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Matthildi Apostolou
MINES ParisTech, PSL Research University, CES - Center for energy Efficiency of Systems, France / EDF R&D Division, EDF Lab Les Renardières, France, matthildi.apostolou@edf.fr

Sahar Salame
MINES ParisTech, PSL Research University, CES - Center for energy Efficiency of Systems, France, sahar.salame@mines-paristech.fr

Stéphanie Barrault
MINES ParisTech, PSL Research University, CES - Center for energy Efficiency of Systems, France, stephanie.barrault@mines-paristech.fr

Assaad Zoughaib
MINES ParisTech, PSL Research University, CES - Center for energy Efficiency of Systems, France, assaad.zoughaib@mines-paristech.fr

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Matthildi APOSTOLOU[1,2] , Sahar SALAME[1], Stéphanie BARRAULT[1], Assaad ZOUGHAIB[1*]

[1]MINES ParisTech, PSL Research University, CES - Center for energy Efficiency of Systems,
[2] EDF R&D Division, EDF Lab Les Renardières, France

* Corresponding Author assaad.zoughaib@mines-paristech.fr

ABSTRACT

Use of geothermal heat in district networks allows increasing the share of renewable energy in the production mix. However, in many cases, this share is limited by the district heating required temperature and seasonal load variation. Heat pumps permit upgrading geothermal heat by further increasing the temperature while pumping residual heat from the network's return. Therefore not only they substitute boilers for upgrading the temperature but also increase the used share of the geothermal heat source by reducing the return temperature.

This paper presents a methodology for heat pumps architecture optimization enhancing the use of geothermal heat. The methodology allows, by considering the total consumed exergy as an objective to minimize, the increase of renewable energy share while considering the best heat pump integration. Many configuration options are considered for the disposal of heat pumps.

A case study is presented optimizing the use of a 60°C geothermal source connected to a district in the north of France. The geothermal well has two constraints: a limited mass flowrate and a minimal reinjection temperature of 25°C.

1. INTRODUCTION

District heating systems can be found all over Europe today, but levels of expansion differ significantly between the Member States. Although national heat market shares are between 40-60% in some Scandinavian and Baltic Member States, district heating systems only cover 13% (Figure 1) of the current European heat market for buildings in the residential and service sector. The corresponding market share for the industrial sector is about 9% (Persson, 2011)

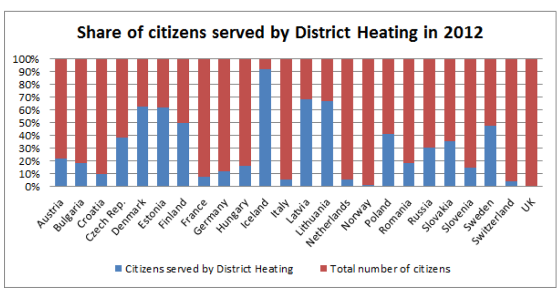

Figure 1 Share of citizen served by district heating (source: District Heating and Cooling Barometer 2014)

Since district heating is mainly an urban occurrence, due to the dependency on concentrated heat demands for feasible heat distribution, it is relevant to express levels of expansion in terms of urban heat market shares. As a European average, district heat constitutes about 16% of current urban heat markets, while these fractions can reach more than 90% in some cities with mature district heating systems.

Beside the valorization of incinerated municipal solid waste heat (20% of the MSW) and some biomass based district heating networks, the main energy source is fossil. In the overall energy sources, industrial waste heat is almost negligible and so is the solar energy.

Some attempts to valorize low temperature heat sources exist; such as heat recovery from waste water or recovery of heat rejected from air conditioning by the use of high temperature heat pumps. The potential of energy consumption and carbon emissions reduction thanks to heating and cooling networks integration is quantified by Maatouk *et al*. (2010) for the district heating and cooling networks of the business district in the West of Paris in France. Office buildings of north-west of Paris are characterized by simultaneous heating and cooling needs (Figure 2): apart from seasonal changes in consumption, a detailed analysis of heating and cooling capacity shows that in winter, part of the buildings are in need of cooling, while in summer, a minimum heat load is needed primarily for domestic hot water. Buildings are connected to a district heating and cooling (DHC) networks.

