Optimal Configuration of Power-to-Cool Technology in District Cooling Systems

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ABSTRACT

In a multi energy framework, power-to-heat technology is becoming increasingly attractive. This interest is mainly due to the possibility of exploiting excesses and unbalances of electricity, that are becoming more and more common with the increasing capacity of the renewable sources. An interesting option consists in using heat pumps to convert excess of electricity produced by photovoltaic systems (especially in the midday hours) into cold to be provided to district heating and district cooling networks. This paper aims of proposing a methodology to select the best heat pump location in district cooling system. The analysis is performed with the aim of minimizing the cost of network construction and pumping. The procedure includes the best heat pump location and the design of the pipeline. Results show that distributed heat pumps allow one reducing both the costs and the average pipeline diameters by about 50% with respect to concentrated production. Furthermore, the optimal location of distributed heat pumps allows reducing costs of about 7% with respect to a uniformly distributed production.

Keywords: power-to-heat, p2c, smart energy systems, thermal network model, heat pump localization, best position

1. Introduction

The increasing exploitation of low-grade and intermittent resources makes the flexibility a crucial characteristic of future energy systems. The integration of different types of energy infrastructures represents an indisputable chance of increasing flexibility in future smart cities [1, 2]. Low grade resources in thermal field are waste heat from industrial plants [3-5], low grade heat from CHP plants [6] and heat from renewable sources, such as geothermal [7] and thermal solar [8]. Concerning the electricity the increasing exploitation of renewable source makes the time evolution of the production much more fluctuating in time. As *integration of energy infrastructure* is intended the possibility emerges of connecting various energy grids (electrical, thermal and gas), through the exploitation of the various infrastructure: networks, storages, energy vectors conversion systems [9] together with the suitable platforms [10] and optimization/diagnosis techniques [11-13].

One of the most interesting opportunities offered by the integration of the various types of energy infrastructure consists in the use of excess electricity to feed district heating and cooling networks. This can be achieved by means of the power-to-heat and power-to-cold technologies. This allows exploiting large amount of electricity excess by feeding the thermal network and thermal storages avoiding the installation of expensive electricity storages. This can be done in both district heating and district cooling network. In case of large photovoltaic capacity, the option of power-to-cold is very attractive since during the summer period the renewable production is significant (and largely fluctuating) and at the same time the cooling demand is large.

Heat pumps are increasingly widespread in district heating. Denmark supported 13 large heat pump projects with more than 3 M€ in funding [14]. 41 large heat pumps, most of which are for district heating projects, have been installed with the heat pump capacities that range from 0.2 to 10 MW [15]. Some heat pumps installed to feed district heating by exploiting waste heat and renewable sources are located in Rødkærsbro (a heat pump using the waste heat from a dairy), in Farstrup-Kølby and Dronninglund (groundwater heat pumps) [16] and the large Helsinky district cooling [17].

Concerning the European framework, the FLEXYNETS project, supported by the Horizon 2020 European research program is aimed at the integration of decentralized HPs in low-temperature district heating networks [18]. Interesting research themes in this field concern the system design [19, 20], the analysis of different

configurations [21] and different sources to increase the heat pump performances; the most widespread source are besides air [22], groundwater [23], waste heat [24] seawater [25] or drinking water [26].
If various works exist concerning installation of heat pumps in district heating, analyzed from an energy and economic viewpoint [27, 28], few research is performed in the field of district cooling. Integration of reversible heat pumps in hybrid renewable trigeneration systems in micro-district heating and cooling networks is investigated in [29]. Results show that the reversible heat pump installations are capable of reducing by 7% the equivalent annual cost, increasing the installed power of renewables up to 23%, and lowering by 11% carbon dioxide emissions, compared to conventional gas-driven system. In this framework, the analysis of design and operations [30] of district cooling fed by heat pumps are interesting. In particular, use of centralized or decentralized production and the location of the heat pump can significantly affect the performances of the district cooling system, as shown in the result section of this work.
In this paper, a model for the optimal localization of heat pumps in district cooling systems is proposed. This is aimed at determine the best position for a given number of heat pumps to feed a district cooling system such that the cost are minimized. In particular the two cost that are minimized are: 1) the pipeline investment cost 2) the pumping cost that is particularly high because of the large mass flow rates in district cooling respect to district heating (due to a smaller temperature gap between supply and return line). The model is used to design intelligently a heat pump driven district cooling for the city of Turin, where currently a large district heating network already exists.
The two main strength of the analysis are:

1. The work compares the concentrated cold production (few heat pumps located only in CHP sites) and distributed cold production (various heat pumps located along the pipelines), showing the benefits of distributed production in case of district cooling network.
2. The work proposes a new methodology to evaluate the best heat pump localization from a cost viewpoint. This allows comparing a uniformly distributed cold production (installing the heat pumps in the various areas of the network) with an optimized cold production.

2. Methodology

2.1 Configurations taken into account

Different configurations have been explored in order to analyze the importance of a) using distributed cold production in district cooling and b) optimally select the location of the heat pumps. This allows estimating which are the benefits that can be achieved by using an optimization approach to set the heat pump position. The various configurations are schematized in Table 1.

