THE WORLD'S LARGEST GEOTHERMAL DISTRICT HEATING USING GROUND WATER UNDER CONSTRUCTION IN MILAN (ITALY): AEM UNIFIED HEAT PUMP PROJECT

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Introduction

Large scale modular district heating using groundwater geothermal energy is under development in Milan (Italy) by AEM, the local public company, which meets a large part of the city energy needs, including gas, electricity and district heating.

Unione Geotermica Italiana (UGI), the Italian non-profit association for geothermal energy, promotes the exploitation of this renewable resource.

Milan, capital of the Lombardy Region, is the second most important city in Italy, leader in tertiary activities, technological markets and up to recently highly industrialized. Its present population is 1.25 million, while surrounding municipalities, especially to the North, are inhabited by some 2.5 million people.

Groundwater resources are abundant and have been used since long ago for human consumption as well as for complementary scopes: agricultural, industrial and energetic.

Energy production by geothermal heat pumps improves the environmental quality of both air and groundwater, beside providing sensible energy savings.

THE RESOURCE

Hydrogeological notes

The underground water resources of Milan and surroundings ("Greater Milan") are dependent both on natural factors (climate, geographical setting, surface and subsurface geology) and on human activities (hydrological works, irrigation and water extraction). Their quality is often altered by man-caused pollution.

Greater Milan is located in a broad, low-lying plain (Po Valley) bordered to the North and West by the Alpine system and to the South by the Appennines. The Po river flows from W to E for several hundred km, terminating in the Adriatic Sea. Winds are limited and average temperature of the area varies from 4°C in winter to 25°C in summer. Rainfall in proximity of the Southern Alps is generally abundant (from 1000 to 2200 mm/y) and diminishes to 880-1300 in the Greater Milan area. Dry and humid periods, sometimes lasting several years, alternate. The present surface hydrological setting at a regional level (**Fig.1**) is composed by a N-S river system (Ticino and Olona to the West of Milan; Seveso, Lambro and Adda to the East). A dense network of artificial canals exists in and around Milan, including the Villoresi North of Milan which joins Ticino and Adda rivers.They are presently used for irrigation and regulatory purposes.

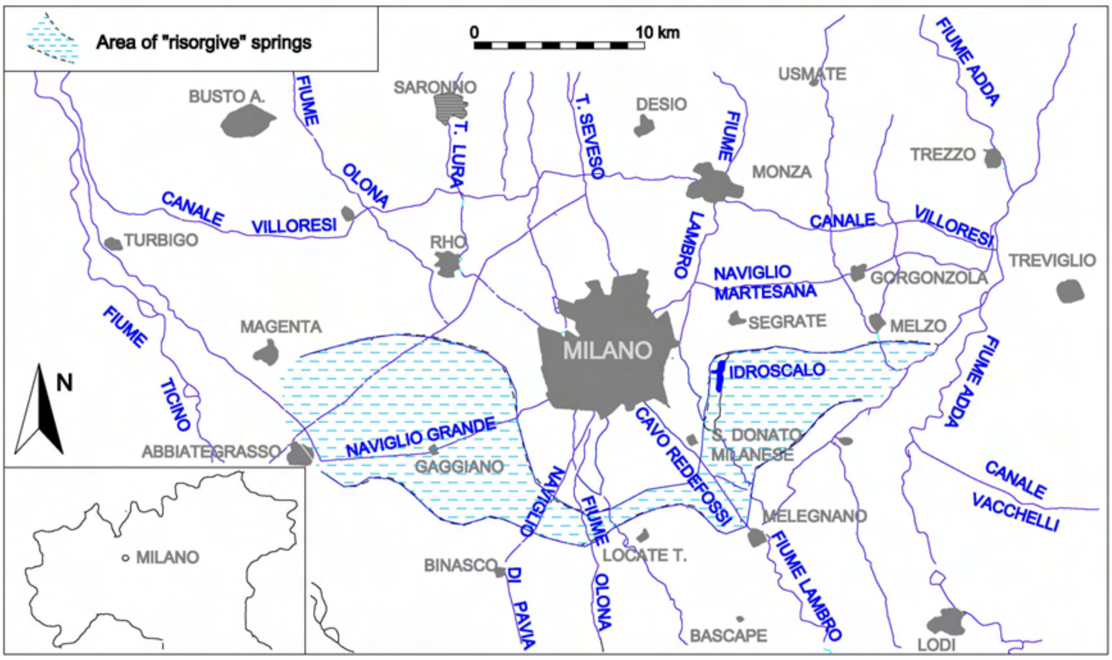

Fig.1 – Milan, location and surface water network (Barnaba P.F., 1998, mod.)

Springs called "risorgive" occur in a several km wide band running E-W along the Northern Po Plain (passing through the central-southern part of Milan territory) (Fig. 1) where the phreatic water accumulated in the thick alluvial fans deposited at the foot of the Alps emerges in the plain after meeting the obstacle of a poorly permeable clayey section.
The abundance and constant mild temperature (13-15°C) has led in the past to a widespread use of this resource, especially in agriculture.
Geologically (1, 2) Greater Milan is built on Quaternary continental clastic sediments which underlie the area for several hundred m (**Fig.2**) .