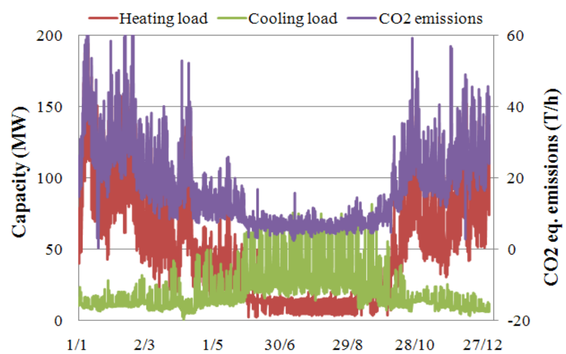

Figure 2 Heating, cooling load and GHG emissions of the La Defense district network (Maatouk *et al*., 2010)

The CO2 emissions represented in the Figure 2 are mainly due to the fuel boiler that provides the heat to the heating network. The district cooling is operated separately from the district heating and uses vapour compression chillers cooled by cooling towers. In their investigations, Maatouk *et al* (2010) considered 3 alternative scenarios. The best one studies the usage of a CHP (gas turbine) and heat pumps recovering the chiller's heat. In this scenario, a mixed centralized and distributed production scheme is proposed (Figure 3).

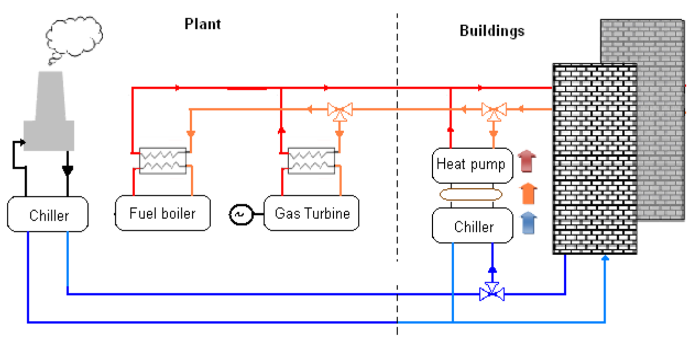

Figure 3 Best integration scenario for heating and cooling networks (Maatouk *et al*., 2010)

By this design, the heat pumps operate all over the year providing the total heat load during the summer period and almost 15% in the winter.

Last but not least, few geothermal district heating networks are being exploited in Europe, and in some cases they are assisted by gas boilers. For most, this share is limited by the required district heating temperature and seasonal load variation. As seen before, heat pumps allow upgrading low temperature sources and so geothermal heat by further increasing the temperature while pumping residual heat from the network's return. Therefore not only they partially substitute boilers for upgrading the temperature but also increase the used share of the geothermal heat source by reducing the return temperature.

This paper presents a methodology for heat networks' architecture optimization associating several heat generation technologies and sources. Here we emphasis on the best integration scheme for heat pumps in order to enhance the use of geothermal heat. The methodology allows, by considering the total consumed exergy as an objective to minimize, the increase of renewable energy share while considering the best heat pump integration (highest COP).

2. METHODOLOGY

2.1 State of the art

The design and optimization of district heating networks is a rather complex task; therefore most of the researchers have been focusing on simulating models allowing performing parametric optimization for proposed architectures. Energy integration techniques combined with thermodynamic second law analysis are a way to perform systematic architecture and parametric optimization of district heating design.

The methods treating energy integration of district networks are numerous. These are divided into two categories: the methods based on the pinch analysis and the mathematical programming methods. Pinch analysis is a graphical energy integration method used to identify the potential heat recovery between different operations, increasing the energy and electricity efficiency. The pinch design method (Linnhoff & Hindmarsh, 1983), (Papoulias & Grossmann, 1983) allows designing the heat exchangers configuration, taking into account a minimum temperature difference between streams. As for mathematical programming methods (Ivanov *et al*, 1993), they represent the energy integration problem by considering the energy balance equation for each component in the network. The mathematical programming methods are more precise and reliable, but need higher calculation capacities.