		Centralized cold production	Uniformly distributed cold production	Optimal cold production
		CASE 1	CASE 2	CASE 3
COLD PRODUCTION	**HOW**	In two centralized positions	In 11 distributed position along the pipeline	In 11 distributed position along the pipeline
	POSITION SELECTION	*Two heat pumps are located in the two sites where CHP plants used for the district heating are located. CHP low grade heat can be exploit to produce cold in proper absorption heat pumps*	*the 11 positions are selected uniformly along the network (sub-optimal distributed production)*	*the 11 positions are selected by means of the tool for the optimal localization of the heat pumps*

Table 1 Considered cases

The configurations selected are:

1. **CASE 1 (Fig 1a)**. At first, the *centralized cold production* is considered. In this case, no booster heat pumps are used along the pipeline since the entire amount of cold is produced in two centralized plants. These are located in the sites where currently the CHP used for district heating are located. Potentially they could be absorption heat pumps. Clearly because of the large amount of thermal power requested more than one heat pump will be located in the two sites.
2. **CASE 2 (Fig 1b).** Secondly, a *uniformly distributed cold production* is considered. In this case some suitable positions along the network pipeline have been selected such that these are uniformly distributed and in each part of the network a heat pump is installed.
3. **CASE 3 (Fig 1c).** In the end the optimization tool has been used to find the best heat pump locations. This allows evaluate the benefits of the *optimally distributed cold production*.

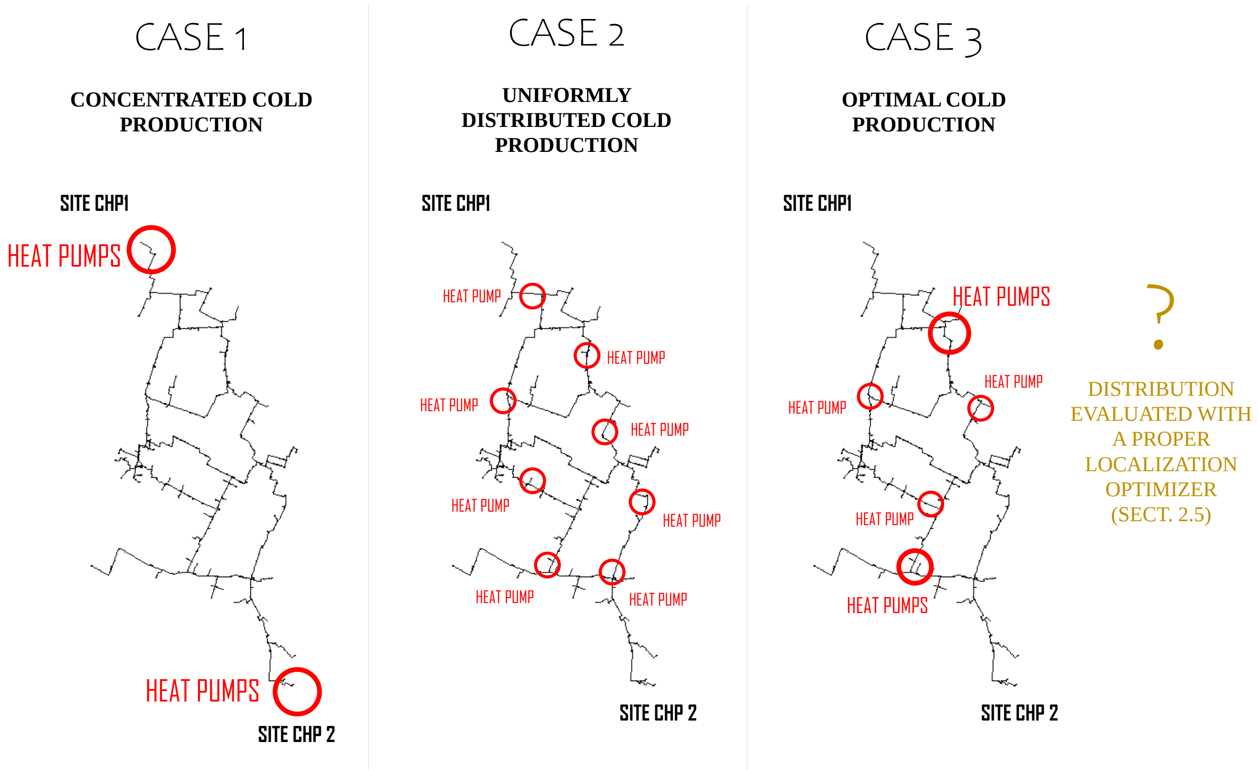

Fig. 1 Considered cases

2.2 Procedure

In this section, the procedure used for analyzing and comparing the three different types of heat pump driven district cooling is described. A schematic is represented in Fig. 2.

For cases 1 and 2 a direct procedure is used since the positioning of the heat pumps is an input of the problem. The procedure is described in the left part of Fig. 2. In this case, the first step consists in the prediction of the cooling load for the district cooling network; this step is explained in Section 2.3. The second step is the selection of the heat pump location, that in cases 1 and 2 cases is pre-determined. The third step concerns the design of the system, and the selection of the diameters for the network. The topology of the existing district heating system is used for the district cooling network. The selection of the diameters is done with the procedure described in Section 2.4 considering the network dynamic with the model described in Section2.6.

For the case 3 the positioning of the heat pumps is selected by means of an optimizer, as shown in the right part of Fig. 2. In this case, an initial guess for the positions is selected and then iteratively the location is changed until the minimum value for the total cost is achieved.

The proposed methodology requires four main kind of data in input:

1. The network topology (geometry and junctions between pipelines);
2. The pipelines data (length, diameters and transmittance);
3. Unit cost for pipeline purchase and laying and the electricity unit cost.
4. The prediction of the building thermal request (in case of small systems), or the request of the distribution networks (i.e. groups of buildings, in case of large systems). In case of existing district cooling networks, the prediction can be done by using data collected in the building substations for billing purposes.

