POLITECNICO DI TORINO

Corso di laurea di 2° livello in
INGEGNERIA ENERGETICA E NUCLEARE

ENERGY AND GEOLOGICAL PERFORMANCE ANALYSIS OF AN OPEN LOOP GEOTHERMAL HEAT PUMP SYSTEM:

The case study of a health assistance residence in Turin

Tesi di Laurea Magistrale

Anno accademico 2018-19

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Introduction

This thesis takes inspiration from the continuous research of alternative ways to satisfy thermal requirement of buildings, in order to reduce energy consumption and CO_2 emission. In particular this thesis is focused on the building conditioning with Open loop Geothermal Heat Pump System. This particular technology is able to extract heat from the underground water to heat buildings during winter seasons. Then, during summer, thanks to its reversibility, it can cool building extracting heat and releasing to the underground water.

This work is realized thanks to the collaboration with "Dipartimento Ambiente e Vigilanza Ambientale" of "Città Metropolitana di Torino". It has permitted to take into account a real Open loop Geothermal Heat Pump System located in Turin as reference case for this thesis.

Initially, during Chapter 1, to introduce the topic, general concepts on geothermal energy are proposed. Hydrological and hydrogeological condition are also reported with general formulations of water flow and heat transport in the subsurface.

Chapter 2 is completely dedicated to the explanation of a Geothermal Heat Pump System. Starting to the resource, it is proposed the classification of Closed loop and Open loop geothermal connection, their relative characteristics and all possible shapes and conformations. A brief description on heat pump technology is present.

The case study of this thesis is presented in Chapter 3, the structure at issue is a health assistance residence of new realization where an Open loop Geothermal Heat Pump System is installed. Thanks to the presence of a data collection of geothermal parameters, it is possible to report an appropriate analysis and some considerations on the real operation of the plant.

To compare this reference case with other possible heating and cooling production scenarios, in Chapter 4, a Cost Optimal analysis is performed. Scenarios are created selecting different devices for production of heating and others for the production of cooling. Final and primary energy consumptions are calculated in accordance with efficiencies of different devices and the used energy vector. CO_2 emission is also reported to have an idea on the environmental impact. Talking about costs, initial investment, replacement, maintenance and energy are considered to compute a global Cost for the reference case and different scenarios. At the end, Cost Optimal analysis results are showed graphically.

Nomenclature

A	Surface	m^2
b	Aquifer saturated thickness	m
c	Mass specific heat capacity	J/kg/K
c_{vol}	Volumetric heat capacity	J/m^3/K
d	Diameter	m
E	Energy	J
f_P	Primary energy vector	-
g	Gravitational acceleration	9.81 m/s^2
h	Hydraulic head	m
i	Hydraulic gradient	-
K	Hydraulic conductivity	m/s or cm/d
k	Intrinsic permeability	m^2 or cm^2
L	Abstraction and reinjection well distance	m
LHV	Lower heating value	kWh/Sm^3
l	Length	m
M	Mass	kg
$\dot{m}$	Mass flow	kg/s
P	Generic power	W
Q	Energy in form of heat	J or kWh
$\dot{Q}$	Heat flux	W
r_w	Well radius	m
q	Heat flux density	W/m^2
S	Storativity	-
S_r	Specific retention	-
S_S	Specific storage / elastic storage coeff.	1/m
S_y	Specific yield	-
s_w	Steady state drawdown	m
T	Temperature	K or °C
t	Time	s
V	Volume	m^3
$\dot{V}$	Volume flow rate	m^3/s
v	Velocity	m/s
α	Compressibility of aquifer skeleton	1/(N/m^2)
β	compressibility of water	1/(N/m^2)
η_{emi}	Emission efficiency	-
η_{dis}	Distribution efficiency	-
η_{reg}	Regulation efficiency	-
η_{gen}	Generation efficiency	-
η_{glob}	Global efficiency	-
ϑ	transmissivity	m^2/day
λ	thermal conductivity	W/m/K
μ	dynamic viscosity	Pa s
ρ	density	Kg/m^3
φ	porosity	-
φ_e	effective porosity	-
∇^2	Laplace's operator	-

Chapter 1: Geothermal energy

1.1. General concept

The Earth has cooled since its formation, yet the decay of radiogenic isotopes, and in particular uranium, thorium and potassium, in the planet's interior provides a continuing heat source. The current total heat flux from the Earth to space is 44.2±1.0 TW (The KamLAND Collaboration, 2011). Before this big amount of heat leaves the earth, it flows through the crust principally by conduction generating a decreasing in temperature from the deepest zones of the crust to the surface. This variation of temperature is known as geothermal gradient and it is influenced by geological characteristics of the crust, but, in general, an average value of geothermal gradient is near to 30°C/km in the crust (Toth et al., 2017).

Due to the alternation of hot and cold seasons and the radiation of the sun, the Earth surface temperature changes cyclically during the year. Almost a third part of the heat radiated by the sun on the Earth flows in the Earth and warms up the first metres of the crust. On the contrary, during winter, the heat stored during summer is released in atmosphere and a decreasing of Earth surface temperature occurs in the first metres (Erdélyi et al., 2014).

In most cases, the heat from the Earth and the atmospheric conditions bring to have, in a 1 km well in dry rock formations, with an average thermal gradient of 25-30°C/km, a bottom temperature near 40°C (assuming a mean annual air temperature of 15°C) and in a 3 km well 90-100°C. Sometimes, due to geothermal anomaly this temperature can rise up fast than before and it reaches hundreds of Celsius degrees.

So far utilisation of energy stored in the Earth has been limited to areas in which geological conditions permit a carrier (water in the liquid or vapour phases) to "transfer" the heat from deep hot zones to or near the surface, principally for power production.

In the last three decades, the appearance of ground source heat pumps makes possible for all countries to use the heat of the earth for heating and/or cooling. As reported on the Intergovernmental Panel on Climate Change, heat pumps can be used basically everywhere (Fridleifsson et al., 2008).

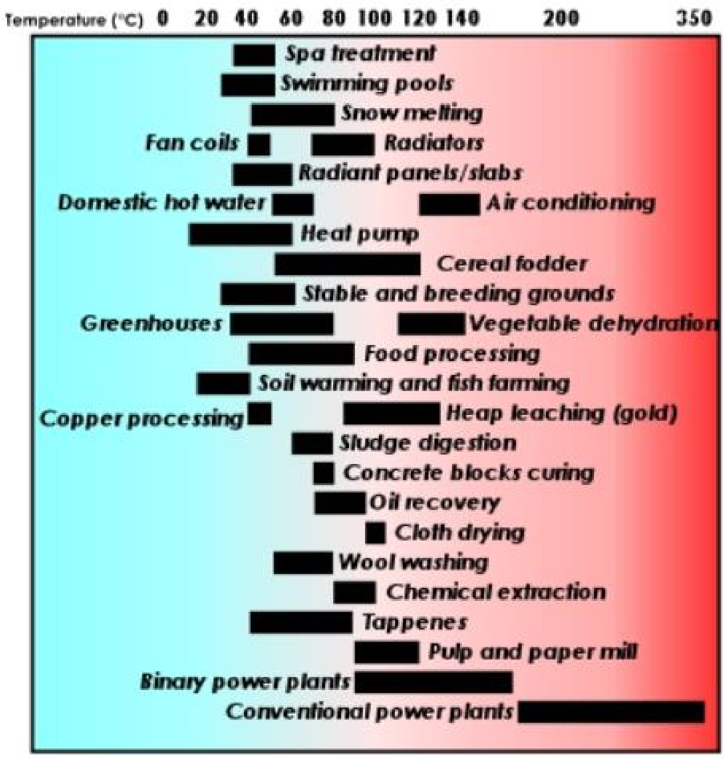
Having the geothermal energy at various temperatures, a classification of the resources is necessary. In the past, considering the temperature of the resource, lot of researchers distinguished three enthalpy levels using different temperature thresholds, this is notable in the table below.

Table 1 Geothermal resources classification by temperature [°C] (Dickson and Fanelli, 2004)

	Muffler and Cataldi (1978)	Hochstein (1990)	Benderitter and Cormy (1990)	Nicholson (1993)	Axelsson and Gunnlaugsson (2000)
Low Enthalpy resources	< 90	< 150	< 100	≤ 150	≤ 190
Intermediate Enthalpy resources	90 ÷ 150	125 ÷ 225	100 ÷ 200	-	-
High Enthalpy resources	> 150	> 225	> 200	> 150	> 190

A first classification can be applied distinguishing the cases where the heat of the ground is used directly for a specific purpose and the cases in which the heat is used to produce electricity. The last use is often related to the availability of high temperature energy typical of high enthalpy resource and water Ranking cycles are used for this aim. When organic fluids began to be exploited in an Organic Ranking cycle, power production was interesting also for low enthalpy resources. The disposal resource at different temperatures can be used for many human activities as Lindal, 1973 shows in this picture.

Fig. 1 Application field of the geothermal resource at different temperatures (Lindal, 1973)



As reported before, low enthalpy geothermal resources can be found in the most superficial layers of the crust. By the geothermal point of view, thermal energy can be extracted from the geothermal resource and in this case the ground is considered as a source of energy. It is also possible to inject an amount of heat from the surface to the ground considering the resource as a sink of energy. These two operations are often registered in building conditioning: extracting the heat from the resource in winter and injecting heat to resource during summer. The stored or storable thermal energy of the resource is function of its substance heat capacity and its temperature variation.

A subsoil can be composed by different minerals in different proportion and in different states of aggregation, then it is very difficult to have exact value for all possible type of subsoil. If it is necessary, the value of a particular subsoil can be found by measurement on a sample of soil. Another approximate way could be to analyse the subsoil to determine the composition in term of relative quantities of the single components which heat capacity are known from literature and calculate the heat capacity value with a weighted average.

Table 2 Principal soil components density, conductivity and heat capacity (Stauffer et al., 2017)

Material	ρ_m *(kg m⁻³)*	λ_m *(W m⁻¹ K⁻¹)*	C_m *(J m⁻³ K⁻¹)*
Clay, silt, dry	1800–2000	0.4–1.0	1.5×10^6–1.6×10^6
Clay, silt, saturated	2000–2200	0.9–2.3	2.0×10^6–2.8×10^6
Sand, dry	1800–2200	0.3–0.8	1.3×10^6–1.6×10^6
Sand, saturated	1900–2300	1.5–4.0	2.2×10^6–2.8×10^6
Gravel, blocks, dry	1800–2200	0.4–0.5	1.3×10^6–1.6×10^6
Gravel, blocks, sat.	1900–2300	1.6–2.0	2.2×10^6–2.6×10^6
Clay, siltstone	2400–2600	1.1–3.5	2.1×10^6–2.4×10^6
Sandstone	2200–2700	1.3–5.1	1.8×10^6–2.6×10^6
Marble	2300–2600	1.5–3.5	2.2×10^6–2.3×10^6
Limestone	2400–2700	2.5–4.0	2.1×10^6–2.4×10^6
Dolomite	2400–2700	2.8–4.3	2.1×10^6–2.4×10^6
Granite	2400–3000	2.1–4.1	2.1×10^6–3.0×10^6
Bentonite		0.5–0.8	$\cong 3.9 \times 10^6$

The pre-mentioned parameters are useful to study and simulate the temperature variation through the geological layers thanks to the general conduction equation.

Eq. 1 $$\lambda * \nabla^2 T = \rho * c_p * \frac{\partial T}{\partial t}$$

To derive the heat flux density, the Fourier law is shown below for a mono-dimensional, homogeneous and isotropic problem.

Eq. 2 $$q = -\lambda * \frac{dT}{dx}$$

1.2. Hydrological and hydrogeological conditions

In a geological formation, it is possible to find void spaces between the grains; taking into account a portion of subsoil, the ratio between the void space volume and total volume is called porosity (φ).

Eq. 3
$$\varphi = \frac{V_{void}}{V_{tot}}$$

Due to the possibility to have void space, it is possible to find also water that is infiltrated through the grains. The groundwater can be found in different states: moisture, liquid or vapour.

Moisture is often find in the first metres of the ground due to the meteoric precipitation; in this case water is suspended in the soil grains and it not very interesting for geothermal purposes.

Liquid water in the ground layers is moved by gravitational attraction force downward until it finds an obstacle. When water occupies all void space of a geological formation, we talk about of saturated zone; instead when it doesn't occur we talk about of unsaturated zone.

Water vapour is present if the water temperature is higher than the boiling point at a certain pressure. The presence of water vapour stored under pressure in the ground is due to a concatenation of specific geological aspects.

Groundwater can move through the ground layer thanks to the porosity of the soil available for fluid flow called effective porosity (φ_e). Not all void spaces are available for fluid flow; for this reason, effective porosity is less than the total one.

Two important factors are: the specific yield (S_y), that is the ratio between the volume of water that drains from soil by gravity and the total volume, and

Eq. 4
$$S_y = \frac{V_{extractable\ by\ gravity}}{V_{tot}}$$

the specific retention (S_r), which considers the portion of volume occupied by the pendular water. Pendular water is a part of water that remains on the grains surface for water surface tension.

Eq. 5
$$S_r = \frac{V_{pendular\ water}}{V_{tot}}$$

The sum of the specific yield and specific retention is the total porosity.

Eq. 6
$$\varphi = S_y + S_r$$

Each type of soil can have a proper intrinsic permeability (k), which is the ability for fluids to flow through rocks measured in Darcy (1 D = 9.87x10^ (-9) cm^2). This parameter can be obtained with the relation below.

Eq. 7 $$k = \text{Shape factor} * {d_{\text{mean pore}}}^2$$

Taking into account the intrinsic permeability is possible to distinguish different types of geological formations. With an intrinsic permeability greater than 10^ (-2) Darcy, a portion of soil filled of water is called aquifer. An aquifer is characterized by a relatively high specific yield to store groundwater and a relative easy movement of the groundwater between the soil grains, allowing an economic useful. Below the value before, the geological formation is a confining layer (Lo Russo, 2018).

Table 3 Principal soil intrinsic permeability (Lo Russo, 2018)

Ranges of Intrinsic Permeabilities and Hydraulic Conductivities for Unconsolidated Sediments		
Material	**Intrinsic Permeability (darcys)**	**Hydraulic Conductivity (cm/s)**
Clay	$10^{-6} - 10^{-3}$	$10^{-9} - 10^{-6}$
Silt, sandy silts, clayey sands, till	$10^{-3} - 10^{-1}$	$10^{-6} - 10^{-4}$
Silty sands, fine sands	$10^{-2} - 1$	$10^{-5} - 10^{-3}$
Well-sorted sands, glacial outwash	$1 - 10^{2}$	$10^{-3} - 10^{-1}$
Well-sorted gravel	$10 - 10^{3}$	$10^{-2} - 1$

It is necessary to precise that the intrinsic permeability and also other characteristics, can have different values taking into account different directions of different portion of soil. In the reality, it is much common to dispose heterogeneous and anisotropic subsoil respect to a homogeneous and isotropic one. Due to this factor, sometimes it is very difficult to represent correctly the ground and its properties under the Earth surface.

As it will be explained later, the possibility to have to disposal an aquifer from geothermal purposes can bring at the realization of an open loop circuit where the groundwater is pumped out of the aquifer for a geothermal use. When the intrinsic permeability or the stored water are not enough, to use low enthalpy geothermal energy, it is necessary the realization of a closed loop circuit, in which an heat transfer fluid flows to exchange heat with the resource (Stauffer et al., 2017).

1.3. Fundamentals of water flow and heat transport in the subsurface

By the geothermal point of view, we are interested to the heat exchange between the ground and a surface device that makes possible to use the heat of the resource or to inject it. It is necessary to know what are the parameters, characteristics and laws useful for this purpose.

First of all, it is useful to study the movements of groundwater in the subsoil. The fundamental parameter for this aspect is the hydraulic conductivity (K), get from the relation below.

Eq. 8
$$K = k * \frac{\rho_{water} * g}{\mu_{water}}$$

Hydraulic conductivity is the ability of a water-bearing geological material to transmit water. It is function of properties of both porous media and the fluid passing through it. These water parameters are not fixed, but they depend from water temperature, pressure and salinity.

To evaluate the quantity of water that flows in a permeable layer the Darcy relation is necessary.

Eq. 9
$$\dot{V} = -K * A * \frac{dh}{dl}$$

In the equation before dh/dl is the hydraulic gradient; it is also represented with “i”.

Darcy equation is valid only for laminar flow and when the Reynolds number is confined between 1 and 10 (Lo Russo, 2018).

Eq. 10
$$Re = \frac{\rho_{water} * v_{seepage} * d_{pore}}{\mu_{water}}$$

Hydraulic processes are important for heat transport whenever advective heat flux, by flowing water, is significant. Also in the case of stagnant or static conditions, the water content plays a role in the thermal parameters (Stauffer et al., 2017). This is due to the relatively high heat capacity of the water, which brings an increasing of the thermal energy stored by geothermal resource. As the other properties, the specific heat is dependent by the water conditions.

Taking into account a cubic metre of an underground layer, it is possible to calculate how much thermal energy can be extracted/injected from/to it. The total thermal energy is the sum of the contribution of energy of solid particles and water, if it is present and it occupies the total void spaces. Thus, it is possible to consider the different materials as a single substance and derive the specific heat per unit of volume, as it is shown below (Lo Russo, 2018).

Eq. 11
$$c_{vol} = \frac{E_{tot}}{V_{tot} * \Delta T} = (1 - \varphi) * \rho_{soil} * c_{soil} + \varphi * \rho_{water} * c_{water}$$

In this elaborate only unconfined aquifers are considered as an interesting geothermal resource, therefore some useful parameters of unconfined aquifer are reported.

The distance between water table and the confining layer is the aquifer saturated thickness (b).

To measure the amount of water that can be transmitted horizontally through a unit width by the full saturated thickness of the aquifer under a hydraulic gradient of 1, transmissivity (ϑ) can be used.

Eq. 12 $$\vartheta = K * b$$

The variable that permits to know the amount of water per unit volume of a saturated formation stored or expelled by the mineral skeleton and water compressibility is the specific storage, called also elastic storage coefficient (S_S).

Eq. 13 $$S_S = \rho_{water} * g * (\alpha + \varphi * \beta)$$

For an unconfined aquifer, the volume of water, absorbed or expelled from the storage, per unit surface area, per unit change in head is the storativity (S), called also storage coefficient.

Eq. 14 $$S = S_y + b * S_S$$

Being the "$b * S_S$" product several order of magnitude smaller than S_y for an unconfined aquifer, the previous equation can be reduced as follow.

Eq. 15 $$S = S_y$$

Storativity of unconfined aquifers can be comprised from 0.02 to 0.30.

From the assumption before, volume of water drained from an aquifer as the head is lowered may be found from the formula below.

Eq. 16 $$V_{water} = S * A_{aquifer} * \Delta h$$

Normally, in an aquifer, Δh and generically h can be measured by a particular device called piezometer. Nowadays, it is an electronic device installed in a detection well principally to have information on the precise site where the detection well is drilled. In addition, comparing data from other detection well it is possible to reconstruct the water table of a real unconfined aquifer of a particular zone using triangulation method (Lo Russo, 2018).

Chapter 2: Geothermal heat pump system

Low enthalpy geothermal energy is the amount of heat extracted by a low enthalpy geothermal resource which doesn't exceed the thresholds reported in Table 1.

Among the different geothermal energy applications of Fig. 1, "Heat pump" represents the only technology capable to use geothermal energy at very low temperature which doesn't represent an interesting source of energy for other applications. Before heat pump, this portion of geothermal energy wasn't an interesting source of energy although it is easy to obtain everywhere on the Earth surface.

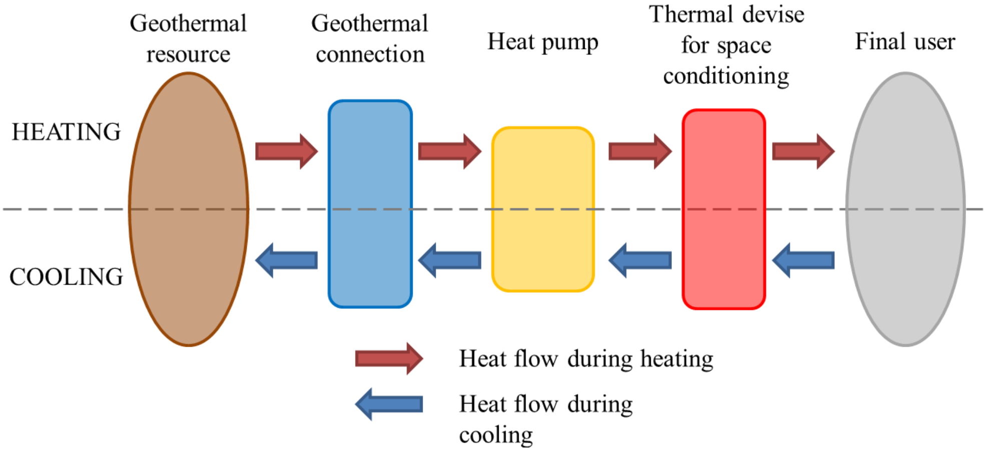
In most cases geothermal heat pump systems have a double role on the space conditioning. During the cold seasons these systems are used to heat the spaces, in particular heat pump bring an amount of heat from the geothermal resource to the thermal user. On the opposite, during hot seasons geothermal heat pump systems can extract heat from the thermal users to carry it to geothermal resource which, in this case, is considered as a thermal sink. In this way the geothermal resource can be accounted as a tank of energy rather that a pure source of heat.

Conceptually a geothermal heat pump system is composed by five elements:

- Geothermal resource;
- Geothermal connection;
- Heat pump;
- Thermal devise for space conditioning;
- Final user.

Each of these components have a precise scope in the system, but it can be of different typologies for different field of application.

Fig. 2 Block diagram of a geothermal heat pump system with heat flow representation during heating and cooling conditioning



2.1. Geothermal resource

The geothermal resource, as reported before, is a portion of subsoil at a specific condition of temperature, which doesn’t change strongly during the year.

Also groundwater and the union of these are considered a geothermal resource. Furthermore, sometimes water of: rivers, ponds, lakes, lagoons and sea can be used for thermal conditioning for its availability. Also superficial water can be assumed as a geothermal resource. The reason is due to the fact that this water, over to exchange heat and mass with the atmosphere and to receive heat radiation of the sun, exchanges heat and mass with the ground having a near link with the underground water and a low thermal resistance with the ground. By an engineering point of view, the superficial water can be an interesting source or sink of thermal energy, but more restrictions can be adopted for the presence of particular chemical species and for the possible interaction between devices and flora and fauna present in the superficial water.

2.2. Geothermal connection

Geothermal connection is the way or the device used to extract/inject the heat from/to the geothermal resource. The first distinction between geothermal connections is possible for the absence or present of water extraction from the resource. These two typologies are called: closed loop geothermal system and open loop geothermal system.

2.2.1. Closed loop geothermal system

In general, a closed loop geothermal system is a pipes circuit in thermal contact with the geothermal resource and its entrance and its exit are connected to the heat pump. In the pipe circuit a heat transfer fluid flows to extract a heat flow from the resource for the difference between the fluid and resource temperature. This system can be considered as a heat exchanger.

It is possible to classify the closed loop geothermal systems in different way; each component can be realized in different way or to have different characteristics.

Taking into account the area where the future analysis will be conducted, it is advisable to observe DD. 3 marzo 2016, n. 66 ("Determinazione Dirigenziale") of Piedmont region and it is called: "Linee guida regionali per l'installazione e la gestione delle sonde geotermiche". In fact, it gives some guide lines for the geothermal heat exchanger: design, installation, test, management and decommissioning. This document is realized in order to obtain an acceptable impact of the geothermal heat exchangers on the water resource. Thus, it discusses in detail the heat exchangers with a depth higher than 5 metres, in particular, vertical one. In this document, only classification between systems is adopted taking into account the thermal or cooling power, as below:

- Small plant: thermal or cooling power less or equal to 30 kW;
- Big plant: thermal or cooling power more than 50 kW or system with more than 10 boreholes.

In this elaborate, a different distinction is realized and the category described more in detail in "DD.3 marzo, n. 66" is the vertical heat exchanger one realized in field in thermal contact with the ground; other closed loop typologies are grouped together.

- **Location of a closed loop geothermal system**

A closed loop geothermal connection can be situated almost everywhere in the world and in almost all geological formations.

It is normally located in thermal contact with the ground reaching depths that doesn't exceed 200 metres (Casasso and Sethi, 2014).

Often, also underground water is present, as it is reported before, the storable energy increases. The movement of the underground water can strongly increase the performance of the system for the presence of heat transfer by convection and the presence of advection due to the mobility of the water between the grains of the ground (Casasso and Sethi, 2014).

As written before the superficial water can be an interesting source of energy; it necessary also to evaluate the possibility to dispose this water during the year without excessive temperature variation. In particular, as regards the temperature drop during the winter that could freeze the water and to compromise the circuit of its performance.

Nowadays, some studies are focusing on the installation of the geothermal heat exchangers in correspondence of the construction of buildings, tunnels and sewers. From the realization of certain constructions, it is possible to reach a depth in which the ground is not influenced by atmospheric seasonal perturbation decreasing excavation costs. In all cases the geothermal heat exchanger mustn't have negative interaction with the structures and it doesn't compromise the principal function of these realizations.

During a realization of building piles, a geothermal pipe circuit can be fixed at the iron frame to realise successively a reinforced concrete pile. The underground pillars arrangement, being dictated by structural necessity, couldn't be interesting from a geothermal point of view; also their number and dimensions can't correspond with the ones necessary to provide the required thermal power. Concrete and earth have almost the same thermal conductivity (~1.4W/m/K), therefore this different material that surround the pipe circuit not influence the performance. After the construction is impossible to find and repair a leakage in a pile, in this case only possible to exclude the failed pile (Makasis et al.,2018).