Moreover, taking into account the time fluctuation of the flows, either for heating or cooling purposes, at the production and/or the demand level, is of great importance in district networks. Multi-period mathematical programming optimization methods are therefore investigated (Fazlollahi *et al*.,2014). Considering furthermore computational power and time, linear methods are preferred over non linear ones, primarily because of the robustness and uniqueness of the solution calculated (Yokoyama *et al*.,2015).

The proposed method in this paper is derived from the method developed by Salame *et al*., in which the optimal design of energy integration network is treated, with regard to the exergy consumption (Salame, 2015). It combines energy conversion technologies reduced order modeling based on second law analysis and energy integration techniques in a multi-period mixed integer linear (MILP) optimization framework. Power and operating temperatures of the heat pumps, as well as the energy production mix are optimized. In its original formulation, the operating temperatures of the heat pumps were considered constant over the different periods of time. This point will be covered in detail in the following paragraphs.

2.2 Mathematical formulation

The heat integration problem consists on defining the structure's configuration that optimizes the heat exchanges between variable flows. Intermediate fluid, water in this case, circulating in the network transports the heat from hot to cold flows. Conversion systems as well as thermal storage can provide a good solution in order to encounter the fluctuation of energy requirements.

The model developed is extensively described in the article (Salame & Zoughaib, 2015). In the current study, the integration of heat pumps with variable operating temperatures imposes modifications to the algorithm. These modifications are detailed in §2.3.

Further considered assumptions are stated below:

- A pinch "Pinch,net" is imposed between the intermediate fluid circulating in the network and the operating fluxes. This results to a different discretization for the network's temperatures. (§2.3 (Salame & Zoughaib, 2015)).
- The heat pumps are placed into the network, and therefore considered to operate between TS temperatures. A constant pinch is taken into consideration at the heat pump's condenser and evaporator.
- Hot and cold utilities are used for fulfilling the net heating and cooling needs after having energetically integrated the flows.

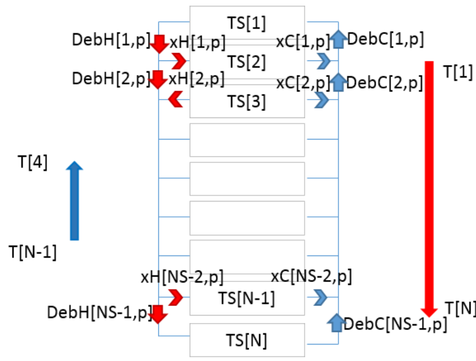

Figure 4 Heat integration network layout

As far as the inputs are concerned, we consider in addition:

- The pinch in the condenser "Pinch,cond" and evaporator "Pinch,evap"
- The exergy efficiency "η" related to the second law of thermodynamics. It represents the efficiency of the heat pump compared to the ideal Carnot cycle.
- The maximal number "nb_HP" and maximal compressor power "MaxHP" of the heat pumps to be used

To the outputs of the model we could add:

- The operating temperature of the HP for the evaporator "TS[o]" and the condenser "TS[l]", varying in function of the time period "p".
- The compressor input power of each HP "CompHP".

The constraints on the variables are the following:

- Energy balance applied to each interval of temperature 'i' of each hot flow 'j' at a certain period of time 'p'.

$$CP_{H[i,j,p]} \cdot (\mathrm{T}_{[i]} - \mathrm{T}_{[i+1]}) = \sum_{k=1}^{NS-1} Deb_{C[k,i,j,p]} \cdot (TS_{[k]} - TS_{[k+1]}) + U_{cold[i,j,p]} \tag{1}$$

Where U_{cold} is the additional cooling power and DebC is the partial heat capacity flow (m.Cp) that exchanges with the hot flow.