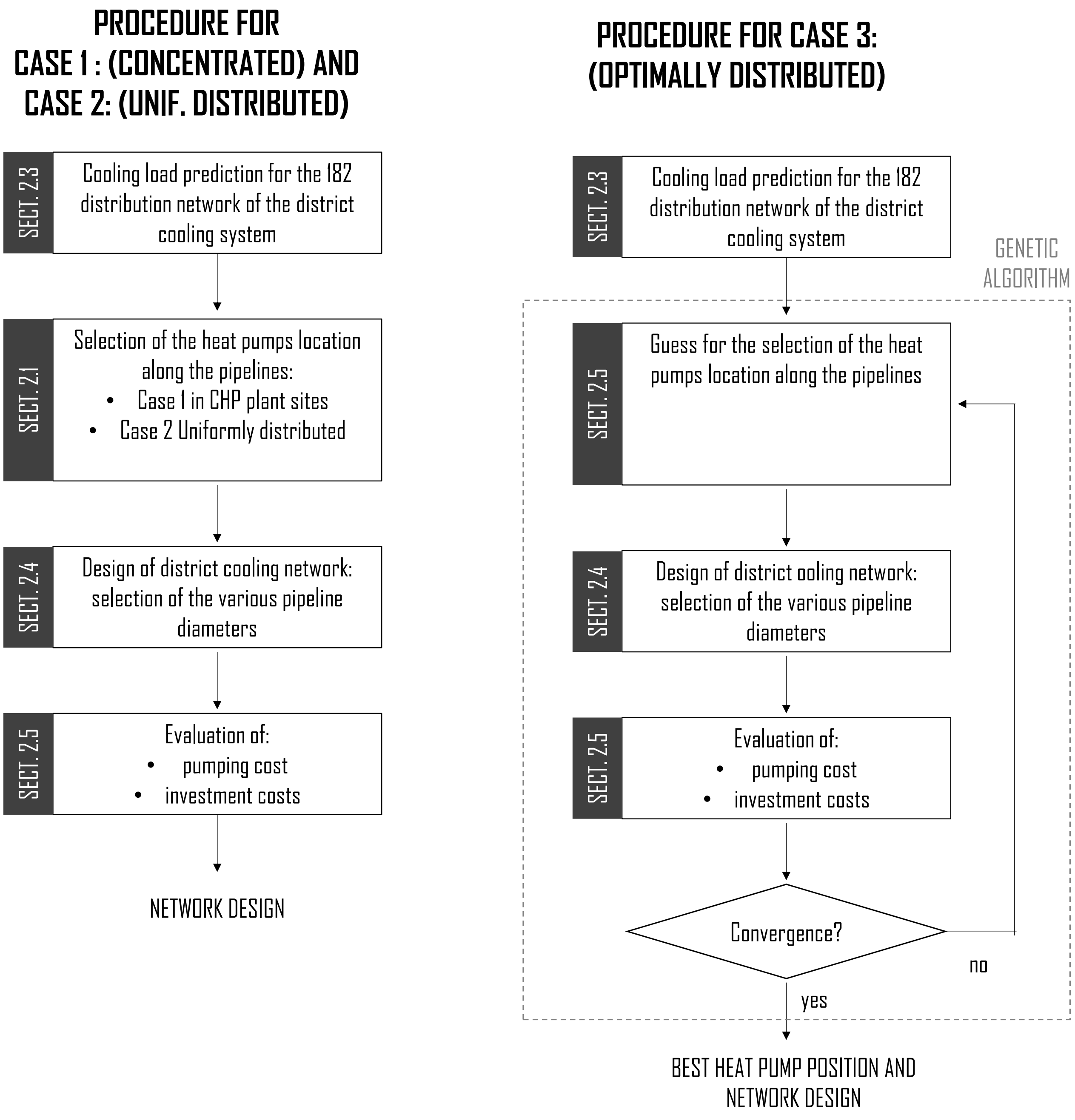

Fig. 2 Schematic of the procedure followed for the comparison. Left: concentrated and uniformly distributed cold production. Right: Optimal cold production

2.3 Thermal demand prediction

Since currently in Turin a district heating system is operating but a district cooling system does not exists, the cooling annual request have been estimated. This is done by using the Degree Days concept [31, 32]. Degree Days are the summation of the differences between the environmental and the indoor temperature per each day of the yearly heating period. This methodology has the aim of estimating the energy used for space heating and cooling in a specific area. For the city of Turin, the hot Degree Days are approximately 2671 while the cold Degree Days are 133. The comparison of the two values suggests that the cooling demand is significantly lower than the heating demand. This value confirms the statistical data coming from European studies and stating the total cooling energy demand is expected to be around 1/27 of the total heating demand. Starting from a value of the heating energy delivered of 2050 GWh, the resulting cooling energy the DC network will be supplying during the year is then fixed at 75 GWh.

In order to evaluate the maximum thermal power (that needs to be taken into account in the network design) an analysis based on the Cumulative Frequency Distribution Curve was carried out. This is done considering the temperature during three summer months (1th June - 31th August). Only the daily period from 5 am and 11 pm is included in the analysis since the hours where Degree Days are larger than zero. The weather data are reported by mean of an hourly average and they have been collected from one representative weather station over a total period of 5 years (2014-2018); thus they constitute a reliable and statistically significant data-set. By means of the cooling energy and the power curve it was possible to estimate the power required. The maximum cooling demand was estimated to be 220 MW. This has been spatially distributed among the various distribution networks (i.e. group of costumers) according to the winter load distribution, and the design mass flow rate are evaluated consequently.