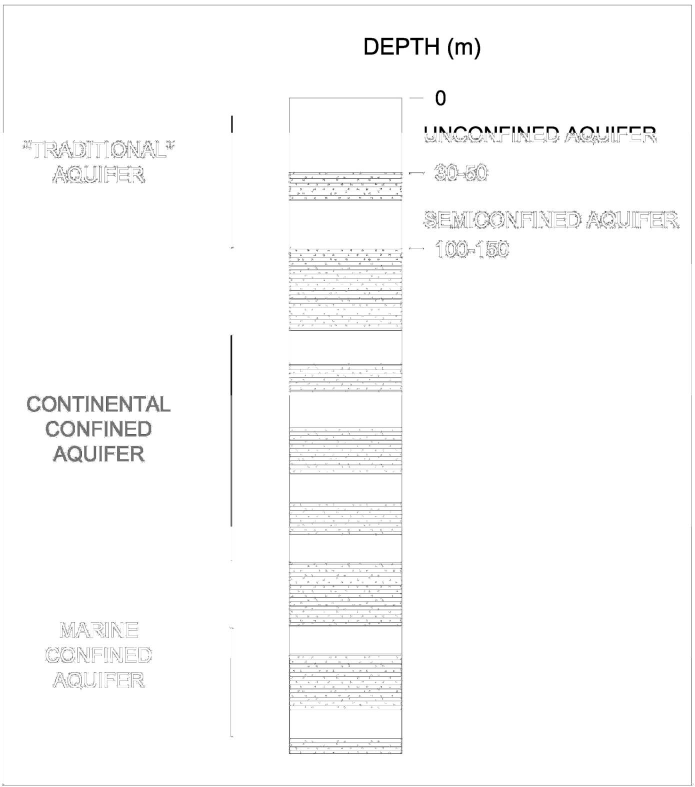

Fig.2 – Greater Milan, aquifer scheme (Avanzini M. et al., 1996 mod.)

They are composed at the top (first 30-50 m) by prevailing gravel and coarse sand, very permeable (representing an unconfined aquifer) separated under most of the city by a thin clay level from a lower section, up to 150 m deep in the South. This second unit is made up of coarse to medium sand, with local gravel and clay episodes, with good permeability and confined to semi-confined behaviour; the aquifer is limited at the bottom by a relatively thick and continuous clay horizon. The two freshwater aquifers constitute the traditional source of domestic water for Greater Milan and overlie a dominantly clayey section with medium to fine-grained sand beds moderately permeable and still freshwater bearing (confined aquifer) many hundred m thick. The series, continental to partly marine, is of Quaternary to Upper Pliocene age.
The fresh-brakish water interface lies at a depth between 300 m to the West and nearly 800 m to the East of Milan.
Natural flow of groundwater is from N and NW (recharge-area) to South, towards the Po river.
The groundwater resource is very abundant and its recharge is mainly made up of precipitations, both at the front and foot of the Alps, and locally and of infiltration from surface water of upstream rivers, surrounding canals and irrigation (3). It must be noted that urbanization of the territory, especially North of Milan, has greatly reduced the absorption capacity of the ground. Discharge consists mainly of water extracted from wells for human consumption and industrial (subordinately agricultural) uses and, in lesser quantities, of water outflowing from the "risorgive" springs; additionally drainage by Ticino and Adda occurs when the river bed is lower than the groundwater table.

Past and present use of groundwater

The shallowness, abundance and quality of groundwater in the Milan territory has led to its use in increasing quantities since ancient times mainly for human consumption and irrigation. It is recorded that in the XIII century water was produced in Milan from around 6000 wells, few meters deep. In the same period irrigation by "risorgive" allowed to harvest multiple crops from fields surrounding the city, early example of energy use of warm groundwater.
The growth of population and health concerns led in 1888 to the public management of groundwater for domestic use. The Municipality of Milan drilled hundreds of wells which produced increasing quantities of water up to a maximum of 350 million cu.m in 1971.
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 Seventies 'was estimated 2.5 billion

cu.m/y (4) 1.1 of which by industry (5).
The enormous quantity extracted (possibly exagerated but still a realistic order of magnitude) 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 cu.m/y in 1980 (3) and around 1 billion in 2002 (Arduini C., Provincia di Milano, personal communication 2007) of which 756 million for human use (12). Milan municipality has delivered in the last few years 250 million cu.m/y of drinking-water from some 400 wells. Wells in all the Province are estimated over 7,000 (9).
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