- Energy balance applied to each interval of temperature 'i' of each cold flow 'j' at a certain period of time 'p'.

$$CP_{C[i,j,p]} \cdot (\mathrm{T}_{[i]} - \mathrm{T}_{[i+1]}) = \sum_{k=1}^{NS-1} Deb_{H[k,i,j,p]} \cdot (TS_{[k]} - TS_{[k+1]}) + U_{hot[i,j,p]} \tag{2}$$

Where U_{hot} is the additional heating power and DebH is the partial heat capacity flow (m.Cp) that exchanges with the cold flow.
It is pointed out that exchanges are only allowed if the flow's temperature interval T[i]- T[i+1], increased in the case of cold flows (or reduced in the case of hot flows) by the Pinch, is lower (or higher) than the networks' corresponding interval.

- Law of mass conservation applied to all the heat capacity flows entering or exiting each node 'k' in the network at a certain period of time 'p'.

$$Debh_{[k+1,p]} - Debh_{[k,p]} + xh_{[k,p]} = 0 \tag{3}$$

$$Debc_{[k+1,p]} - Debc_{[k,p]} + xc_{[k,p]} = 0 \tag{4}$$

Terms are positive when entering the node and negative when leaving it.

2.3 Heat pump reduced order model

The aim of this work is to propose a strategy for the design of a network, taking into account different conversion technologies while reducing the exergy consumed over a whole cycle. Therefore the equipments' models are not highly detailed; in particular, a reduced model is proposed for the heat pump.

The changes on the methodology presented in (Salame & Zoughaib, 2015) related to the inclusion of heat pumps are presented and explained in the following paragraphs.

The efficiency of a heat pump "COP" decreases when the difference between the condenser and evaporator operating temperatures increases. The initial optimization formulated by Salame (2015) consists in placing the HP in the 'best' temperature interval, for the entire period of study. However, a given heat pump will usually operate between different temperatures, depending on the energy demands at each time period. A variable operating temperature for each heat pump is therefore considered at every time step. This approach is more realistic and allows higher flexibility for the design.

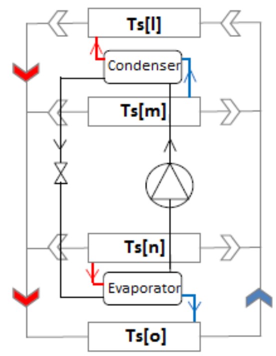

Figure 5 Schematic representation of the heat pumps' integration in the network

The new constraints, related to the heat pumps and integrated to the model are:

- A constraint that forces the number of heat pumps to be under a certain parameter desired by the user.

$$\sum_{l=1}^{Ns-2}\sum_{m=l+1}^{Ns-1}\sum_{n=m}^{Ns-1}\sum_{o=n+1}^{Ns}\sum_{p=1}^{temp} b_{[l,m,n,o,p]} \leq nb\_HP \tag{5}$$

Where b is a binary equal to 1 if the heat pump operating in between T[k] and T[t] is implemented at the period l, and 0 if not.

- A constraint that forces the maximal compressor power of a heat pump to be under a certain parameter defined by technological limitations (or by the user).

$$\sum_{l=1}^{Ns-2}\sum_{m=l+1}^{Ns-1}\sum_{n=m}^{Ns-1}\sum_{o=n+1}^{Ns}\sum_{p=1}^{temp} Comp_{HP[l,m,n,o,p]} \leq b_{[l,m,n,o,p]} \cdot Max\_HP_{[l,m,n,o]} \tag{6}$$

- A constraint that relates the coefficient of performance of each heat pump to the evaporator's and condenser's power. This coefficient of performance is also modeled as a fraction of the ideal Carnot COP.

$$COP_{HP[l,m,n,o,p]} = \eta_{HP} \cdot \frac{Ts_{[l]} + Pinc_{cond,HP}}{(Ts_{[l]} + Pinc_{cond,HP}) - (Ts_{[o]} - Pinc_{evap,HP})} = \frac{P_{cond,HP[l,m,n,o,p]}}{P_{comp,HP[l,m,n,o,p]}} \tag{7}$$

- A constraint that connects the compressor's power to the evaporator's and condenser's power (1st law).

$$P_{comp,HP[l,m,n,o,p]} = P_{cond,HP[l,m,n,o,p]} - P_{evap,HP[l,m,n,o,p]} \tag{8}$$

The integration of multiple indexes, i.e. larger number of variables, in order to describe the heat pumps, increases significantly the computational time. Several constraints (concerning maximum temperature difference in the evaporator and the condenser *etc.*) are implemented to the algorithm so as to overcome this difficulty and reduce the size of the problem.