2.4 District cooling network design

Since the district cooling network does not exists up to now this has been designed based on the topology of the district heating network. In order to obtain the correct amount of mass flow rates to be supplied to each distribution networks of the system and therefore the correct diameters of the pipelines, the following iterative procedure is used (schematized in Fig.3):

1. A value for the thermal power required by each distribution network has been estimated (see section 3.1).
2. The temperature difference between the supply network and the return network is fixed. In this case, the nominal temperatures for the supply and the return network are respectively 7°C and 12 °C.
3. The vector of the mass flow rate required by each distribution networks is evaluated. This is done considering the spatially distribution of the cooling load similar to the heating load distribution.
4. The mass flow in every pipeline is evaluated using the incident matrix, by means of the mass conservation equation in matrix form, as described in the section related to the thermos-fluidynamic network model (Eq. 8).
5. A value for the velocity within the pipelines is set. The value selected is lower than the maximum admitted value in order to have proper room for manoeuvre, especially in case of malfunctions or network expansion.
6. The diameter required is evaluated as the function of the circulating mass flow rate and the fixed velocity. Then, the commercial diameter immediately over the required diameter is chosen.
7. The heat transfer is studied with the energy conservation equation in matrix form, as shown in Eq. 7, described in the section related to the thermo-fluidynamic network model. This allows evaluating the actual temperature the water reach each distribution network due to the thermal losses.
8. The entire calculation has been performed iteratively, using in input different values of heat request, including the thermal losses that change iteratively. This is done until each distribution network receive the correct amount of thermal power.

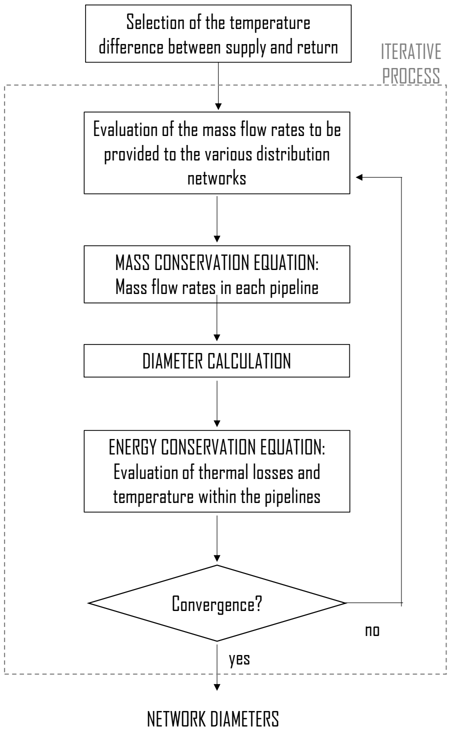

Fig.3 Schematic of the procedure for the pipeline dimensioning

The choice of the water velocity in the pipes has a great influence in both the grid cost and the power required by the pumps. Also, the thermal dispersions are strongly dependent on this variable. Higher velocities lead to lower diameter of the pipes and a lower cost of the network, but bigger pumps are required, and the electrical energy consumption increases. A proper compromise has been selected for this study. The same approach can be used for heat pump localization in district heating systems. In case of district heating, the impact of thermal losses is larger because of the larger temperature difference between the water and the ground, while the impact of pumping power is lower since the mass flow rates are lower.

2.5 Optimization Procedure

The optimization is done with the aim of evaluating the best positioning for the heat pumps

The *Objective Function* to be minimized is the cost of the system, including both a) the construction cost of the pipelines and b) the cost of the electricity for pumping (actualized to the construction year). Other costs are not been considered (like heat pump installation and maintenance) since they are not expected to depend on the independent variables. In fact the number and size of the heat pumps are considered equal in all the cases. Also in case 1 (concentrated cold production) these are all located in two sites instead of being distributed along the network. The objective function is reported in Eq. 1:

$$Objective\ Function: \min(PC(\boldsymbol{x}) + EC(\boldsymbol{x})) \quad (1)$$

where PC is the pipe cost and EC is the electrical pumping cost; both are dependent on **x**, which is the vector including the independent variables.

To calculate PC the following equation is used:

$$PC = \sum pc_i \cdot L_i \ [M€] \quad (2)$$

where pc_i is the pipe specific cost per meter while L_i its length.

The electrical pumping cost (EC) is estimated considering the yearly energy consumption (*E*), the electricity specific cost (*sc*). It is then actualized to the construction year assuming an interest rate *r* of 5% and 30 years as the life-time period of the system *a*.

$$E = \sum P_i \cdot h_i \left[{}^{MWh}/_{y}\right] \tag{3}$$

$$EC = \sum_{k=1}^{a} E \cdot sc \cdot \frac{1}{(1+r)^k} \; [M€] \tag{4}$$

The *independent variables* are the positions of the heat pumps. In particular one independent variable is used for each position. This can assume the value 0 if in the position no heat pumps are installed or an integer number *n* if *n* heat pump is installed, 2 if two heat pumps are installed and 3 if three heat pumps are installed. In the optimization, 30 possible positions have been selected in strategic areas of the district cooling network. Therefore 30 is the number of independent variables of the optimizations. The size of the single heat pump is fixed at 20 MW. 11 heat pumps are thus installed since the cooling load is 220 MW.

As concern the *constraints* it has been chosen to install in each possible location a maximum number of 3 heat pumps for a maximum installed power per site of 60 MW. This is done since it is reasonable to assume there could be enough space to install big plants in these sites. Therefore each strategic position can host 0, 1, 2 or a maximum of 3 heat pumps. The constraints the algorithm has to respect are:

- the number per site of heat pumps:

$$0 \leq x_i \leq 3 \tag{5}$$

- and the total number of installed heat pumps:

$$\sum x_i = 11 \tag{6}$$

The *algorithm* used for the optimization is heuristic. This allows avoiding local minima in case of irregular functions (when gradient based approach are unsuitable). A genetic algorithm with integer variables is used since only values 0, 1, 2 and 3 can be admitted for each independent variable.

