Low-enthalpy geothermal energy: An opportunity to meet increasing energy needs and reduce CO_2 and atmospheric pollutant emissions in Piemonte, Italy

Stefano Lo Russo [a,*], Cesare Boffa [b], Massimo V. Civita [a]

[a] Politecnico di Torino-Dipartimento di Ingegneria del Territorio, dell'Ambiente e delle Geotecnologie (DITAG), Corso Duca degli Abruzzi, 24-10129 Torino, Italy
[b] Politecnico di Torino-Dipartimento di Energetica (DENER), Corso Duca degli Abruzzi, 24-10129 Torino, Italy

ARTICLE INFO

ABSTRACT

The scope for diffusion of very low-enthalpy geothermal plants in the Piemonte region of Italy, using groundwater heat pumps (GWHP), was analyzed to check environmental sustainability and the benefits in terms of reducing greenhouse gas emissions from fossil fuels. GWHP implementation seemed particularly suitable to the specific characteristics of the Piemonte plain. An important thick and productive shallow aquifer is present across the entire plain beneath the major energy users and is therefore appropriate for geothermal energy development purposes. The building stock could be adapted to heat pumps in different ways, but objective-oriented policies will be required to reach the best results in terms of environmental benefits.

© 2008 Elsevier Ltd. All rights reserved.

1. Introduction

The European Union Energy Efficiency Action Plan (EC, 2006) set a target of reducing global primary energy use by 20% by the year 2020 and reversing the trend under current energy and transport policies for CO_2 emissions to increase by about 5% by 2030 (EC, 2007). This, together with the increasing of costs of non-renewable (fossil) energy resources, has stimulated efforts by public administrations and private stakeholders to investigate new technologies by means of research activities and industrial applications. The successful implementation of very low-enthalpy geothermal plants for heating and cooling buildings in several European countries has highlighted one such technology, and this paper reports on an investigation of its potential impact in the Piemonte region of northwest Italy.

There are two basic ground source heat pump systems: an earth-coupled (closed-loop) type and a groundwater (open-loop) type (Rafferty, 2000). In the first type heat exchangers are located underground either horizontally (ground source heat pump, GSHP), vertically (downhole heat exchanger, DHE) or obliquely, and a heat-carrying medium is circulated within the exchanger, transferring the heat from or to the ground via a heat pump. The GSHP configuration is usually the most cost-effective when adequate yard space is available and trenches are easy to dig, especially while a building is under construction. DHEs are widely used when there is a need to install sufficient heat exchange capacity under a confined surface area, such as when the soil is rocky close to the surface or where minimum disruption of the landscape is desired.

Open-loop groundwater heat pumps (GWHP) typically withdraw groundwater to provide heat (PDEP, 1996). In the winter, the GWHP extracts heat from the water to provide space heating. With reversible heat pumps, the heat-transfer process can be reversed in the summer and the groundwater absorbs heat from the living or working space and cools the air (DOE, 1999). GWHPs are suited to regions with extended shallow aquifers, from which it is relatively easy and not very expensive to extract groundwater (Drijver and Willemsen, 2001).

There are three types of commonly used open-loop systems. Direct open-loop heat pumps, where the water is passed directly through the heat exchangers of the heat pump, are largely used for residential and very small commercial applications (Rafferty, 2001). This system is most suitably applied where low-salinity groundwaters are available, because the direct use of high-salinity waters can cause scaling, i.e. the deposition of mineral scales in pipes, valves and/or heat exchangers (PDEP, 1996). Standing column systems (SCW) are used in locations where groundwater wells do not produce sufficient water for a conventional open-loop system and where water quality is also good. In SCW systems, groundwater is re-circulated from one end of the column well (static water level) to the heat pump, and back to the other end (bottom) of the deep bore. Usually, only one well is required for conventional buildings; larger projects may have several wells in parallel. SCW systems

* Corresponding author. Tel.: +39 011 090 7648; fax: +39 011 090 7699.
E-mail address: stefano.lorusso@polito.it (S. Lo Russo).

can be thought of as a cross between closed-loop earth-coupled systems and open-loop groundwater source systems.

The indirect open-loop systems generally involve a heat exchanger between the building loop and the groundwater, which eliminates exposure of any building components to groundwater (Rafferty, 2001). The most important consideration in GWHP design is to obtain a plentiful amount of groundwater with a very stable temperature. Generally, a highly productive, shallow (within 30 m of surface) aquifer would favor successful and efficient functioning of the GWHP.

In practice, all geothermal plants based on GSHP, DHEs or GWHP systems have several advantages over traditional air source heat pumps,

- lower consumption of primary energy to meet the same level of energy end uses;
- good energy performances over the entire heating season, even with very low air temperatures (when the performance of air source heat pump is poor);
- quiet operation, due in particular to the absence of fans;
- most heating elements, such as radiant floors, are almost totally silent;
- when air conditioning is required, the use of GWHPs in standard ventilation and air conditioning (VAC) units yields important savings in terms of primary energy sources;
- high overall energy efficiency;
- reduction of CO_2 and atmospheric pollutants emission (NO_x; particulate matter less than 2.5 μm in diameter) both at global and local levels. If the heat pump is driven by an electric motor, no emissions are produced at the local level;
- the flameless operations simplify fire-prevention procedures.

Against this, uncertainty linked to the long-term environmental effects – especially for DHE and GWHP systems – is currently the main constraint on the wide implementation of GWHP systems in Piemonte. The lack of a regional legal framework for environmental permits creates excessive administrative restrictions by public agencies, a situation that should be resolved as soon as possible. Consequently, several actions have been taken by the regional environmental authority and an intense program of research activities was developed to better characterize the environmental effects due to GWHP installation and operation. These included the characterization of the aquifers in the region, determination of their potential, and the evaluation of what improvement of the building stock might be feasible on the regional scale, the aim being to estimate what reduction of fossil fuel use might be achieved by the installation of DHE and GWHP systems.