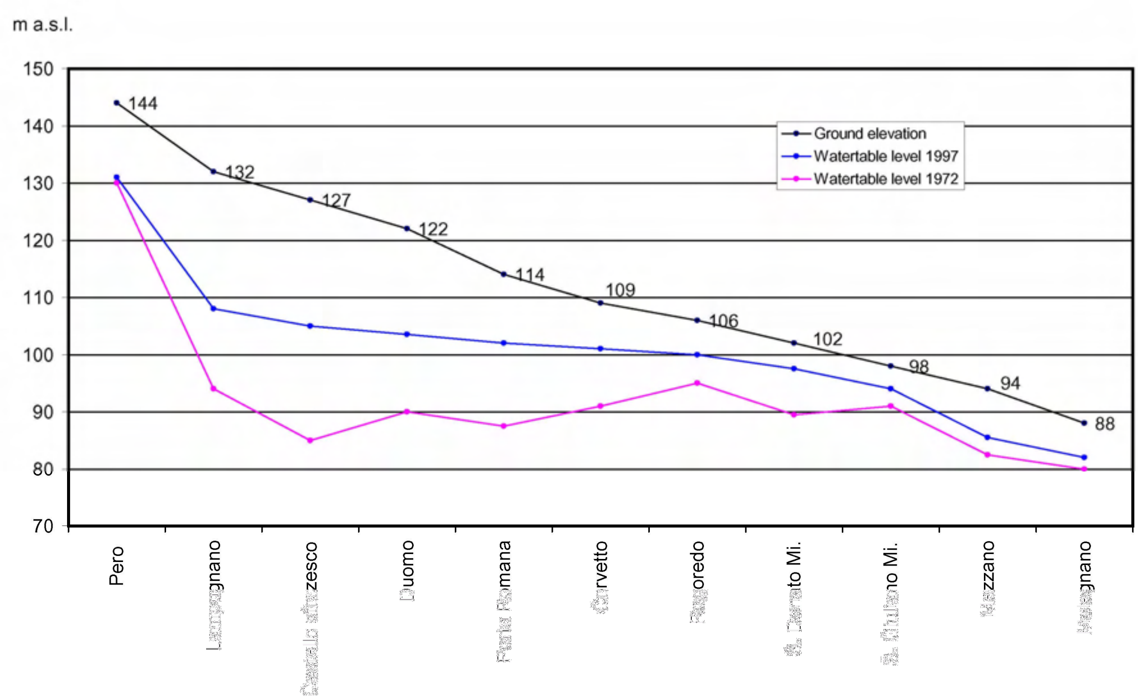

Fig.3 – Greater Milan NW-SE cross-section of groundwater table levels 1972 and 1997 (Barnaba P.F., 1998 mod.)

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.

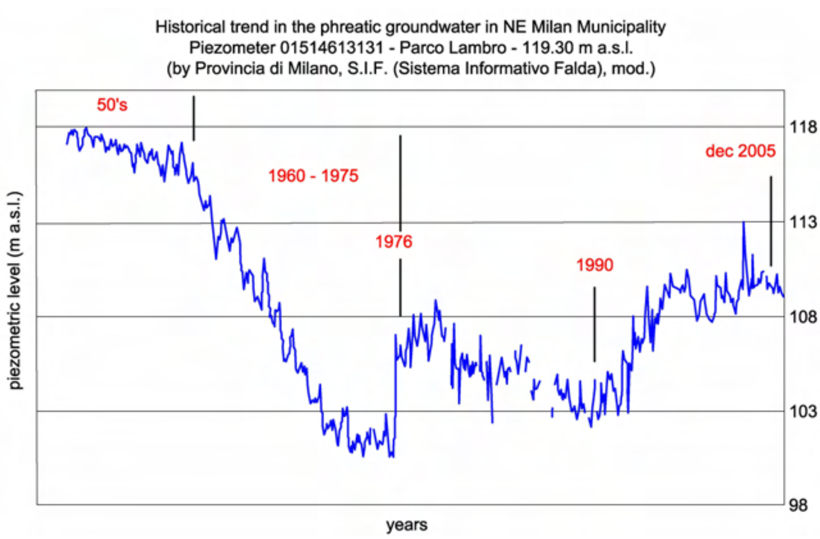

Fig.4 – Evolution of groundwater table in a tipical NE Milan well between 1952 and 2006 (by Provincia di Milano, S.I.F. (Sistema Informativo Falda), 2006)

The behaviour of the water table in Milan during the last decades is illustrated in **Figg.3** and **4** and the present setting below ground and above sea level is shown in **Fig.5**. An additional concern, relating mainly to the uppermost aquifer, is pollution because of past industry spills and of chemicals used in agriculture. Other contamination factors include leakages from corroded underground tanks, disposal of noxious materials in abandoned quarries and faulty drainage systems (7, 8). These problems are being dealt with by several specific measures, including draining polluted water from wells (7, 9).

The above elements have played an important role in the decision to use the available groundwater excluded from human use for large-scale space heating through geothermal heat pumps (10, 11) with the relevant benefits of air pollution reduction and energy saving which will be discussed farther on.

Lombardy Region, aware of the advantages of geothermal energy use, has approved a deliberation (VIII/3944 dated 27/12/2006) to promote in particular ground-water heat applications, also simplifying bureaucratic procedures. The Province regulates groundwater heat pumps activities under the regional law.

It is to be noted that Milan was the seat of the first geothermal heat pumps installed in Europe. In 1937-38 equipment-of Italian design and construction-using groundwater was installed in two large buildings in the city centre (the press palace in Cavour square and a bank headquarter) and operated until the Seventies.

In the last few years several important Milan buildings such as the Regional palace, Bocconi university, the historical Castello Sforzesco and Scala theater, the Museum of Natural Sciences, the Archbishopry archives, etc. have been equipped with geothermal groundwater heat pump systems for year-round heating and cooling. In the AEM district heating project under development, which will serve 250,000 people, groundwater extracted, at temperature of 15°C will average 180 l/s corresponding to 5.7 million cu.m/y per plant, to be discharged at 8°C in the surface water network (10). The five planned plants, adequately spaced around the periphery of Milan, will thus produce 28 million cu.m/y of groundwater, less than 6% of the total city withdrawals.