2.6 District Cooling Network model

The evaluation of the effects of the heat pump installation is done relying on a physical model of the district cooling network. In particular, this is used to evaluate the mass flow rate and the temperature distribution within all the pipelines. The model includes mass and energy conservation equations, for all the pipeline of the network. The problem is one-dimensional since the water flows in the main heat propagation direction. In order to describe the topology of the network (i.e. the connection of nodes and branches), a graph approach is used. Nodes correspond to the junctions of various pipelines while branches correspond to the pipelines. The sections of the pipelines connecting the district heating network with the distribution networks (groups of buildings) are also nodes. The mass conservation equation written for a node is reported in Eq. (7).

$$\mathrm{G_{in}} - \mathrm{G_{out}} = 0 \tag{7}$$

Where G is the mass flow rate in kgs^{-1}. The same can be written for all the nodes of the network by relying on the incidence matrix **A**, that allows to describe the topology of the network, including the mass flow entering and exiting the network in the vector $\mathbf{G}_{\mathrm{ext}}$:.

$$\mathbf{A} \cdot \mathbf{G} + \mathbf{G}_{\mathrm{ext}} = 0 \tag{8}$$

Similarly, the energy conservation equations can be written for a single node:

$$\rho\, c_p \frac{\partial T}{\partial t} + \rho\; c_p\, v \cdot \nabla T = \nabla \cdot k \nabla \mathrm{T} + \varphi \tag{9}$$

The first is the unsteady term while the second term includes the convection. On the right-hand-side are reported the conductive term and φ, the term related to the heat gain and losses.

Taking into account only the main propagation direction the problem becomes 1 D. An upwind scheme [33] is used, that assigns to a branch the temperature of the previous node considering the actual fluid flow direction. Then neglecting the contribution of the diffusion and integrating the equation within the control volume of a node (including half of each of the interconnected branches) the following equation is achieved:

$$\frac{\partial(\rho c\Delta T)_i}{\partial t}\Delta V_i + \sum_j cG_j T_j = U\,(T_i - T_{env}) \quad (10)$$

The equation can be rewritten for the nodes of the entire networks, reorganizing the quantities by means of a mass matrix M that multiplies the first derivative of the temperature and a stiffness matrix K and g the vector of known terms. The final equation results to be:

$$\mathbf{M}\cdot\dot{\mathbf{T}} + \mathbf{K}\cdot\mathbf{T} = \mathbf{g} \quad (11)$$

The equations can be easily solved in a matrix form by the systems of linear equations. The detailed model can be found in [34].
Concerning the pumping power necessary to pump water along the network this is the product of the pressure losses times the volumetric flow rate, as shown in eq. 12.

$$W = G\,f\,\frac{L}{D}\frac{v^2}{2} \quad (12)$$

In case mass flow rates are set, as for district cooling, pumping power decreases with larger diameter. At the same time investment costs increase while increasing the pipe diameter. The optimization allows evaluating the best compromise.

3. TEST CASE

The test case is the Turin city. Turin is actually served by a large district heating system (more than 8000 buildings connected for a maximum heat load of 1.4 GW). Currently the district cooling system does not exist. This has been supposed to have the same topology of the district heating system, with different pipeline diameters. The whole study is done on the transportation network, reported in Fig. 1. This includes the largest pipelines and this is used to distribute heat in the different areas of the city. 182 distribution networks distribute the heat transfer fluid from the transportation network to the various buildings. In this analysis, only the transportation network is taken into account since this is the part of the network where the largest amount of mass flow rates occurs. Thus these are the most convenient pipelines where installing a heat pump.
The district heating network is currently fed by 2 large CHP plants, some heat only boilers and some thermal storage system. The nominal temperatures of the supply network and the return network that are usually adopted for district cooling design are respectively 7°C and 12 °C. The velocity field explored goes from 1 m/s to 5 m/s.
Various metering sensors are installed in the costumer substations in order to collect data on mass flow rates and temperature. These data are used by the company managing the district heating for billing purposes. The data are collected each 5 minutes. These data can be used for the evaluation of the evaluation of the thermal demand of district heating costumers.

4. RESULTS

4.1 Temperature and mass flow rate distribution

- *CENTRALIZED PRODUCTION (Case 1)*

In Figure 4 it is possible to observe the distribution of temperatures and the mass flow rates within the transport network pipelines in case of centralized production. The positions of the two heat pumps are identified with red circles. As discussed before these are the positions of the CHP plants currently used in winter for district heating. In the figure the fluid temperature is represented by the color of the pipelines, as shown in the color-bar. In order to show the amount of mass flow rate in the same graph this is represented by the thickness of the pipelines on the map. In case of concentrated distribution, the mass flow rates in the neighborhood of the two heat pumps are very large, since the entire amount of cold used to cover the overall supply of the city is provided in the two heat pumps in the north and in the south of the system. Concerning the temperature of the fluid, the temperature increase during the water flowing is only of few centesimal points. The temperature is subjected to a less significant increase in the return network because the temperature difference between the water and the ground is lower. However it is necessary to consider that in district cooling the temperature difference between the supply and the return line is very small compared to district heating. In the first case he temperature difference is 5 (7°C supply and 12°C return), while in case of the Turin heating network the temperature gap between supply and return is 50-70°C. This means that a variation of 0.05°C in case of cooling network correspond to a variation of 0.5-0.6°C in case of the heating network. However the heat flux exchanged with the ground does not affect significantly the system performance.