In the plain area of Piemonte (roughly the planning areas identified in Fig. 1) the groundwater quality, hydrogeological setting and shallow aquifer characteristics seemed particularly suitable for a wide implementation of GWHP direct open-loop systems.

2. Materials and methodology

2.1. Geothermal energy resources

Piemonte is poor in geothermal energy resources even though its present geologic structure was developed during the recent Alpine orogeny. The central plain area of continental sediments, presenting extensive alluvial fans and moraine deposits, is bounded by the arcuate orogenic belt of the Western Alps (crystalline and carbonate rocks); see Fig. 1. The Western Alps are a thick-skinned thrust belt formed by the subduction of the European Plate beneath the Adriatic Plate that began in the Late Cretaceous. Final colli-

sion and nappe staking took place in the Late Eocene (Coward and Dietrich, 1989; Gebauer, 1999; Vezzosi et al., 2004).

The Alpine orogenic wedge was the result of a complex geodynamic process due to plate convergence, characterized by mainly "horizontal displacements" involving lithosphere oceanic subduction followed by continental collision (Polino et al., 1990). The post-collisional, "late-Alpine" (Pliocene to Recent; Hunziker and Martinotti, 1987) history of the chain is mainly dominated by "vertical movements" (either uplift or subsidence), due to both active tectonics and isostatic rebound (Debelmas, 1986; Cadoppi et al., 2007).

In the southern sector of Piemonte the transition from the plain to the Apennines is gradual, being characterized by the intermediate presence of hilly terrigenous sectors (Monferrato and Langhe) belonging to the Piedmontese Tertiary basin. The plain area covers 9349.6 km² (36.8% of the total surface area of 25,392 km²).

The stratigraphic relationships among the various continental units in the region are the results of different exogenous processes linked to Quaternary glacial and alluvial dynamics. Generally, these units are lithologically represented by coarse gravel and sandy sediments (locally cemented) with limited amounts of thick clayey–loamy horizons related to lacustrine facies. An unconfined high-productivity aquifer connected to the surface water drainage network is found across the entire Piemonte plain and in the major valleys in the mountain sector. Confined productive aquifers are also widespread; they represent the main regional source of water for human consumption (Civita et al., 2004).

Thermal (55–70 °C) springs exist only in rare geological circumstances in the southern part of the region (Vinadio, Valdieri, Acqui Terme); they have been used since Roman times, mainly as thermal spas. A few less important hot springs occur in other parts of the Alpine chain, linked to particular local tectonic settings, but energy recovery from these resources could have only local significance. On the other hand, geological bodies and groundwater in the Piemonte plain could represent an important source of clean geothermal energy through the widespread implementation of GWHP technology.

In the Piemonte plain, the vertical separation between the unconfined and deeper confined aquifers varies from a few meters to several tens of meters depending on local hydrogeological conditions. Deep, high-quality groundwater bodies are legally preserved for human consumption. To avoid potential pollution of the deeper aquifer, they should not be intersected by the wells to be used to operate the DHE plant. Moreover, GWHP could be used only with shallow groundwater. Nevertheless, where the local hydrogeological conditions are such that no confined aquifer is present below the water table or the top of the confined aquifer is below 60 m depth, it may be appropriate to consider 60 m as the maximum depth for injecting GWHP discharges or of DHE wells.

To evaluate the hydro-geothermal energy potential that might be exploited by the use of GWHP systems in the shallow aquifer across the entire plain, groundwater temperature data collected by the regional groundwater-monitoring network during the period 2000–2005 were used in combination with the hydraulic parameters from the regional database on pumping tests carried out in productive Piemonte wells since 1990 (Regione Piemonte, 2007). For data clustering and basic statistical analysis the 14 planning areas (Fig. 1) separated by hydrogeological boundaries and defined in the Water Protection Plan (WPP) were considered (Regione Piemonte, 2007). Note that temperature-monitoring network points did not coincide with the wells where the pumping tests were conducted (see Table 1).

