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Geothermal Heat Pump for A2A District Heating Service in Milan (Italy)

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ABSTRACT

District Heating (DH) service is a system for distributing heat generated in a centralized location for residential and commercial heating requirements such as space heating and water heating. Heat is distributed to the customers by means of a network of underground insulated pipes.

The A2A District Heating in Milan started in the early 90s, mainly based on heat production from Waste to Energy plants and from natural gas fuelled Combined Heat and Power (CHP) plants. Currently, a plan to strongly expand the district heating service in the city is under development according with the 'fundamental idea' behind modern DH systems: use local renewable energy sources, local heat and energy sources that under normal circumstances would be lost or remain unused. The main goal of the plan is to improve the air quality in the city enhancing at the same time energy saving.

Milan area is plentiful of underground water which allows the exploitation of geothermal renewable energy for DH from groundwater. Groundwater, at a temperature of about 288 K, is not directly channelling to DH network but heat pump can be used to extract low temperature heat from the groundwater and transfer it to DH network hot water at 363 K.

The first applications of heat pump fed by groundwater in Milan DH systems have been realized in Canavese and Famagosta plants where the heat pump is integrated with a high efficiency natural gas fuelled CHP plant. The heat pumps of Canavese and Famagosta have started operating respectively in 2010 and 2011, and they showed high performance, reliability and operative flexibility.

The DH systems are still under development, mainly by mean of network extensions. At their maximum capacity production, heat pumps will product about 216 TJ/year of thermal energy which involves an estimated energy saving of about 72 TJ/year of primary energy and avoids the emission of about 3,200 Mg/year of CO_2. Locally, will be also avoided the emission in the urban area of about 12 Mg/year of NO_x, 3 Mg/year of SO_x and 0.3 Mg/year of particulate matter (PM10).

1. INTRODUCTION: DISTRICT HEATING SYSTEM IN MILAN

The City of Milan has a population of about 1,300,000 inhabitants; the total primary energy demand for heating requirements of buildings is about 46,000 TJ/years (Agenzia Mobilità e Ambiente, 2007). The A2A DH service in Milan started in the early 90s, mainly based on heat production from Waste to Energy plants and from natural gas fuelled CHP plants (gas turbine and engines) located in different sites.

The heat produced is fed to the buildings by means of several large district heating networks. A2A district heating is present in other municipalities close to Milan: Sesto San Giovanni, Cinisello Balsamo and Novate Milanese (Fig. 1).

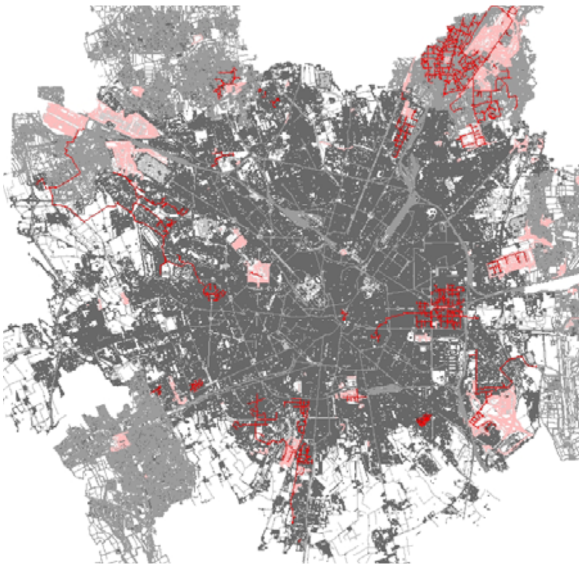

Figure 1: District Heating networks in Milan metropolitan area (2012).

At present (December 31th, 2012) the district heating distribution networks in Milan metropolitan area have an extension of about 200 km and serves about 250,000 inhabitants, corresponding to a peak power demand of 530 MWt. In 2012 the system distributed about 845 GWh of heat to the costumers.

A plan to strongly expand the district heating in Milan is under development by mean of an increase in the thermal power and efficiency of existing production plants and a significant extension and integration of the heat distribution networks. Also, new production plants and district heating networks associated to them could be realized.

The goal is to deliver the service to more than 500,000 inhabitants equivalent and to increase at 800 MWt the peak power requested by the system.