Taking into account tunnels it is possible to reach very deep areas. Tunnels are realized in an urban contest for car or subway, but it is possible to find tunnel crossing hills, mountains or where is necessary to overcome particular geological formations. Simultaneously, with a tunnel is possible to dispose a huge surface for heat exchange considering diameters of order of 10 metres and length of order of some kilometres. As energy piles, a pipe circuit is present inside the structure and is very difficult to repair it. Considering to cover totally a tunnel, the possible extractable thermal power is very high; it is necessary to dispose a thermal user relatively close to the tunnel to have an economic interest (Tinti et al., 2017).

As it is reported in DD.3 marzo, n. 66, it is good practice to maintain 1 metre of distance from underground services, like: potable water, sewer, gas pipes, electrical cable; to avoid a future interaction between tree roots, 2 metres from high stem tree. It is also advisable to respect minimal distances for the property limits.

- **Heat transfer fluid for closed loop geothermal system**

The heat transfer fluid permits to carry the heat from the earth to the heat pump. Nowadays, in the most of cases, heat transfer fluid is in form of liquid. Rarely, it is possible to find geothermal installations in which a changing phase fluid is present, these types of heat transfer fluids are used in direct circuit. With direct circuit we mean that the geothermal connection is a part of the heat pump; any secondary circuit is present. In special cases, there are geothermal heat exchanger directly connected to a ventilation system. An underground pipe captures the external air and pre-heating or pre-cooling it reduces the thermal consumption related at an air conditioning system.

Taking into account the liquid heat transfer fluid (or the air, though these systems are not treated in this elaborate), the principle upon which the heat is exchanged between the ground and the heat is based on the capacity of the fluid to store energy changing its temperature. From the First Principle Balance it is possible to obtain the thermal power captured from the ground by the fluid.

Eq. 17
$$\dot{Q} = \dot{m} * cp * |T_{out} - T_{in}|$$

Designing a geothermal heat exchanger, it is necessary to know what is the minimum temperature that the liquid can reach. To do this is necessary also to consider the periods in which the system doesn't work during winter season for possible temperature drop in shallow portion of the pipe circuit. The best liquid for its cost, thermal property and absent environmental impact is water; only the relative high freezing point (0°C) could result a problem. To reduce the water freezing point is possible to mix some chemical compounds; unfortunately, also positive water properties will be altered. The possible chemicals are called anti-freeze substances and their relative quantity in water affect proportionally the characteristics of the mixtures. To consider an anti-freeze solution as a heat transfer fluid we need to know also: thermal conductivity (λ), specific heat (c), density (ρ) and the dynamic viscosity (μ). The thermal conductivity affects the convective heat exchange, therefore rising λ, the heat transfer coefficient increases. Instead the total amount of thermal energy carried by the fluid is directly proportional to heat capacity. The volume filled by the substance is dependent by its density and a higher value of dynamic viscosity gives greater hydraulic losses which increase the energy consumed by the circulation pump. By an environmental point of view, it is desirable to choose chemicals with a fast degradability for not compromise the underground health which need long time period to re-establish itself.

Table 4 Physical properties of the anti-freeze solutions (Casasso and Sethi, 2014)

Fluid	$T_{freezing}$ [°C]	λ_f [W m^{-1} K^{-1}]	c_f [J kg^{-1} K^{-1}]	ρ_f [kg m^{-3}]	μ_f [mPas]
Prop.glycol 25%	−10	0.45	3974	1026	5.51
Ethanol 24.4%	−15	0.426	4288	972	5.85
Prop.glycol 33%	−15	0.416	3899	1015	8.17
$CaCl_2$ 20%	−20	0.54	3030	1186	4

In table before, some anti-freeze in water solutions, used in the reality, are reported with a precise weight percentage. The calcium chloride at 20% weight is the most performing one between reported ones. This is due to the combination of the highest thermal conductivity and density values and the lowest dynamic viscosity, though its heat capacity is the lowest one (Casasso and Sethi, 2014).

DD.3 marzo, n°66 restricts the possible fluid typologies to air, water and mix of water and propylenic glycol. Anti-algae, alcohol or ethylene glycol must be avoided. Not harmful fluids for human and environment health and biodegradable fluids are advised.

- **Pipes of a closed loop geothermal system**

To realize a pipe circuit, first of all it is necessary to choose the material of the pipes. On the market lot of materials are available with substantial differences.

There are metal and plastic materials: the first ones have a relative high thermal conductivity, but they are more expensive than the plastic ones. In addition, metal ones are more sensible at the corrosion respect to the plastic ones. For these reasons, nowadays plastic material pipes are chosen to realize a geothermal heat exchanger. Plastic material can be of: HDPE (High density polyethylene) and PEX (Cross-linked polyethylene). Both types of PE (Polyethylene) are used for many different purposes, but they are also used in buildings for domestic water distribution or for building conditioning pipe circuit. Nowadays they act very well in geothermal applications with little differences between two types for flexibility and simplicity of installation. Sometimes, on market it is possible to find pipes composed different substances in different layers; this is due to the necessity to make a union of the better characteristics of each substance.

Taking into account a pipe cross section with circular shape it is possible to identify two dimensions: internal diameter (d_i) and the thickness. The first one is related to the mass flow rate that crosses the pipe, the medium velocity and the density of the liquid.

Eq. 18 $$d_i = 2 * \sqrt{\frac{\dot{m}}{\pi * \rho * v}}$$

The mass flow rate is obtainable from Eq. 2 or considering a portion of this for parallel connections. Concerning the medium velocity, some considerations are necessary. Increasing the fluid velocity, it is possible to enhance the heat exchange rate of the geothermal heat exchanger (thermal power gets by a length unit), although not help to reduce much the total thermal resistance. The fluid velocity should guaranty a full turbulence flow regime without excessive hydraulic losses. The optimum value should be considered combining the performance of GHE and the pump power. Possible indicative values are in the range from 0.3 m/s to 0.9 m/s with 0.6 m/s as an interesting compromise (Jun et al, 2009).

The pipe thickness is principally related to the mechanical stress from: internal pressure, external collision with objects during transport, installation and cutting piece of rock. For all two dimensions fixed value are available on the market, therefore the choice is limited.

The pipe length for the geothermal heat exchanger is directly proportional to the total amount of heat that must be extracted. To choose this parameter it is usually necessary to simulate the behaviour of a geothermal heat exchanger with a specific shape and specific underground characteristics. Changing the dimension of the heat exchanger is possible to find the value that is capable to satisfy the heat requirements. This value is the active one, interested to the heat exchange; other pipes are present to connect the geothermal heat exchanger with the heat pump, these are often thermally insulated.

From the entrance and the exit of the pipe circuit, different ramifications can be found depending on its shape and dimension. The geothermal heat exchanger can be composed by active pipes connected only in series (small power) or with parallel connection. If a pipe circuit has two or more parallel branches, it is necessary each branch has the same hydraulic resistance to distribute the flow rate in equal parts. It is usually common to find different parallel branches in series composing a mix circuit.

As it is reported in DD.3 marzo, n°66, the geothermal heat exchanger pipes must be produced for this scope with quality and not recycled material.

The geothermal heat exchanger shape is a design choice; this can be designed taking into account: the geological formations, the superficial land to disposal, available economic resources, the nominal power and other aspects. The principal difference occurs between the orientation of pipes: horizontal or vertical.

- **Vertical geothermal heat exchanger**

The main characteristic of a vertical geothermal heat exchanger is the realization of one or more borehole to hold the pipe. The borehole diameter and depth is related to: the shape, the conformation and the dimension of the pipe circuit.

The principal typologies are: U-pipe, coaxial and coil.

U-pipe heat exchanger is composed with 2 linear pipes connected at the bottom of the borehole; the heat transfer fluid goes down in a pipe and it goes up in the other. It possible to find also multiple (2 or 3) U-pipe in a single borehole which can be connected in series or in parallel. The distance between the pipe can interact with the borehole heat exchanger efficiency, in particular higher is the distance between the two (or four or six) pipes less is the total length of the pipe heat exchanger to use to have the same amount of heat (Zhang et al., 2015). Ideally the pipes should be in contact with the lateral surface of the borehole, but sometimes is more easy to install U-pipe with reduced internal distance specially for big depths. To assure the distance between the pipes remain the same during the installation, spacers are present and lot of types are present on the market. This is a common technology in geothermal field and lot of different studies are conducted with this type of geothermal heat exchanger.

Fig. 3 Single and double crisscross U-pipe geothermal heat exchanger (Zhang et al., 2015)

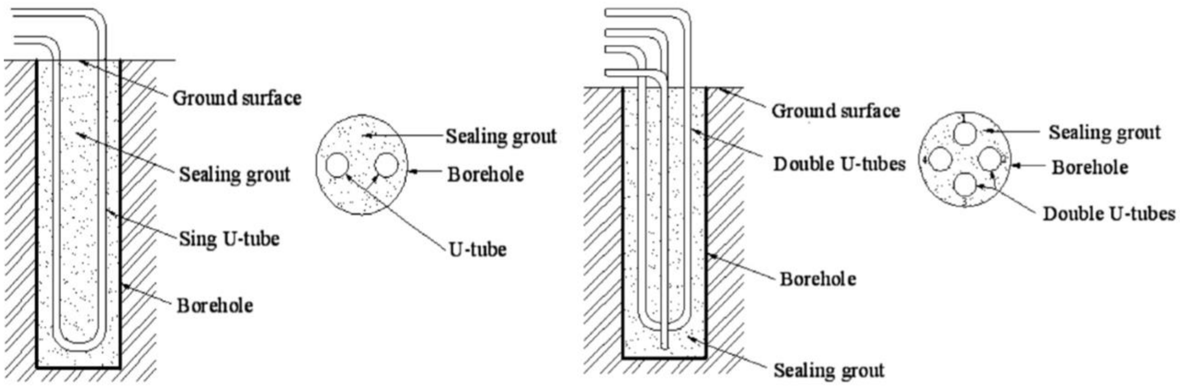
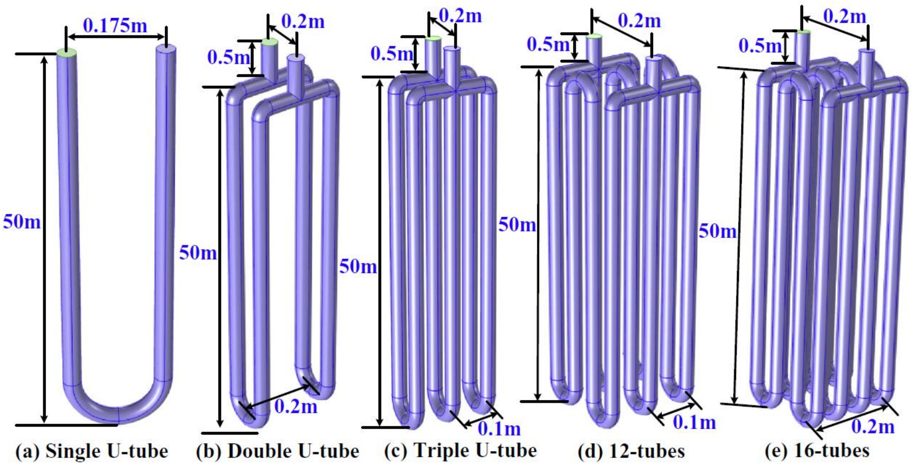
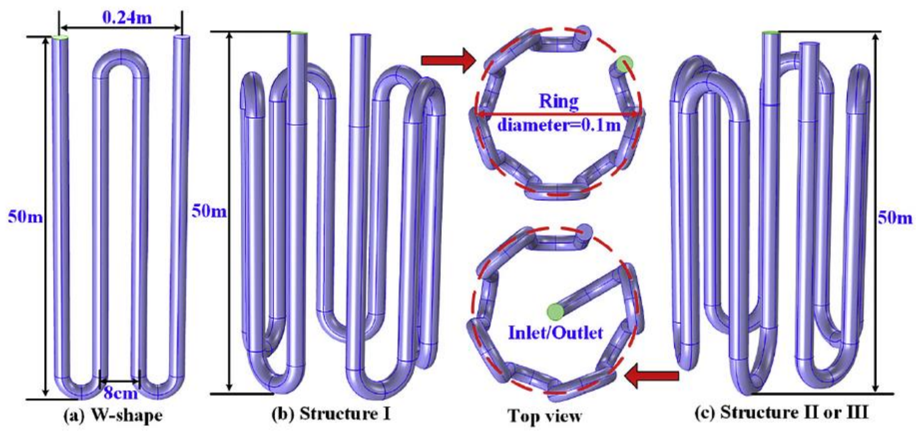


Fig. 4 Parallel U-pipe geothermal heat exchangers (Song et al., 2017)



For what concern the heat exchangers represented before, a parallel of series connection is chosen. Increasing the number of U-pipe, keeping constant boundaries and initial conditions, the outlet temperature and thermal power increase. However, when a critical number of pipes is reached, the previous ones remain constant. The critical value is not fixed, but it depends by the case conditions. This is due to the fact that the central pipes are unable to receive the heat from the external ground, therefore they can be also eliminated (Song et al., 2017).

Fig. 5 Ring series U-pipe geothermal heat exchangers (Song et al., 2017)



For circular series U-pipe geothermal heat exchangers, the better one is the "Structure I", with the inlet and the outlet in the ring. As is clear, increasing the ring diameter or increasing the number of pipes, more thermal power can be extracted, but a reasonable value doesn't exceed 10 pipes (Song et al., 2017).

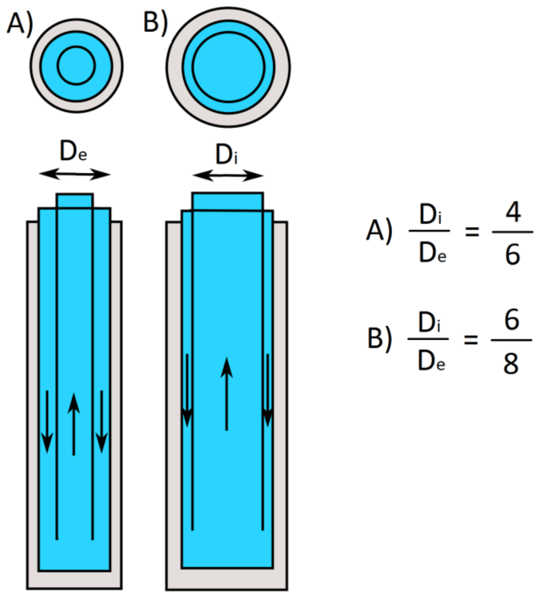
Coaxial pipe is realized with a smaller internal pipe and a bigger external pipe, which have the same axis. With this arrangement two different spaces are realized where the fluid can flow: one corresponds with the smallest pipe area and the other with the biggest pipe area minus the smallest one. In most cases the heat transfer fluid flows down in the external area warming-up and reached the bottom of the borehole it goes up in the internal area. For this reasons, the external pipe materials and dimensions are designed to enhance the heat transfer. Instead, the internal ones are design to reduce as much as possible the heat transfer from the internal hotter fluid to the external colder one.

Kurevija and Strpić, 2018 proves that extraction rate of a coaxial heat exchanger is lower than those of classical 2U loop vertical heat exchangers for an higher equivalent borehole thermal resistance.

Raymond et al., 2015 explained, before Kurevija and Strpić, that the large coaxial GHEs with a high heat storage capacity provided more enhancement in term of bore length reduction than the double U-pipe GHEs even though the borehole thermal resistance was higher.

For the realization of a large coaxial heat exchanger is necessary to assemble HDPE pipes with a large diameter. This can complicate the installation process because large pipes are commonly shipped in sections to be joined with fusion tools in the field. While efficient technology to install coaxial pipes may not be available at the moment, installation of double U-pipe can be achieved with current tools and expertise (Raymond et al., 2015).

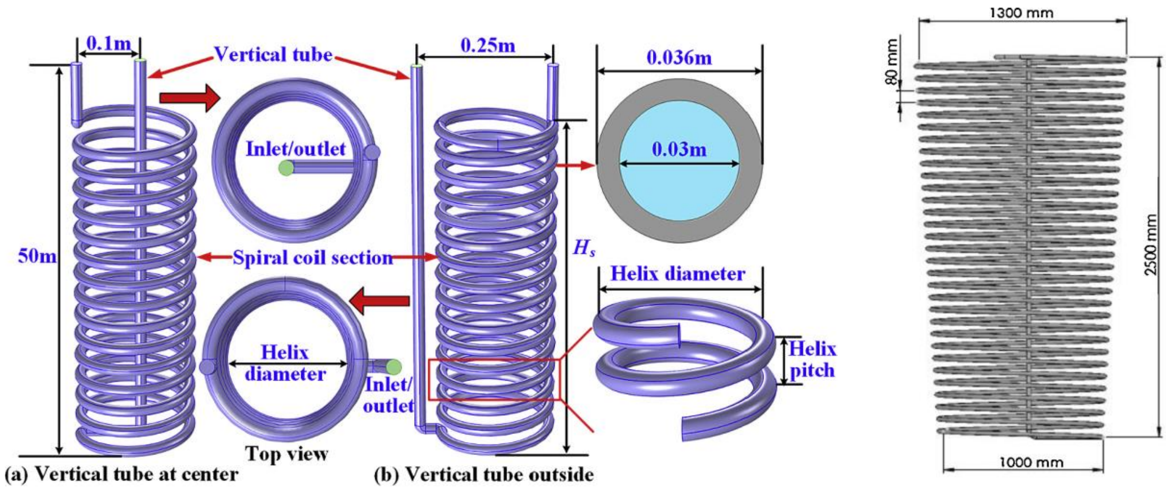
Fig. 6 Coaxial geothermal heat exchanger with different diameter dimensions modified by Raymond et al., 2015



Coil pipe is realized with a relative flexible material, for example PEX. The pipe is collocated in a vertical borehole to form a helix which goes down near the surface of the borehole. When the pipe reaches the bottom, it goes up linearly exiting from the borehole avoiding the thermal contact with the helix. This type of vertical geothermal heat exchanger is characterized by: helix diameter, helix pitch, number of windings, coil length and pipe length. The minimum coil diameter is dependent by the maximum curvature applicable to the pipe; the diameter borehole is usually bigger respect to the U-pipe and coaxial one. The total length of the pipe per borehole meter in this case is much higher respect to the previous ones, but not deep zones are usually reached with coil arrangement. In a coil arrangement, the pipe must remain with a helix form during the installation; due to the complicate shape this is difficult without any mechanical support. In fact, the coil arrangement is often used in the energy piles and the pipe is fixed on the iron frame. For the ground application sometimes it is possible to find coil with different forms, such us, conic basket. In addition, respect to the types represented before, the spiral heat exchanger doesn't need of any pipe connection at the bottom of the borehole; this aspect can reduce the probability of a future leakage.

Fig. 7

At left vertical coil geothermal heat exchangers (Song et al., 2017) and right vertical conic basket heat exchanger (Boughanmi et al., 2015)

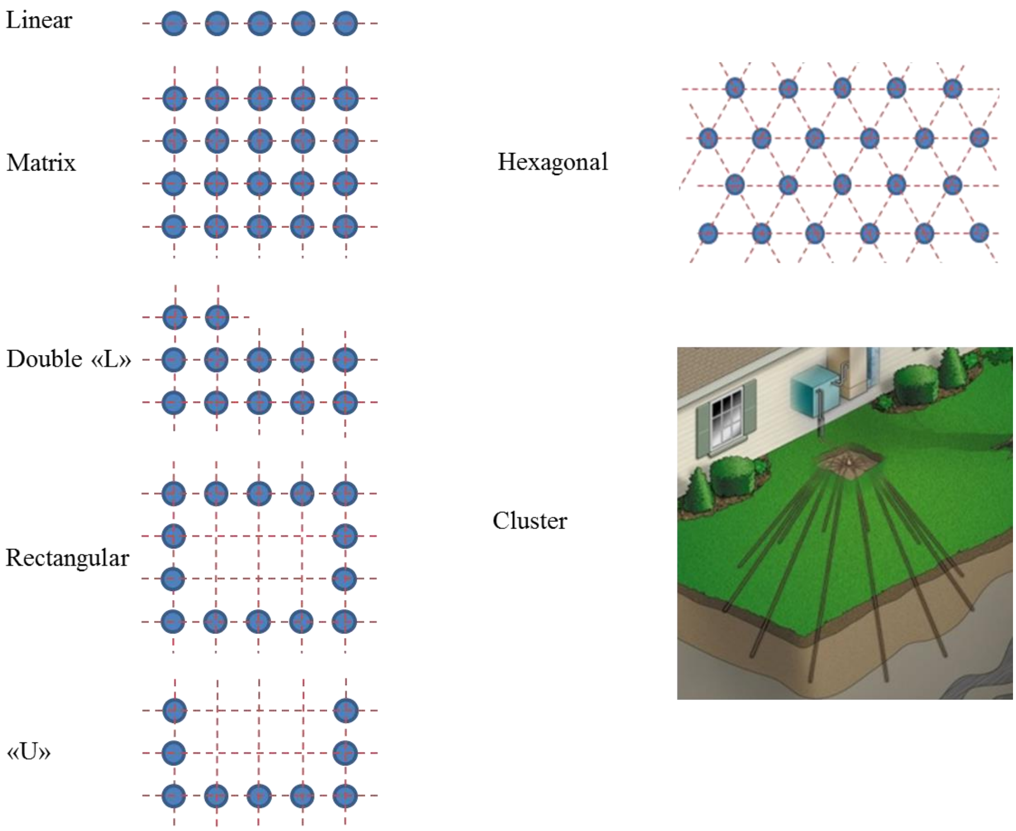


The spiral heat exchanger with the vertical pipe at the centre of coil section and set as the inlet, displays the greatest heat extraction performance among different categories. In addition, a larger helix diameter and longer coil length enhanced the heat exchanger performance, while the helix pitch had an insignificant effect. Thus, this type of heat exchanger should be designed as a spiral coil with a large helix diameter (Song et al., 2017).

Focusing on the arrangement of the boreholes in which these three vertical heat exchangers can be located, it is possible to distinguish different types of installation: linear, matrix, double “L”, rectangle, “U” (Zhang et al., 2015), hexagonal and cluster [1].

The definitive arrangement of a geothermal heat exchanger is usually dictated by the field in which this device must be placed. In most cases, the land to disposal limits the application of some types of geothermal heat exchangers also in term of dimension and shape.

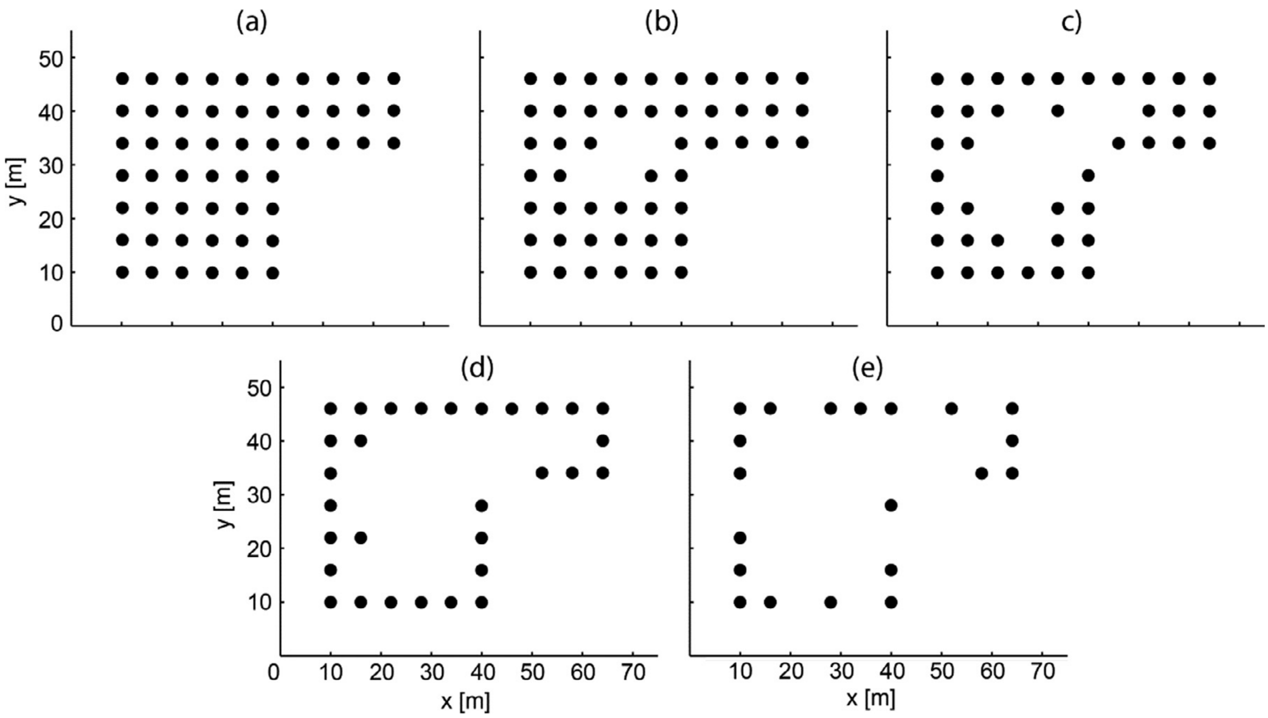
Fig. 8 Different arrangement of geothermal heat exchanger field (cluster [1])



The arrangements showed on the left are based on a square scheme and it is possible to adapt these configurations with the field to disposal. The rectangular and “U” shape are for example used when only a restricted perimetric field is free to use, for example a small house garden. In general, the hexagonal shape is used to enhance the compacting factor and in the geothermal field is useful to exploit more efficiently the geothermal resource. It is often used for a high number of boreholes and also to design a circular geothermal field. Not more used is the cluster shape, which is a very particular way to dispose boreholes. Although oblique boreholes are present it can be considered as a vertical geothermal heat exchanger. As it is possible to notice in the figure before, the tops of the boreholes occupy a small part of ground surface, but due to a certain slope of the hole drilled the heat exchanger can reach a big volume respect to the surface involved. It could be useful when too much small surface is available.