2.4 Objective function

The objective of this method is to optimize the net heating and cooling demands. Since different forms of energy are used (heat and electricity) and in order to find one criteria that relates them all, exergy is used. Hence, the function to minimize is the total exergy consumption in the process. This can be written as:

$$\min : Ex_{tot} = \sum Ex_h + Ex_c + Ex_{HP} \tag{9}$$

Where Ex_h is the exergy required for heating, Ex_c the exergy required for cooling and Ex_{HP} the exergy consumed by the heat pump.

At a certain reference temperature T_{ref} the exergies consumed are calculated as follows:

$$Ex_h = \sum_{i=1}^{NT-1} \sum_{p=1}^{t} U_{h[i,p]} \cdot per_{[p]} \cdot \left(1 - \frac{T_{ref}}{T_h}\right), \; T_h > T_{ref} \tag{10}$$

$$Ex_c = -\sum_{i=1}^{NT-1} \sum_{p=1}^{t} U_{c[i,p]} \cdot per_{[p]} \cdot \left(1 - \frac{T_{ref}}{T_c}\right), \; T_c < T_{ref} \tag{11}$$

Electricity being considered as pure exergy, the exergy consumption of the heat pump is equal to its compressor energy consumption:

$$Ex_{HP} = \sum_{l=1}^{Ns-2} \sum_{m=l+1}^{Ns-1} \sum_{n=m}^{Ns-1} \sum_{o=n+1}^{NS} \sum_{p=1}^{t} P_{comp[l,m,n,o,p]} \cdot per_{[p]} \tag{12}$$

Future works could determine cost-objective functions, taking into account investment and operational costs of the equipments and utilities considered. A first approach is presented in (Salame, 2015).

3. CASE STUDY DESCRIPTION

3.1 Presentation of the case study

The presented methodology is applied trying to maximize the use of an available geothermal potential in a city in the north of France. The heat network supplies the city for heating and domestic hot water generation.

Figure 6 shows the heat demand of the network as a function of the ambient temperature. The points plotted are the ones where both heating and domestic hot water demands occur. For ambient temperatures higher than 15°C, the demand is of an order of 4.4 MW corresponding to domestic hot water needs only.

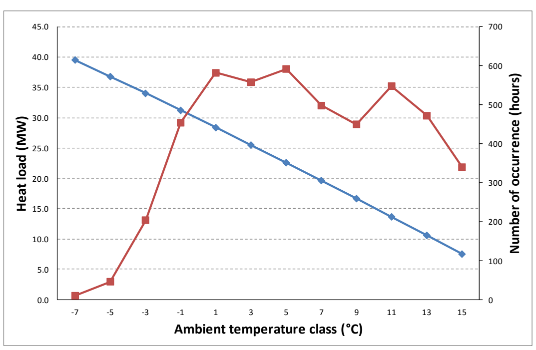

Figure 6 Network heat demand for different ambient temperature intervals (left scale) and temperature occurrences (right scale)

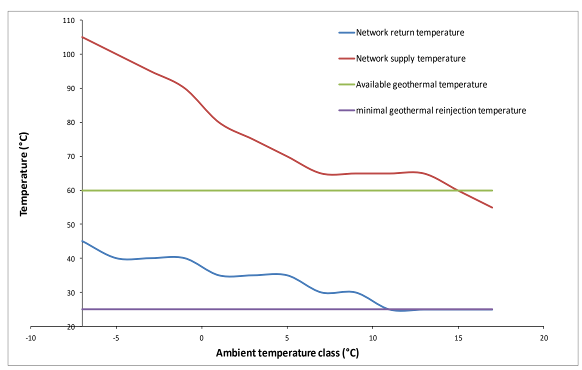

Figure 7 Network operating conditions and geothermal potential

The design of the network is out of the scope of this paper but its operating conditions were chosen in order to fulfill the needs of the oldest buildings leading to relatively high supply temperatures. The network integrates a cascade usage of the hot return from these buildings in newer buildings which leads to a relatively cold return temperature. This cascade design allows a better compatibility with an available geothermal potential at 65°C (by considering a