Chemical analyses of the waters derived from the shallow aquifer have been performed twice a year since 1990 through the regional groundwater-monitoring network (414 measurement
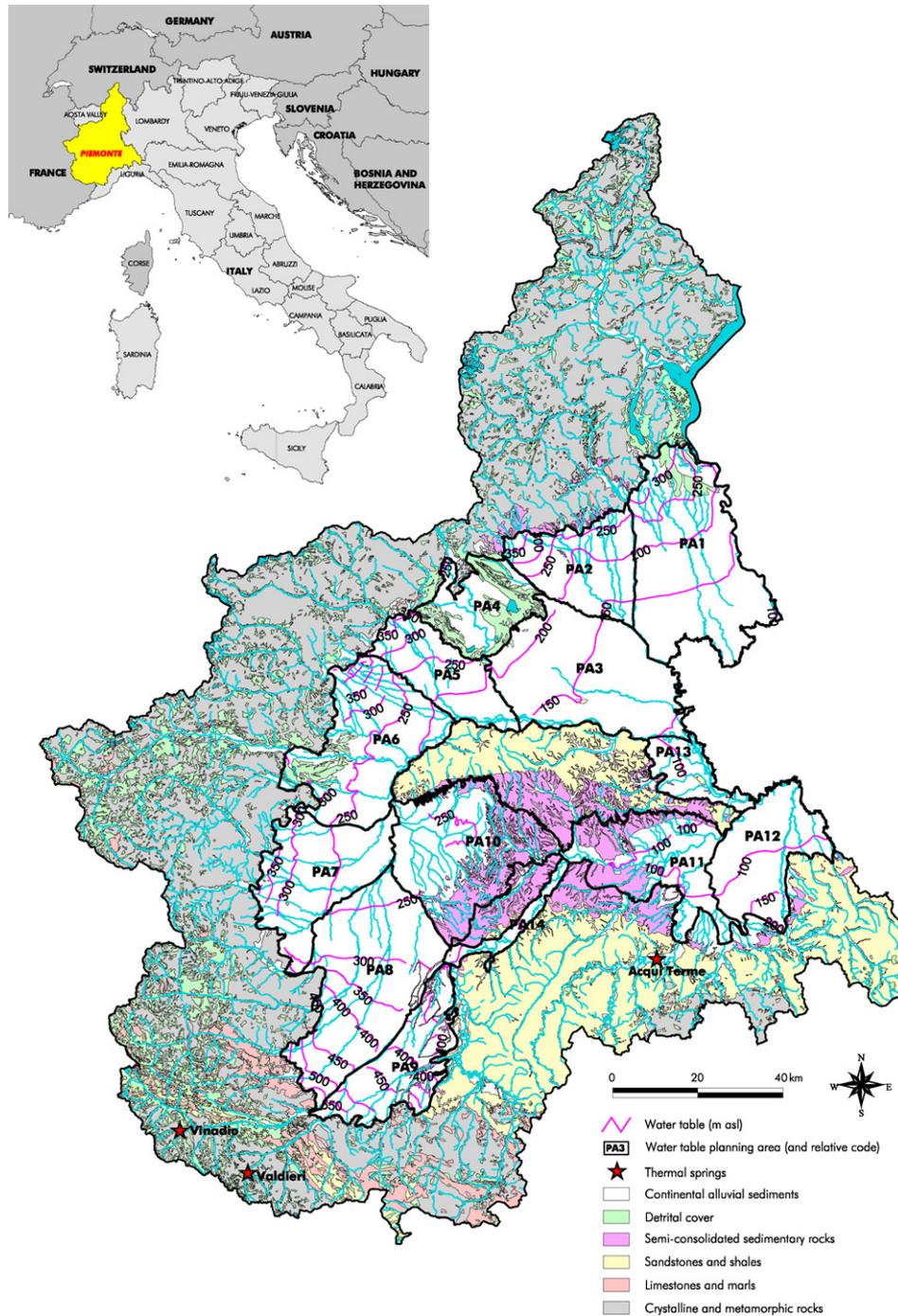
Fig. 1. Hydrogeologic map of Piemonte (modified after Civita et al., 2004).

points). The analyses showed a strong geographical and temporal variability in water quality, and identified some chemical pollution phenomena probably linked to urban and industrial areas. Occasionally, nitrates and phosphates, as well as agricultural runoff, were also present in shallow groundwaters of rural areas (Regione Piemonte, 2007). In general, though, water quality at the regional scale is still good enough to be used without the need for secondary exchangers in the heat pump systems. In exceptional cases (i.e. in the more polluted sites) groundwater quality is unsuitable to be used directly and secondary exchangers are recommended. This technical option would significantly affect both the capital and running costs of the heat pump plant. For this reason, the characteristics of a prospective site (including water chemistry) should be carefully studied before choosing the heating system in order to verify the real economic benefit of installing a GWHP system.

2.2. Typical application of ground coupled heat pumps plant (in particular GWHP)

For a conventional standard (direct) electricity-driven GWHP coupled with a low-temperature heating plant [temperature of the fluid entering the building heating system (t_f) of 28 °C] with a condenser temperature (t_c) of 33 °C and an evaporation temperature (t_e) of 8 °C, the theoretical coefficient of performance (COP), assum-

4 S. Lo Russo et al. / Geothermics xxx (2008) xxx–xxx

Table 1
Summary of temperature data for shallow aquifers derived by the regional monitoring network (2000–2005 studies) and hydraulic parameters derived by pumping tests conducted since 1990

Planning area (PA) code	Area	Surface (km²)	Number of temperature-monitoring wells	Monitoring density ratio (number of monitoring wells/10 km²)	Total number of measurements	Mean groundwater temperature (°C)	Number of pumping tests	Density ratio (number of pumping tests/10 km²)	Mean specific capacity (L s⁻¹ m⁻¹)	Mean saturated thickness (m)	Mean transmissivity (m² s⁻¹)
PA1	Pianura Novarese	1173.2	42	0.36	301	13.6	22	0.19	8.5	34	8.5×10^{-3}
PA2	Pianura Biellese	545.4	38	0.70	359	14.2	6	0.11	6.4	16	1.4×10^{-3}
PA3	Pianura Vercellese	1031.9	60	0.58	483	15.0	7	0.07	1.4	19	1.7×10^{-2}
PA4	Anfiteatro morenico di Ivrea	440.6	15	0.34	104	14.0	15	0.34	10.0	21	1.0×10^{-2}
PA5	Pianura Canavese	453.4	10	0.22	85	14.6	11	0.24	10.6	14	1.1×10^{-2}
PA6	Pianura Torinese	888.0	12	0.14	90	14.1	177	1.99	11.1	19	1.1×10^{-2}
PA7	Pianura Pinerolese	693.8	34	0.49	300	13.7	315	4.54	16.9	27	1.7×10^{-2}
PA8	Pianura Cuneese	1117.0	42	0.38	241	13.7	249	2.23	14.3	21	1.4×10^{-2}
PA9	Pianura Cuneese in destra Stura di Demonte	523.5	39	0.74	256	13.5	28	0.53	10.8	17	1.1×10^{-2}
PA10	Altopiano di Poirino e colline Astigiane	896.1	11	0.12	120	14.2	71	0.79	13.5	23	1.3×10^{-2}
PA11	Astigiano-Alessandrino occidentale	669.6	33	0.49	220	13.2	23	0.34	5.9	24	5.9×10^{-3}
PA12	Pianura Alessandrina orientale	582.5	52	0.89	341	13.3	82	1.41	8.6	20	8.6×10^{-3}
PA13	Pianura Casalese	223.9	13	0.58	97	15.5	8	0.36	7.5	22	1.4×10^{-2}
PA14	Fondovalle Tanaro	110.7	13	1.17	82	14.7	4	0.36	9.8	21	1.3×10^{-2}
Total	Piemonte plain	9349.6	414	0.44	3079	14.0	1018	1.09	13.5	23	1.4×10^{-2}

ing the GWHP runs on an inverse Carnot thermodynamic cycle, is given by

$$COP = \frac{1}{\eta} = \frac{T_c}{T_c - T_e} = 12.24 \tag{1}$$

where η is the thermodynamic efficiency of the direct cycle; $T_c = (273.16 + t_c)$ is the condenser temperature (in Kelvin); $T_e = (273.16 + t_e)$ is the evaporator temperature (in Kelvin); see Appendix A.