Bayer et al., 2014 elaborated a mathematical procedure to optimize the position and the number of boreholes. How it is reported, this method is very useful in the cases in which heat is extracted in heating mode and is not all returned to the ground during cooling seasons. This proposed procedure is a simulation of a geothermal field and it has as initial condition the total surface to disposal totally covered by a regular scheme of boreholes spaced with a chosen distance (a). To start the first step, each borehole efficacy is calculated for a specific amount of years with a certain thermal request and the least effective are removed forming a new configuration of the borehole field. With the new arrangement another step can start. After each step, the number of boreholes reduces and the relative field cost decreases linearly, but the total efficacy of the geothermal field declines very slowly. This procedure is stopped before that total field efficacy drops down more quickly (e).

Fig. 9 Different steps of the optimization proposed by Bayer et al., 2014



How it is possible to notice the most middle boreholes are removed step by step; this aspect proves that the most distant boreholes heat exchangers are the most effective.

Taking into consideration what DD.3 marzo, n°66 recommends about vertical heat exchangers located on field, it is necessary to observe different aspects in addition to the previous ones. For example, the drilling of boreholes must be optimized, depending on the case, maintaining at least 4.5÷5 m distance from building foundation and 8÷10 m from other boreholes. Other advices are reported in the guide lines.

- **Horizontal shape**

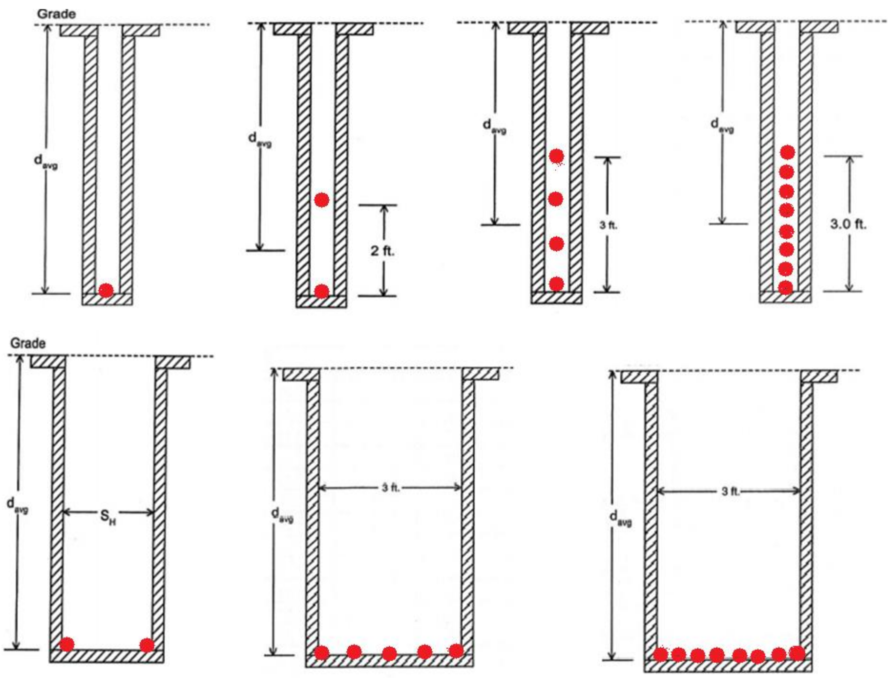
The main characteristic of a horizontal geothermal heat exchanger is the realization of an or more excavations, called trenches, which permit to hold the pipe circuit to allow a prevalent horizontal flow of the heat carrier fluid. The excavation dimensions are related to: land to disposal, the shape pipe, the connection and the dimensions of the pipe circuit.

Increasing the pipes installing depth, the ground temperature variation during seasons is smoothed, bringing an increasing of the heat exchanger efficiency. In the other hand, the cost of excavation increase proportionally. The trench has normally a parallelepiped shape and in this case the inlet and outlet pipes could be relatively near each other, slowly reducing the heat exchanger efficiency. The trenches can be realized with a ring shape, allowing to inlet and outlet pipes to maintain a certain distance to avoid thermal interaction.

The principal typologies are: linear, slinky and spiral.

Linear pipe is a simple pipe usually disposed in trench as it is shown below with transversal view.

Fig. 10 Different linear horizontal arrangement [2]

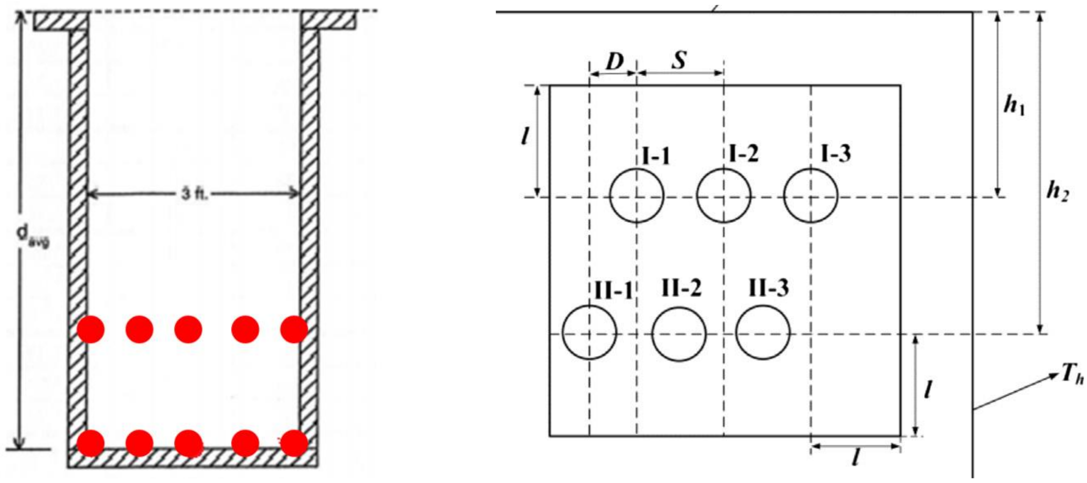


Considering the first row of pictures, we can say that this configuration is less expensive than the second row one, this is due to the minor quantity of ground that it is necessary to remove. On the opposite, it requires a not conventional excavator to realize a narrow trench and a relative accurate installation procedure to guaranty a correct position also during the filling of the trench with the ground. In most cases, the designed position is assured with the fixing of the pipes at a metal structure, as example lattice for reinforced concrete. Instead, the second row shows configuration more easy to install. The pipes number and distance must choose considering a simulation of the thermal requirements.

To determine the optimum configuration of a horizontal heat exchanger can be simulated a single finite soil body with different pipes configurations inside. For this type of problem increasing bending number of single pipe appropriately is an effective way to improve the thermal performance of horizontal heat exchanger (Pu et al., 2018).

Starting from the second row configuration of the previous figure it is possible to realize also multiple layers of pipes.

Fig. 11 Different linear horizontal arrangement with multiple layers (left: edited from [2], right: edited from (Pu et al., 2018))



Compared with in-line arrangement (left one), the staggered pipes (right one) have great advantages. However, when the relative offset displacement D/S ⩽ 1/3, the thermal performance in in-line arrangement is better than that of staggered pipes. The thermal interference between adjacent buried pipes is the significant factor affecting the thermal efficiency of an horizontal heat exchanger, unless the pipe spacing reaches the critical pipe spacing. The critical pipe spacing is affected by buried depth, inlet temperature and Reynolds number (Pu et al., 2018).

Slinky pipe is the name owned by a geothermal heat exchanger pipe when it is installed with a curtate cycloid. It allows to increase the length of pipe per meter of trench. To create this shape is usually used a PE pipe for its flexibility. It is relatively easy to install it, because PE pipes are often provided in coils and it is only necessary to increase the distance between each winding to realize this arrangement. In this case, it is necessary to fix every wrapping to near ones, without the use of metal structure. Slinky pipe can be installed in different way with different consequences,

Fig. 12 Single slinky pipe and principal dimensional parameters [3]

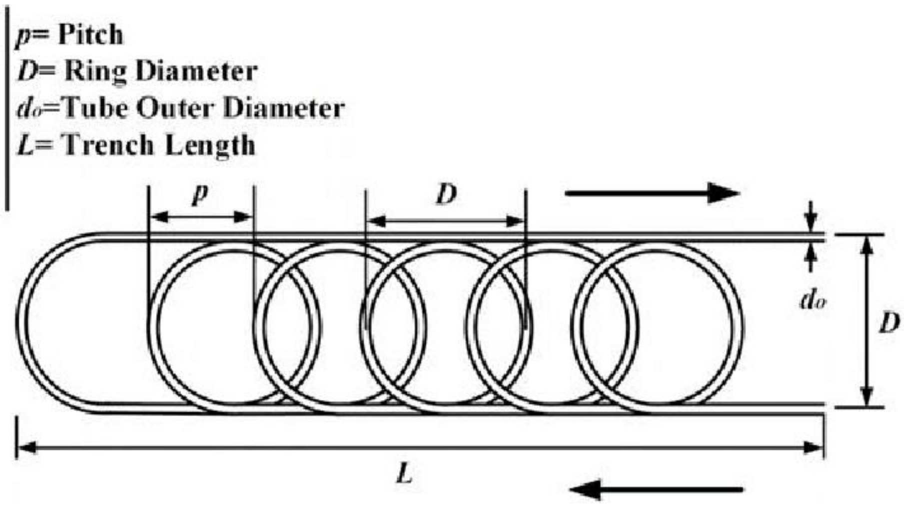
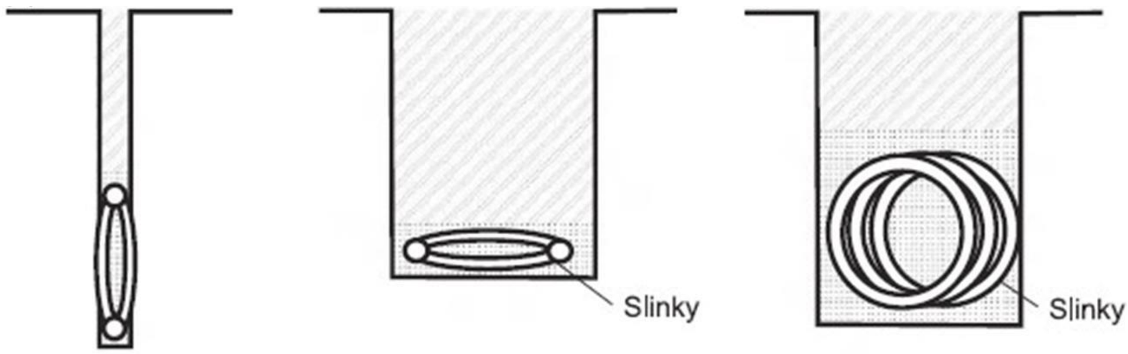


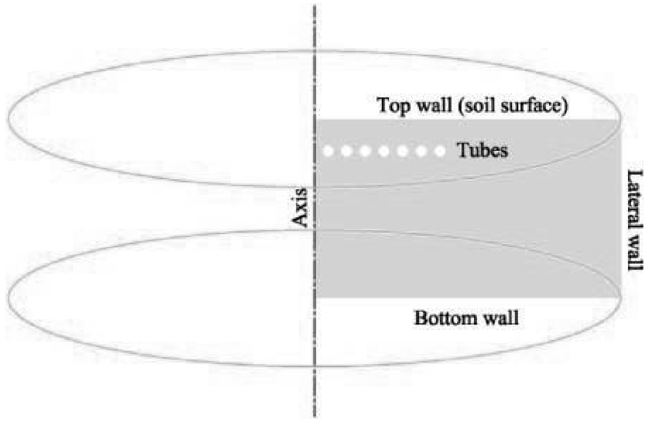
Fig. 13 Different orientation of slinky pipes (Lo Russo, 2018)



Wu et al., 2010 analyzed the thermal performance of a portion of slinky GSHP at different coil diameters and different coil central interval distances, using a validated 3D model. When the heat exchanger starts to run, it has the same specific heat extraction per pipe length respect to linear ones, but, during utilization, the decreasing is higher in the slinky type. This is probably due to the very reduced distance between the initial and final portion of the single winding. It is also necessary to notice that the specific heat extraction per meter of soil is higher in the slinky arrangement. It is particularly interesting the independence between coil diameter (D) and performance. Instead, increasing the coil interval distance (p), the heat extraction per pipe meter starts to increase, for the possible minor interaction between near windings. On the other hand, the heat extraction per meter length of soil for a slinky decreased with the increase of coil central interval distance.

Spiral pipe is a single flexible pipe that create a geothermal heat exchanger with a spiral shape. This arrangement is realized starting from the centre of the spiral, placing each winding at a fixed distance from the inner one. In this case the realized trench must have a cylindrical shape, but sometimes it is possible to fill a trench with different shape changing the distance between pipes during the installation. An interesting aspect of the spiral pipe is the absence of pipe connection, reducing the possibility to have leakage. However, two or more parallel pipes can be placed in the same spiral increasing the flow rate. Especially more external windings can be considered as rings of pipe with the same centre and thanks to this aspect it is more easy to simulate the behavior of this arrangement.

Fig. 14 Single spiral pipe approximation in a 2D problem (Benazza et al., 2011)

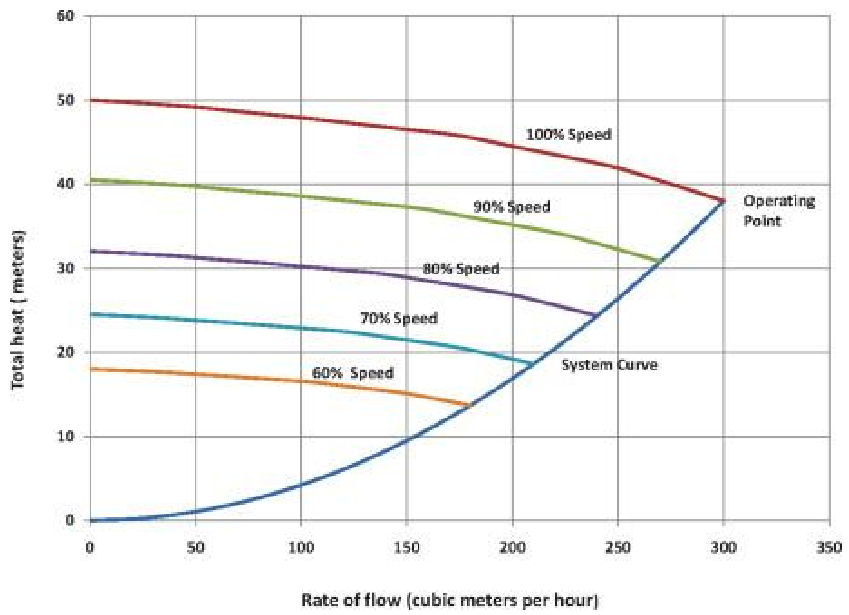


Benazza et al., 2011 using the previous approach simulated the behaviour of the spiral heat exchanger in stationary regime, keeping constant the occupied area. They found out that reducing the distance between the pipes (increasing the total length to maintain the constant area), heat flux increases until an asymptotic value. Also increasing the pipe diameter, it is possible to enhance the performance.

- **Circulation pump**

The circulation pump is the device that permits the circulation of heat transfer fluid in a closed loop system through the geothermal and heat pump heat exchanger. It gives the force to the fluid to win the hydraulic losses of a pipe circuit. First of all, it is necessary to analyze different aspects: mass flow rate during time that guaranties the thermal requirements (considering also partial load) and the hydraulic losses (or prevalence) of the pipe circuit versus mass flow rate. To choose the correct circulation pump, the pump characteristic curve must be superimposed to the hydraulic losses. The two curves have in community a single point, called working point. The working point represents on the x-axis the desired mass flow rate and the corresponding prevalence in ordinate. Especially for big systems, mass flow rate variation can occur and it is possible to use different methods to induce a modulation. Throttling and by-pass can be easy and economic method to regulate the flow rate, but nowadays variation of rotation speed is preferred. This last one needs an electronic inverter that permit the variation of electric motor alimentation frequency that moves the pump. Although this method is the most expensive in term of capital cost, a long term economic analysis proves that it reduces the operating cost for electric consumption. In most cases centrifugal pumps are used for this purpose.

Fig. 15 Centrifugal pump characteristic curves with rotation speed variation (Adjustable Speed Pumping Applications, 2010)



In some applications, it is necessary to reach very low modulation percentage, compromising the pump performance. To avoid useless losses, multiple parallel pumps equipped with inverter can be used to provide small flow rate with a relative high efficiency.

Another essential device for all closed loops is the **expansion vessel** that absorbs volume variation due to heat carrier fluid temperature changing. To evaluate its size, it is necessary to consider: the minimum and maximum reachable temperature, thermal expansion coefficient and total volume of fluid.

2.2.2. Open loop geothermal system

An open loop geothermal system is a pipe circuit that permits to extract and to re-inject water in the environment. The water is returned at a different temperature permitting a use of heat contained by the water. It is possible to classify different types of open loop geothermal systems respect to the abstraction and restitution manifold location.

- **Location of abstraction manifold**

Possible locations of abstraction manifold are water bodies, characterized by the possibility to extract water during the total conditioning period. The extraction of water should guaranty the sustainability of the water body without compromise the pre-existing environmental equilibrium and/or other pre-existing anthropological use. A first distinction can be adopted between: superficial water bodies and aquifers.

To respect the current regional legislation, it is necessary to request a concession for public water derivation normed by: D.P.G.R. 29 luglio 2003, n° 10/R.

Superficial water body, as reported before, can be an interesting location from which to extract water. Possible superficial water body are: rivers, channels, lakes, lagoons, ponds and sea.

The most important parameter needed for the choice of a water body is the water mass flow rate during time to be used for the purpose of the system. A mass balance equation can be computed to have a clear impact of the open loop system on the water body. Secondly it is advisable to analyze the temperature variation of the water resource during the year to have a preliminary idea of the efficacy of the geothermal system.

Aquifer is another location where it is possible to extract water and, in most cases, only unconfined aquifers are used for this purpose; for this reason, only these are taken into consideration. Unconfined aquifer is an aquifer in which groundwater possesses a free surface open to the atmosphere. The upper surface of the saturation zone is called water table and the bottom is marked by a confining layer. Unconfined aquifer is the shallowest and easiest to reach for extraction of ground water. Aquifer is reached through one or more wells drilled observing designing aspects, showed below.

- **Location of reinjection manifold**

Possible locations of reinjection manifold are characterized by the possibility to re-inject water during the total conditioning period. The reinjection of water should guaranty the sustainability of the site without compromise the pre-existing environmental equilibrium and/or other pre-existing anthropological restitution of water. A first distinction can be adopted between: superficial water body, superficial soil, sewer and aquifer.

To respect the current legislation, it is necessary to request a water discharge authorization at a specific authority for the different types of discharges. However, this water must be considered as discharge of industrial waste water and it is subjected to prior authorization pursuant to art. 124 of Legislative Decree no. 152/06 and in accordance with the regulations of sector in the field of water and protection of the subsoil.

Superficial water body can be an interesting location towards which to release the processed water. Possible superficial water body are: rivers, channels, lakes, lagoons, ponds and sea.

The most important parameter needed for the choice of a water body is the water mass flow rate during time to be re-injected for the purpose of the system. A mass balance equation can be computed to have a clear impact of the open loop system on the receiving body which must have an adequate auto-depurative capacity. Secondly, it is necessary to consider the released water temperature or the variation respect to the abstraction to have a preliminary idea of the efficacy of the geothermal system. These two parameters must be designed to not exceed the current legislation: "Tabella 3, Allegato 5, parte III, D.Lgs. n. 152/06". The previous table obliges to have a maximum average temperature variation less than 3°C between any section, before and after the discharge in a natural water stream. For artificial ones, average temperature of each section must be less than 35°C and the previous restriction is considered only for sections over 1000m distance after the discharge.

Superficial soil is normally used as waste water delivery especially for isolated housing unit. Also for a geothermal purpose, it is possible to release water in the superficial soil layers when technical impossibility and excessive cost are certified respect to a restitution on a superficial water body. The processed water can be dispersed through an absorbent pit or a sub-irrigation trench. There aren't any indications of restriction in term of temperature in the current legislation; only chemical composition of the discharge is normed in: "Tabella 4, Allegato 5, parte III, D.Lgs. n. 152/06".

Sewer can be considered as an interesting site where discharge this processed water also for the pre-existence of infrastructure. The sewer operator doesn't accept to treat the discharge water of a geothermal system for the huge amount of water released in a year.

Aquifer is another location where it is possible to return water and, in most cases, only unconfined aquifers are used for this purpose; for this reason, only these are taken into consideration. The reinjection well/s can have different dimensions for certain reasons.

Standing column well system is a particular open loop connection where extraction and reinjection wells are the same, this could be used for small geothermal systems. In this case, the only one drilling have relative big dimension to have possibility to have big store of energy. Thanks to stratification in the well, is possible to have to disposal water at different temperature at different depth using the abstraction and restitution manifolds how it is convenient. This wells can be realized with two different well screens to increase water exchange with the near aquifer (Capilongo, 2018).

Taking into consideration the site on study, the well doublet system is the only one method used; for this reason, it is the most treated in this elaborate.

- **Well doublet system**

A well doublet system is composed by one or more extraction and reinjection wells. It is the most used open loop system for geothermal heat pump systems and not only. It offers high potential of thermal energy useful for big final users with relatively high total performance. On the other hand, this type of geothermal connection is closely related to the availability of ground water at an interesting temperature. Thus in not all parts of the world this system is realizable.

Subsequently, theoretical aspects will be treated for well doublet system with a single extraction well situated immediately up the hydraulic gradient from a reinjection well.

From extraction to reinjection wells the water is cooled or warmed depending on conditioning season. Heat extracted or released in the aquifer is simply calculated with the formula below.

Eq. 19 $$\dot{Q}_{aquifer} = \dot{V} * \rho * cp * |T_{extraction} - T_{reinjection}|$$

How it is visible with the equation before, the aquifer is perturbed in term of water mass and in term of temperature. An important question that rises spontaneously is: “Can the aquifer provide or absorb the total requested heat sustainably for all requested period?”.

First of all is necessary to clarify two concepts. The hydraulic feedback is the partial or total re-extraction of ground water already extracted and processed before. The thermal feedback is the extraction of ground water at a different temperature respect to the aquifer one, this is due to the warming or cooling of ground water from the re-injected water. From a geothermal point of view, it is advisable to avoid the thermal feedback, to not reduce the efficiency of the geothermal system.

Related to the previous question, a fundamental design parameter, that permits to have a sustainable well doublet system, is the distance between extraction and reinjection wells.

Hydraulic feedback well distance is the distance between extraction and reinjection wells beyond which hydraulic feedback is not induced for a continuous operation. This value of distance is the most conservative, but, in most of cases, a not continuous operation permits to reduce the distance without to reduce the efficiency of the system.

Eq. 20 $$L > \frac{2*\dot{V}}{\vartheta*\pi*i}$$

It is also possible to rewrite the previous equation as it is reported, using "β" coefficient.

Eq. 21 $$\beta = \frac{2*\dot{V}}{\vartheta*\pi*i*L} \qquad \beta < 1$$

Hydraulic breakthrough time is the time in which in a well doublet system, with a precise extraction and reinjection wells distance, can occur the hydraulic feedback.

Eq. 22 $$t_{hyd} = \frac{L*\varphi_e}{K*i} * \left[\frac{\beta}{\sqrt{\beta-1}} * \tan^{-1}\left(\frac{1}{\sqrt{\beta-1}}\right) - 1\right]$$

Thermal breakthrough time is the time in which in a well doublet system, with a precise extraction and reinjection wells distance, can occur the thermal feedback. It is possible to notice that the heat in the aquifer is slower to move respect to the water. The thermal breakthrough time is higher than the hydraulic one for a retardation. The ratio between the thermal and hydraulic one is called: Retardation factor; thus this value is higher than 1.

Eq. 23 $$t_{the} = \frac{L*c_{vol_{aquifer}}}{c_{vol_{water}}*K*i} * \left[\frac{\beta}{\sqrt{\beta-1}} * \tan^{-1}\left(\frac{1}{\sqrt{\beta-1}}\right) - 1\right]$$

The previous values of time, compared with the conditioning season period, show if during the system operation and hydraulic or thermal breakdown occur.

Steady state drawdown/upconing, in the abstraction/reinjection well of a well doublet system, is the drop/increase between the abstraction/reinjection well and the unperturbed aquifer. This value is useful to understand if the single wells are able to provide or release water.

Eq. 24 $$s_w = \frac{\dot{V}}{2*\pi*T} * \ln\left(\frac{L}{r_w}\right)$$

The relations and equations treated before are related to wells drilled for all the aquifer thickness. For other wells, the results could be different, but they can be considerate as a good approximation (Lo Russo, 2018).

For Citta Metropolitana of Turin, well doublet systems are very interesting especially for building condition, some of these are also used for other purposes. Città Metropolitana is the authority which approves the ground water systems. It divides the well doublet systems of open loop geothermal systems taking into consideration the abstracted and re-injected water:

- Small system $\dot{V} \leq 2\,{}^{l}/_{s}$;
- Medium system $2\,{}^{l}/_{s} < \dot{V} \leq 10\,{}^{l}/_{s}$;
- Big system $\dot{V} > 10\,{}^{l}/_{s}$.