5K pinch on the heat exchanger it is available at 60°C for the network). The geothermal potential has two limitations; its reinjection temperature has to be higher than 30°C (25°C from the network side) and its mass flow rate is limited to 320 m3/h. The heat network supply and return temperatures and the geothermal potential temperature are plotted as a function of the ambient temperature intervals in the Figure 7.

As shown by the above, the network design is based on a variable supply temperature which allows further reducing of the return temperature when the heat load is lower. This technical choice helps to better valorize the geothermal potential since the difference between the network's return and the geothermal supply temperature increases. However, if we consider ambient temperatures between -1 and 5°C, where we have both high occurrence level and high load, the return temperature allows valorizing merely the half of the geothermal potential. This is the main motivation to explore the heat pump's integration potential. This will be presented in the section 3.3.

3.2 Reference situation

Before presenting the results concerning the heat pump's integration scenarios, a simulation is performed without any heat pump in order to characterize the reference situation. Figure 8 shows the results in term of demand fulfilling share between geothermal source and gas boiler for each ambient temperature interval.

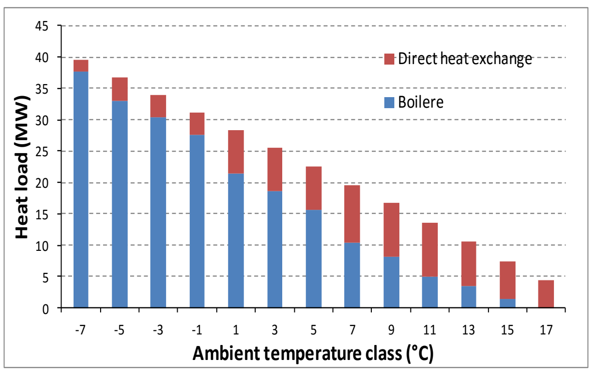

Figure 8 Reference case heat generation share

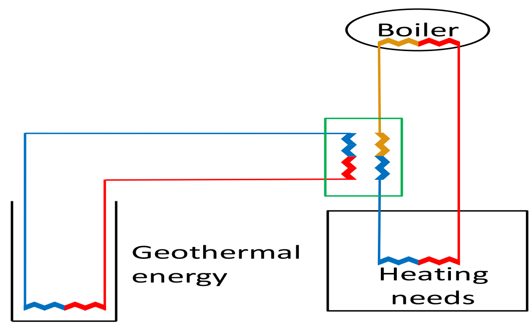

Figure 9 The network's configuration for reference situation

Figure 8 confirms the analysis above and we see that for none of ambient temperature conditions, the full potential of the geothermal energy could be exploited. In energy terms, the results are presented in the Table 1below.

Table 1 Heat generation by source for the reference case

Total heat (MWh)	Gas boiler heat (MWh)	Goethermal heat (MWh)	Geothermal max potential (MWh)	Geothermal use rate	Geothermal to total ratio
117 211	66 385	50 826	113 880	44.6%	43.4%

3.3 Heat pumps integration scenarios

In order to make use of a bigger part of geothermal energy, heat pumps can be used. Two scenarios are studied using the algorithm described in paragraph 2. In the first scenario the maximum number of heat pumps allowed is limited to one. In the second, the use of two heat pumps is allowed. The following assumptions are taken into consideration:

- the pinch in the heat pump's evaporator and condenser is 2 K;
- the pinch of the heat exchanger between the flows and the network is 5 K;
- thermal storages are not allowed.

The architecture proposed by the algorithm for both scenarios are presented in Figure 10 and Figure 11 respectively.