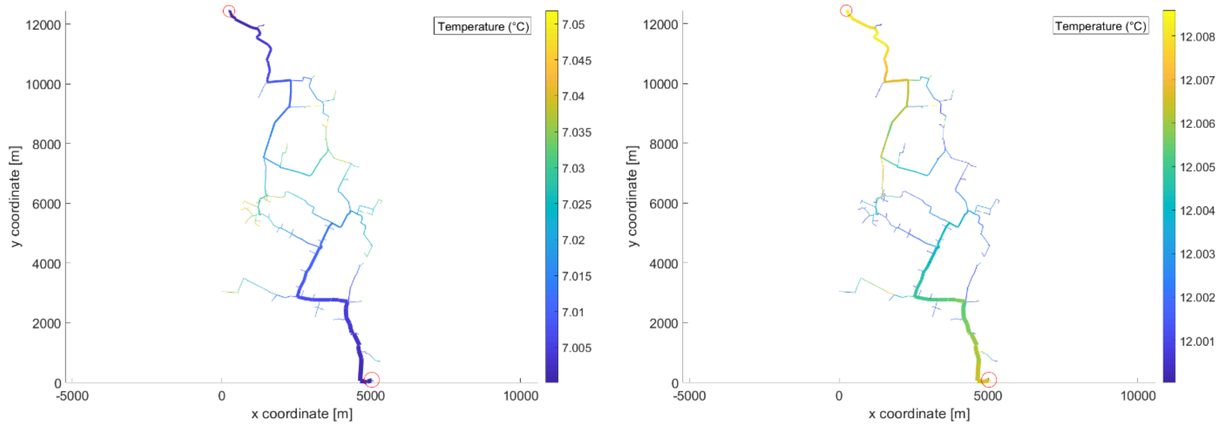

Fig. 4 Temperature and mass flow rates distributions in case of concentrated generation a) supply line (on the left) b) return line (on the right)

- <u>*DISTRIBUTED PRODUCTION NON-OPTIMIZED (Case 2)*</u>

In Figure 5 is possible to observe the distribution of temperatures and the mass flow rates in case of distributed cold production. As in the previous case, a) the heat pump positions are identified with red circles b) the amount of mass flow rate is represented by the thickness of the pipelines and c) the fluid temperature is represented by the pipeline colors. In this case, the maximum amount of mass flow rate flowing in the pipelines is lower since the cold production is distributed along the network and the total amount of mass flow rate provided to the costumer is processed in various heat pumps instead of two. The main consequence is that the maximum dimension of the pipes is lower. This provides great benefits also from an economical viewpoint since pipelines with smaller diameters are significantly cheaper.

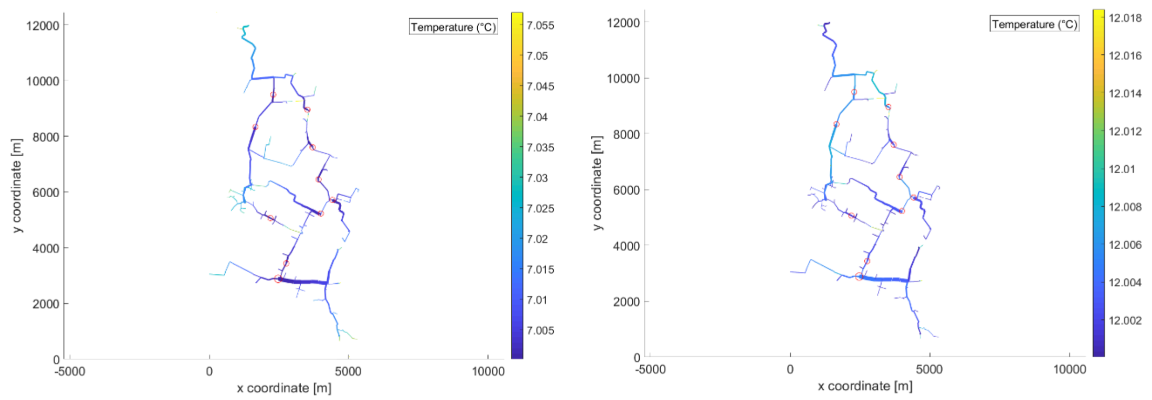

Fig. 5 Temperature and mass flow rates distributions in case of distributed generation a) supply line (on the left) b) return line (on the right)

- <u>*DISTRIBUTED PRODUCTION OPTIMIZED (Case 3)*</u>

As explained in section 2.5 an optimizer tool is used to evaluate the best localization of the heat pumps with the aim of minimizing the cost of the pipes and the cost of the electricity consumed. Heat pump positions, temperature, and mass flow rate distributions are reported in Fig. 6. The optimization algorithm provides the following locations for the 11 heat pumps:

- Only 7 positions over 30 have been selected by the algorithm. This means that in the same site more than one heat pump is installed.
- Two sites host 2 heat pumps for a total installed power of approximately 40 MW
- One site host three heat pumps
- The remaining 4 heat pumps are located in other 4 positions along the network.

Mass flow rates are smaller than in case of concentrated production (Case 1), as can be noticed by comparing the thickness of the pipelines drawn in Fig. 6 and those reported in Fig.4. Nevertheless, in some pipes mass flow rates are larger than in case of the non-optimal distributed production (Case 2).