Milan is located in Po plain an area strongly afflicted by air pollution caused by anthropic activities (Fig. 2). The area is also affected in several period of the year by climatic conditions (atmospheric stability) which do not help the improvement of the air quality.

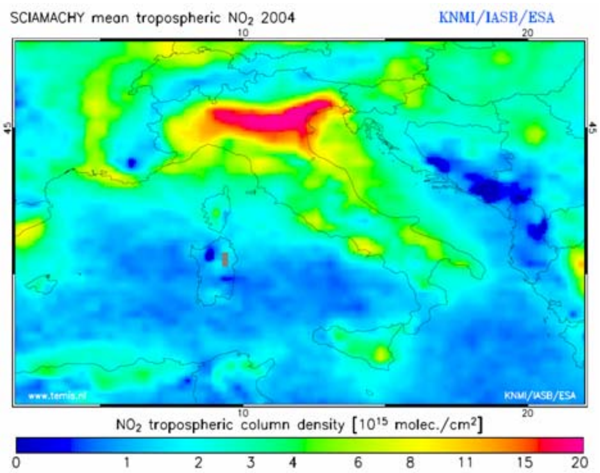

Figure 2: Tropospheric NO2 on Po plain (Sciamachy, 2004).

NOx and particle are the most critical parameters. In autumn and winter seasons, the emissions from thermal plants installed on residential building contribute for about 35% to the total anthropic emissions, which decreases at 20% considering the year period (Agenzia Mobilità e Ambiente, 2007 – elaboration of A2A).

DH systems could help in a substantial way in improving the air quality in the city.

The design of combustion plants fed by fossil fuel has to fulfil the strict limitations stated by the local authority: the Regional Government enacted environmental laws to achieve the air quality objectives for the protection of public health. The criteria to authorize building and operation of combustion plant (including DH production plant) are very strict. First, best available technology (BAT) have to be adopted to maximize efficiency and contain pollutants emission in atmosphere. Second, the emission factors of pollutants for unit product must be lower than those of thermal plant installed on buildings.

Moreover, the 'fundamental idea' behind modern DH systems is to use local renewable energy sources, local heat and fuel sources that under normal circumstances would be lost or remain unused with the aim of improving the environmental quality of air and enhancing energy saving.

In Milan, the source of renewable energy has been identified in the geothermal energy from groundwater which is plentiful in the Milan area. Geothermal renewable energy from groundwater at a temperature of about 288 K, is not directly channelling to DH network. Using heat pumps, however, it is possible to increase the temperature up to 363 K and to utilize the heat in a DH system.

The heat pump installed in Canavese new DH plant (the most recent one realized in Milan) and in the existing Famagosta DH plant have been designed specifically with the main aim of enhance the use of locally available renewable energy to supply thermal energy requirements of buildings. Canavese and Famagosta heat pump have started operating respectively in 2010 and 2011.

2. BEHAVIOUR OF GROUNDWATER IN MILAN AREA IN THE LAST 40 YEARS

The behaviour of the water table in Milan during the last decades is illustrated in the Fig. 3. Since Fifties, industrialization of the territory, especially in its Northern outskirts, caused a contemporaneous increasing use of groundwater by private concerns with the drilling of several thousand wells. Groundwater production in the province of Milan in the early 70s was estimated 2.5 billion m^3/year, 1.1 of which by industry.

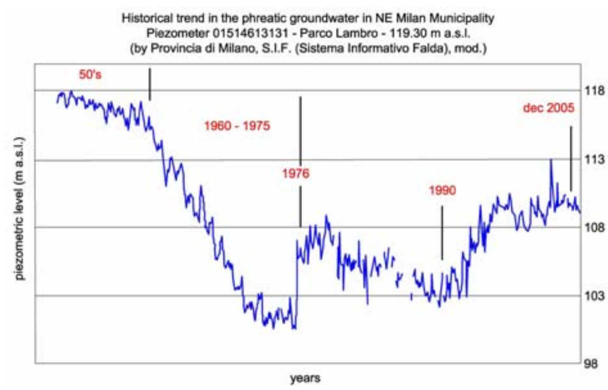

Figure 3: Evolution of groundwater table in a tipical NE Milan well between 1952 and 2006 (Provincia di Milano, S.I.F. Sistema Informativo Falda, 2006).