The operating period will be limited to the heating season allowing the groundwater to recover during the rest of the year.

The number of wells per plant, 40 to 50 m deep, will depend on productivity, which varies from 15 to 40 l/sm on pump; spacing should be around 25-50 m.

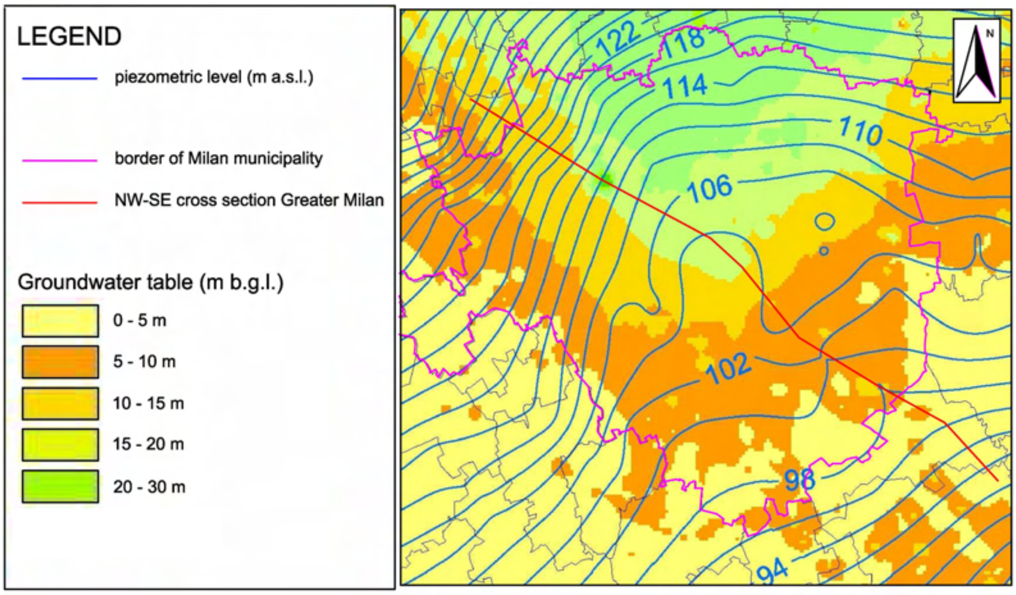

Fig.5 – Milan municipality – Groundwater table map 2006, october – by Provincia di Milano, S.I.F.

THE UNIFIED HEAT PUMP PROJECT

AEM's experience in cogeneration and heat pumps and the groundwater availability in Milan has led to its deciding to opt for the design of a standard plant that combines the advantages of both technologies; the new plant design is being implemented in its new district heating systems, which will perform better both in terms of environmental protection and energy saving.

This engineering solution allows for the rationalisation of primary conventional energy sources used, such as electricity and natural gas (13) and to the use of a renewable geothermal resource.

AEM has therefore launched a development plan for a new line of heat pump plants that will be constructed on five of its own sites (Canavese, Gonin, Ricevitrice Nord, Ricevitrice Sud, and Bovisa), currently used for technological purposes.

This standard type of plants will also be proposed for other existing district heating initiatives in the built-up areas of Garibaldi-Repubblica, Quartiere Santa Giulia, Bocconi.

Figure 6 (**Fig.6**) shows a map of Milan, illustrating sites where aforementioned developments will take place.

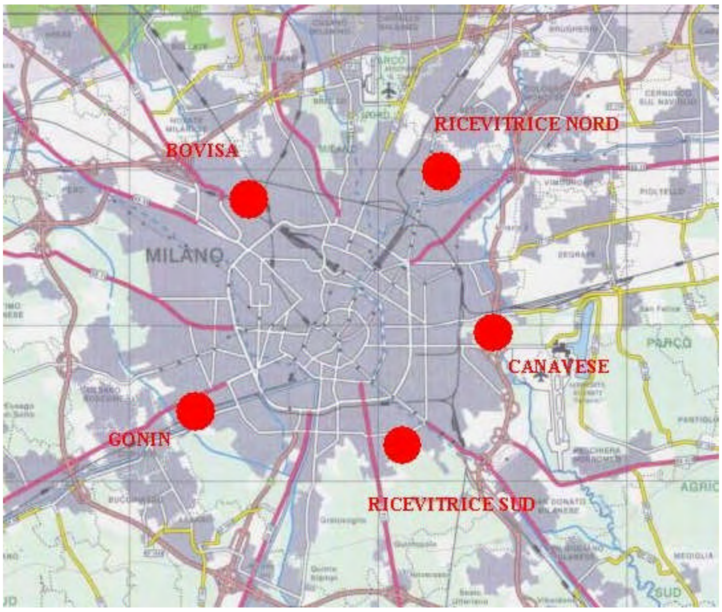

Fig. 6 – Map of Milan illustrating sites of district heating, as foreseen by unified geothermal heat pumps project

The standard cogeneration plant based on heat pumps

The unified project uses a standard size and shape for its plant, which serves the purpose of simplifying its construction and management.
Figure 7 (**Fig.7**) illustrates a diagram of design in question. It is made up of a cogeneration section, a heat pump system, a boiler section and a heat storage tank. The heat pump section, which represents the most innovative part of the project, guarantees a significant heat production, integrated thanks to the contribution of the cogeneration and heat boilers sections.