Before the realization of a well doublet system, as it is reported in D.Lgs. n. 152/06 and D.P.R. n. 59/2013, according to its dimension, it is necessary to report or realize partially or totally the points below:

1. The impossibility to the reuse or discharge in an alternative way;
2. Cartographies / Planimetries of the system to realize;
3. Report and scheme of the circuit (from extraction to the discharge), indication of the designed maximum temperature of the discharge water, absence of interference between the reinjection and the near infrastructures (considering also the soil discharging capacity);
4. Placing hypothesis of at least one control piezometer downstream of the discharge;
5. Technical relation on the aquifer characteristics;
6. Identification of a discharged water temperature threshold of warning and a the operation procedure in case of threshold exceeding;
7. Prevision of thermal plume evolution in the aquifer during time, simulating the interesting operation to predict the plume duration and amplitude.

For:

- Small systems, only 1,2,3 points must be taking into consideration without overlapping with other systems, reducing how much is possible the recycling, the stagnation and significant temperature alteration of the water;
- Medium system, except the point 7, all previous ones must be respected;
- Big system, all points must be respected.

During operation of a well doublet system Città Metropolitana advises to do what it is subsequently listed:

A. Volumetric flow rate measurement during time, data-center stored;
B. Extraction and reinjection temperature measurement during time data-center stored;
C. Aquifer level, temperature and electrical conductivity in the monitoring well placed downstream of the reinjection well;
D. Water treatment with chemical species is denied;
E. To Carry out procedure to maintain the temperature between the legal levels;
F. To dispose a sample detection point of extracted and re-injected water;
G. To send annually a report to authority which contain data of point: A, B and C (reworking the point 7) (Capilongo, 2018).

- **Pipes of an open loop geothermal system**

To realize a pipe circuit, to bring the ground water from the abstraction well/s to the heat exchanger and then from the heat exchanger to the reinjection wells, the types of tube utilized are similar to the same used in the hydraulic field. They mustn't have particular thermal characteristics; sometimes where it could be necessary, coating of thermal insulation is used to cover some interested portion of the pipe circuit.

Nowadays plastic materials are used for this purpose: HDPE (High density polyethylene) and PEX (Cross-linked polyethylene), but stainless steel pipes are also used mostly for big dimensions.

Taking into account a pipe cross section with circular shape it is possible to identify two dimensions: internal diameter (d_i) and the thickness. The first one is related to the mass flow rate that crosses the pipe, the medium velocity and the density of the liquid.

Eq. 25

$$d_i = 2 * \sqrt{\frac{\dot{m}}{\pi * \rho * v}}$$

The mass flow rate is obtainable from Eq. ## or considering a portion of this if there are more than one extraction and reinjection wells. Concerning the medium velocity, same fluid-dynamic considerations of every pipe circuits are necessary.

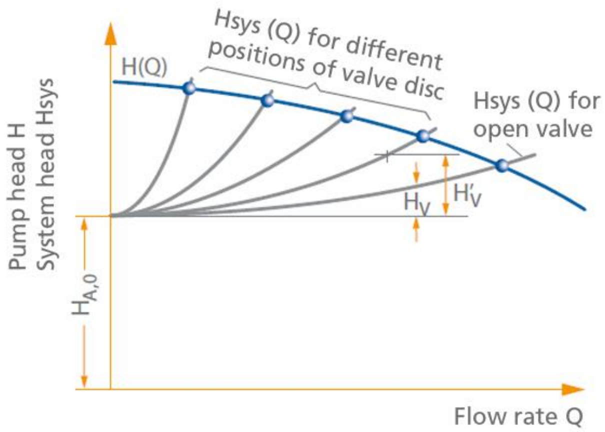
The pipe length is directly proportional to the well depth and the wells distances from the heat exchanger. Increasing the pipe circuit length, capital cost and electricity expenditure rise. Another negative effect is the increasing of the thermal leakages from the water toward the external environment.

From the possibility to have more than one extraction well, different ramifications can converge in the same heat exchanger and from it, different pipes branching out toward the reinjection well/s.

- **Abstraction pump**

The abstraction pump is the device that permits the circulation of ground water from the abstraction and the reinjection well/s through the heat exchanger. It gives the force to the fluid to win the hydraulic losses of a pipe circuit and the hydraulic haed. First of all, it is necessary to analyze different aspects: mass flow rate during time that guaranties the thermal requirements (considering also partial load) and the hydraulic losses (or prevalence) of the pipe circuit versus mass flow rate. To choose the correct abstraction pump, the pump characteristic curve must be superimposed to the circuit hydraulic curve. How it is explained for the circulation pump of the closed loop systems, the two curves meet in the working point. Also for these systems, mass flow rate variation can occur and it is possible to use different methods to induce a modulation. The preferred method needs an electronic inverter that permit the variation of electric motor alimentation frequency that moves the pump. Although this method is the most expensive in term of capital cost, a long term economic analysis proves that it reduces the operating cost for electric consumption. In most cases axial pumps are used for this purpose, also for their relative reduced diameter. In most cases, the abstraction pump/s is/are located in the abstraction well/s down to the water level because they aren't self-priming.

Fig. 16 Pump characteristic curves and possible open loop system curves [4]



In some applications, it is necessary to reach very low partialization percentage, compromising the pump performance. To avoid useless losses, multiple parallel pumps equipped with inverter can be used to provide small flow rate with a relative high efficiency.

In open loops, the **expansion vessel** that absorbs volume variation due to temperature changing is not necessary.

2.3. Heat Pump

The heat pump, called also reverse cycle machine, is a device capable to bring an amount of heat from a termostato at a certain temperature to another one at higher temperature; to realize this, it is necessary to spend work.

From them invention, inverse cycle machines were used principally to extract heat from something, highlighting its cooling capacity. In minor way, they were utilized as warming machine, but, thanks to technology development, nowadays they have become more and more important in building conditioning also for its capacity to change from cooling to heating mode, in relation to the season.

The heat pump works thanks to the reverse cycle principle; which it is based on four gas, or refrigeration fluid, thermodynamic transformations: compression, cooling, lamination and heating. Starting from the gas at a relatively low pressure, spending work, the gas is compressed warming up itself. The gas, passing through an heat exchanger, releases part of its thermal energy at a higher temperature outside from the heat pump, than, with a lamination valve, the gas is expanded reducing drastically its pressure and temperature. Through another heat exchanger, the refrigerant gas is warmed by the termostato at minor temperature and the cycle can restart again.

- **Refrigeration fluid**

Refrigeration fluid choice is crucial for a good working operation of the reverse cycle. In most cases, to increase the efficacy of the machine, a particular type of refrigerant fluid are used; they have a characteristic curve that consents to reach liquid state in saturation and sub-cooling condition. These fluids advantages are: the possibility to exploit the latent heat of the phase change and the possibility to have at disposal a fluid at the same temperature for the heat exchange. Another interesting aspect is the thermal exchange coefficient increase, due to the presence of a condensation or boiling process.

The refrigeration fluids are grouped in different families in relation to the chemical species that compose them, for example: chlorofluorocarbons (CFC), hydrochlorofluorocarbons (HCFC), hydrofluorocarbons (HFC) and Hydrofluoro-Olefin (HFO).

The table proposed below shows some refrigeration fluids and the relative most important parameters for the evaluation of environmental impact. The most common environment impact of a refrigeration fluid are: degradation of ozone and the greenhouse effect. The first one is represented by the Ozone Depletion Potential (ODP), which is the ratio between the ozone degradation contribution of the considered gas over the R22 one. The second is the Ground Warming Potential (GWP), which is the ratio between the ground warming contribute of the considered gas over the CO_2 one.

Fig. 17 Environmental parameters of common refrigeration fluids [5]

Product information (sorted by Product Type and Name)

Type	Product R- Number	ODP[1]		GWP[2]	
CFC	12	1	High	10900	High
	502	0,33	High	4657	High
HCFC	22	0,055	Medium	1810	Medium
	123	0,060	Medium	77	Low
	401A	0,033	Medium	1182	Medium
	401B	0,036	Medium	1288	Medium
	402A	0,019	Medium	2788	High
	402B	0,030	Medium	2416	Medium
	408A	0,024	Medium	3152	High
	409A	0,046	Medium	1909	Medium
HFC	23	0	Zero	14800	High
	32	0	Zero	675	Medium
	134a	0	Zero	1430	Medium
	404A	0	Zero	3922	High
	407A	0	Zero	2107	Medium
	407C	0	Zero	1774	Medium
	407F	0	Zero	2088	Medium
	417A	0	Zero	2346	Medium
	422A	0	Zero	3143	High
	422D	0	Zero	2729	High
	423A	0	Zero	2280	Medium
	424A	0	Zero	2440	Medium
	427A	0	Zero	2138	Medium
	428A	0	Zero	3607	High
	434A	0	Zero	3245	High
	437A	0	Zero	1805	Medium
	438A	0	Zero	2265	Medium
	442A	0	Zero	1888	Medium
	507A	0	Zero	3985	High
	508B	0	Zero	13396	High
	MO89	0	Zero	3805	High
HFO	1234yf	0	Zero	4	Low
	1234ze	0	Zero	6	Low
Natural/Not in Kind	170	0	Zero	6	Low
	290	0	Zero	3	Low
	600a	0	Zero	3	Low
	717	0	Zero	0	Zero
	744	0	Zero	1	Low
	1150	0	Zero	4	Low
	1270	0	Zero	2	Low

In 1987, after to have proved the relationship between the refrigeration gas emission and the ozone hole, The Montreal Protocol was stipulated to reduce in particular CFC production and use. The EU from 1994 made operative the Montréal Protocol and from 2010 prohibited CFC use.

From 01/01/2015, CFC and HCFC are forbidden [6].

For what concern the ground warming effect of refrigerant gases emission, nowadays, any regulation obliges to not use the remaining fluids. In future, it will be possible, that new restrictions will occur in the utilization of refrigeration fluids.

In according to the application, the refrigeration fluid is chosen for its thermodynamic characteristics and the possibility to generate a relative high performance in an heat pump. Some of the applicable refrigeration fluids in an heat pump system for building conditioning are: R32, R134a, R410a (50% R32 and 50% R125), R1234yf.

- **Compressor**

The compressor of an heat pump is the device which permits to increase the pressure and, in consequence, the temperature of the refrigeration fluid. It works thanks to mechanical power provided by an electrical motor, in some cases internal combustion engine are used especially where electricity is not guaranty. The inlet and outlet pressure of the compressor are related to the requirement of the system that bring to use the refrigeration fluid between a certain range of pressure.

Reciprocating, centrifugal, Scroll and screw compressors are the most used in heat pump application; the compressor type choice can be related to technical aspect: size, modulation capacity, reliability, noise, efficiency and cost. All of these aspects are evaluated by heat pump manufactures during its design. The continuous technologies evolution allows to have at disposal more efficient and cheaper compressors respect to the past one, for this reason the heat pump use can be more and more convenient.

In most applications more than one compressor is installed to increase the total machine availability in case of failure and the total modulation capacity.

- **Lamination valve**

The lamination valve is, relatively, the simplest component of and heat pump. It divides, with the compressor, the high and low pressure parts of an heat pump. At the contrary of the compressor, it reduces the pressure of the refrigeration fluid decreasing also its temperature. In small machines, where a modulation is not necessary, it is realized with a small diameter pipe, which creates a concentrate pressure drop proportional to the refrigeration fluid flow rate.

- **Condenser and Evaporator**

The condenser is and heat exchanger used to conduct heat from the refrigeration fluid to the outside of the machine. In this device, the refrigeration fluid condenses giving its latent heat to another fluid, normally water, that brings it away. If this amount of heat can be useful, it is processed, otherwise it is released to the environment.

The evaporator is an heat exchanger, but at the contrary of the condenser is useful to extract heat from a fluid, such as water, in order to give it to the refrigeration fluid. It is warmed until the saturation temperature of the low pressure, allowing refrigeration fluid evaporation.

Both heat exchangers, have a relatively high efficiency thanks to the presence of a changing phase fluid that increase the heat exchange coefficient.

On market are available different type of heat exchanger which can be used for this application. Shell and tube heat exchanger is one of the most used by heat pump manufacturers, especially for big power machine.

In the reversible heat pump, condenser and evaporator are of the same type and size and thanks to a **reverse valve** two heat exchangers invert their role.

Chapter 3: Case study

3.1. RSA Il Trifoglio

RSA Il Trifoglio is an health assistance residence managed by Cooperativa Sociale Bios S.C.S. Onlus. It provides social and health care activities in favour of people who are not self-sufficient.

RSA Il Trifoglio is chosen as case study for this thesis for different reasons.

First of all this is a new structure built in 2011 in the city of Turin (Via Andorno 17, Turin) and a Open Loop Geothermal Heat Pump system works to guaranty heating, cooling and hot water requirements. Secondly, this plant is active for some year at full power and geothermal data are available for consultations. It is also important to notice that it is relative big plant, considering other Open loop Geothermal systems of Turin.

Fig. 18 RSA Il trifoglio [7]

Thanks to relations composed by Studio Tecnico Associato Geostudio during the realization of the plant, it is possible to understand what is the geological and hydrogeological condition in which the geothermal system is located. The structure stands on a site characterized by a stratification reported below.

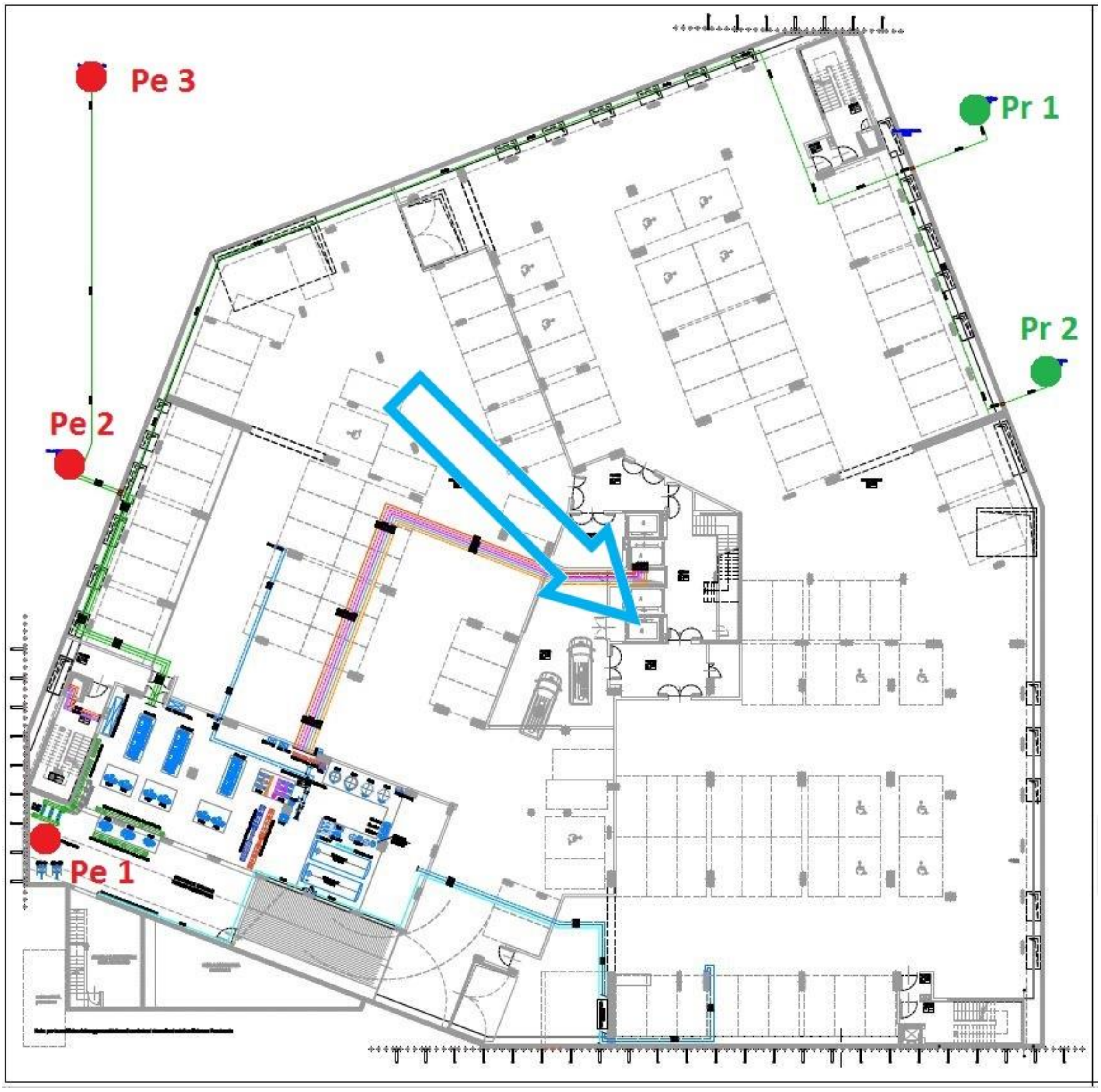
Table 5 Site stratification (Geostudio, 2013)

DEPTH	DESCRIPTION
0 – 2 m	Reported ground
2 – 11 m	Gravel with scree and sand
11 – 20 m	Gravel with conglomerate lenses
20 – 21 m	Sandy Clay

Below 21 meters under ground level, an impermeable layer of clay is present and any detection of subsoil wasn't done. This last impermeable layer is the basement of an unconfined aquifer, present in all part of city of Turin. In this precise site the free surface of aquifer is located at almost 9-10 meters below the surface (Geostudio, 2013).

In this case a well doublet system utilizes the water of the unconfined aquifer, more precisely this configuration is composed by 3 extraction wells and 2 reinjection wells. The aquifer is exploited, by the wells, for all its thickness and the relative position of wells is chosen taking into account the aquifer direction and available areas without any designed constructions. The figure below represents an excerpt of design project with disposition of extraction wells (red) and reinjection wells (green), thanks to Geostudio, 2013 it is possible to show the direction of the flow of aquifer, approximately from West-Nord-West to East-South-East.

Fig. 19 Position of the extraction and reinjection wells (Mediapolis, 2013) and aquifer direction (Geostudio, 2013)



Pe: Extraction well *Pr: Restitution well*

The thermal power station of this structure is located at basement of the building near to the parking. The simplest way to divide the system is to consider the different water circuits and

- **Open loop geothermal circuit**

The task of the open loop geothermal circuit (or primary circuit) is to make possible the thermal connection between the resource and the thermal power station. To do this, from each extraction well, groundwater is pumped to ground level thanks multistage variable pumps. An electronic inverter feeds the pump electric motor in order to modulate the water flow rate if it is necessary. Through a cumulative water meter, the extracted water is measured for each well, then water flows in a single collector. In order to prevent possible damage, malfunction and reduction of performance, at this point water flow in three parallel filters. In this way, possible solid particles can be kept by the filtration system and removed manually by an operator. To extract or release heat from or to groundwater, two heat exchangers are designed. At the end, water returns in the aquifer through the reinjection wells.

Fig. 20 Open loop geothermal circuit project (Mediapolis, 2013)

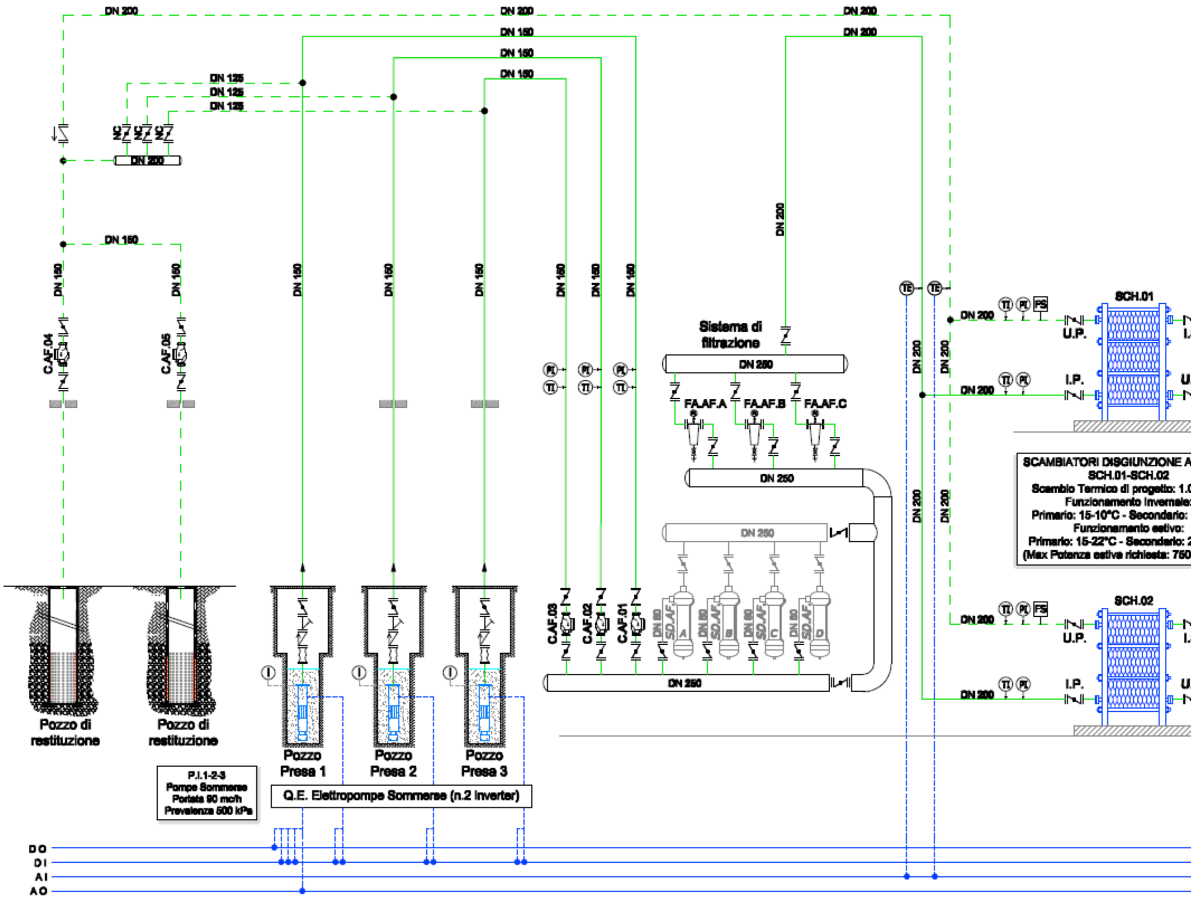


Fig. 21 Top of Extraction well 1 photo

From the previous photo, realized during the site visit, it is possible to see the top of the extraction well 1 (grey portion tube), the extraction pipe connected to the extraction pump at the bottom of the well (red one) and the power supply cable of the pump (green cable).

- **Disjunction heat exchangers**

A disjunction heat exchanger, how its name suggests, is useful to separate two parts of a circuit for reasons explained below. During the realization of the project, two equal heat exchangers are designed, probably in order to guaranty a no-stop working condition during a possible failure and maintenance of one of the two. From the different types of heat exchangers, plate ones have been selected for them compactness and them relative easy maintenance during cleaning operations.