The enormous quantity extracted caused a dramatic lowering of the water table which reached its minimum in 1975, indicative of an excessive withdrawal. Remedial measures including drastic limitations and controls over private users and the beginning of local industry relocation, which accelerated in the 80s and early 90s, resulted in groundwater production decline in the Milan Province to 1.1 billion m^3/year in 1980 and around 1 billion in 2002 of which 756 million for human use. Milan municipality has delivered in the last few years 250 million m^3/year of drinking water from some 400 wells. Wells in all the Province are estimated over 7,000. The water table rose abruptly in 1976-77 and then behaved differently depending on location (with significant lowering to the North and marginal variations elsewhere). Since 1992-1993 a new general upraise, culminating in 1998, caused the flooding of several underground works in Milan and its Southern outskirts. The urgent remedial actions undertaken included groundwater extraction from some 100 newly drilled wells and its discharge in existing canals. In the last few years the water table has remained generally stable, with small fluctuations, at a still relatively high level, generally correspondent to the 1993-1994 situation, which leaves many infrastructures in the wet.

The above elements have played an important role in the discussion and decision to use the available groundwater excluded from human use for large-scale space heating through geothermal heat pumps (recovering in this way a great quantity of renewable energy) with the relevant benefits of air pollution reduction and energy saving which will be discussed farther on.

3. HEAT PUMP TECHNOLOGY INTEGRATED IN AN COGENERATION PLANT FOR DISTRICT HEATING

Canavese and Famagosta plants consist of a natural gas fuelled high efficiency CHP section and an heat pump fed by groundwater for the production of hot water at maximum temperature of 363 K. The plant also includes peak load boilers and thermal storage tanks (Fig. 4).

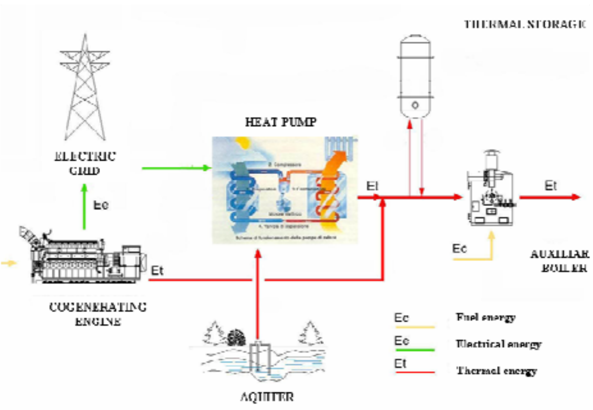

Figure 4: Principle scheme of Canavese and Famagosta plants

The CHP plant is composed by natural gas fuelled engines for a total of 15,300 kW (Canavese) and 19,200 kW (Famagosta) of electric power installed. The engines also produce heat which is recovered by exhaust gas and by intercooling. The total thermal power recovered is about 13,200 kW (Canavese) and 18,000 kW (Famagosta).

The thermal power generated by the heat pump is about 15,000 kW. The heat pump is fed by groundwater and absorbs about 5,500 kW of electric power to transfer the heat from groundwater to the district heating water return at 338-343 K of temperature.

The thermal energy produced by CHP engines or by heat pump can feed directly the district heating network or can be accumulated in the storage tanks.

Hot water can be also produced by auxiliary boilers, mainly used for backup and integration, natural gas fuelled for a total of 45,000 kW (Canavese) and 60,000 kW (Famagosta) of thermal power installed.

Finally, a pumping station guarantees the circulation in the distribution network.

The total thermal power installed is about 75,000 kW in the Canavese plant (Fig. 5) and about 95,000 kW in Famagosta plant.

Figure 5: Canavese thermal plant for District Heating.

The base-load thermal energy demand is supplied by CHP engine. The electrical energy production can be sold to the electricity distribution network or, in case of increasing heat demand, fed the heat pump to produce more thermal energy.

The peak of thermal energy request by customers is satisfied with the integration boilers production, with thermal efficiency more than 90%, or with discharge of thermal energy previously accumulated in the storage tanks.