Heat pump

A heat pump is a machine that can transfer thermal energy from one body at a lower temperature to another body at a higher temperature, thanks to the addition of external work supplied by a compressor powered by electrical energy.
The parameter used to measure the performance of a heat pump in terms of its efficiency is known as the COP (Coefficient of Performance), which is defined as the ratio between the thermal energy produced and the electrical energy required to power the heat pump.
The heat pumps used in the project in question make use of specific know-how developed in Sweden for urban district heating applied to powerful machines with more than 10 MWth power (14). These heat pumps guarantee excellent performance (COP ratio of about 3) producing water heated at 80-90 °C.

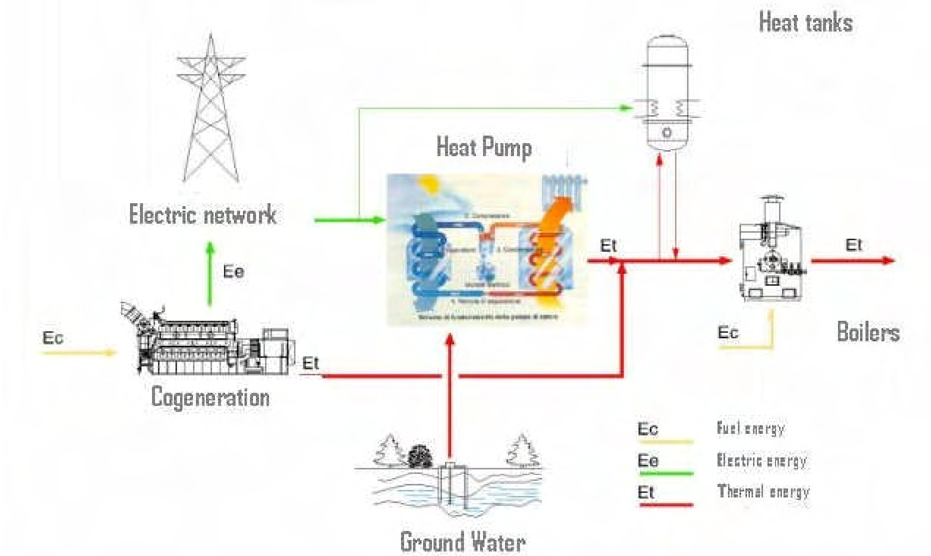

Fig. 7 – Diagram of the standard plant based on heat pumps

Effect on the electricity system

Heat pumps are powered by electrical energy; connection to the electricity network combined with heat storage tanks ensure that the plant's functioning can be modulated.
It should be noted that the extensive use of heating systems powered by electricity, especially heat

pump systems with heat storage tanks, guarantees an important contribution to equilibrating the national electric demand increasing the load at night-time.

The Unified Project

Upon completion of all five the standard plants foreseen under the project, 650,000,000 kWh/year of thermal energy will be produced for district heating for approximately 20,000,000 m^3 of buildings volume and 250.000 of inhabitants eq. supplied (15).

The feasibility study

The feasibility study was set up for the purpose of identifying the best configuration for the plant in terms of main machines and accumulators size, taking account of potential consumers which present a thermal load profile with the typical characteristics found in Milan. The thermal profile of users has been defined, as is described below, on the basis of AEM’s experience in district heating.
The basic data on the standard users taken into consideration are the following:

- thermal power absorbed at plant outlet: 90 MWth
- thermal energy distributed: 150 GWhth/year
- equivalent hours: 1,700 h/year

In order to identify the optimal configuration for the AEM plant, the method adopted was the one used by AEM for its own feasibility studies carried out in relation to cogeneration plants: mathematical programming and specifically mixed integer linear models.

The mathematical model for plant optimization

This model was developed to guide the design towards a plant configuration, which, in addition to complying with binding environmental norms, also has to be economically sustainable and profitable, and offer a state-of-the-art technical solutions. By developing the mathematical model in a specific software environment, it has been possible, using optimisation algorithms, to make comparisons between different plants configurations, starting from process parameters and operative conditions.
The input data for the model is the thermal load of users, known for every day of the year and calculated on the basis of day degrees of the area in which the plant will be constructed; the objective function to optimise is the profit of the investment, whilst complying with binding supply obligations for energy carriers and environmental norms.
These types of problems, which require the minimisation or maximisation of an objective function, can be analysed by referring to a special category of mathematical models: i.e. *mathematical programming (MP)* models.
These are defined by the following elements:

- decision variables, which are the quantities that can be controlled;
- constraints dictated by mathematic relationships, which correspond to relationships in the real world such as technological relationships, physical laws, marketing requirements, binding legal obligations, social obligations;
- an objective function that can be, for example, profit maximisation or cost minimisation.