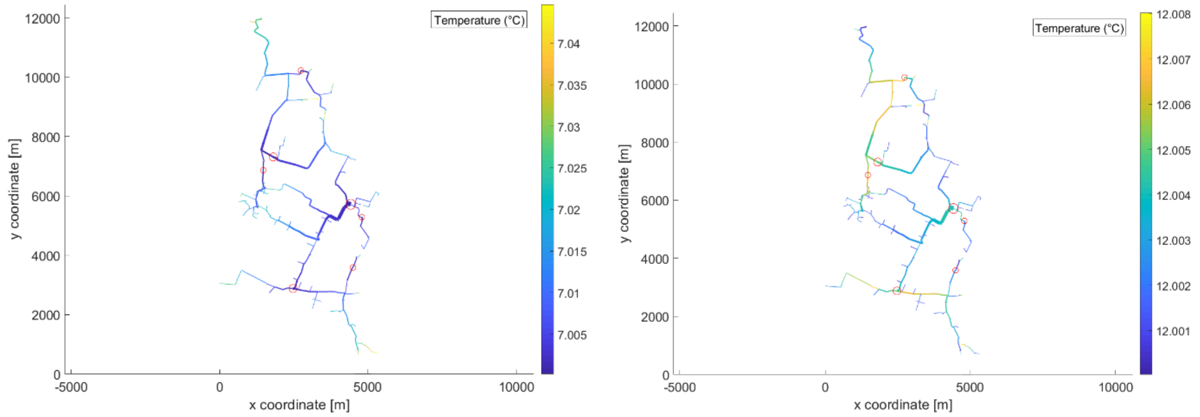

Fig. 6 Temperature and mass flow rates distributions in case of optimal distributed generation a) supply line (on the left) b) return line (on the right)

4.2 COMPARISON

In this section, the results obtained in the tree cases are compared in terms of a) pipeline diameter size b) heat losses c) costs. Results are reported in Fig. 7 (diameter and heat losses) and 8 (costs). In particular, the comparison has been shown in two steps:

- In the first step, a comparison between the concentrated (CASE 1) and distributed production (CASE 2) has been performed, in order to analyze which are the benefits in installing a series of medium size heat pumps instead of few large size heat pumps.
- Secondly, a comparison between a distributed production sub-optimal, achieved by distributing uniformly the heat pumps (CASE 2), and an optimal production (CASE 3) is described. This is done with the aim of highlighting the effects of selecting the localization of the heat pumps with a proper tool.

These two analysis are described hereafter sequentially.

- *<u>CONCENTRATED vs DISTRIBUTED PRODUCITON (comparison Case 1 and Case 2)</u>*

In case of concentrated production the maximum diameter in the network is 1.5 m, while in case of distributed production the maximum diameter is 0.8 m. In both the cases, the dimension of the largest pipeline is significant. This clearly show that another important issue in case of district cooling is the diameter dimension: the cold production sites must be selected taking into account the diameters of the pipelines. This is a different point respect to district heating, where the problem of the pipelines is less significant (adopted diameters are usually lower than 0.5 m); this is because the temperature differences between supply and return in case of district heating are larger than in district cooling, therefore the same amount of heat flux can be carried with a lower amount of mass flow rate. However, the maximum dimension of the pipes is strongly reduced with the distributed production because the cooling demand is supplied from different stations with benefits for the mass flow rate that is lower in the pipelines connecting the two production sites to the downtown.

Concerning the losses, in case of concentrated production the heat losses amount to 1.2 MW, i.e. 0.5% of the total thermal power, while in case of distributed production the thermal losses are only 0.6 MW; the heat loss is thus halved.
Referring to Fig. 8 it is possible to notice that from an economical perspective, the decentralized production of the energy allows significant savings. Although the pumping cost increases, the benefit coming from the reduction of the pipe cost has a strong impact on the final total cost, that reduce of 45% the initial investment cost. This allows achieving large improvements in terms of both pipeline diameters and total cost; however this positioning of the heat pumps is still sub-optimal. The low average diameter of the pipes causes high pressure drops leading to high electrical consumptions in the booster pumping stations for distributing water in all the areas of the city. The analysis of possible convenient combinations is performed by means of the optimization tool in order to minimize the grid final cost. Results are presented in the following section.

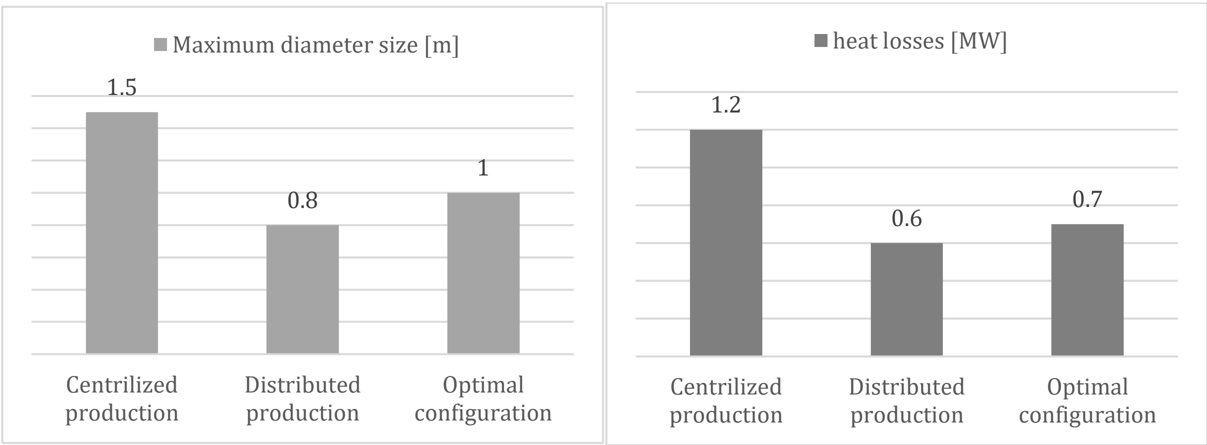

Fig. 7 Comparison between centralized production/distributed production and optimal distributed configuration: a) maximum diameter b) overall heat losses along the network

- *DISTRIBUTED SUB-OPTIMAL vs OPTIMAL HEAT PUMP LOCALIZATION (comparison Case 2 and Case 3)*

Referring to Fig. 7, it is possible to notice that the heat lost is slightly higher than that achieved with the sub-optimal distributed configuration. The largest diameter in the network is also larger in case of optimized distribution (1 m vs 0.8 m in the sub-optimal configuration). The larger diameters allows reducing the pumping costs that in Case 2 (sub-optimal configuration) are very high. The comparison from a cost perspective is shown in Fig. 8. The cost of the pipes is higher in case of the optimal configuration because of bigger average diameter in the network (+17%). The largest diameter achieved in the optimal configuration lead to lower pressure losses in the system and lower electricity cost for pumping, during the lifetime of the plant. This allows achieving a pumping cost that is almost halved. This result highlight the fact that the optimal configuration is not necessarily related to the smaller diameter as possible but this is a tradeoff. Comparing the total cost (i.e. the summation of investment cost and electricity cost for pumping, that correspond to the objective function), this decreases of 7%. In Fig. 7 the contribution of the thermal losses has not been reported since this is much lower than the contribution of pumping.