A large district heating network consists of double (supply and return tubes) underground pre-insulated pipes of various diameter. The principal feeder is 600 mm inner diameter; the tee joint to final customers are 50 mm inner diameter.

The district heating networks of Canavese and Famagosta serve the east city area and the south city area respectively, which are characterized for an high density population and an high heat buildings demand (Fig. 6).

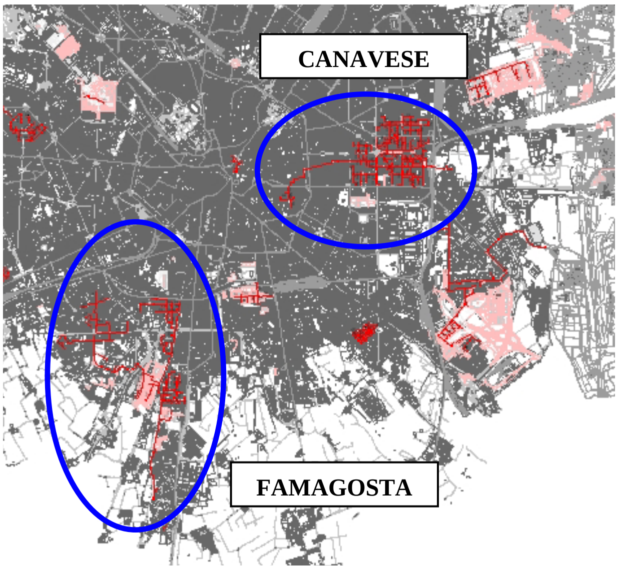

Figure 6: Canavese and Famagosta DH networks

At 31th December, 2012 the district heating networks are characterized by the data summarized in Table 1.

Table 1: Canavese and Famagosta DH networks principal data (2012).

	Canavese DH network	Famagosta DH network
Length [metres]	29,822	17,402
n. of heat exchangers	378	228
Thermal power installed [kW]	108,440	140,790
Thermal Energy sold to customers [MWh]	79,690	139,671

4. HEAT PUMP: PROCESS DESCRIPTION AND OPERATING DATA

The heat pumps (HP) installed in the Canavese and Famagosta plants are Heat Pump Unit Unitop® 50FY supplied by Friotherm AG (Fig. 7).

Figure 7: Canavese heat pump during the installation (2009).

The main components of the HP plant are:

- evaporator;
- electric motor coupled at the compressor;
- condenser
- subcooler
- expansion valve.

The HP plant works with a circular process using a closed refrigerant cycle. By means of the work of compressor fed by electrical power and the chemical-phisical properties of the refrigerant liquid contained in the cycle (R134a – Tetrafluoroethane) HP can transfer thermal energy from a low temperature to an high temperature body.

At the evaporator, a low temperature energy source (groundwater) transfers heat to the refrigerant liquid which evaporates at low pressure and corresponding low temperature. The refrigerant vapour is drawn in the centrifugal compressor (1^{st} stage and 2^{nd} stage) and compressed to a higher pressure level.

In the condenser the compressed gaseous refrigerant liquifies at high pressure and corresponding high temperature. The heating capacity of the condensation process is transferred to the heat transfer fluid (district heating water return at low temperature) which is entering the condenser and its temperature raises. The liquid refrigerant pass through a subcooler where it is cooled and trough the expansion valve to the evaporator again. The cycle is closed.

In the Canavese and Famagosta heat pump plants, the application of this cycle and the particular technical characteristics of the centrifugal compressor that can bring refrigerant R134a at high pressure and high temperature conditions, allow to produce hot water at 363 K exit from condenser which can be directly channelled to the network.

The main design operating data of the heat pump systems in Canavese and Famagosta applications are:

- Low Temperature Heat Source: groundwater
- Cooling Capacity: 9,732 kW
- Groundwater Temperature in/out at the evaporator: 288.0/280.6 K
- Groundwater flow rate: 1,150 m^3/h
- District Heating Water Temperature in/out at the condenser: 338.0/363.0 K
- District Heating Water Flow Rate: 546 m^3/h
- Electrical Power to fed centrifugal compressor: 5,768 kW
- Thermal Power fed to the District Heating Network: 15,500 kW

- Coefficient of Performance: 2.68

5. APPROACH FOR A SUSTAINABLE GROUNDWATER EXPLOITATION

In A2A's heat pump plants for district heating, geothermal exploitation is limited to the shallow aquifer, the temperature of which, below the first meters underground, remains roughly constant throughout the year. The Po Valley and Milan city are situated in these areas, defined as "cold" compressional basins, where the geothermal gradient is between 288 ÷ 298 K/km depth and the groundwater temperature varies between 285 and 288 K from 10 to 100 m depth (Beretta, 1985).