The authors' experience in Piemonte shows that a practical COP value of 7.5 can be achieved using heat pumps with extended evaporator and condenser heat-transfer surfaces, which permit very small operating temperature differences (i.e. 2–3 °C) both under steady-state and transient conditions. It is important to point out that the condenser and evaporator temperatures, which directly affect the COP, can be maintained quite constant during the entire heating season because of unchanging groundwater withdrawal temperature.

As Eq. (1) shows, the energetic performance of heat pumps increases with a reduction of either the temperature of the heat-transfer fluid that transports the heat from the heat pump to the heated building spaces (T_e, the evaporation or output temperature) or of the difference between input (T_c, the condenser temperature) and output temperatures. The use of low-enthalpy geothermal energy from favorable aquifers is very advantageous from the standpoint of technical and energy efficiency (Mendrinos et al., 2007). For a notional generic building, if hydrogeological conditions are suitable, the capital and running/maintenance costs of GWHP systems are lower than for a DHE plant of the same size/capacity (IEA, 2007).

The economic benefits of GWHPs are further enhanced, by comparison with traditional fossil fuel solutions, when associated with their environmental benefits in terms of CO_2 emission reductions. These advantages become increasingly important against the background of a growing trend in non-renewable energy costs. This is especially true in Italy, a country highly dependent on energy imports to satisfy domestic consumption. To illustrate these benefits, an example was developed considering three possible options (natural gas, oil and GWHP) to heat a notional residential building with a footprint of 200 m², built to average standards of insulation and air-tightness and equipped with a boiler or heat pump with a 10-year lifetime.

For the GWHP case the average temperature of the source groundwater was taken as 14 °C and the required groundwater flow rate was estimated to be 1 L/s. The average cost of electricity for household appliances is 0.18 €/kWh, with a conversion factor in the regional electricity grid of 9.2 MJ/kWh. Natural gas for domestic uses costs about 0.75 €/S m³ (0.078 €/kWh), whilst the cost of oil for domestic heating is 1 €/kg (0.079 €/kWh); the quoted costs are those prevailing in Piemonte in 2007. The CO_2 emission factor for electric energy from the regional grid is 0.575 kg CO_2/kWh, for natural gas combustion (lower calorific value: 34.5 MJ/S m³)[1] it is 2.91 t CO_2/toe[2] (0.231 kg/kWh), and for heating oil it is 3.53 t CO_2/toe (0.280 kg/kWh). The quoted values for natural gas are those used by suppliers in the Piemonte region in 2007.

The average net energy demand of Piedmontese houses over the heating season is 110 kWh/m². In the case of gas-fired heating systems, seasonal consumption of natural gas is 13.50 S m³/m², which (allowing for the fact that householders may benefit from a 7% discount on the base price) corresponds to a cost of 9.44 €/m²

---

[1] MJ/S m³: 10⁶ J per standard cubic meter.
[2] toe = tonne (1000 kg) of oil equivalent.

Table 2
Comparative summary of costs and emissions for a notional residential building with a footprint of 200 m^2, built to average standards of insulation and air-tightness equipped with a boiler or heat pump with a 10-year life

System	Running costs for energy over a 10-year period (€)		Cost of plant (€)		Total cost (€)	Total CO$_2$ emissions (t)
Gas-fired	18,800		10,000		28,800	59.7
Oil-fired	21,300		9000		30,300	75.2
GWHP	9000		18,500		27,500	23.3
	6000 for the HP	3000 for the GW	15,000 for the HP	3500 for the wells		

GW: groundwater; GWHP: groundwater heat pump; HP: heat pump.

with seasonal emissions of 29.9 kg CO$_2$/m^2. In the case of oil-fired heating systems, oil consumption per season is 11.3 kg/m^2, which corresponds to values of 11.3 €/m^2 and 37.5 kg CO$_2$/m^2, respectively. In these calculations, the efficiency for the gas-fired and oil-fired boilers was assumed to be 0.85 and 0.82, respectively.

In the case of the GWHP plant with a COP of 7.5, an overall plant efficiency of 0.85 (including auxiliary pumps) was adopted. The electrical energy needed to heat the above-mentioned house with an electricity-driven heat pump is therefore 17.25 kWh/m^2 per season, which corresponds to a cost of 3.1 €/m^2 and the emission of 9.9 kg CO$_2$/m^2 per season. To this must be added the emissions due to the operation of the auxiliary pumps, which may be conservatively estimated at about 3 kWh/m^2 per season (1.75 kg CO$_2$/m^2). Two wells (a production and an injection well) should be considered for the open-loop GWHP. A standard drilling operation for a fully equipped system of two 30-m deep wells with an average withdrawal (and injection) rate of 1 L/s costs on average about 3.500 € and about 300 €/year for the running and maintenance of the electrical pumps (functioning on average 8 h/day). Due to the limited water extraction, no significant fee needs to be paid for groundwater use.

Comparative results in terms of total costs and emissions for the different technical solutions are presented in Table 2, which illustrates the real benefits associated with the GWHP option. The scenarios analyzed in this study are designed assuming the implementation of GWHPs on a regional scale.