Fig. 22 Disjunction heat exchangers (Mediapolis, 2013)

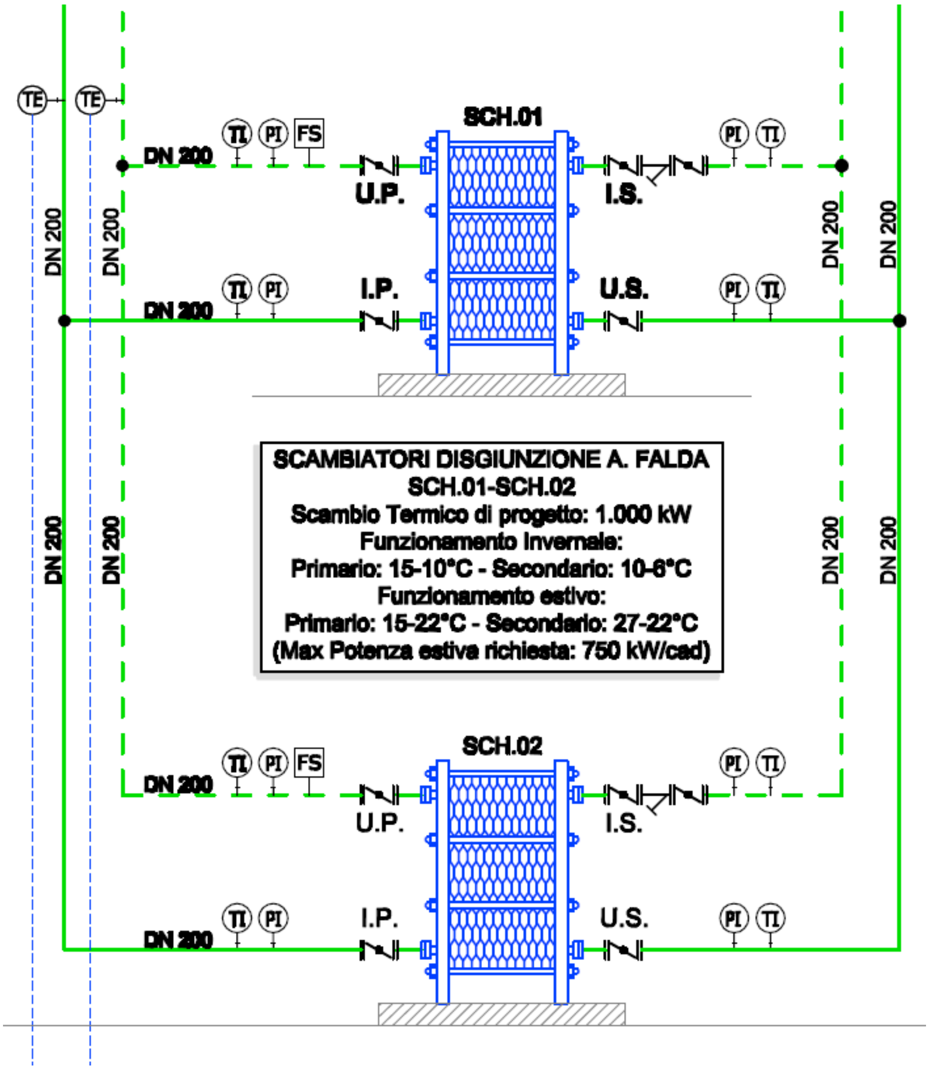


Fig. 23 Disjunction heat exchangers photo

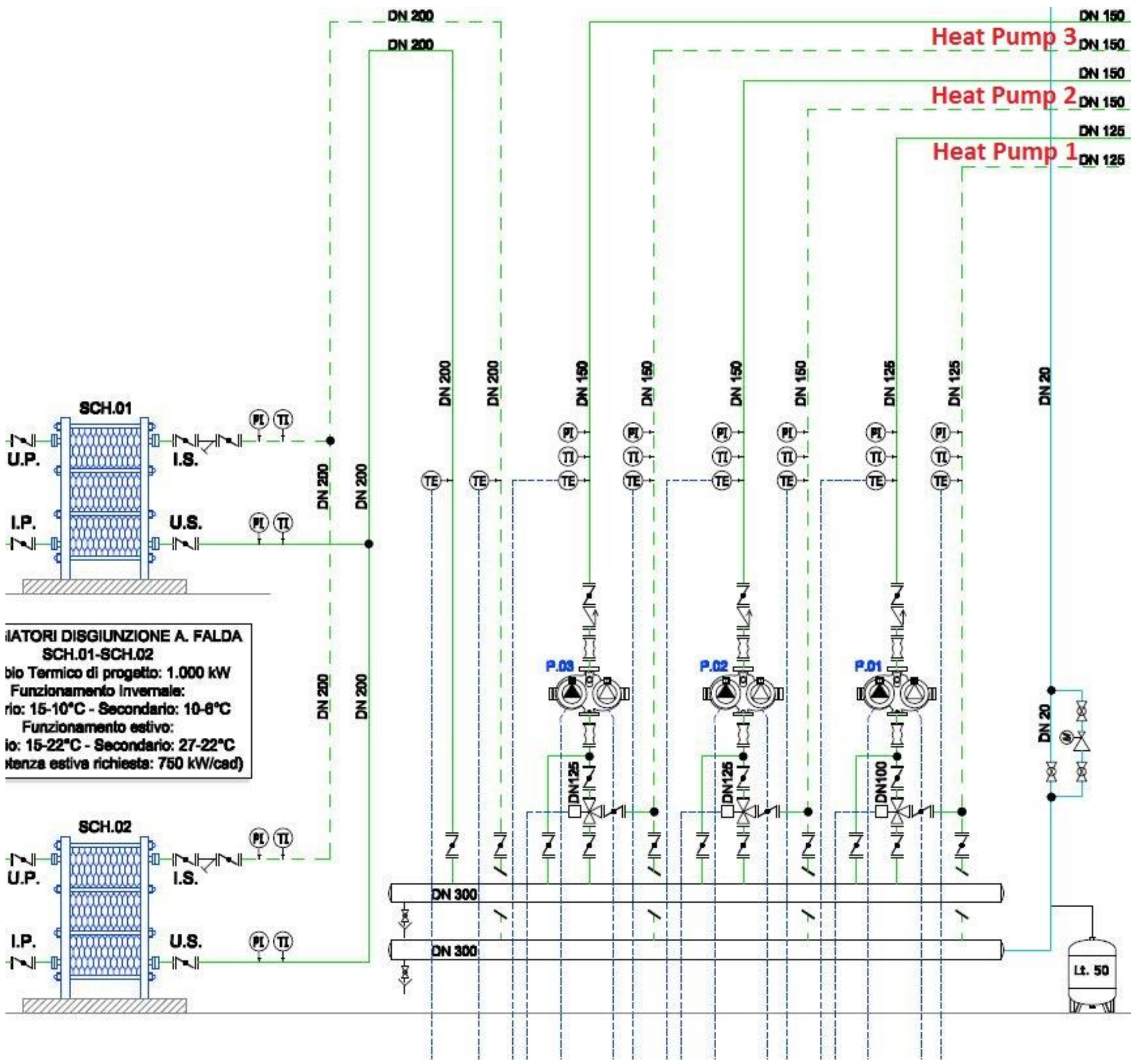
From the previous photo, realized during the site visit, it is possible to notice how a plate heat exchanger is constituted. It is also possible to understand how the operation cleaning can occur. In case of obstruction of the heat exchanger, operators can remove the left and blue part in order to extract the single stainless-steel plate and the membranes. After an accurate washing of all the parts, the heat exchanger can be reassembled.

- **Disjunction circuit**

The disjunction (or secondary) circuit is a closed pipe circuit; it joins thermally the geothermal system and the heat pumps. This circuit is not strictly necessary in a general open loop geothermal heat pump system; its presence is due only to a security reason. Without this disjunction circuit, pumped underground water should flow directly in the shell and tubes heat exchanger of the heat pumps and, in this case, possible solid particles, pumped with water and not kept by filtration system, could have to obstruct the tubes of the heat exchangers. When this type of problems occurs, maintenance operation with high cost and long out of service time are necessary to clean and restart the heat pump. On the other hand, disjunction circuit introduction brings to have a relative higher cost of investment due to presence of heat exchangers, pumps and pipes. It is also noteworthy a relative lower efficiency of the heat pumps because of temperature unfavorable variation.

The water of the disjunction circuit, flowing out to the disjunction heat exchangers, reaches a water collector from witch 3 circulation pumps bring it to 3 relative heat pumps. Then water processed by heat pumps returns to the disjunction heat exchangers.

Fig. 24 Disjunction circuit (Mediapolis, 2013)



- **Heat Pumps**

The heat pumps are the core of this thermal power station; thanks to them it is possible to provide heating, cooling and also domestic hot water.

During the realization of project, three heat pumps are installed in order to generate heating, cooling power or domestic hot water. After some time, it is chosen to use only one of the three heat pumps to generate domestic hot water, giving to the other two the aim to produce heating and cooling power for conditioning system.

Taking into account this concept and having chosen to consider only heating and cooling conditioning, only two of the pumps are treat in this thesis.

Fig. 25 One of the heat pumps of the thermal power station (Mediapolis, 2013)

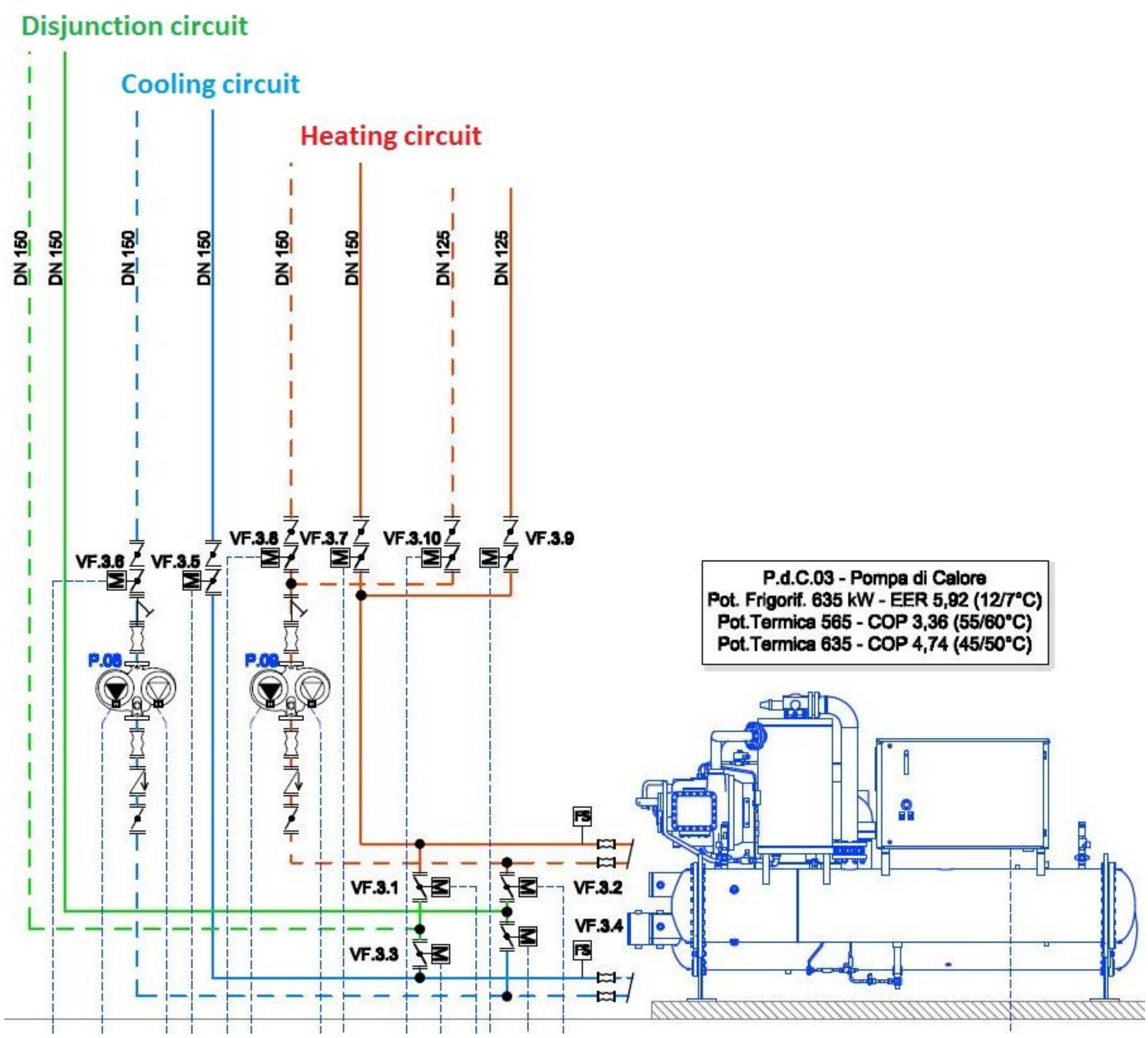
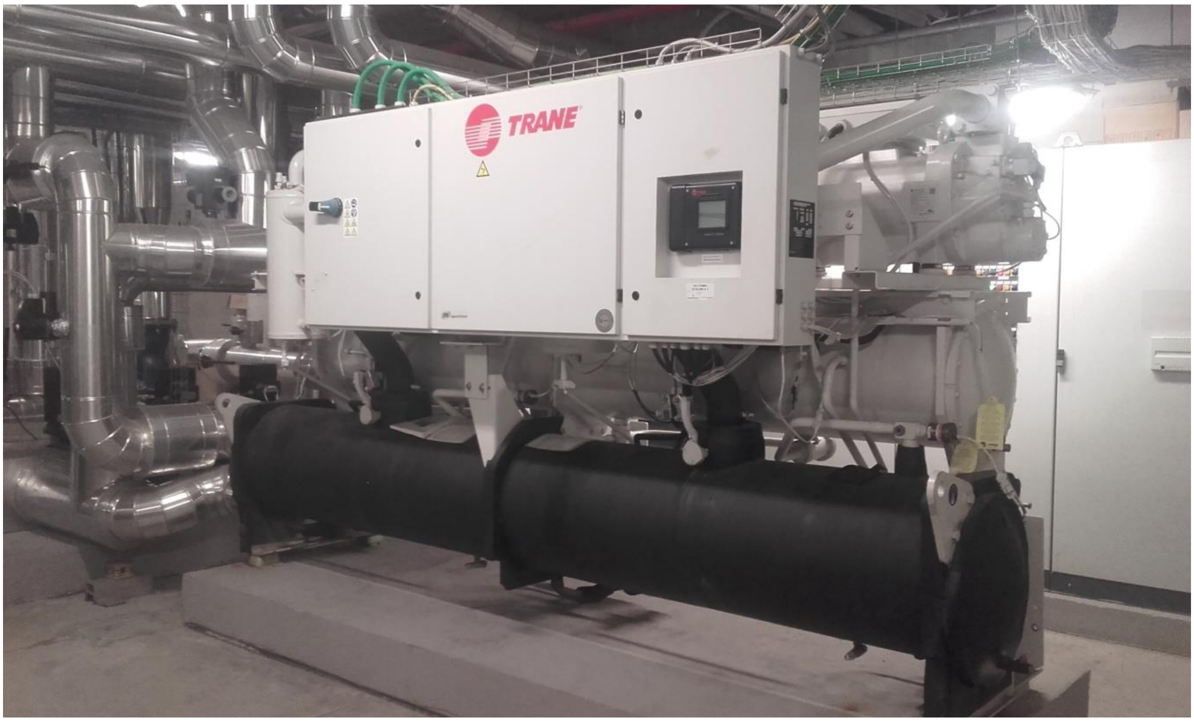


Fig. 26 Heat pump photo



From the previous photo, realized during the site visit, it is possible to see one of the installed heat pumps.

Heat pumps are Trane's products; the two heat pumps considered are equal and his code on the Trane's catalog is: RTWD 170 HE G. Trane's datasheet will be useful for energetic consumption calculation of next steps.

- **Distribution circuit**

The distribution (or tertiary) circuit is designed in order to carry the thermal or cooling power to the devises which use them. Air Handing Units, fan-coils and ceiling radiant panel are located in this structure in order to satisfy all conditioning requirements. For each type of device, a proper distribution circuit with circulation pumps were installed. Each distribution circuit leaves the thermal power station, located in the underground floor, to reach the centre of the basement floor. Risers cross vertically the centre of the building and in each floor the distribution pipes are fine ramified in order to reach all thermal devices.

3.2. Geothermal Data Analysis

After a brief description of the “RSA Il Trifoglio” and its open loop geothermal system, in this section an analysis on geothermal data is realized for 2017 and 2018.

The most important data, useful to manage and control an operative open loop geothermal system are: water flow rate from extraction to reinjection wells, extraction water temperature and reinjection water temperature. If three previous data are present in a real measurement collection computed at the same instant also thermal power extracted or re-injected from/in to the aquifer can be computed.

- **Underground water extraction measurement**

Talking about water flow rate, any water flow rate measurement device is installed, but for each extraction well a cumulative water counter is present. In this way, only total water extraction value is reported on the device and it is the total volume of water extracted from the first operation of the single well until the moment in which meter reading occurs.

For a decision of the operators, a monthly meter reading of each extraction well is performed, so for each month is possible find the total extracted water from each well make a subtraction between the present meter counter and the previous month.

Table 6 2017 underground extraction cumulative measurement

2017		Extraction well 1	Extraction well 2	Extraction well 3	Total Extraction
JAN	End Month Reading [mc]	833,338	848,569	0	-
	Monthly Extraction [mc]	29,283	35,900	0	65,183
	Average Consumption [l/s]	10.93	13.40	0.00	24.34
FEB	End Month Reading [mc]	860,417	877,899	0	-
	Monthly Extraction [mc]	27,079	29,330	0	56,409
	Average Consumption [l/s]	11.19	12.12	0.00	23.32
MAR	End Month Reading [mc]	889,617	908,024	0	-
	Monthly Extraction [mc]	29,200	30,125	0	59,325
	Average Consumption [l/s]	10.90	11.25	0.00	22.15
APR	End Month Reading [mc]	913,807	932,138	0	-
	Monthly Extraction [mc]	24,190	24,114	0	48,304
	Average Consumption [l/s]	9.33	9.30	0.00	18.64
MAY	End Month Reading [mc]	939,689	956,127	0	-
	Monthly Extraction [mc]	25,882	23,989	0	49,871
	Average Consumption [l/s]	9.66	8.96	0.00	18.62
JUN	End Month Reading [mc]	965,616	980,597	0	-
	Monthly Extraction [mc]	25,927	24,470	0	50,397
	Average Consumption [l/s]	10.00	9.44	0.00	19.44
JUL	End Month Reading [mc]	995,109	1,009,780	0	-
	Monthly Extraction [mc]	29,493	29,183	0	58,676
	Average Consumption [l/s]	11.01	10.90	0.00	21.91
AUG	End Month Reading [mc]	1,024,699	1,037,899	0	-
	Monthly Extraction [mc]	29,590	28,119	0	57,709
	Average Consumption [l/s]	11.05	10.50	0.00	21.55
SEP	End Month Reading [mc]	1,052,315	1,061,611	0	-
	Monthly Extraction [mc]	27,616	23,712	0	51,328
	Average Consumption [l/s]	10.65	9.15	0.00	19.80
OCT	End Month Reading [mc]	1,079,294	1,087,901	0	-
	Monthly Extraction [mc]	26,979	26,290	0	53,269
	Average Consumption [l/s]	10.07	9.82	0.00	19.89
NOV	End Month Reading [mc]	1,106,588	1,114,874	0	-
	Monthly Extraction [mc]	27,294	26,973	0	54,267
	Average Consumption [l/s]	10.53	10.41	0.00	20.94
DEC	End Month Reading [mc]	1,137,943	1,147,767	0	-
	Monthly Extraction [mc]	31,355	32,893	0	64,248
	Average Consumption [l/s]	11.71	12.28	0.00	23.99
Total 2017		**333,888**	**335,098**	**0**	**668,986**

Graph. 1 2017 underground extraction cumulative measurement

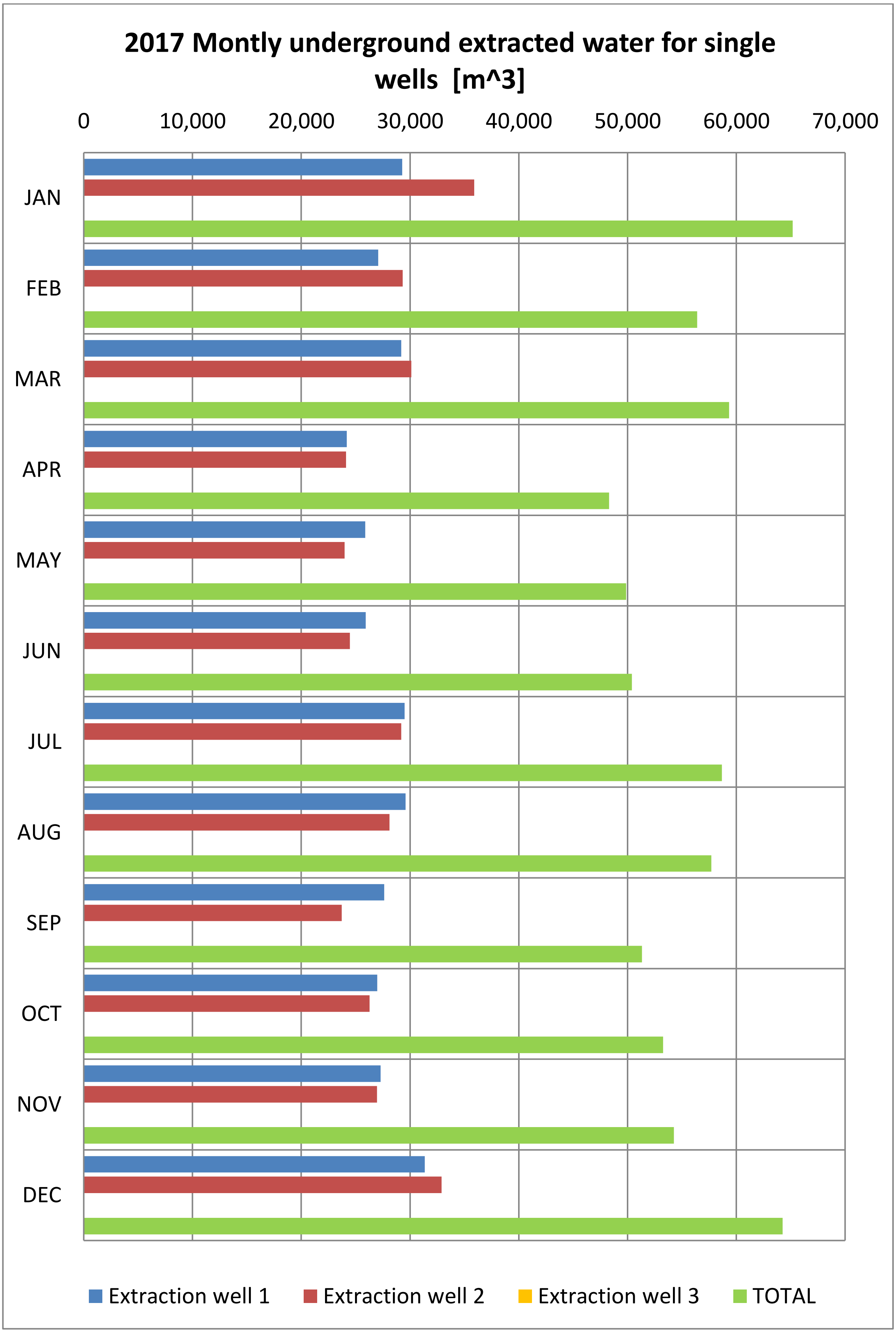
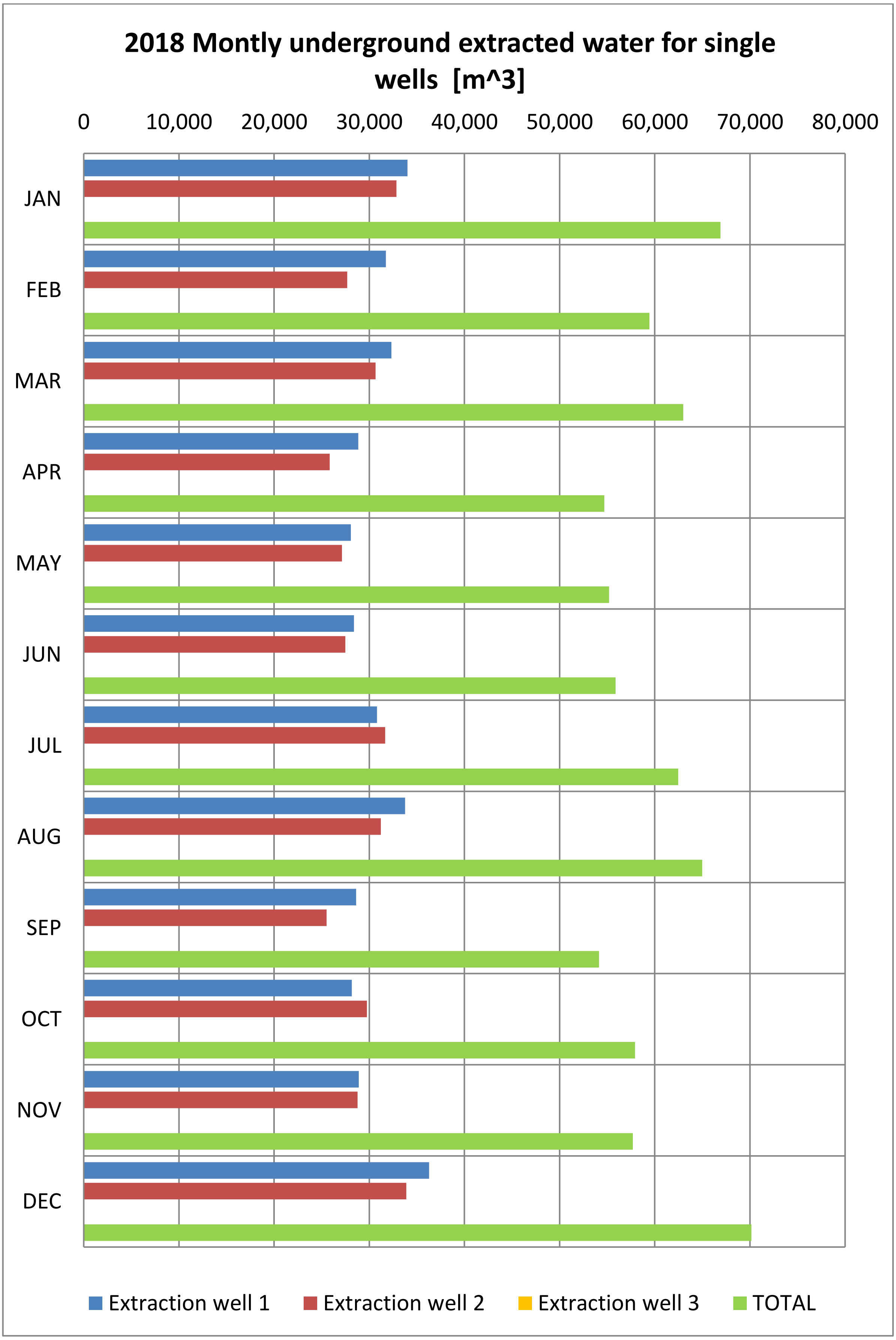


Table 7 2018 underground extraction cumulative measurement

2018		Extraction well 1	Extraction well 2	Extraction well 3	Total Extraction
JAN	End Month Reading [mc]	1,171,969	1,180,633	0	-
	Monthly Extraction [mc]	34,026	32,866	0	66,892
	Average Consumption [l/s]	12.70	12.27	0.00	24.97
FEB	End Month Reading [mc]	1,203,728	1,208,315	0	-
	Monthly Extraction [mc]	31,759	27,682	0	59,441
	Average Consumption [l/s]	13.13	11.44	0.00	24.57
MAR	End Month Reading [mc]	1,236,062	1,238,981	0	-
	Monthly Extraction [mc]	32,334	30,666	0	63,000
	Average Consumption [l/s]	12.07	11.45	0.00	23.52
APR	End Month Reading [mc]	1,264,910	1,264,836	0	-
	Monthly Extraction [mc]	28,848	25,855	0	54,703
	Average Consumption [l/s]	11.13	9.97	0.00	21.10
MAY	End Month Reading [mc]	1,292,986	1,291,965	0	-
	Monthly Extraction [mc]	28,076	27,129	0	55,205
	Average Consumption [l/s]	10.48	10.13	0.00	20.61
JUN	End Month Reading [mc]	1,321,391	1,319,440	0	-
	Monthly Extraction [mc]	28,405	27,475	0	55,880
	Average Consumption [l/s]	10.96	10.60	0.00	21.56
JUL	End Month Reading [mc]	1,352,194	1,351,113	0	-
	Monthly Extraction [mc]	30,803	31,673	0	62,476
	Average Consumption [l/s]	11.50	11.83	0.00	23.33
AUG	End Month Reading [mc]	1,385,957	1,382,326	0	-
	Monthly Extraction [mc]	33,763	31,213	0	64,976
	Average Consumption [l/s]	12.61	11.65	0.00	24.26
SEP	End Month Reading [mc]	1,414,582	1,407,835	0	-
	Monthly Extraction [mc]	28,625	25,509	0	54,134
	Average Consumption [l/s]	11.04	9.84	0.00	20.89
OCT	End Month Reading [mc]	1,442,740	1,437,593	0	-
	Monthly Extraction [mc]	28,158	29,758	0	57,916
	Average Consumption [l/s]	10.51	11.11	0.00	21.62
NOV	End Month Reading [mc]	1,471,647	1,466,377	0	-
	Monthly Extraction [mc]	28,907	28,784	0	57,691
	Average Consumption [l/s]	11.15	11.10	0.00	22.26
DEC	End Month Reading [mc]	1,507,928	1,500,263	0	-
	Monthly Extraction [mc]	36,281	33,886	0	70,167
	Average Consumption [l/s]	13.55	12.65	0.00	26.20
Total 2018		369,985	352,496	0	722,481

Graph. 2 2018 underground extraction cumulative measurement



From the previous tables and graphs, it is possible to understand how the extraction of water is subdivided in the months of a year and also make considerations from relative comparison.