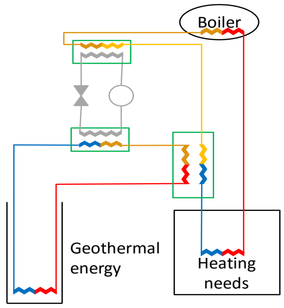

Figure 10 The network's configuration for the first scenario

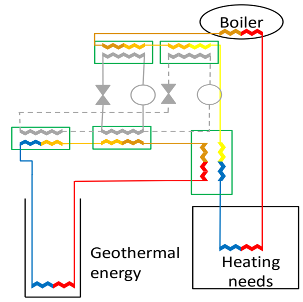

Figure 11 The network's configuration for the second scenario

The utilities shares to satisfy the heat demand are represented in Figure 12 for the single heat pump option. The operating temperatures of the heat pump are plotted in Figure 13.

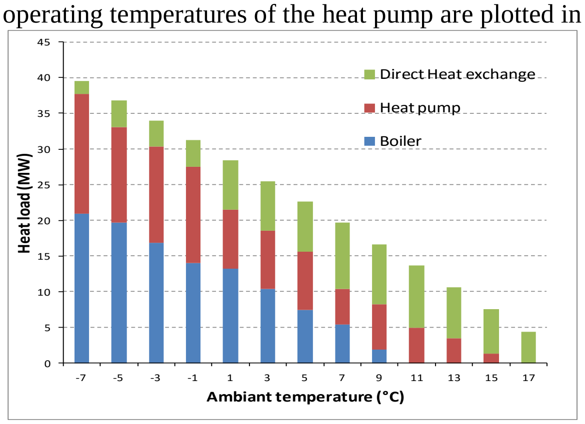

Figure 12 Heat load distribution for the first scenario

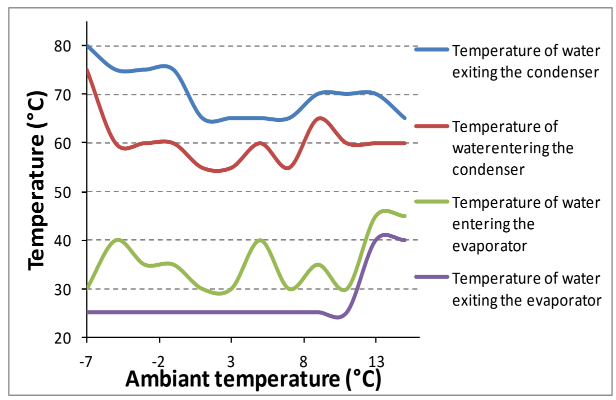

Figure 13 The operating temperatures at the heat pump's exchangers for the first scenario

Table 2 Heat generation by source for the first scenario

Total heat (MWh)	**Gas boiler heat (MWh)**	**Goethermal direct heat exchange (MWh)**	**Heat pump condenser (MWh)**	**Geothermal use rate (including heat exchanged with evaporator)**	**Geothermal to total ratio (including heat exchanged with evaporator)**
117 211	32 355	50 826	34 030	66.3 %	64.46 %

The seasonal coefficient of performance of the heat pump over the whole cycle is 3.663. In this scenario, the heat pump's evaporator is placed after the exchanger between the geothermal fluid and the network (Figure 10). The residual heat existing in the geothermal fluid is exchanged with the evaporator allowing the heating of the network's return fluid before entering to the boiler. Therefore, the energy spent on heating using gas becomes lower. The shares of each utility in satisfying the heating needs are shown in Table 2. It should be noted that the heat exchanged between the geothermal fluid and the heat pump's evaporator is taken into account for the calculation of the geothermal's share.

For the solution with two heat pumps, the configuration of the network is shown in Figure 11. The idea is to reduce the temperature difference between the evaporator and the condenser and consequently increase the coefficient of performance of each heat pump. The seasonal coefficient of performance of these heat pumps is 4.453. Hence, for almost the same heat exchanged at the heat pump's condenser, the consumption of electricity is lower. The shares of each utility are shown in Table 3.