2.3. Regional building stock and the scope of installing GWHP systems

The Regional Energy Plan (Regione Piemonte, 2004) provided detailed knowledge of the energy consumption for indoor space heating, and drew up different possible scenarios on how it might evolve in Piemonte. Fig. 2 shows the distribution of population as a function of degree-days. From the graphs it can be seen that more than 99% of the population lives in areas with degree-day values between 2422 and 3420 °C-days; the assumed reference temperature (t_r) was 20 °C.

The building stock existing in Piemonte can be divided into three groups on the basis of the required heat-transfer fluid temperatures:

(I) Buildings with low-temperature heating systems (heated floors or ceilings): with working fluid temperatures in the 25–40 °C range;
(II) buildings with medium-temperature heating systems (fan coils, particularly in office buildings) with working fluid temperature in the 45–65 °C range;
(III) buildings with standard high-temperature heating units, with working fluid temperatures in the 60–70 °C range.

Buildings belonging to Group I are the most suitable for coupling to a GWHP. In this case the direct substitution of a standard boiler by a GWHP greatly improves the energy and environmental performance without any additional modifications.

The use of GWHPs in Group II buildings yields better energy performances than standard plants, although the improvement is lower than in Group I. It is possible, however, to obtain performance improvements comparable to those of the previous case by lowering the required temperature level of the heat-transfer fluid. This can be achieved in different ways, by means of interventions which are technically simple and of limited cost; for example, by increasing the number of banks in the building's heat exchanger or increasing the flow rate of the fan operating on the heating elements. The additional cost of these interventions could be minimized if they are performed at the same time as a major maintenance operation of the heating plant (when the fan coils are routinely replaced). The marginal cost of installing a fan coil with one extra heat-transfer element may be considered negligible.

In Group III buildings, equipped with high temperature heating elements, the use of a GWHP, directly coupled to the plant as such, yields only small improvements in the energy and environmental performance with respect to the standard plant. In this case, as before, the performance can be strongly improved if the temperature levels of the heat-transfer fluid are suitably reduced. However, unlike Group II, the retrofitting which is necessary to achieve lower temperature levels of the heating elements is not simple and requires modification of the architectural elements as well. In fact it is necessary to increase the heat-transfer surface of the heating units (by adding new elements or by installing new ones with larger surfaces). Dimensional problems might arise if the units are inserted, as is usual, into ad hoc spaces inside the walls or under the windows.

2.4. Hypothesis of compatible GWHP implementation

The evaluation of the effects of installing GWHP systems in the building stock of Piemonte having average standards of insulation and air-tightness is based on the following assumptions:

- All multifamily buildings equipped with single-family heating systems have been excluded from the potential stock.
- In Group I plants (i.e. plants for Group I buildings) the existing boilers can be substituted by GWHPs only if the boilers are more than 10 years old. In this case the major cost due to GWHP substitution is fully compensated by the decrease in running costs over a 10-year period.
- In Group II plants the GWHPs may replace standard existing boilers only when extraordinary maintenance is under way. Such work takes place, on average, every 15 years. Also in this case the investment cost increase is fully compensated by the decrease in the running costs for fuel. (As a matter of fact, rising fossil fuel costs will probably compensate significantly for the fact that the new (bigger) heating systems could be more expensive).
- In Group III plants, GWHPs might replace existing standard boilers only when major retrofitting of the building and of its internal plumbing is under way. Such operations take place, on average,
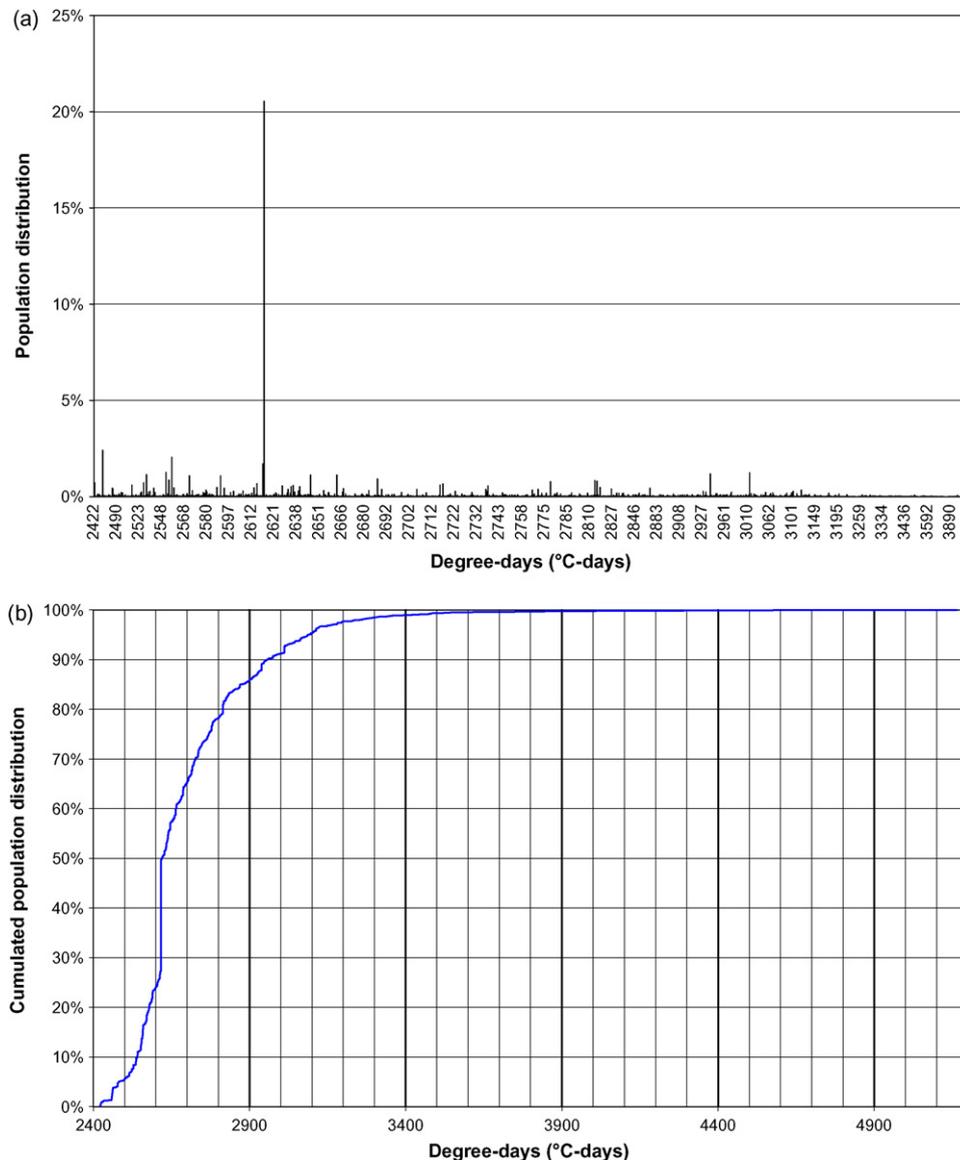
Fig. 2. Human population in the Piemonte region. (a) Distribution with respect to degree-days. (b) Cumulative distribution with respect to degree-days (data from Regione Piemonte, 2004). Assumed reference temperature: 20 °C.