First of all, it is clear that “Extraction well 1” and “Extraction well 2” are used almost in the same way, whit similar monthly water extraction. At the contrary, “Extraction well 3” is never used; this choice is probably due to the sufficient extraction capacity of first and second wells.

From graph it is also possible to see a variation of the monthly water extracted during the year: high values characterizes the beginning of the year, during the spring water extraction slightly decreases, in summer it returns at high values and in autumn the behavior is similar to the spring, at the end of the year values increase again. This perceptible fluctuation is related to the variation of thermal requirement of the structure during the year. In winter and summer, an high heating and cooling demand has as consequence an high water consumption. Instead during spring and autumn conditioning requirement are moderate, therefore water extraction is reduced.

From year to year total underground water extraction doesn’t have a significant variation; it probably could change if heating and cooling demand are more different between years.

- **Extraction and reinjection water temperature**

For what concern the extraction and reinjection water temperature, sensors and data center are present to measure and store the relative parameters.

Before to show and understand these values, a brief introduction on data collection method is treated. Storing of measured data cannot be computed continuously; a measurement is effectuated in a precise instant and two successive ones are separated by a time gap. This time gap can change in dimension in relation to other aspects.

The simple way to measure an store data is to collect a single value with a cadence fixed at a certain gap time. It means that equal time period have the same number of sampling and the number of measurement can be chose. A the same time, this method doesn't consider any parameter variation between two consecutive measurement; to reduce this problem a reduction of time gap can be adopted, but the total number of sampling increases proportionally.

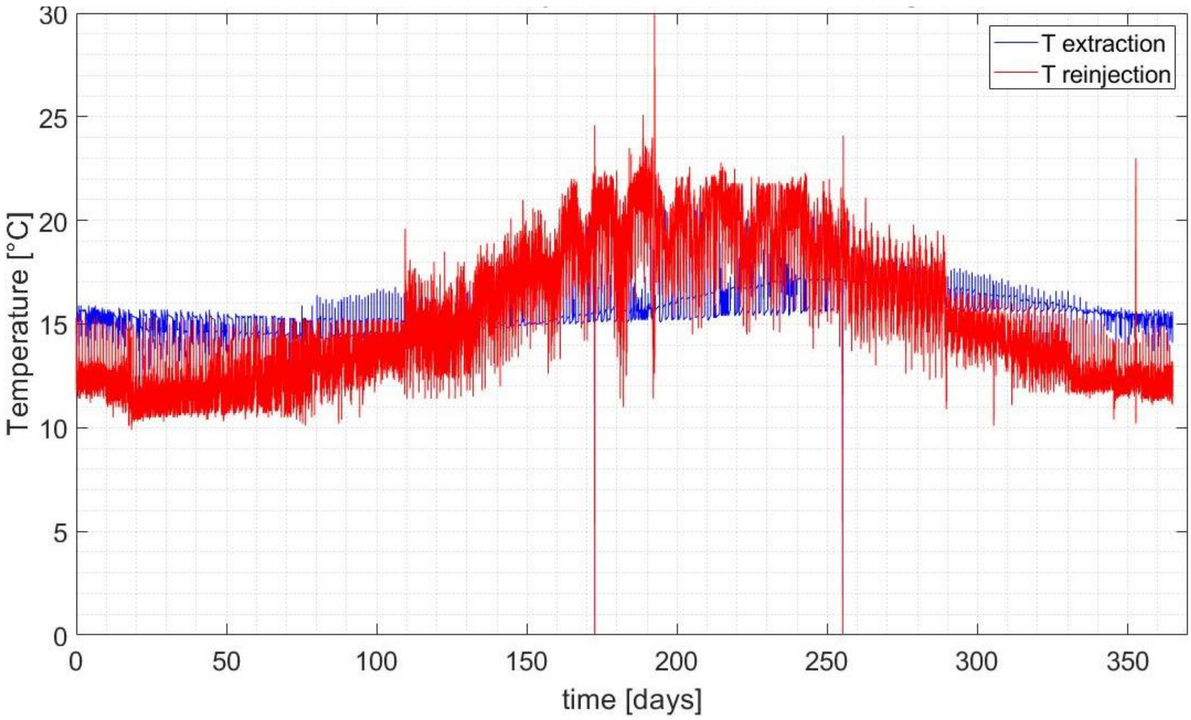
A second method to measure and store data is to collect a single value when the parameter varies over at fixed value. Whit this approach, time gap is not fixed and is not possible to know how many samples will be collected. Respect to the previous one, this optimizes the numbers of sampling maximizing the precision also for short parameter variation too fast to be perceived by the first method.

In the case study, the second collection data approach is used for extraction water temperature measurement and the fixed time gap one (10 minutes) is used for the reinjection one.

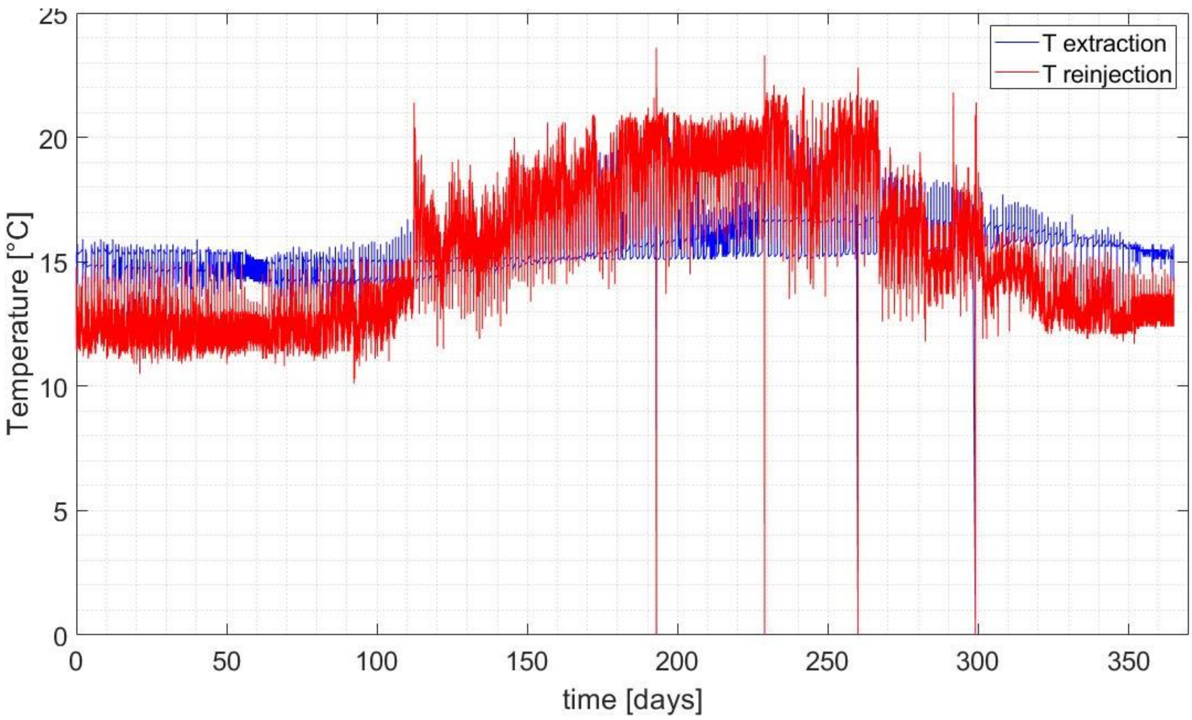
Even if there are three extraction wells only one sensor is installed, as the reinjection ones. The temperature sensors are installed shortly before the disjunction heat exchanger.

Also in this case, 2017 and 2018 data are reported below.

Graph. 3 2017 Extraction and reinjection temperature



Graph. 4 2018 Extraction and reinjection temperature



These previous graphs report all data of extraction and reinjection water temperature how are collected by the sensors.

First of all, it is necessary to point out that there are some data collected with errors which report a temperature equal to zero.

The alternation between heating and cooling seasons is visible. During winter, reinjection water temperature is colder than extraction one, this is due to the need to extract heat from water to be allocated to the building. At the contrary, during summer, reinjection water temperature is hotter respect to the extraction one, for the necessity to disperse in the aquifer the heat extracted by the building.

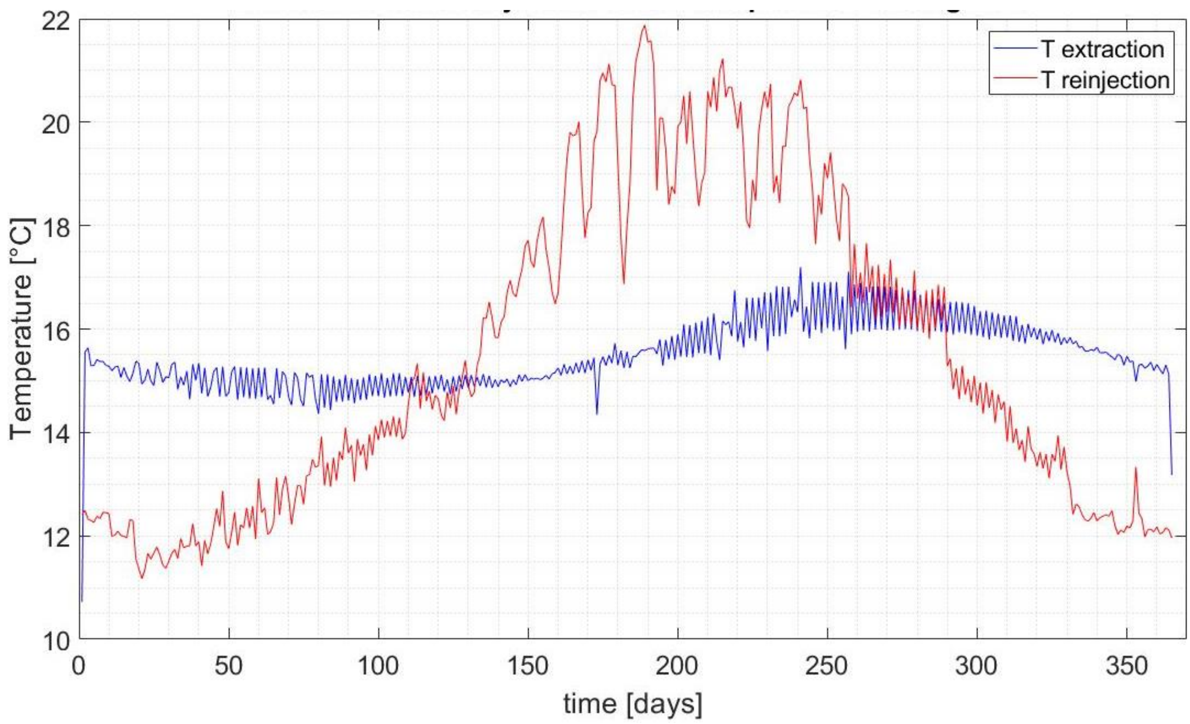
In the reinjection water temperature representation, it is also possible to see a behavior similar to a ideal building conditioning requirements. In fact, in the middle of the summer and winter seasons, peaks are concentrated. In general, it is possible to say that reinjection water temperature have a sinusoidal behavior.

Talking about extraction water temperature, a more constant representation was expected, because the temperature of aquifer doesn’t change so quickly, but other consideration can be done with next detailed analysis.

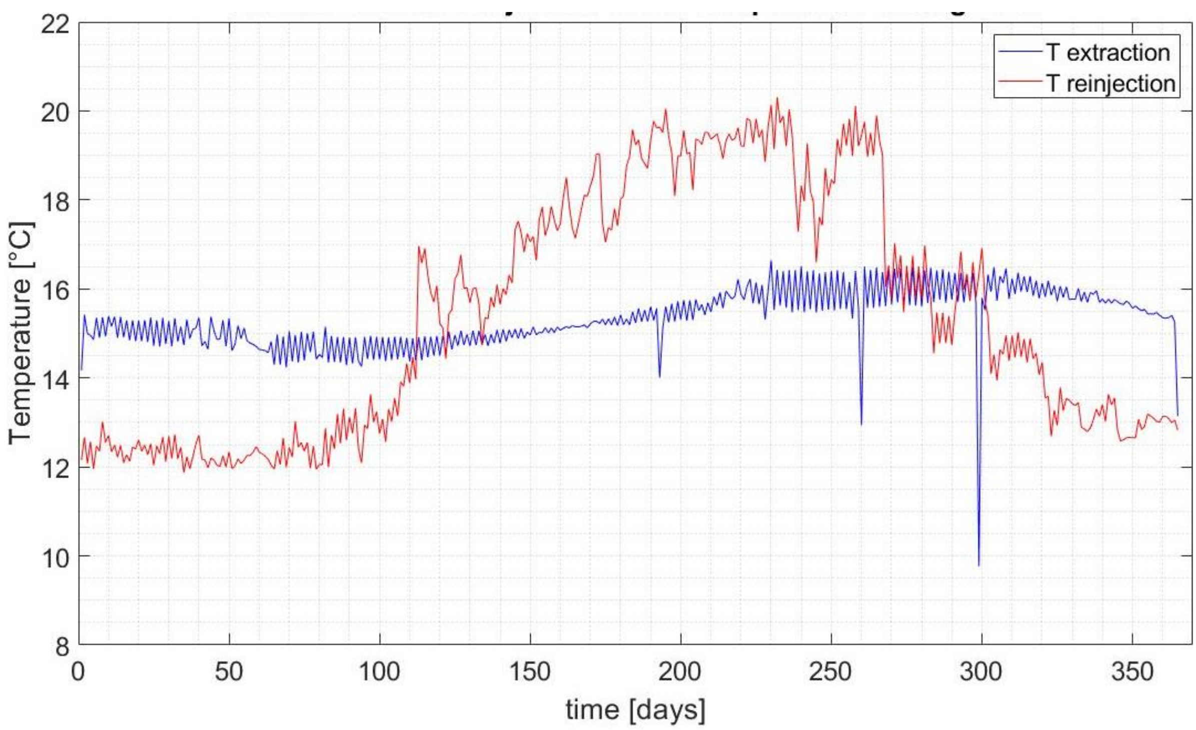
In order to analyze more in detail and compare the extraction and reinjection water temperature, a Matlab® script is realized. The first aspect to treat is the realization of the same sampling of data; it is chosen to adopt a time gap of a second. This choice could be considered excessive for this case, but it is necessary for how the extraction water temperature was collected.

Thanks to a new set of data, a daily average temperature can be computed.

Graph. 5 2017 daily average extraction and reinjection temperature



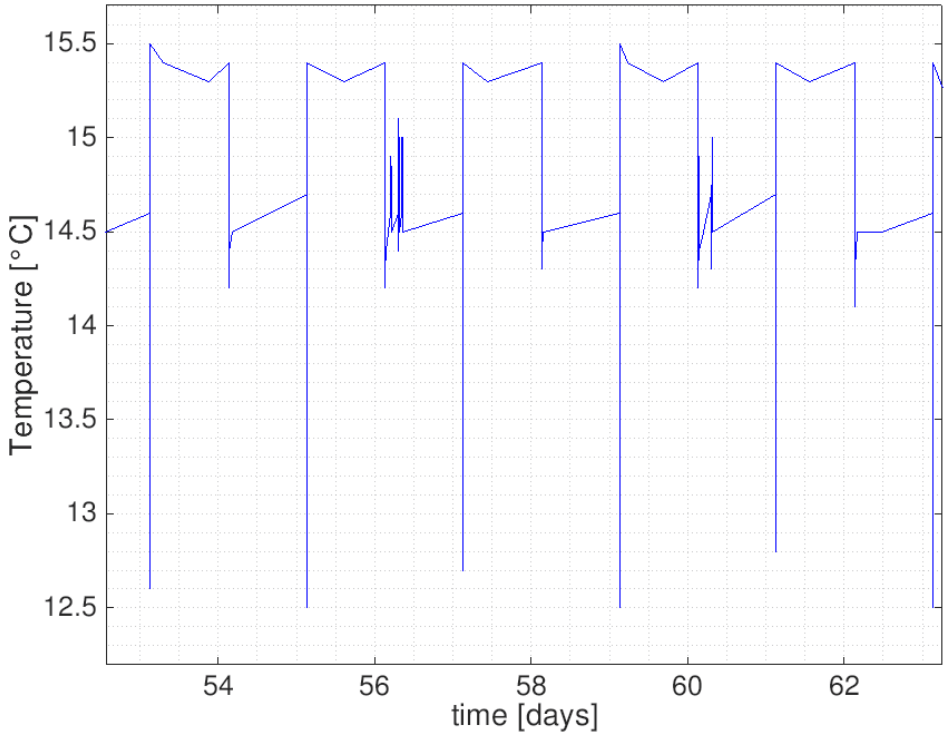
Graph. 6 2018 daily average extraction and reinjection temperature



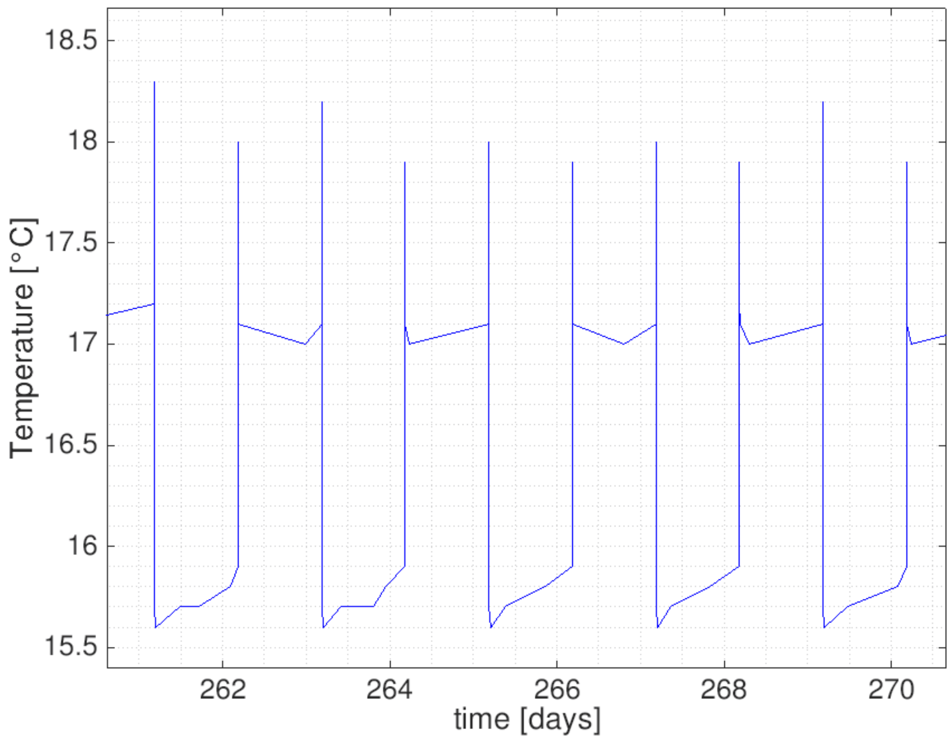
The previous graphs are more clear to understand, because number of points is drastically reduced. In the other hand, this representation can’t show a real behavior of the parameters.

For what concern the quickly variation of the extraction water temperature, a focus on the graph is necessary.

Graph. 7 Extraction water temperature and alternation of extraction well during winter



Graph. 8 Extraction water temperature and alternation of extraction well during summer



Thanks to the previous graphs it is possible to put in evidence a continuous alternation of almost constant temperatures with a period of a day and troughs or peaks are present between the periods. This behavior is due to the fact that an automatic control system extracts water only from a well in a day and in the next one from the other well. Day by day the extraction of the water is alternated on the two wells, but, when only one well is not sufficient to extract the water needed also the other one starts to work.

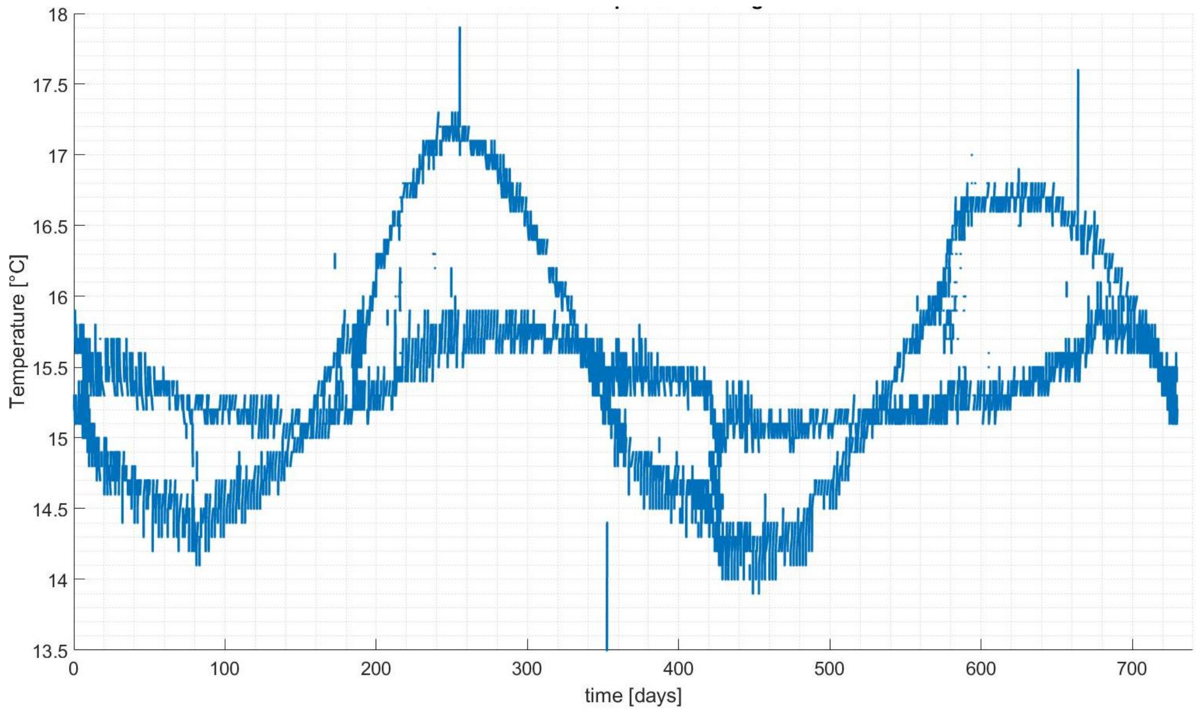
In normally condition, from two different abstraction well of the same open loop geothermal system which reach the same aquifer, is not possible to extract water at different temperatures. Excluding malfunctions of the temperature sensors, the only one possible reason for this happening is the presence of a thermal short-circuit.

After the restitution of the water in the reinjection wells, water with a different temperature respect to the aquifer one, crosses the permeable layer between reinjection and extraction wells. During the transit, perturbed water mixes with the aquifer one reducing the difference in temperature. The transit of the water from extraction to reinjection wells can request lot of time depending by aquifer characteristics, water flow rate of the system, wells distance and aquifer direction.

At this point it is not possible to exclude the presence of a thermal short-circuit in the other well. Instead, it is possible to attribute the wells at the relative perturbed temperatures with other considerations or directly in the site, during the operation of the geothermal system.

To have a more clear idea on the extraction water temperature variation due to the thermal short circuit is necessary to exclude the fast variations between periods. To do this, with the Matlab® script, data are filtered, erasing the values if the variation of the temperature exceeds a certain threshold, imposed equal to 0.5 °C/h.

