction, with an average environmental temperature of 0°C, is about 0.8% if the current variability situation is considered, where only 30 users thermal request can be varied. If an higher fraction of variable users is considered the percentage of primary energy savings exceeds the 1% of the total primary energy consumption of the distribution network. Furthermore the maximum thermal load obtained using the optimizer is lower respect to the current strategy; the maximum load minimization is an important point related to the possibilities for new users connections.

The use of the building model shows that the imposed thermal profile anticipations generate negligible indoor temperature reductions respect to the current situation and therefore the preservation of the comfort standard is guaranteed.

7. References

[1] Lund H, Moller B, Mathiesen BV, Dyrelund A. The role of district heating in future renewable energy systems. Energy 2010; 35: 1381–1390.

[2] Hassine I B, EickerU. Impact of load structure variation and solar thermal energy integration on an existing district heating network. Applied Thermal Engineering 2013 ;50: 1437-1446.

[3] Roos A, Bohlin F, Hektor B, Hillring B. Woodfuel procurement strategies of district heating plants. Energy 2003 ;28: 127–140.

[4] Verda V, Guelpa E, Kona A, Lo Russo S. Reduction of primary energy needs in urban areas trough optimal planning of district heating and heat pump installations. Energy 2012 ; 48: 40–46.

[5] V Verda, G Baccino, A Sciacovelli, S Lo Russo. Impact of District Heating and Groundwater Heat Pump Systems on the Primary Energy Needs in Urban Areas. Applied Thermal Engineering 2012; 40: 18-26.

[6] Verda, V, Colella, F. Primary energy savings through thermal storage in district heating networks. Energy 2011; 36(7): 4278-4286.

[7] Lindenberger, D, Bruckner, T, Groscurth, H M, Kümmel, R. Optimization of solar district heating systems: seasonal storage, heat pumps, and cogeneration. Energy 2000; 25(7), 591-608.

[8] Pini Prato A, Strobino F, Broccardo M, Giusino LP. Integrated management of cogeneration plants and district heating networks. Applied Energy 2012; 97: 590-600.

[9] Verda V, Baccino G. Primary energy reductions in District Heating Networks through variation of the thermal load profile of the users. Proceedings of ECOS 2014. Turku, Finland, June 15-19.

[10] Jokinen E, Kontu K, Rinne S, Lahdelma R. Demand side management in District Heating buildings to optimize the heat production. Proceedings of ECOS 2014. Turku, Finland, June 15-19.

[11] Ancona MA, Melino F, PerettoA. An Optimization Procedure for District Heating Networks. Energy Procedia 2014 ;61: 278-281.

[12] Bojic M, Trifunovic N, Linear programming optimization of heat distribution in a district-heating system by valve adjustments and substation retrofit. Building and Environment 2000 ; 35: 151-159.

[13] Harary F,Graph TheoryNarosa Publishing House, New Delhi;1995.

[14] Sciacovelli A, Verda V, Borchiellini R Numerical Design of Thermal Systems. Clut, Torino2015

[15] Verda V, Guelpa E, Sciacovelli A, Acquaviva A, Patti E. Thermal peak load shaving through users request variations. International Journal of Thermodynamics 2016; 19(3): 168-176.