Resolving a problem of mathematical programming means choosing variable values that satisfy binding constraints whilst at the same time optimising the objective function:

$$\begin{cases} \min f(x) \\ x \ \hat{I} \ S \end{cases} \qquad (1)$$

where the function *f(x)* is the objective function, and *S* represents all admissible solutions.
Using mathematical formula, solving the problem consists in calculating *x★ Î S ? f(x★) = f(x)* for every *x Î S.*
Linear programming models (LP) are another important category of mathematical programming models, in which both the objective function and the constraints are linear functions of decision variables; software has been developed for these models that can resolve very complex problems in an efficient way taking into consideration thousands of variables and constraints.
Mixed Integer Linear Programming, (MILP) is a further extension of the category of linear programming models, in which certain decision variables are integer or binary numbers; binary variables represent logical conditions as yes/no decisions, such as the choice amongst various investments.
The problem of optimisation that has been analysed and solved, concerning the cogeneration plant based on heat pumps, can be successfully undertaken using a mixed integer linear model, which from a computation perspective is very complicated; in fact, in addition to having to manage a high number of real variables, integer and binary variables (Boolean variables) have to be introduced in the model

to determine which and how many machines to install. The Boolean variables are also necessary to ensure compliance, in the event that a category of generators is required for production, with daily minimum quantities of thermal energy produced using a single category of machines.
In particular, the problem in question belongs to those that fall in the category of mathematical models to determine the optimal size of the plant and optimise production; they are used to calculate the most economical way to produce goods or services (in the case in point thermal energy generated at the heat pump and cogeneration plant) by optimising investment costs for systems and the machines(gas engines, boilers, heat pumps) required to produce them.
More specifically, in the case in question, the objective function to be optimised is defined as the difference between income received from sales of electric and thermal energy, and the sum of the costs of setting up the plant itself, set off over a number of years "n", and the cost of purchasing fuel as well as the cost of managing the plant.
The solution found used a series of numeric constraints; for those relating to the primary engines, in other words the gas engines – heaters – heat pumps, the constraints relate to respect for the operative conditions of the installed machines, in terms of minimum daily produced energy and satisfaction of heat load on hourly basis.
Other constraints that have to be respected include the following conditions:

- for each category of generators only one type of machine can be installed, which is chosen by the mathematical model;
- there is a linear dependency between thermal and electrical energy generated and fuel/electrical energy that enters into the generators; in other words, the thermal and electrical efficiency of a machine is assumed constant;
- the water temperature for district heating is a function of measured day degrees, according to a given algorithm.

The model developed using the guidelines and methodology described above, and compiled using AMPL language with a CPLEX 7.0 solver, requires several minutes' calculation time, working on an INTEL Pentium IV processor. (16)

Results from simulations
In relation to each configuration taken into consideration, and for a predetermined value for minimum energy to be produced using heat pumps, the mathematical model was able to calculate the following annual statistics on an hour-by-hour basis: thermal flows produced by individual machines, fuel consumption, electrical energy produced, electrical energy sold and purchased by the electricity network. Moreover the size of the heat storage tanks required to uncouple heat production from the user heat requirements has been correctly calculated. Careful analysis of the results meant that we were able to choose what is currently considered to be the preferred plant configuration, in terms of its guaranteed economic performance and operating flexibility; such flexibility has to be ensured, in the IPEX (Italian Power Exchange), where the prices of electricity vary on an hourly basis and in a way that cannot always be easily predicted; energy systems are preferred if they can easily modify their electricity production, according to market prices recorded during the previous day's trading.
The "optimum" configuration on the basis of the calculations carried out is that of a plant with 15 MW_{th} gas engines + 30 MW_{th} heat pumps + 30 MW_{th} gas boilers, which are installed together with a hot water storage tank with a capacity of 80 – 100 MWh_{th}.
Figures 8, 9 and 10 (**Fig. 8-9-10**) illustrate the production plan for a standard plant in terms of thermal energy produced by the various sections of the plant, electrical energy produced and natural gas consumed.