Graph. 9 2017 and 2018 filtered extraction water temperature



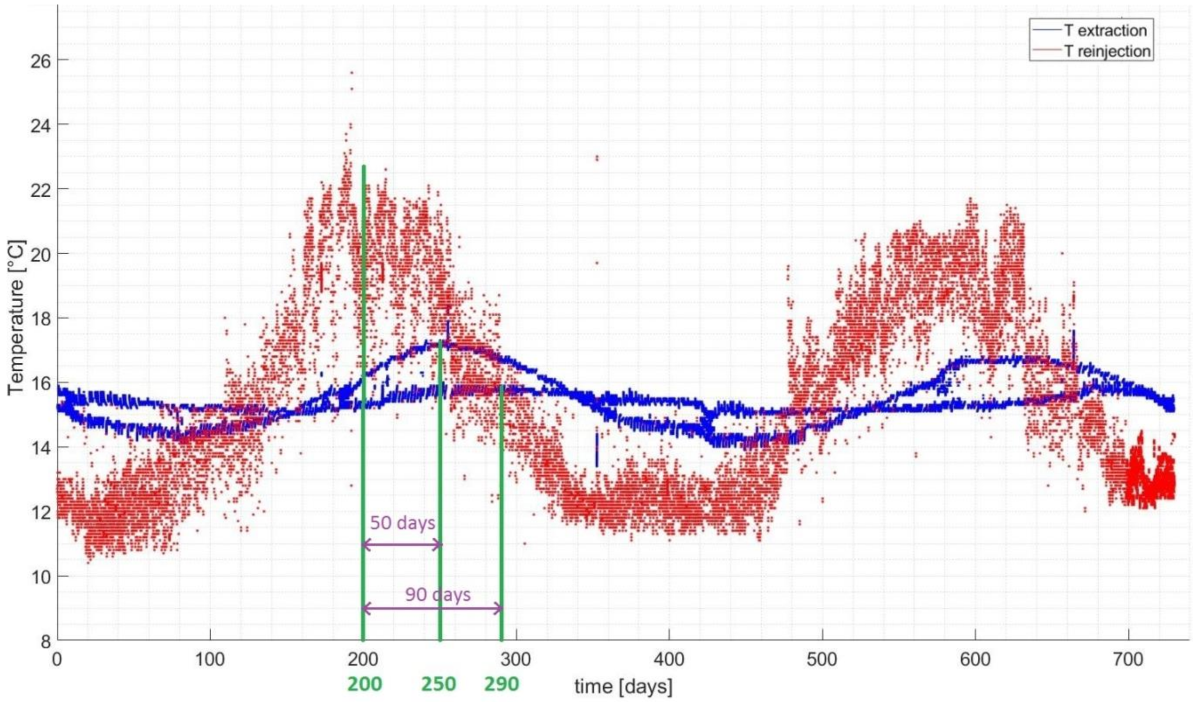
Thanks to this representation of the extracted water temperature, what explained before is more clear. From the same sensor two different functions seem to be reported. The constant alternation of the two extraction wells has ensured a continuous collection of information of both wells during the two analyzed year. Two visible sinusoids represent the temperature variation of the water of "Extraction well 1" and "Extraction well 2", therefore both wells are affected by thermal short circuit. The two "functions" have obviously the same period (an year), but different amplitudes and a relative phase shift between each other. These different characteristics are both due to the different amount of time spent by the perturbation to reach the two extraction wells.

However, as it is visible in the graph, the absolute variation in term of Celsius degrees is very limited: the sinusoid with greater amplitude varies from a minimum of 14°C to a maximum of 17.3°C and the other one from 14.9°C to 15.9°C. It seems a no relevant variation for the operation of a thermal system, but this happening can be disadvantageous.

From current legislation, during summer the reinjection water temperature can't exceed 22°C and in winter can't reduce under 9°C to preserve the chemical properties of the aquifer (Capilongo, 2018). Considering an unperturbed aquifer temperature of 15.5°C, the useful temperature variation is 6.5°C in summer and also in winter. With a thermal short-circuit the projected temperature difference is not maintained. In worst case, previous oscillations in extraction water temperature bring to have a useful temperature variation of 4.7°C (22°C - 17.3°C) in summer and 5°C (17°C – 9°C) in winter. The new temperature differences can result not equal to the projected ones; probably, with thermal short-circuit, the thresholds imposed by the legislation can be reached more easily.

Thank to the filtration method, it is possible to plot filtered extraction and reinjection water temperature to underline the close relationship between the two parameters.

Graph. 10 2017 and 2018 filtered extraction and reinjection water temperature with phase shift



First of all is useful to notice that reinjection water temperature has more oscillations during its operation respect to the extraction one, but a sinusoidal behavior is clearly represented.

For what concern the phase shit of the sinusoids, the retardation in time can be approximated like in the previous graph.

At this point, considering the relative positions of the wells and aquifer direction, it is probably true the association of "Extraction well 1" with the extraction temperature with the greatest amplitude, having a shorter retardation time. As consequence, the extraction water temperature sinusoid with minor amplitude is associated at "Extraction well 2".

Even if "Extraction well 1" is slightly more distant from reinjection wells, it is reached faster than "Extraction well 2" by the thermal perturbation, because it is located too downstream in the aquifer.

Taking into account the previous consideration, to avoid or reduce future thermal short-circuit it should be advisable to stop the extraction of water from "Extraction well 1" and start to use "Extraction well 3". The alternation of the extraction wells will occur in future, but only from 2 and 3 extraction well. A minor thermal perturbation is expected from "Extraction well 3", because it is located more upstream respect to the reinjection ones.

Chapter 4: Cost optimal analysis

In this thesis a cost-optimal analysis has been performed on different heating and cooling production systems. The aim of this work is to compare the choice of an Open Loop Geothermal Heat Pump system with other possible plant configurations normally installed in buildings with characteristics similar to the ones of "RSA Il Trifoglio" in Turin.

To operate a cost-optimal analysis, it is necessary to compute energy consumptions, energy costs, primary energy consumption and Global cost for all cases. At the end of this Chapter a graph will give a summary comparisons between different scenarios reporting both the specific primary energy consumption and the specific global cost.

All different scenarios consider to keep constant building characteristics and thermal requirements for heating and cooling conditioning. Only heating and cooling production systems vary from a scenario to another.

The cost-optimal analysis is performed starting from 2018, this is named starting year τ_0.

4.1. Different scenarios

Based on the presence of an heat pump, as the reference plant, there are also other systems which are able to provide heating and cooling power thanks their reversibility. They differ from an open loop geothermal heat pump system only for the way they extract or re-inject heat, or for the location where the extraction occurs. They are: Closed loop Geothermal Heat Pump system and Air Heat Pump system.

About other possible systems for heating power production only, referring to the city of Turin it is possible to have: Condensation methane Boiler and District heating provided by Iren's district heating network.

Talking about systems for cooling power production only, we can consider: Air-cooled chiller and absorption chiller with a methane alimentation.

Composing the previous simple systems it is possible to generate different combination of thermal power station with different results.

A general rule observed is to consider two equal machines for each scenario, to use the same approach of the project designer, who chose to divide the total requirement between two equal heat pumps.

A brief description of each system is further reported; the next pages also show real machines in order to give an idea on the relative performances and efficiencies thanks to the provided datasheets.

- **CGHP: Closed Loop Geothermal Heat Pump system**

As explained in Chapter 2, a closed loop geothermal heat pump system, is a technology that allows to produce both heating and cooling power, extracting or re-injecting heat in the underground layers. The difference compared to an Open Loop Geothermal Heat Pump system is the absence of wells and the presence of a close heat exchanger in thermal contact with the terrain.

The same heat pumps of Open Loop Geothermal Heat Pump system are used excluding disjunction heat exchangers and disjunction circuit, for the impossibility that an obstruction will occur.

Excluding disjunction heat exchangers, the operative temperatures of water of the disjunction circuit can be associate with operative temperatures of a Closed Loop Geothermal heat exchanger. Therefore, in this scenario, the behaviour and the performances of the heat pump are considered the same compared to the Open Loop case.

Taking into account the geothermal connection, vertical boreholes seem to be the best geothermal heat exchanger configuration for this case. The urban context offers only small available areas, so an horizontal shape for geothermal heat exchanger turns out to be impossible to install. A huge amount of soil would have to be removed for the installation and, probably, it would be necessary to perform an installation of the horizontal geothermal heat exchanger also below the structure.

For the realization of a borehole heat exchanger, a long process of numerical simulations must be performed to guarantee correct design and dimension. For small plants, it is possible to adopt fix values of heat flux per meter of borehole, in order to define the dimensions and amount of boreholes. Also, in this case a simplify method has been adopted considering an heat flux of 80 W/m of borehole, taking into account the gravel and sand subsoil with an high hydraulic flow (Baietto et al., 2010).

- **AHP: Air heat pump**

An Air Heat Pump system is a device that allows the production of both heating and cooling power, extracting or re-injecting heat on the external air. Also, this is based on a vapour compression process like previous ones.

Differently than subsoil layers and underground water, external air temperature varies considerably during the year. The performance of an heat pump is strictly related to the temperature of its termostatos and if their temperature difference increases, the performance of the machine falls down. This problem occurs whether in heating or in cooling seasons.

In addition to this unfavourable behaviour, if the external temperature remains low during heating season, ice formations could appear between the ranks of the external heat exchangers for a sublimation process of the humidity of the air. This particular occurrence obstructs the transit of the external air on the heat exchanger so that the heat pump must be stopped. A short inversion of the cycle allows to melt just sublimated ice and restart the work but, in order to do this, an amount of heat must be extracted from the building, reducing the total performance and reducing the residents' comfort.

For this work, a real component is taken into account: the Air Heat Pump CXAF SE 190 AC fans, a product of Trane.

Fig. 27 Air Heat Pump CXAF SE 190 AC fans, a product of Trane

- **MTB: Condensing Methane Boiler**

Condensing Methane Boiler is one of the most used technology for heating generation in Italy. It is progressively replacing non-condensing Methane Boiler with a lower efficiency. It is present on market in lot of models, from very low to high power.

For this work, a real component is taken into account: the Condensing Methane Boiler ARES 660 TEC ERP, a product of Immergas.

Fig. 28 Condensing Methane Boiler ARES 660 TEC ERP, a product of Immergas

- **DSH: District Heating**

The heating of a building with District Heating is strictly associated to the presence of a District Heating network. In the city of Turin, IREN Energia manages one of the largest district heating in Europe. In this specific case, the location of "RSA Il Trifoglio" is too far to realize a connection with the actual network configuration. Nevertheless, considering the fact that Turin District Heating could be an important alternative for heating production for this type of building in other parts of the city, it is important to evaluate this option too.

On the other hand, about other systems, any producer catalogue that contains systems and components for connections with district heating is taken into consideration.

The generation efficiency of a District Heating substation is calculated through the evaluation of losses at operating conditions proposed by UNI/TS 11300-4.

- **ACC: Air-Cooled Chiller**

Air-Cooled Chiller is the most used technology to provide cooling power. It is based on a reverse cycle and include compressors of refrigeration fluid, which are moved by electricity. The chiller extracts heat from the water of the distribution circuit and gives it back to the environment through an external air heat exchanger. For these reasons, Air-cooled Chiller can be used everywhere.

For this work it has been used the real component used in the Air Heat Pump scenario. Air Heat Pump CXAF SE 190 AC fans, a product of Trane, is used to provide only cooling power, therefore it can be defined as an Air-Cooled Chillers.

- **MAC: Methane Absorption Chiller**

Absorption chiller like the previous one, is useful to provide cooling power, but it works with an absorption process that requires a thermal power input. This input can be provided by many different sources, but this technology is less used than the vapor compression one. It can be installed in order to use wasted heat from industrial process, or however low cost thermal energy. It is often supplied by the direct combustion of a fuel, like, for example, methane.

Sometimes, Absorption chillers can use heat provided by a District heating system, but IREN Energia allows a maximum water temperature of 80 °C after the substation [8]. This threshold is too low to Absorption chillers available on market which should work in unusual condition. Possible future technology developments could reduce the alimentation water temperature of absorption chillers, or more likely IREN Energia authorization could allow to increase the imposed threshold.

However, independently from supply typology, the amount of heat extracted by the building and generated by the supply (in this case: combustion of methane) must be dispersed. In order to make it happen, an absorption heat exchanger is often connected to an evaporative tower system. Thanks to the evaporation of a fraction of processed water, this is able to evacuate more efficiently heat in external air compared to closed circuit.

For this work, real components is taken into account: the Absorption Chiller WCDH 018, a product of LG.

Fig. 29 Absorption Chiller WCDH 018, a product of LG

Considering all previous machines, different combinations can be created:

Table 8 Reference case and different scenarios coded, reporting different machines used

CODE	HEATING	COOLING
MTB.ACC	Condensing Methane Boiler	Air-Cooled Chiller
MTB.MAC	Condensing Methane Boiler	Methane Absorption Chiller
DSH.ACC	District Heating	Air-Cooled Chiller
DSH.MAC	District Heating	Methane Absorption Chiller
AHP	Air Heat Pump	
CGHP	Closed Loop Geothermal Heat Pump	
OGHP	Open Loop Geothermal Heat Pump	

Not hybrid combination are considered at this point.

4.2. Performances and energy cost

The calculation procedure of: energy consumptions, energy costs, primary energy consumption and CO_2 emission are treated in this subchapter.

- **Energy consumption**

In order to estimate the real energy consumption due to the conditioning of the structure, the consultation of the Energy Performance Certificate turns out to be the most reliable method. Unfortunately, other kind of considerations are not possible because, first of all, heat counters are not placed in any part of the plant and, secondary, electric energy bills consider all electric energy consumed in the residence in a month.

Starting from the Energy Performance Certificate, related in 2014, it is possible to know the requirement of the building for heating and cooling.

About heating requirement for conditioning, the certifier esteemed a value of:

Eq. 26 $$Q_{H,need} = 11.45 \frac{kWh}{m^3 * year}$$

Talking about the cooling requirement for conditioning a precise value it is not represented. In the certificate is reported the Summer Thermal Quality of the Building equal to III degree, in accordance with the DM. 26 giugno 2009.

Table 9 Summer Thermal Quality of the Building (DM. 26 giugno 2009)

EPe,invol (kWh/m^2anno)	**Prestazioni**	**Qualità prestazionale**
EPe,invol < 10	ottime	I
10≤ EPe,invol < 20	buone	II
20≤ EPe,invol < 30	medie	III
30≤ EPe,invol < 40	sufficienti	IV
EPe,invol ≥ 40	mediocri	V

At this point, an average value can be adopted; the value of 25 kWh/(m^2*year) can be considered how the cooling requirement for conditioning referred to a unit of useful surface of the building. Considering the values of conditioned gross volume (54.325 m^3) and useful surface of building (12.318 m^2), reported in the certificate below, the cooling requirement for conditioning referred to a unit of volume is:

Eq. 27 $$Q_{C,need} = 5.67 \frac{kWh}{m^3 * year}$$

Fig. 30 "RSA Il Trifoglio" Energy Performance Certificate (Italian acronym: APE) (Part 1)

REGIONE PIEMONTE

ATTESTATO DI PRESTAZIONE ENERGETICA

ANAGRAFICA EDIFICIO

Comune: TORINO
Indirizzo: VIA ANDORNO

NCEU: f. 1276 n. 340 sub.
Piano: n.0 N.3

Progettista:
Direttore dei Lavori:
Costruttore:

DATI GENERALI

Destinazione d'uso: E3
Anno di costruzione/ultima ristrutturazione: 2011
Tipologia edificio: edificio isolato
Volume lordo riscaldato (m^3): 54325
Superficie disperdente totale (m^2): 16052
Fattore di forma S/V (m^{-1}): 0,2955
Trasmittanza media superfici opache (W/m^2k): 0,2
Trasmittanza media superfici trasparenti (W/m^2k): 1,84
Zona climatica e Gradi Giorno: E / 2617
Superficie utile Su (m^2): 12318
Tipologia impianto di riscaldamento: Autonomo
Fonte energetica per riscaldamento: Energia elettrica
Fonte energetica per acqua calda sanitaria: Energia elettrica

FOTO

CLASSE ENERGETICA

Basso consumo

A+ A B C D E F G NC — A

Alto consumo

Indice prest. energ. reale: 11,5646 kWh/m3

Quota di energia coperta da fonti rinnovabili: 0 %

INDICI DI FABBISOGNO DELL'EDIFICIO

Fabbisogno di energia termica utile ideale = 11,45 kWh/m3

0 — 400 kWh/m² a

limite di legge 11,5 kWh/m3

Fabbisogno di energia termica primaria per acqua calda sanitaria = 3,88 kWh/m3

0 — 100 kWh/ m² a m²

EMISSIONI DI GAS AD EFFETTO SERRA

ETTARI DI BOSCO = 1,32961 Ha

0 [Kg/m³anno] EMISSIONE DI CO_2 2,4475 Kg/m³anno 100

RACCOMANDAZIONI

SISTEMA	INTERVENTO	PRIORITA'	TEMPO DI RITORNO
EDIFICIO			
IMPIANTO	Inserimento pannelli solari 50%	BASSA	7

N. certificato: 2014 110887 0001 C1 Scadenza: 07/04/2024

Fig. 31 “RSA Il Trifoglio” Energy Performance Certificate (Italian acronym: APE) (Part 2)

REGIONE PIEMONTE

ATTESTATO DI PRESTAZIONE ENERGETICA

ULTERIORI INFORMAZIONI ENERGETICHE

N. certificato: 2014 110887 0001 C1

Classe energetica globale nazionale dell'edificio	A
Prestazione energetica raggiungibile	9 kWh/m3
Indice di prestazione energetica riscaldamento nazionale	7,07 kWh/m3
Limite normativo nazionale per il riscaldamento	12,21 kWh/m3
Qualità termica estiva edificio (D.M. 26/06/2009)	III
Rendimento medio globale stagionale dell'impianto di riscaldamento	1,49
Limite normativo regionale impianto termico (D.G.R. 46-11968)	0,8542
Coefficiente di prestazione della pompa di calore (se installata)	
Limite normativo per prestazione energetica della pompa di calore (se installata)	

ULTERIORI INFORMAZIONI

Motivazione di rilascio del presente attestato: Nuova costruzione

Data titolo abilitativo a costruire/ristrutturare:

Rispetto degli obblighi normativi in campo energetico ( )

DICHIARAZIONI

Il sottoscritto certificatore VALENTINA SERGI, nato a TORINO (TORINO), il 07/10/1983 residente a TORINO (TORINO), CF SRGVNT83R47L219L ai sensi degli articoli 46 e 47 del D.P.R. 445/2000, consapevole delle responsabilità e delle sanzioni penali previste dall'articolo 76 dello stesso D.P.R. per false attestazioni e mendaci dichiarazioni, ai fini di assicurare indipendenza ed imparzialità di giudizio, dichiara:

- [x] nel caso di certificazione di edifici di nuova costruzione, l'assenza di conflitto di interessi, ovvero il non coinvolgimento diretto o indiretto nel processo di progettazione e realizzazione dell'edificio oggetto della presente certificazione o con i produttori dei materiali e dei componenti in esso incorporati nonché rispetto ai vantaggi che possano derivarne al richiedente;
- [ ] nel caso di certificazione di edifici esistenti, l'assenza di conflitto di interessi, ovvero di non coinvolgimento diretto o indiretto con i produttori dei materiali e dei componenti in esso incorporati nonché rispetto ai vantaggi che possano derivarne al richiedente;
- [ ] nel caso di certificazione di edifici pubblici o di uso pubblico, di operare in nome e per conto dell'ente pubblico ovvero dell'organismo di diritto pubblico proprietario dell'edificio oggetto del presente attestato di certificazione energetica e di agire per le finalità istituzionali proprie di tali enti ed organismi.

Il sottoscritto acconsente al trattamento dei dati personali per i soli fini istituzionali ai sensi delle disposizioni di cui al d.lgs 30 giugno 2003 n. 196 "Codice in materia di dati personali".

Li Torino il 07/04/2014

Firma digitale del Certificatore

VALENTINA SERGI N. 110887

To evaluate, from heating and cooling requirements, the energy consumption of the different energy vectors, for all relative combinations, it is necessary to take into account several efficiencies of the conditioning systems.

The global efficiency η_{glob} of a conditioning system depends by: efficiency of the emitter devices, how the conditioning circuit is regulated, how the distribution circuit is composed, and efficiency of the generation. Each previous aspect is described by a proper efficiency factor, that are relatively: η_{emi}, η_{reg}, η_{dis} and η_{gen}.

Eq. 28

$$\eta_{glob} = \eta_{emi} * \eta_{reg} * \eta_{dis} * \eta_{gen}$$

The previous equation is valid for the heating and the cooling systems and it must be calculated for both of them.

In the case of "RSA Il Trifoglio", how has been explained in Chapter 3.1., the emitter devices are: air-handling units with relative air distribution circuit, fan-coils and ceiling radiant panel. They are used to deliver heating and cooling power according to the requirement. For this reason, also distribution circuits and regulation devices are the same for the two different conditioning seasons.

Talking about the heating power supply, η_{emi}, η_{reg} and η_{dis} are reported on online version of the Energy Performance Certificate of the building [9]. Thanks to this parameters, imposed by the certifier consulting UNI/TS 11300-2, it is possible to trace back to the assumptions and other characteristics of the conditioning system. Instead, these relative efficiencies are not present for cooling power supply, so they must be hypothesized.

On online version of the Energy Performance Certificate of the building [9], emission efficiency η_{emi} is reported with a value of 0.96. Confronting: emission efficiencies for heating supply (UNI/TS 11300-2) and emission efficiencies for cooling supply (UNI/TS 11300-3) of the considered emission devices, it is possible to declare that they are almost the same. For this reason, emission efficiency for cooling supply is considered equal than the heating one.

For what concern η_{reg} for cooling supply, a control for single room with a modulating regulation of 2°C is assumed, and it is selected a value of 0.96(UNI/TS 11300-3).

Taking into account η_{dis} for cooling supply, for this distribution circuit ramified horizontally in each one of the 3 floors, the value of 0.98 is chosen (UNI/TS 11300-3).

Table 10 Emission, distribution and regulation efficiency for heating and cooling supply

	HEATING	COOLING
η_{emi}	0.96	0.96
η_{reg}	0.95	0.96
η_{dis}	0.99	0.98

Generation efficiency η_{gen} is the generator efficiency or performance expressed as energy provided by the generator in one year over the final energy that it used. This last parameter can be provided from the relative generator datasheet, therefore it might change according the different scenarios.

For the reference case and the different scenarios energy consumption of the conditioning systems can be evaluated for heating:

Eq. 29
$$Q_{H,use} = \frac{Q_{H,need}}{\eta_{H,glob}}$$

and cooling:

Eq. 30
$$Q_{C,use} = \frac{Q_{C,need}}{\eta_{C,glob}}$$

The calculated energy can be made by different forms, related to the energy vector used by the generator.

- **Energy cost**

First of all is necessary to clarify what energy vectors are used by the different scenarios.

Table 11 Reference case and different scenarios with relative energy vectors

CODE	HEATING	COOLING
MTB.ACC	Condensing Methane Boiler	Air-Cooled Chiller
MTB.MAC	Condensing Methane Boiler	Methane Absorption Chiller
DSH.ACC	District Heating	Air-Cooled Chiller
DSH.MAC	District Heating	Methane Absorption Chiller
AHP	Air Heat Pump	
CGHP	Closed Loop Geothermal Heat Pump	
OGHP	Open Loop Geothermal Heat Pump	

Natural Gas	Turin's District Heating	Electricity

The dispatching of an energy vector provides for the payment of an energy bill. The expenditure reported in an energy bill is proportional to the quantity of the energy bought, but in most of cases, fix costs are considered.

This work is elaborated for the reference year 2018, so energy costs are referred to this year.

Below a brief description of the calculation of the energy costs for the different energy vector is proposed.

For the **Natural Gas**, ARERA (Autorità di regolazione per energia reti e ambiente) makes available the cost of this energy vector and the relative dispatching cost. For each quarter of year, a different set of value is provided. The cost of a single Sm^3 depends by the total yearly consumption, but this cost varies during the year. The fixed cost is only dependent by the size of the gas meter and it is naturally constant during the year.

In this work, it is necessary to calculate the cost of Natural Gas for the pre-mentioned generators. To do that, it is possible to consider average values in two conditioning season. The costs of the first and last quarters of year compose the winter costs, while the second and third quarters compose the summer one.

Table 12 2018 variable and fixed cost of Natural Gas modified by ARERA database [10]

WINTER Energy cost (€/Sm^3) Sm^3/year Consumption	NATURAL GAS	TRANSPORT AND COUNTER	TAX OF SYSTEM
from 0 to 120	0.297117	0.053220	0.020100
from121 to 480		0.136414	0.057700
from 481 to 1.560		0.129366	0.041800
from 1.561 to 5.000		0.129686	0.037400
from 5.001 to 80.000		0.110356	0.032100
from 80.001 to 200.000		0.082162	0.024300

SUMMER Energy cost (€/Sm^3) Sm^3/year Consumption	NATURAL GAS	TRANSPORT AND COUNTER	TAX OF SYSTEM
from 0 to 120	0.266723	0.044821	0.020100
from121 to 480		0.128015	0.057700
from 481 to 1.560		0.120967	0.041800
from 1.561 to 5.000		0.121287	0.037400
from 5.001 to 80.000		0.101957	0.032100
from 80.001 to 200.000		0.073763	0.024300

YEAR Fixed cost (€/year) Counter flow Class	NATURAL GAS	TRANSPORT AND COUNTER	TAX OF SYSTEM
until G6	78.82	60.25	-27.01
from G10 to G40		449.72	
over G40		1,057.28	

The attribution of a Lower Heating Value for Natural Gas will become very useful for the next steps. Knowing that this value can change according to many factors, a mean constant value can be adopted.