For each plants, the groundwater is extract from the surface aquifer by a system of six wells forty meters deep. Every well can operate at a maximum flow rate of 0.06 m^3/s.

The "open loop" heat pumps system returns the groundwater to the environment at a discharge temperature of about 280 K. Generally, groundwater can be discharged in natural watercourse.

In Canavese plant an half of groundwater used in the heat pump is put back in the surface aquifer to save natural resource by means three recharge wells (Fig. 8).

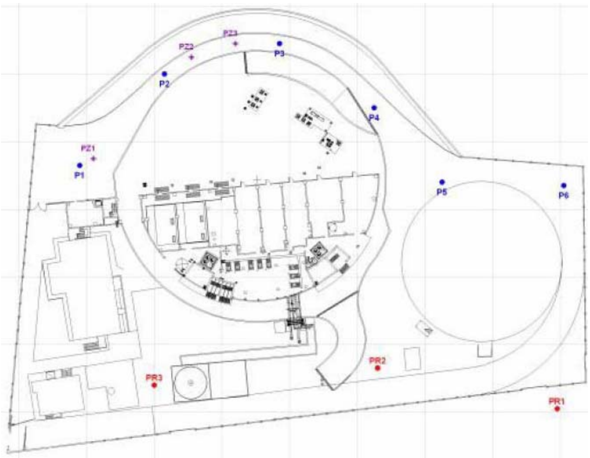

Figure 8: Canavese plant, six pumping wells (blue) and three recharging wells (red).

The recharge of groundwater is very important to restore the hydraulic potential and to ensure the sustainability of the resource as, within a given distance from pumping and recharge wells, the thermal potential of groundwater.

Infact, if hydraulic interference occurs between pumping and recharge wells a partial short-circuiting of water could be generated. This phenomenon can be problematic in a heat pump geothermal system because water, depleted of its thermal potential, is fed into the subsoil at a lower temperature than that of the groundwater (around 288 K) and it's again exploited by thermal machine. The water at evaporator will have a less thermal potential resulting in a decrease of efficiency of the heat pump and then a decrease of production of thermal energy.

For Canavese plant, hydraulic and thermal interference between pumping and injection wells have been studied in order to create a representative model of sustainable exploitation of low enthalpy geothermal resources, giving indications of the operative conditions that could determine a worsening of the efficiency of the process.

The study has been conducted simulating groundwater flow and heat transfer in the subsurface using a numerical model to evaluate how different operation plant condition impact on technical and environmental long-period sustainability.

The simulation of heat transfer in the aquifers has not been performed by means of dedicated numerical codes in the area of "Canavese" power plant, but by means a suitable adaption of normally used for solute transport. MT3DMS is in fact a numerical code, combined with MODFLOW (McDonald and Harbaugh, 1988), that allows to simulate three-dimensional solutes transport in groundwater, and it was used to simulate heat transport thanks to the analogy between the two physical processes.

To set the model, have been defined a conceptual model of the aquifer in the study area (Fig. 9). The model has been calibrated in stationary state and transient state also.

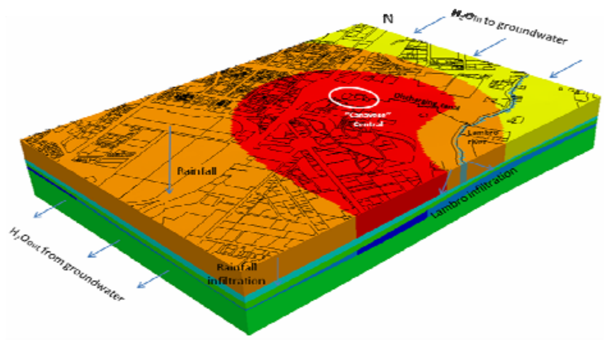

Figure 9: Three-dimensional visualization of the model parameters: colored areas represent homogeneous hydraulic conductivity zones

In the following figures are showed some of the model results in different scenarios which could be explanatory of the possibility of short-circuiting and its critical effects.