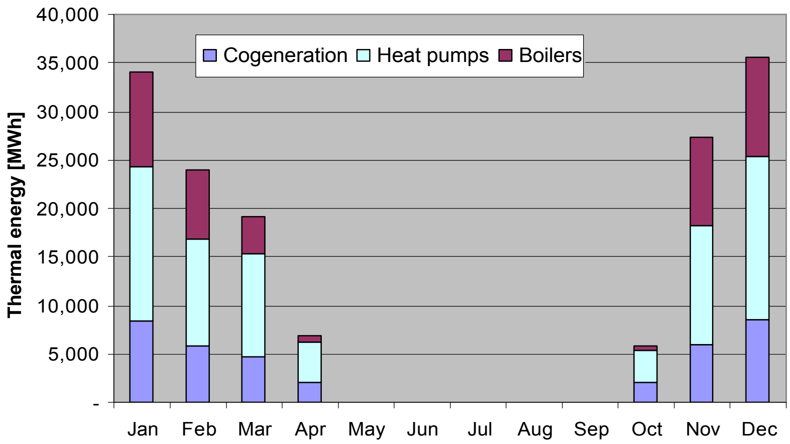

Fig. 8 – Thermal energy supplied at a standard plant

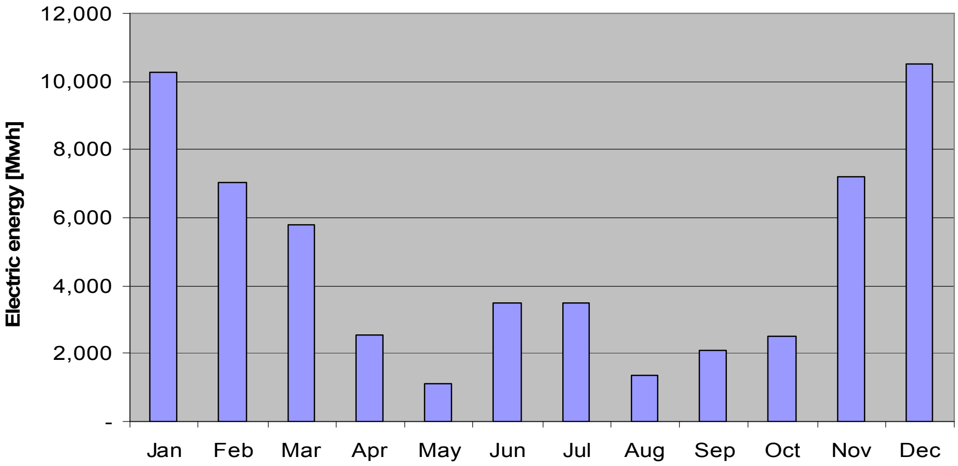

Fig. 9 – Electric energy production at a standard plant

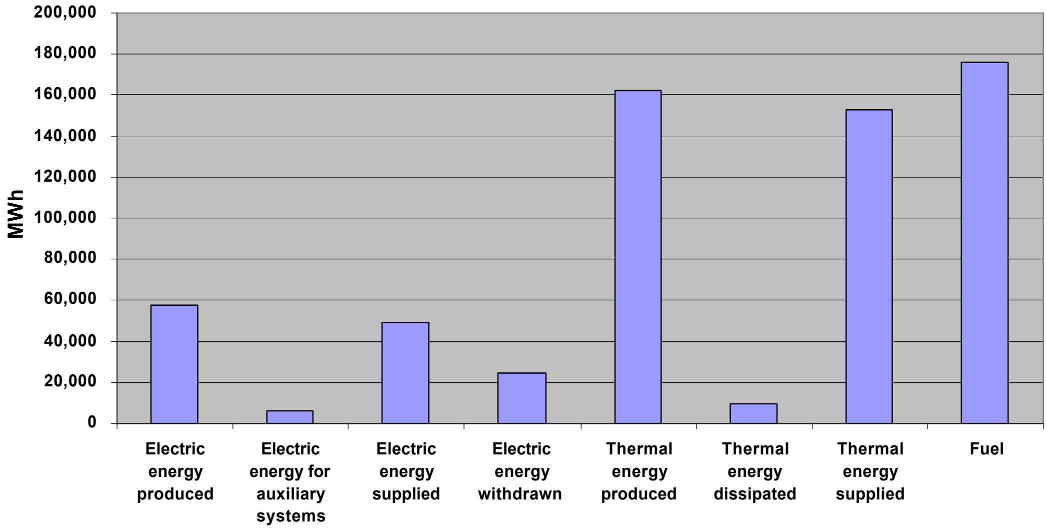

Fig. 10 – Energy flows deriving from a standard plant

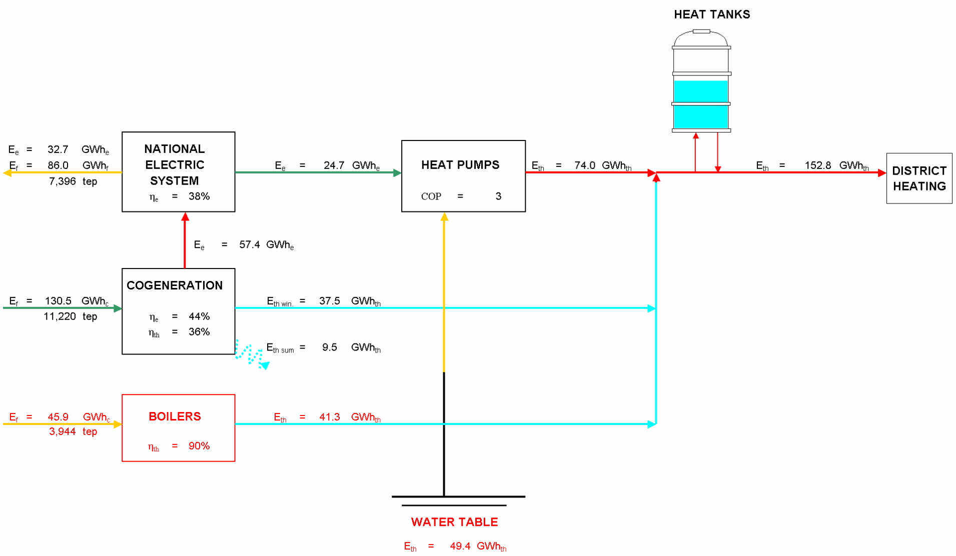

Fig. 11 – Annual energy balance

The previous diagram (**Fig. 11**) illustrates the plant's energy balance on the basis of its functioning throughout the year.