every 30 years. In this case also the extra costs of the heat pump is fully compensated by the decrease in running costs.

As far as new buildings are concerned, the assumption was made that all could be fitted with GWHPs. To be on the safe side, it has been assumed that the yearly renewal rate for the existing building stock will be limited to 2%. It must be stressed that, under the assumptions made for this analysis, the energy savings are related only to those cases in which the installation of GWHPs will lead to increased expenditures that would be fully compensated by the reduction of 10-year running costs, caused by the decrease in energy consumption due to the use of the heat pumps. No credit has been taken for (probable) rising fossil fuel costs.

3. Results and discussion

3.1. Thermal potential of the aquifer

In the Piemonte plain the average groundwater temperature ranges from 13.2 °C (minimum) to 15.5 °C (maximum), with a mean of 14.0 °C on a regional scale (Regione Piemonte, 2007). Higher temperatures in the data set were typical of summer (June and July) measurements in all the areas considered; the lower values were recorded in winter (January and February). It should be noted that where the depth to the groundwater exceeds 9.5 m the variations in recorded temperature at any given measurement point throughout the year are small (1–3 °C) and seasonally controlled. The density of the groundwater temperature-monitoring network is far from the optimal target represented by one measurement point per 10 km^2; only area PA14 (Fig. 1) could be considered sufficiently covered by the network.

The pumping test data are similarly patchy: low densities are due to the scarcity of productive wells in areas (e.g. PA1 and PA3) characterized by shallow depth to groundwater (<1–4 m), while higher values are typical of areas (e.g. PA6, PA7 and PA8) with many wells used for irrigation and a deeper (25–30 m) water table.

On a regional scale, the aquifer is generally characterized by high productivity (average specific capacity: 13.5 L s^{-1} m^{-1}) and good saturated thickness (average: 23 m). These two factors and the relative stability of the groundwater temperature confirm the
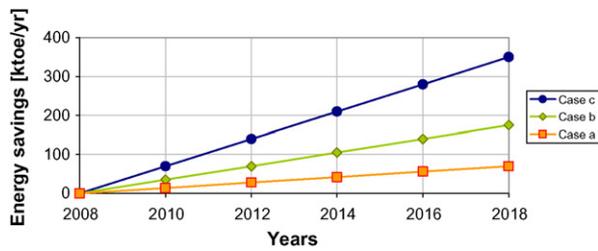
Fig. 3. Potential for primary energy savings in the Piemonte region due to the installation of GWHP systems.

hypothesis that the shallow aquifers are regionally suitable for installing GWHP plants. High values of transmissivity and saturated thickness ensure good heat dispersion in a restricted area around the injection wells. Therefore, thermal interference between wells will be limited, and one could design heat pump systems in such a way that changes in aquifer temperatures near injection wells are as high as 10 °C. Well-designed GWHP systems could optimize thermal energy extraction from the aquifers without causing undue environmental effects.

Quite apart from building design considerations, numerical modeling studies should be carried out to analyze the behavior of the aquifer during the initial (i.e. 1–2 years) experimental phase of a progressive installation of GWHP systems in the region. This would assist in the correct evaluation of the subsurface environmental effects and acquisition of information about subsoil thermal parameters (West et al., 2007) that would be needed when developing technical guidelines for the wide implementation of the technology at a regional scale.

3.2. GWHP systems and environmental effects

The results of different possible improvements in the regional building stock are given in Fig. 3. The hypotheses formulated in Section 2.4 are compatible with the environmental conditions in relation to the characteristics of a good aquifer (i.e. specific capacity and saturated thickness). The timescale also assumes that existing norms and standards will allow an easy procedure to obtain administrative permissions, which is not currently the situation in Piemonte.

Curve 'a' in Fig. 3 represents the case in which GWHP systems are installed in only 20% of the suitable building stock. Experience shows this would correspond to a situation in which the campaign to promote GWHP use has limited effect and does not include significant incentives. Curve 'b' refers to when GWHPs are installed in 50% of the cases where the installation is technically and economically feasible. Experience shows that this occurs when the promotional campaign is effective, and includes information and training services for salesmen and technicians in charge of selling and installing the GWHP systems. Curve 'c' corresponds to when GWHPs are installed in 100% of the cases where it is technically and economically feasible, i.e. the result of a "perfect" promotional campaign. None of the three cases necessarily require significant economic incentives.