In Fig. 10 it's shown the piezometric heads at the end of the heating season (simulated period), with a depression on the three most used pumping wells and a rise in the neighborhood of the reinjection wells.

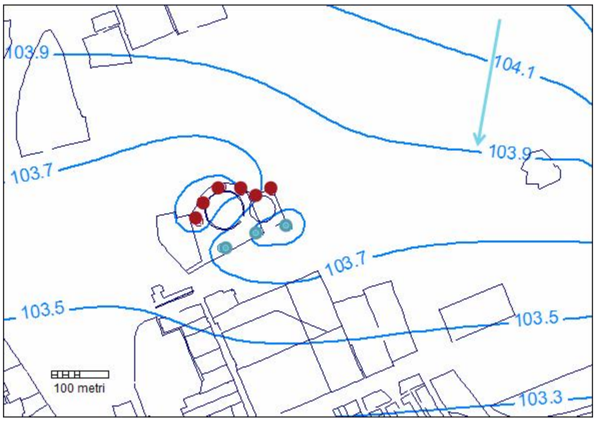

Figure 10: Hydraulic interference between pumping (red) and recharge (blue) wells of “Canavese” power station.

The Fig. 11 shows the pathlines simulated with the code MODPATH in conjunction with MODFLOW.

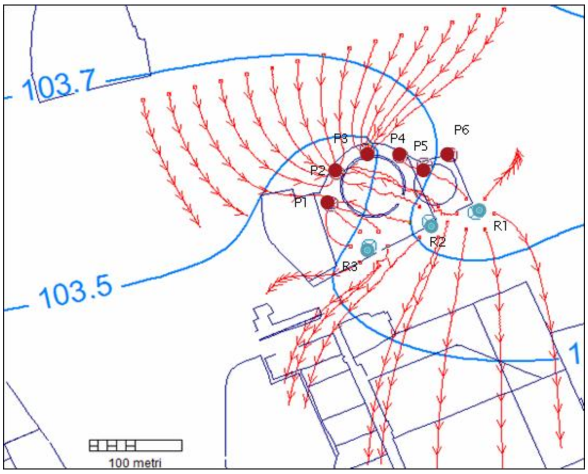

Figure 11: Pathlines from recharge to pumping wells.

Fig. 12 shows the heat plume at the end of the season of the thermal heat pump, generated by the reinjection of water at different temperature compared to that of the surrounding groundwater. The thermal front expands starting from the reinjection wells in the subsoil with a velocity about to 1/3 of the groundwater effective velocity (Beretta, 1985), since it has been calculated for a retardation factor of 3.08. Although it has a lower velocity than that of groundwater flow, the phenomenon of short-circuiting is evident.

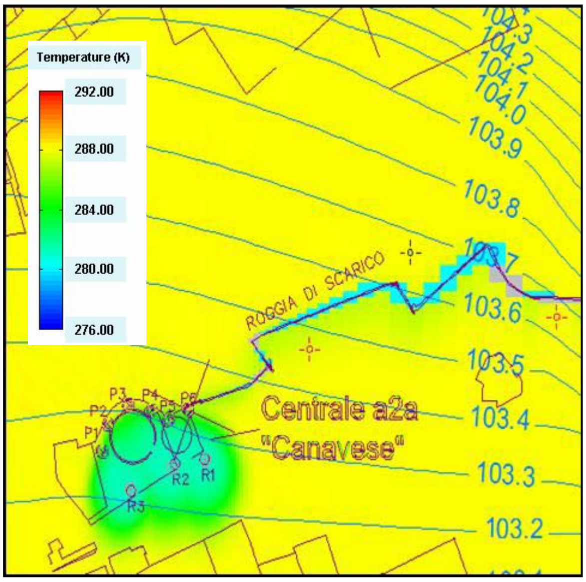

Figure 12: Thermal interference in the aquifer under “Canavese” station at end of simulated period.