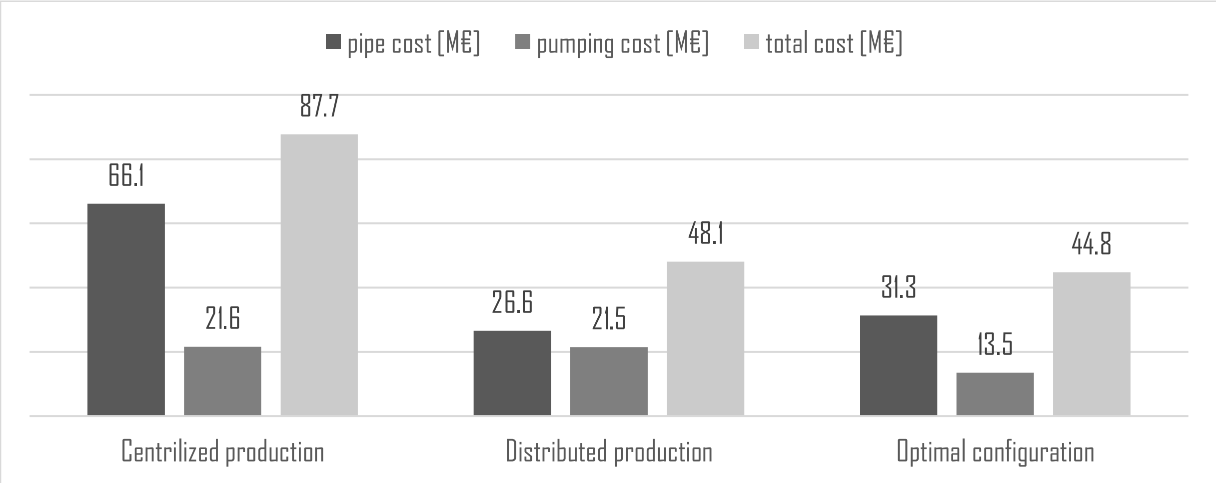

Fig. 8 Comparison of costs among centralized production/distributed production and optimal distributed configuration

5. CONCLUSIONS

In this paper, installation of heat pump in district cooling system is analyzed. The two main aims of the work are:

- Propose a model for the best location of heat pumps in district cooling networks, with the aim of minimizing the summation of the pumping and the investment cost.
- Compare the benefits achieved by a distributed cooling production instead of concentrated cooling production
- Estimate the benefits obtained using the optimal configuration of heat pumps, distributed along the pipeline achieved by the optimization model proposed.

The analysis is done taking into account the Turin city, where a large district heating network exists but up to now no district cooling system has been designed. The Turin cooling demand is predicted and on the basis of the results the district cooling network has been designed. Three solutions have been compared:

1) Concentrated cold production: all the cold load is produced in large groups of heat pumps located in the two CHP plants of the city
2) Distributed cold production: the cold is produced in 11 heat pumps homogeneously distributed in the network
3) Optimized distributed production: the cold on produced in 11 heat pumps located in the sites evaluated by the developed optimizer. This allows minimizing the costs.

Results show that the use of distributed production allows reducing the largest diameter of the pipelines from the 20%. This is an important result, since very large diameters are necessary in district cooling network where the temperature gap between supply and return is low.

The tool for the optimal localization of heat pumps returns a largest maximum diameter than the sub-optimal distributed option. This is because when the distribution of the heat pump is homogeneous along the pipelines the diameters selected are often smaller but the pressure losses larger. For this reason, the optimal solution is characterized by larger diameters. This makes the investment cost larger (+17%), but the pumping cost lower (-38%). The overall cost difference is 7% in case of optimal distributed network compared with the sub-optimal distributed network. Comparing the optimal solution with the concentrated production the total cost is halved.

6. ACKNOWLEDGEMENT

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7. NOMENCLATURE

A: incidence matrix
c: specific heat, J/(kg K)
EC: electric cost, M€
G: mass flow rate, kg/s
k: thermal conductivity W/(m K)
K: stiffness matrix
M: mass matrix, kg
L: length, m
Pc: specific pipe cost, M€/m
PC: pipe cost, M€
R: interest rate
t: time, s
T: temperature, °C
U: pipe transmittance, W/kg K
v: velocity m/s
V: volume, m3
X: independent variable

Greek symbols
ρ: density, kg/m3
φ: heat losses, W
Φ: heat power W

Subscripts and superscripts
env: environmental
ext: external
in: inlet
out: output

8. REFERENCES

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9. NOMENCLATURE

A	[-]	incidence matrix
cp	[kJ/kgK]	specific heat
d	[m]	diameter
E	[kJ]	energy consumption
G	[kg/s]	mass flow rate
sc	[€]	electricity specific cost
r	[-]	interest rate
T	[K]	temperature
t	[s]	time
v	[m/s]	velocity
ρ	[kg/m^3]	density