Advantages for the environment

Achieving all five the plants foreseen by the unified project will have the effect making considerable energetic and environmental improvements, appreciable on urban scale too, in terms of:
- considerable energy saving;
- reduction of atmospheric pollution;
- controlling the level of the water table.

Energy saving

The combined effects of cogeneration and heat pumps are a constant reduction in fuel consumption: it has been calculated (table 1) that upon termination of the project, in terms of primary energy (fuel), consumption will be reduced by 40,900 toe/year (equivalent tons of petroleum) equivalent to an energy saving of 35%.

Table 1: Energy saving (toe)

Fuel not used by users	Fuel saving by cogeneration	Fuel used by the plant	Decrease	**Decrease %**
79,700	37,000	75,800	40,900	*35*

Reduction in atmospheric pollution

The effect of inserting new district heating plants in terms of air quality is evidenced by Table 2. It can be seen that, on the one hand SO_2 and particles have been totally eliminated, as a result of powering the stations exclusively with natural gas, and on the other, a 50% reduction in NOx emission; this is achieved thanks to the heat pumps, which produce heat energy with zero emissions. On the basis of simulations carried out, it was seen that 50% of the heat distributed will be produced by heat pumps and therefore there will be "zero emissions" locally. Most of this heat (i.e. 2/3) will be extracted from the water table, in other words from natural springs, which is totally renewable energy, that can be found in abundance in the Milan metropolitan area.

Table 2: Reduction in polluting emissions in Milan (t/y)

Pollutant	Emissions from users of current plants	Unified project emissions	Decrease	**Decrease %**
NO_x	190	95	95	*50*
SO_2	150	2	148	*99*
PM_{10}	14.5	0.5	14.0	*97*

The positive effect for air quality in Milan also makes an appreciable improvement on the overall reduction of pollution in the city of Milan. In fact, it is as if a considerable number of inhabitants (about 120,000) had turned off their heating system thus eliminating related emissions.

Reduction in CO_2

Use of renewable energy on a large scale (water table) allows a very positive impact to be made in terms of reduction in CO_2 emissions. Table 3 illustrates how a reduction of approximately 145.000 t/year can be expected, equivalent to a 45% reduction.

Table 3: Reduction in CO_2 emissions (t/y)

Emissions from users of current plants	Emissions saving by cogeneration	Unified project emissions	Decrease	**Decrease %**
210,000	113,000	178,000	145,000	*45*

Conclusions

The new geothermal district heating will be the largest groundwater heat pump powered system and the second largest (in terms of connected clients) geothermal system in the world (after Paris).
The geothermal district heating system being developed in Milan can find applications in many other towns in the Po plain, North of the river, with a similar aquifer situation, as well as in other locations in

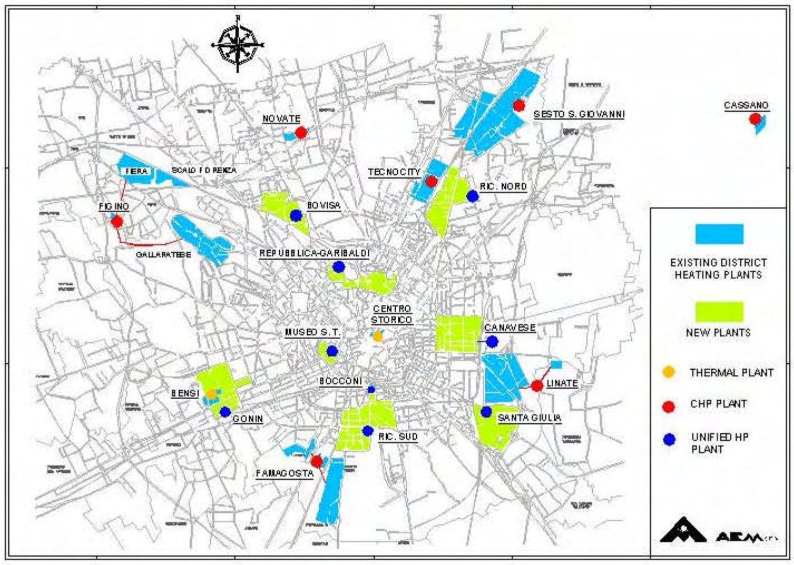

Fig. 12 – AEM's district heating in Milan – state after completing of project

Italy and abroad.

Taking into account the groundwater situation in Milan previously described AEM's unified project intends to rationalise controls on water table levels through the use of its own plants, combining this activity with the continuous and efficient production of heat for district heating.

Actually, the plants of unified heat pump project under construction are the Canavese Plant, a totally new plant, and Famagosta Plant, where it is planned to insert the heat pump in the existing cogeneration plant. Both the plants will be started before the end of October 2007 during the next heating season.

Figure 12 (**Fig.12**) illustrates how, subsequent to completion of the unified project, the geothermically heated portion of the city of Milan will represent a considerable proportion of the district heated area.

By 2010, the objective is to supply heat for a total of approximately 1,000 MW_{th}, of which about half geothermal, will be equivalent to a CO_2 reduction of 400,000 t/y.

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