Curve "c" in Fig. 3 refers to the case in which GWHPs are installed in all the buildings as soon as it becomes economically and technically feasible. This is highly theoretical since in many buildings by the time a decision has to be made (i.e. in 20–30 years), other heating technologies might be chosen even if GWHP are economically competitive. In order to take this uncertainty into account, some more realistic assumptions (curves 'a' and 'b') have been developed. In any case, the actual situation and the corresponding avoided CO_2 emissions will be linked to the (uncertain) effectiveness of

future GWHP promotion campaigns by the Piedmontese regional government. If these campaigns *do* include significant economic incentives, a sizable increase in the gradient of the curves given in Fig. 3 should be expected. Similar arguments hold if energy prices increase and/or if the GWHP systems costs decrease.

4. Conclusions

The results of simulating different cases for the refurbishment and/or replacement of heating and cooling plants in the building stock of Piemonte show that a significant amount of fossil fuel could be saved by the large-scale installation of ground coupled heat pump systems.

The use of standing column wells and other low-enthalpy geothermal technical solutions (GSHP, DHE, etc.) could augment the positive economic and environmental effects on Piemonte if implemented in parallel with the GWHPs. Appropriate incentives for these technologies, including easier authorization procedures, should therefore be put in place by the public authorities. Wide diffusion of ground-coupled heat pumps could then make a good contribution to reducing emissions of CO_2 and other atmospheric pollutants.

In Group I plants GWHP systems can be installed by simply replacing the boiler without any other modification, greatly enhancing energy and environmental performances. GWHPs can be installed in Group II plants by replacing the boiler, as in Group I; however, in this case the improvement in energy and environmental performances is smaller. Major enhancements can be obtained if limited amounts of heating equipment adaptations are undertaken. No architectural retrofitting is needed.

GWHPs in Group III plants can lead to useful improvements in energy and environmental performances only after significant retrofitting of both the heating elements and the building itself. It must be pointed out that we consider the performance of a GWHP to be good when the extra heat pump costs are fully amortized in strictly economic terms by the reduction in plant running costs (i.e. through savings due to reduced consumption of other type of energy). This does not take into account the avoided environmental costs associated with reduced emissions.

The simulations discussed above focused only on heating usage. It is important to point out that the majority of the housing stock in Piemonte is not equipped with HVAC (heating, ventilation and air conditioning) plants and that, thanks to local climatic conditions, good passive architecture solutions can guarantee reasonable thermo-hygrometric comfort during the summer. The growing utilization of reversible heat pumps able to provide building cooling as well could represent a further benefit and improve the general environmental and economic advantages linked to policies promoting the installation of GWHP systems at a regional scale.

Environmental conditions and the widespread distribution of a suitable shallow aquifer in the entire Piemonte plain encourage the use of GWHPs. Energy demand is concentrated in the urban and industrial areas, which are located preferentially in the plain where low-enthalpy geothermal energy associated with the shallow aquifer is ready available. The collocation of the geothermal energy source and of potential final users represents another important factor that suggests that ground-coupled heat pumps should be considered as a key element in reducing greenhouse gas emissions and primary energy imports in the Piemonte region.
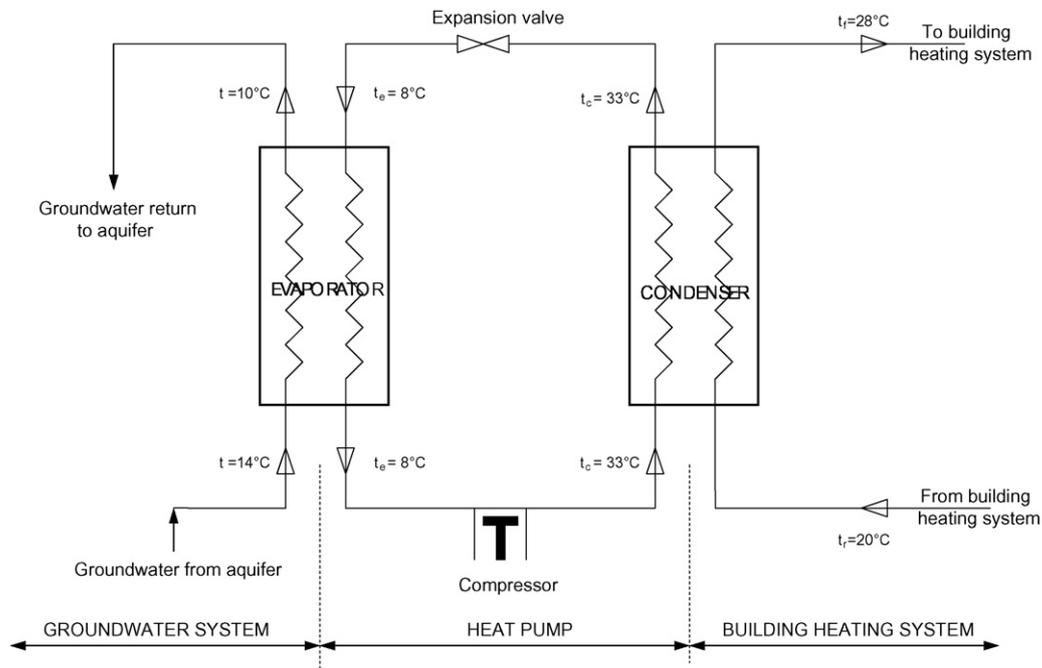
Fig. A1. Schematic diagram of a groundwater heat pump system. Note that here temperatures are given in degrees Celsius (e.g. t_c) while in the text they are given in Kelvin (e.g. T_c).

Appendix A. Schematic description of a groundwater heat pump system

A GWHP captures heat from the groundwater through its evaporator and "pumps" it into to the building heating system through its condenser (see Fig. A1).

The fluid that circulates through the heat pump system (i.e. its condenser, compressor, evaporator, expanding valve and connecting pipes) is a refrigerant, which used to be Freon. Now, for environmental reasons, ammonia or a refrigerant without fluorine is utilized.