In the second scenario, the large decrease in electrical consumption leads to a small increase in the gas consumption, but the solution is exergetically more efficient.

Table 3 Heat generation by source for the second scenario

Total heat (MWh)	Gas boiler heat (MWh)	Goethermal direct heat exchange (MWh)	Heat pump condenser (MWh)	Geothermal use rate (including heat exchanged with evaporator)	Geothermal to total ratio (including heat exchanged with evaporator)
117 211	34210	50 826	32 175	66.5 %	64.65 %

3.4 Heat pumps operating conditions and consequences

In order to study in detail the scenario with one heat pump, the variation of the electrical power input of the heat pump's compressor is shown in Figure 14.

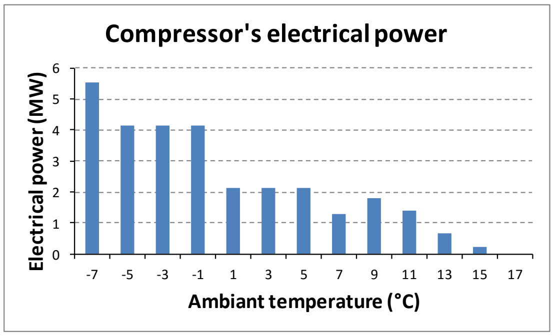

Figure 14 Variation of the heat pump's electrical consumption

This figure shows that the heat pump compressor operates between its maximum power (5.5 MW) and 0. This kind of operating conditions are not feasible in reality. An equivalent solution, using several heat pumps functionning in a parallel mode is needed. In this case, two heat pumps may be used. Considering that each heat pump can operate, without high performance degradation, between 50 % to 100 % of its capacity, the first one will operate for ambiant temperature between -7 °C and -1 °C. The second heat pump operates for the rest of ambiant temperatures.
The same analysis can be applied to the second scenario, where four heat pumps may be used instead of the two proposed in the solution above.

4. CONCLUSIONS

This paper presents a methodology for design and optimization of the configuration for district heating networks, including the integration of heat pumps coupled with geothermal energy source. This methodology is applied to a case study. Different scenarios were studied and compared. The results show the advantage of the integration of heat pumps allowing an increase in the share of geothermal energy used. The share of gas based heat is hence reduced from 56.6 % to 27.6 % by using a heat pump. The scenario with an additional heat pump was also investigated and the results were presented showing higher seasonal COP leading to less exergy consumption. These results are the first step in the design where the next steps are the detailed design of the heat pumps.

NOMENCLATURE

Subscript

C	Related to cold flows	(–)
H	Related to hot flows	(–)
HP	Related to the heat pumps	(–)
t	instant of time	(s)

Index (between brackets)

i	the node in the temperature range of operating flows	(–)
l,m	the nodes in the temperature range for the condenser (from m to l)	(–)
n,o	the nodes in the temperature range for the evaporator (from n to o)	(–)
j	the number of operating flows	(–)
k	the number of heat storage	(–)

p	the number of the period of time	(–)
Notions		
MILP	Mixed Integer Linear Programming	(–)
HP	Heat Pump	(–)
COP	Coefficient of performance	(–)
Terms		
b	binary determining if the HP exists or not	(–)
Cp	Specific heat capacity	(KJ/kg/K)
CP	Heat capacity flow	(KW/K)
Ex	Exergy	(KJ)
Deb	Partial heat capacity flow	(kJ/K)
Nb_HP	the maximum number of HP required by the user	(–)
NFC	Number of hot flows to be cooled	(–)
NFF	Number of colf flows to be heated	(–)
NT	Number of temperature nodes in the range of temperature of the operating flows	(–)
Pinc	Pinch of the heat exchanger between the intermediate fluid circulating In the network and the operating fluids	(K)
T	The temperature of the node	(K)
Temp	The duration of each period in the process	(sec)
Tref	The reference temperature for exergy calculations	(K)
Uhot	The heating power of the hot utility exchanged with the cold flow	(KW)
Ucold	The heating power of the cold utility exchanged with the hot flow	(KW)

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