The groundwater temperature recorded for each pumping well can be represented versus the flow rates of extraction (Fig. 13). In the heating season, when the heat pump starts (November-March) the temperature reduce gradually because the cold water front is abstracted by the pumping wells in the northern part of the plant.

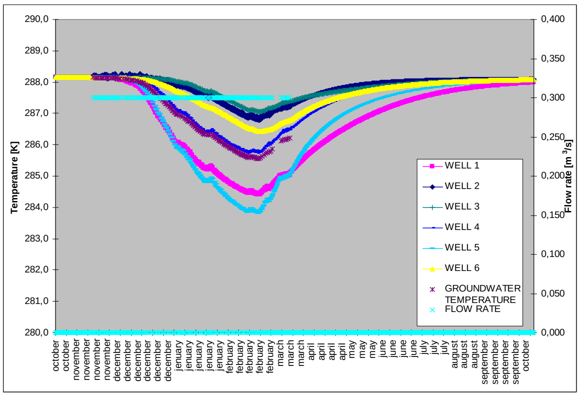

Figure 13: Temperature recorded at pumping wells during the simulation period. In the coldest time of the year there is a decrease in the temperature of groundwater as a result of the its heat exploitation.

The curves for the different pumping wells have different trends:

- some undergo intense changes: correspond to wells of the plant that are located closest to the re-injection wells, retrieving the majority of the water particles from the same;
- others just reduced fluctuations over time: corresponds to wells which remain "protected", because the flow of cold water does reach them only marginally.

Groundwater temperature (purple line) is the temperature of the water that reaches the heat pump evaporator: the water that enters in the heat pump will have an intermediate temperature value between those observed for each well, being connected by a single collector.

6. ENVIRONMENTAL BENEFITS OF THE GEOTHERMAL RENWVABLE ENERGY EXPLOITATION

The thermal energy production from heat pumps and their contribution to the total thermal energy production of the plants is shown in Tab. 2

Table 2: Canavese and Famagosta heat pump production and – in brackets – their contribute to the total thermal production of the plants (2010-2012).

Year	Canavese [MWh]	Famagosta [MWh]
2010	4,144 (9.5%)	-
2011	11,991 (19.3%)	36,401 (24%)
2012	14,744 (16.0%)	41,815 (27%)

The district heating system continuously increases his capacity according with the plane to strong expand the service. At the maximum, total annual heat production from heat pumps is estimated in 216 TJ/year which will correspond energy saved of about 72 TJ/year and avoided CO_2 emissions of about 3,200 Mg/year.

Locally, this contribution will avoid emissions of about 12 Mg/year of NOx, 3 Mg/year of SOx and 0.3 Mg/year of particle.

7. CONCLUSION

The application of heat pump tecnology for geothermal exploitation to supply thermal energy in district heating process showed high performance, reliability and operative flexibility.

The use of local renewable energy sources contributes to save primary energy and improve air quality.

It's fundamental to guarantee the sustainability of groundwater exploitation also. Designing the plant quantitative impact of the groundwater abstraction on hydrogeological system must be considered; in case of reinjection of the groundwater after use, the thermal potential of groundwater must be guaranteed and the short-circuiting between pumping wells and recharge wells avoided. The use of numerical model is appropriate to simulate these effects. Moreover, during the operation of the plant, heat pump operating data (groundwater in/out temperature, groundwater flow rate, thermal energy production, electrical energy absorbed) must be continually monitored.

Generally, power plant for district heating consists in an integration of different technologies (cogeneration, heat recover from industrial process, boiler, heat pump) and the hour-by-hour operative conditions of each technology depends by the thermal requirements of the customers (thermal energy load) and by the energy market conditions (fuel and electricity cost). The latter, show a variability which can significantly influence the cost of production of thermal energy from each technology.

For the heat pump technology, the economic sustainability of the cost of production of thermal energy depends by the cost of electrical energy used to fed the compressor (and for the pumping wells too). When an heat pump is integrated with cogeneration, the electrical energy can be produced directly for the self-consumption of the plant and not purchased from the net.

This configuration allow to maximize the operative hours of the heat pump, increase the thermal energy produced from renewable source and enhance the efficiency of the process and the environmental benefits associated.

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