The thermodynamic cycle of the refrigerant in the heat pump can be assumed to consist of:

- An adiabatic compression (in the compressor) where mechanical power W_{comp} is fed to the refrigerant;
- a constant pressure (and a constant temperature t_c) condensation, which takes place in the condenser during which thermal power W_1 is taken from the condensing fluid and transferred to the user;
- an isenthalpic cooling in the expansion valve;
- a constant pressure (and constant temperature t_e) evaporation, which takes place in the evaporator, during which thermal power W_2 is taken from the outside (in our case groundwater) and fed to the evaporating fluid.

Under steady-state conditions:

$$W_{comp} + W_2 = W_1 \tag{A1}$$

and

$$\frac{W_1}{W_{comp}} = COP \tag{A2}$$

In Carnot cycle approximation,

$$\frac{W_1}{W_{comp}} = \frac{t_c}{t_c - t_e} \tag{A3}$$

where t_c and t_e is the temperature (in Kelvin) of the condenser and evaporator.

The COP of the heat pump increases with decreasing of $(t_c - t_e)$; to raise the COP it is important to have a low condenser temperature (t_c).

The value of t_c, however, must be higher than the value of the fluid temperature (t_f) that takes the heat from the evaporator to the heating elements in the building. Therefore to have a high COP it is necessary to have low-temperature heating systems in the buildings.

References

Cadoppi, P., Giardino, M., Perrone, G., Tallone, S., 2007. Litho-structural control, morphotectonics, and deep-seated gravitational deformations in the evolution of Alpine relief: a case study in the lower Susa Valley (Italian Western Alps). Quaternary International 171–172, 143–159.

Civita, M., Lo Russo, S., Vigna, B., 2004. Hydrogeological sketch map of Piemonte (NW Italy) 1:250.000. In: Map presented at the 32nd International Geological Congress (32IGC), Florence, Italy, August 21–28.

Coward, M.P., Dietrich, D., 1989. Alpine tectonics—an overview. In: Coward, M.P., Dietrich, D., Park, R.G. (Eds.), Alpine Tectonics, vol. 45. Special Publication-Geological Society London, pp. 1–29.

Debelmas, J., 1986. Intracontinental subduction and mountain uplift: the example of Western Alps. Geologie Alpine 62, 1–10.

DOE, 1999. Renewable Energy Annual 1998: Issues and Trends. U.S. Department of Energy, Office of Coal, Nuclear, Electric and Alternate Fuels, Report DOE/EIA-0603(99), Washington, DC, USA, 117 pp. http://tonto.eia.doe.gov/FTPROOT/renewables/060399.pdf.

Drijver, B., Willemsen, A., 2001. Groundwater as a heat source for geothermal heat pumps. In: International Summer School on Direct Application of Geothermal Energy, International Geothermal Association, Bad Urach, Germany, September 17–20, pp. 156–166.

EC, 2006. Action Plan for Energy Efficiency: Realising the Potential. European Commission, COM, 2006, 545 Final, Brussels, Belgium, 25 pp. http://ec.europa.eu/energy/action_plan_energy_efficiency/doc/com_2006_0545_en.pdf.

EC, 2007. An energy policy for Europe. Communication from the Commission to the European Council and the European Parliament. European Commission, SEC COM, 2007, 12, Brussels, Belgium, 27 pp. http://ec.europa.eu/energy/energy_policy/doc/01_energy_policy_for_europe_en.pdf.

Gebauer, D., 1999. Alpine geochronology of the Central and Western Alps: new constraints for a complex geodynamic evolution. Schweizerische Mineralogische und Petrographische Mitteilungenschweiz 79, 191–208.

Hunziker, J.C., Martinotti, G., 1987. Geochronology and evolution of Western Alps: a review. Memorie della Società Geologica Italiana 29, 43–56.

IEA, 2007. Ground-Source Heat Pumps Overcoming Market and Technical Barriers. International Energy Agency Heat Pump Centre, Annex 29. http://www.heatpumpcentre.org/Projects/Annex_29.asp.

Mendrinos, D., Karytsas, C., Sanner, B., 2007. Project GROUND-REACH reaching the Kyoto targets by means of a wide introduction of ground coupled heat pumps (GCHP) in the built environment. In: Proceedings of the European Geothermal Congress EGC, Unterhaching, Germany, May 30 to June 1, 2007, 6 pp. http://www.egec.net/target/final%20paper%20Groundreach.pdf.

PDEP, 1996. Ground Source Heat Pump. Pennsylvania Department of Environmental Protection Fact Sheet, Harrisburg, PA, USA, 2 pp.

Polino, R., Dal Piaz, G.V., Gosso, G., 1990. Tectonic erosion at the Adria margin and accretionary processes for the Cretaceous orogeny of the Alps. Memoires, Societe Geologique France 156, 345–367.

Rafferty, K., 2000. Scaling in geothermal heat pump systems. GeoHeat Centre Quarterly Bulletin 21, 11–15.

Rafferty, K., 2001. Design aspects of commercial open-loop heat pump systems. GeoHeat Centre Quarterly Bulletin 22, 16–24.

Regione Piemonte, 2004. Piano Energetico Ambientale Regionale. D.C.R. n. 351-3642, Turin, Italy. http://www.regione.piemonte.it/ambiente/energia/piano.htm.

Regione Piemonte, 2007. Piano di Tutela Delle Acque. D.C.R. n. 117-10731, Turin, Italy. http://www.regione.piemonte.it/acqua/pianoditutela/pianoditutela.htm.

Vezzosi, G., Garzanti, E., Monguzzi, S., 2004. Erosion in the Western Alps (Dora Baltea basin). 1. Quantifying sediment provenance. Sedimentary Geology 171, 227–246.

West, M.R., Kueper, B.H., Ungs, M.J., 2007. On the use and error of approximation in the Domenico (1987) solution. Ground Water 45, 126–135.