Eq. 31
$$LHV_{Natural\ Gas} = 9.6\ \frac{kWh}{Sm^3}$$

For what concern the purchase of **heat from Turin's District Heating**, Iren Energia gives to disposal the cost of this energy vector. Also in this case, the cost during 2018 changed between the quarters, and only winter ones are used to compose an average value. No fixed cost are mentioned by Iren Energia, it is only reported the direct cost for a kWh of thermal energy. A further division is adopted, taking into account a customer classification and a tariff typology.

For this work, it was necessary to take into account prices for "terziario" customer, in only heating for conditioning, with a daily constant typology.

Table 13 2018 cost of heat from Turin's District Heating modified by Iren Energia site [8]

WINTER	TURIN'S DISTRICT HEATING
Energy cost (€/kWh)	
kWh/year Consumption	
until 406.972 kWh/year	0.0841568
over 406.972 kWh/year	0.0804549

For **electricity**, ARERA (Autorità di regolazione per energia reti e ambiente) provides the cost of measurement, distribution and transmission of this energy vector. In this case, there are three types of costs: one for a single kWh of electricity, one for each electricity connection and one for the installed electricity power.

For this work, costs for a medium voltage connection are considered. Talking about the electric energy cost, it is taken into consideration the average unit cost of only electric energy reported on the bills of 2018.

Table 14 2018 cost of electricity displacing modified by ARERA database [10] and real electricity bill of "RSA Il Trifoglio"

Medium Voltage Customers	MEASUREMENT	DISTRIBUTION	TRANSMISSION	ELECTRIC ENERGY
Energy cost (€/kWh)		0.00052	0.00664	0.07
Fixed cost (€/year)	227.8857	402.2692		
Power fixed cost (€/kW*year)		30.1111		

- **Primary Energy consumption**

The primary energy consumptions calculation is performed to find the total amount of energy in natural form, from different types of sources, which is consumed. For a single unit of energy vector, a specific quantity of primary energy must be consumed. The primary energy can be considered of renewable nature or not renewable one. For the aim of this work, only not renewable ones are taken into consideration.

Table 15 Not renewable primary energy factor considered from DM. 26 giugno 2015 (*) and Iren Energia, 2017 (**)

ENERGY VECTOR	$f_{P,nren}$
Natural Gas	1.05 *
Turin's District Heating	0.626 **
Electricity	1.95 *

Eq. 32 $$Q_{H,PRIM,use} = Q_{H,use} * f_{P,nren}(i)$$

Eq. 33 $$Q_{C,PRIM,use} = Q_{C,use} * f_{P,nren}(i)$$

- **CO_2 emission**

Although the CO_2 emission calculation is not necessary to realize a cost-optimal analysis, it is performed in order to have an overview about the environmental impact. CO_2 one is not the only emission produced by a thermal generator. The typology, the efficiency and the use of certain energy vector, in addition to many other aspects, can influence the presence or the absence of lot of pollutant type, like, for example, chemicals, heat and sound. It is important to underline that emissions related to any kind of energy use form, could be direct and indirect. In the first case, they are produced close to the place where the energy is used; on the other hand, the second case emissions are not easy to evaluate because they can occurs far from the place where energy is used. However, the indirect emissions must have the availability of the required energy vector.

CO2 emission has always been the most important pollutant for this kind of system, therefore both direct and indirect emission will be calculated. To do this, each energy vector must take into consideration an emission factor.

Table 16 CO_2 emission factor considered from UNI/TS 11300-4 (*) and Vergerio et al., 2018 (**)

ENERGY VECTOR	k_{emi} [kg CO_2/kWh]
Natural Gas	0.1998 *
Turin's District Heating	0.144 **
Electricity	0.4332 *

The previous performances calculation procedure is operated singularly for all scenarios and for the reference case.

Table 17 (MTB.ACC) Condensing Methane Boiler & Air-Cooled Chiller performances and energy cost

MTB.ACC : Condensing Methane Boiler & Air-Cooled Chiller				
CONDITIONING	-	HEATING	COOLING	TOTAL
GENERATION SYSTEM	-	Methane Boiler	Air-Cooled Chiller	-
Energy Vector	-	Natural Gas	Electricity	-
Total installed thermal power	kW	1,296	1,296	-
Emission Efficiency	-	0.96	0.95	-
Regulation Efficiency	-	0.95	0.96	-
Distribution Efficiency	-	0.99	0.98	-
Generation Efficiency	-	1.04	4.15	-
Global Efficiency	-	0.94	3.71	-
Specific energy consumption	kWh/ (m^3*year)	12.19	1.53	-
Energy consumption	kWh/year	662,433	83,025	-
Natural Gas consumption	Sm^3/year	69003	-	-
Primary energy conversion factor	-	1.05	1.95	-
Specific primary energy consumption	kWh/ (m^3*year)	12.80	2.98	15.78
Primary energy consumption	kWh/year	695,554	161,900	857,454
Specific cost of energy	€/kWh	0.04579	0.0772	-
Installed electric power [1]	kW	-	448	-
Specific energy cost	€/ (m^3*year)	0.558	0.118	0.957
Energy cost	€/year	30,331.97	6,406.24	51,967.23
CO2 emission factor	kg CO2/kWh	0.1998	0.4332	-
Specific CO2 emission	kg CO2/ (m^3*year)	2.436	0.662	3.098
CO2 emission	kg CO2/ year	132,354	35,967	168,321

Table 18 (MTB.MAC) Condensing Methane Boiler & Methane Absorption Chiller performances and energy cost

MTB.MAC : Condensing Methane Boiler & Methane Absorption Chiller				
CONDITIONING	-	HEATING	COOLING	TOTAL
GENERATION SYSTEM	-	Methane Boiler	Methane Absorption Chiller	-
Energy Vector	-	Natural Gas	Natural Gas	-
Total installed thermal power	kW	1,296	1,266	-
Emission Efficiency	-	0.96	0.95	-
Regulation Efficiency	-	0.95	0.96	-
Distribution Efficiency	-	0.99	0.98	-
Generation Efficiency	-	1.04	1.51	-
Global Efficiency	-	0.94	1.35	-
Specific energy consumption	kWh/ (m^3*year)	12.19	4.20	-
Energy consumption	kWh/year	662,433	228,183	890,615
Natural Gas consumption	Sm^3/year	69003	23769	92772
Primary energy conversion factor	-	1.05	1.05	-
Specific primary energy consumption	kWh/ (m^3*year)	12.80	4.41	17.21
Primary energy consumption	kWh/year	695,554	239,592	935,146
Specific cost of energy	€/kWh	0.04204	0.03800	-
Specific energy cost	€/ (m^3*year)	0.513	0.160	0.693
Energy cost	€/year	27,848.26	8,670.59	37,627.94
CO2 emission factor	kg CO2/kWh	0.1998	0.1998	-
Specific CO2 emission	kg CO2/ (m^3*year)	2.436	0.839	3.276
CO2 emission	kg CO2/ year	132,354	45,591	177,945

Table 19 (DSH.ACC) District Heating & Air-Cooled Chiller performances and energy cost

DSH.ACC : District Heating & Air-Cooled Chiller				
CONDITIONING	-	HEATING	COOLING	TOTAL
GENERATION SYSTEM	-	District Heating	Air-Cooled Chiller	-
Energy Vector	-	Turin's District Heating	Electricity	-
Total installed thermal power	kW	1,270	1,296	-
Emission Efficiency	-	0.96	0.95	-
Regulation Efficiency	-	0.95	0.96	-
Distribution Efficiency	-	0.99	0.98	-
Generation Efficiency	-	0.994	4.15	-
Global Efficiency	-	0.90	3.71	-
Specific energy consumption	kWh/ (m^3*year)	12.76	1.53	-
Energy consumption	kWh/year	693,089	83,025	-
Primary energy conversion factor	-	0.626	1.95	-
Specific primary energy consumption	kWh/ (m^3*year)	7.99	2.98	10.97
Primary energy consumption	kWh/year	433,874	161,900	595,773
Specific cost of energy	€/kWh	0.08045	0.0772	-
Installed electric power [1]	kW	-	448	-
Specific energy cost	€/ (m^3*year)	1.026	0.118	1.404
Energy cost	€/year	55,762.35	6,406.24	76,288.52
CO2 emission factor	kg CO2/kWh	0.144	0.4332	-
Specific CO2 emission	kg CO2/ (m^3*year)	1.837	0.662	2.499
CO2 emission	kg CO2/ year	99,805	35,967	135,771

Table 20 (DSH.MAC) District Heating & Methane Absorption Chiller performances and energy cost

DSH.MAC : District Heating & Methane Absorption Chiller				
CONDITIONING	-	HEATING	COOLING	TOTAL
GENERATION SYSTEM	-	District Heating	Methane Absorption Chiller	-
Energy Vector	-	Turin District Heating	Natural Gas	-
Total installed thermal power	kW	1,270	1,266	-
Emission Efficiency	-	0.96	0.95	-
Regulation Efficiency	-	0.95	0.96	-
Distribution Efficiency	-	0.99	0.98	-
Generation Efficiency	-	0.994	1.51	-
Global Efficiency	-	0.90	1.35	-
Specific energy consumption	kWh/ (m^3*year)	12.76	4.20	-
Energy consumption	kWh/year	693,089	228,183	-
Natural Gas consumption	Sm^3/year	-	23769	-
Primary energy conversion factor	-	0.626	1.05	-
Specific primary energy consumption	kWh/ (m^3*year)	7.99	4.41	12.40
Primary energy consumption	kWh/year	433,874	239,592	673,465
Specific cost of energy	€/kWh	0.08045	0.04175	-
Specific energy cost	€/ (m^3*year)	1.026	0.175	1.222
Energy cost	€/year	55,762.35	9,526.13	66,397.57
CO2 emission factor	kg CO2/kWh	0.144	0.1998	-
Specific CO2 emission	kg CO2/ (m^3*year)	1.837	0.839	2.676
CO2 emission	kg CO2/ year	99,805	45,591	145,396

Table 21 (AHP) Air Heat Pump performances and energy cost

AHP : Air Heat Pump				
CONDITIONING	-	HEATING	COOLING	TOTAL
GENERATION SYSTEM	-	Air heat pump		-
Energy Vector	-	Electricity	Electricity	-
Total installed thermal power	kW	1,262	1,238	-
Emission Efficiency	-	0.96	0.95	-
Regulation Efficiency	-	0.95	0.96	-
Distribution Efficiency	-	0.99	0.98	-
Generation Efficiency	-	3.22	4.15	-
Global Efficiency	-	2.91	3.71	-
Specific energy consumption	kWh/ (m^3*year)	3.94	1.53	-
Energy consumption	kWh/year	213,953	83,025	296,979
Primary energy conversion factor	-	1.95	1.95	-
Specific primary energy consumption	kWh/ (m^3*year)	7.68	2.98	10.66
Primary energy consumption	kWh/year	417,209	161,900	579,109
Specific cost of energy	€/kWh	0.0772	0.0772	-
Installed electric power [1]	kW	410	448	448
Specific energy cost	€/ (m^3*year)	0.304	0.118	0.682
Energy cost	€/year	16,508.65	6,406.24	37,034.82
CO2 emission factor	kg CO2/kWh	0.4332	0.4332	-
Specific CO2 emission	kg CO2/ (m^3*year)	1.706	0.662	2.368
CO2 emission	kg CO2/ year	92,685	35,967	128,651

Table 22 (CGHP) Closed Loop Geothermal Heat Pump System performances and energy cost

CGHP : Closed loop Geothermal Heat Pump				
CONDITIONING	-	HEATING	COOLING	TOTAL
GENERATION SYSTEM	-	Closed loop Geothermal heat pump		-
Energy Vector	-	Electricity	Electricity	-
Total installed thermal power	kW	1,270	1,270	-
Emission Efficiency	-	0.96	0.95	-
Regulation Efficiency	-	0.95	0.96	-
Distribution Efficiency	-	0.99	0.98	-
Generation Efficiency	-	4.80	6.75	-
Global Efficiency	-	4.33	6.03	-
Specific energy consumption	kWh/ (m^3*year)	2.64	0.94	-
Energy consumption	kWh/year	143,527	51,045	194,572
Primary energy conversion factor	-	1.95	1.95	-
Specific primary energy consumption	kWh/ (m^3*year)	5.15	1.83	6.98
Primary energy consumption	kWh/year	279,878	99,538	379,416
Specific cost of energy	€/kWh	0.0772	0.0772	-
Installed electric power [1]	kW	317	245	317
Specific energy cost	€/ (m^3*year)	0.204	0.073	0.464
Energy cost	€/year	11,074.55	3,938.65	25,179.79
CO2 emission factor	kg CO2/kWh	0.4332	0.4332	-
Specific CO2 emission	kg CO2/ (m^3*year)	1.145	0.407	1.552
CO2 emission	kg CO2/ year	62,176	22,113	84,289

Table 23 (OGHP) Open Loop Geothermal Heat Pump System performances and energy cost

OGHP : Open loop Geothermal Heat Pump				
CONDITIONING	-	HEATING	COOLING	TOTAL
GENERATION SYSTEM	-	Open loop Geothermal heat pump		-
Energy Vector	-	Electricity	Electricity	-
Total installed thermal power	kW	1,270	1,270	-
Emission Efficiency	-	0.96	0.95	-
Regulation Efficiency	-	0.95	0.96	-
Distribution Efficiency	-	0.99	0.98	-
Generation Efficiency	-	4.80	6.75	-
Global Efficiency	-	4.33	6.03	-
Specific energy consumption	kWh/ (m^3*year)	2.64	0.94	-
Energy consumption	kWh/year	143,527	51,045	194,572
Primary energy conversion factor	-	1.95	1.95	-
Specific primary energy consumption	kWh/ (m^3*year)	5.15	1.83	6.98
Primary energy consumption	kWh/year	279,878	99,538	379,416
Specific cost of energy	€/kWh	0.0772	0.0772	-
Installed electric power [1]	kW	317	245	317
Specific energy cost	€/ (m^3*year)	0.204	0.073	0.464
Energy cost	€/year	11,074.55	3,938.65	25,179.79
CO2 emission factor	kg CO2/kWh	0.4332	0.4332	-
Specific CO2 emission	kg CO2/ (m^3*year)	1.145	0.407	1.552
CO2 emission	kg CO2/ year	62,176	22,113	84,289

[1] Installed electric power is useful for the calculation of dispatching cost for electricity. In "HEATING" and "COOLING" columns, values of the "Installed electric power of machines" are reported deducting them from the relative datasheets. In the column "TOTAL", it is reported the maximum between the heating and cooling values, parameter that is used for the cost calculation.

4.3. Global cost

Global cost calculation is a methodology proposed by EN 15459, 2007 useful for comparing of different configurations of systems and building from the conditioning point of view during a calculation period (τ). Taking into consideration that this thesis treats new installations, the calculation period is assumed equal to 50 years. In order to obtain the global cost, there must be considered several components, like initial investment costs, energy costs, maintenance costs, replacement costs and residual value of the components at the end of the calculation period. All costs and values are actualized referring to the starting year. The Global cost $C_G(\tau)$ is obtained through the formula below:

Eq. 34

$$C_G(\tau) = C_I + \sum_j \left[\sum_{i=1}^{\tau} \left(C_{a,i}(j) * R_d(i)\right) - V_{f,\tau}(j)\right]$$

where:

- C_I initial investment costs;
- $C_{a,i}$ (j) annual cost year i for component j (including running costs and periodic or replacement costs);
- $R_d(i)$ discount rate for year i;
- $V_{f,\tau}(j)$ final value of component j at the end of the calculation period (referred to the starting year τ_0).

The **initial investment cost** of a configuration is the result obtained by the sum of all possible costs of each considered component that compose it. In this work, only main devices in terms of capital expenditures are considered. Io order to define the relative costs, two different price lists are consulted: Piedmont public work price list of 2018 (Regione Piemonte, 2018) and Milan public work price list of 2018 (Comune Milano, 2018). Being this case study located in Turin, it is used mainly the Piedmont's one, while Milan's price list is consulted if the first one does not contain the requested prices. How it is remarkable in the next pages, the second one is more complete than the second, in particular for high power components.

In order to compose **discounted annual costs**, is interesting to subdivide what is connected to the replacement, maintenance and energy costs. Talking about this last one, its relative discounted value is calculated multiplying today's hypothetical replacement cost and the discount rate evaluated in a precise year (p) when the replacement occurs. The discount rate for a year (p) is:

Eq. 35 $$R_d(p) = \left(\frac{1}{1+R_R}\right)^p$$

where R_R is the real discount rate, imposed equal to 4%. The real discount rate is the one considering the inflation rate. Actually, replacements occur when components fail or they are too inefficient to operate, case that is not predictable. EN 15459, 2007 helps this evaluation providing lifespan of different devices, components and materials often used in conditioning applications.

For what concern maintenance and energy costs, it is necessary to assume a constant value for each year during the calculation period. Also, in this case it is not possible to know in advance how much maintenance could costs; EN 15459, 2007 provides a table that shows annual maintenance costs for different components in term of a percentage of investment cost. Talking about energy costs, values are taken into account from the chapter before. To compute a discounted cost for maintenance and energy, that consider every years of the calculation period, the single annual cost can be multiplied by the present value factor f_{pv}:

Eq. 36 $$f_{pv}(n) = \frac{1-(1+R_R)^{-n}}{R_R}$$

where n is the number of years of the calculation period.

Year by year, after relative installations, all different components, devices and materials are affected by a reduction of them intrinsic values. For assumption, it is considered equal to zero at the end of the component lifespan. At the end of the calculation period, the residual value of each component is named **final value**. It is calculated thanks to the linear annual amortisation procedure. This result is then discounted from the last to the first year with a proper discount rate.

Table 24 Considered investment and replacement cost from Regione Piemonte, 2018 and Comune Milano, 2018 ; costs computation with relative quantities

MTB : Condensing methane boiler							
N.	**Price list**	**Code**	**Description**	**Number of unit**	**unit**	**Unit value**	**Total value**
1	Piemonte	05.A01.B01.075	Caldaia basamento (650 kW)	2	cad	€ 36,954.54	€ 73,909.08
2	Piemonte	12.P15.A62.005	Smantellamento caldaia fino a 700 kW	2	cad	€ 1,322.09	€ 2,644.18

DSH : District heating							
N.	**Price list**	**Code**	**Description**	**Number of unit**	**unit**	**Unit value**	**Total value**
1	Piemonte	12.P14.A05.055	Sottostazione scambio termico (1270 kW)	1	cad	€ 43,475.35	€ 43,475.35
2	Piemonte	12.P15.A62.005	Smantellamento scambiatore di calore fino a 700 kW	2	cad	€ 1,322.09	€ 2,644.18

ACC : Air-Cooled Chiller							
N.	**Price list**	**Code**	**Description**	**Number of unit**	**unit**	**Unit value**	**Total value**
1	Milano	1M.02.010.0200.j	Refrigeratore d'acqua raffreddato ad aria (650 kW)	2	cad	€ 100,260.04	€ 200,520.08

MAC : Methane Absorption Chiller							
N.	**Price list**	**Code**	**Description**	**Number of unit**	**unit**	**Unit value**	**Total value**
1	Milano	**	Gruppo frigorifero ad assorbimento alimentato a gas raffreddato ad aria (650kW)	2	cad	€ 238,848.86	€ 477,697.72

AHP : Air Heat Pump							
N.	**Price list**	**Code**	**Description**	**Number of unit**	**unit**	**Unit value**	**Total value**
1	Milano	1M.02.050.0070.l	Pompa di calore aria/acqua (680kWt/635kWf)	2	cad	€ 105,048.04	€ 210,096.08

CGHP : Closed loop Geothermal Heat Pump							
N.	**Price list**	**Code**	**Description**	**Number of unit**	**unit**	**Unit value**	**Total value**
1	Piemonte	03.A12.F05.005	Campo geotermico: Sonde verticali (80W/m)	12,500	m	€ 73.85	€ 923,125.00
2	Milano	1M.02.070.0020.n	Pompa di calore acqua/acqua (720kWt/650kWf)	2	cad	€ 61,953.22	€ 123,906.44

OGHP : Open loop Geothermal Heat Pump							
N.	**Price list**	**Code**	**Description**	**Num. of unit**	**unit**	**Unit value**	**Total value**
	-	-	POZZO PRESA	-	-	-	-
1	Piemonte	22.P 03.A 10.0 05	Impianto di cantiere comprensivo di approntamento, carico e scarico, revisione a fine lavori e installazione, in ciascun punto di perforazione compreso il primo, di attrezzature per esecuzione di pozzo per acqua a percussione su aree pianeggianti accessibili ai normali mezzi di trasporto	1	cad	€ 1,036.26	€ 1,036.26
2	Piemonte	22.P 03.A 15.0 20	Perforazione in terreno di qualsiasi granulometria durante l'esecuzione di un pozzo con metodo a percussione, compreso l'eventuale attraversamento di trovanti e manufatti, per ogni diametro impiegato fino a 100 m dal p. c. Per ogni metro lineare, per f = 700 mm	21	m	€ 207.26	€ 4,352.46
3	Piemonte	22.P 03.A 60.0 25	Fornitura e posa di tubazioni già finestrate in maniera continua con sistema tipo Johnson, con finestrature variabili da 0.25 a 2 mm, complete di manicotti d'attacco a saldare in barre da 3 o 6 m in acciaio zincato Per ogni metro lineare, per tubi con fest = 412 mm e fint = 392 mm	12	m	€ 292.60	€ 1,755.60
4	Piemonte	22.P 03.A 55.0 35	Fornitura e posa di rivestimento costituito da tubi in lamiera saldata e zincata a bagno, con giunti saldati in testa su bordi preparati a bisello o con manicotti saldati Per ogni metro lineare, per tubi con fest = 406. 4 mm e spessore pari a 6. 0 mm	8	m	€ 121.93	€ 1,828.95
5	Piemonte	22.P 03.A 65.0 05	Esecuzione di drenaggio in opera con ghiaietto siliceo calibrato e selezionato posto all'esterno dei tratti fenestrati anche in due o tre strati concentrici, compresa anche la fornitura e posa dell'eventuale reticella di contenimento dello strato interno	4.404	m^3	€ 158.49	€ 697.99
6	Piemonte	22.P 03.A 85.0 05	Impermeabilizzazione dell'intercapedine eseguita con argilla di cava posta in opera per gravità	0.777	m^3	€ 152.39	€ 118.41
7	Piemonte	22.P 03.A 90.0 05	Impermeabilizzazione dell'intercapedine eseguita con calcestruzzo posto in opera per gravità	0.518	m^3	€ 152.39	€ 39.47
8	Piemonte	22.P 03.A 95.0 10	Allestimento del sistema di spurgo ed esecuzione dello sviluppo del pozzo mediante motocompressore d'aria a doppia colonna o pistone e sonda, per un minimo di 15 ore effettive di spurgo Per ogni ora	24	h	€ 91.44	€ 2,194.56
9	Piemonte	22.P 06.A 05.0 05	Allestimento del sistema di pompaggio e degli strumenti di misura per esecuzione prova di portata	1	cad	€ 1,036.26	€ 1,036.26
10	Piemonte	22.P 06.A 10.0 05	Esecuzione di prova di portata per la determinazione dei parametri idrodinamici dell'acquifero, compresa la fornitura dell'energia elettrica, la registrazione, l'elaborazione e l'interpretazione dei dati Per ogni ora, con pompa da 25 kW	48	h	€ 60.98	€ 1,463.52
11		-	TOTALE POZZI PRESA	3	cad	€ 14,523.48	€ 43,570.44

OGHP : Open loop Geothermal Heat Pump							
N.	Price list	Code	Description	Num. of unit	unit	Unit value	Total value
12	-	-	POZZO RESTITUZIONE	-	-	-	-
13	Piemonte	22.P03.A10.005	Impianto di cantiere comprensivo di approntamento, carico e scarico, revisione a fine lavori e installazione, in ciascun punto di perforazione compreso il primo, di attrezzature per esecuzione di pozzo per acqua a percussione su aree pianeggianti accessibili ai normali mezzi di trasporto	1	cad	€ 1,036.26	€ 1,036.26
14	Piemonte	22.P03.A15.020	Perforazione in terreno di qualsiasi granulometria durante l'esecuzione di un pozzo con metodo a percussione, compreso l'eventuale attraversamento di trovanti e manufatti, per ogni diametro impiegato fino a 100 m dal p. c. Per ogni metro lineare, per f = 700 mm	21	m	€ 207.26	€ 4,352.46
15	Piemonte	22.P03.A60.025	Fornitura e posa di tubazioni già finestrate in maniera continua con sistema tipo Johnson, con finestrature variabili da 0.25 a 2 mm, complete di manicotti d'attacco a saldare in barre da 3 o 6 m in acciaio zincato Per ogni metro lineare, per tubi con fest = 412 mm e fint = 392 mm	6	m	€ 292.60	€ 3,511.20
16	Piemonte	22.P03.A55.035	Fornitura e posa di rivestimento costituito da tubi in lamiera saldata e zincata a bagno, con giunti saldati in testa su bordi preparati a bisello o con manicotti saldati Per ogni metro lineare, per tubi con fest = 406. 4 mm e spessore pari a 6. 0 mm	15	m	€ 121.93	€ 975.44
17	Piemonte	22.P03.A65.005	Esecuzione di drenaggio in opera con ghiaietto siliceo calibrato e selezionato posto all'esterno dei tratti fenestrati anche in due o tre strati concentrici, compresa anche la fornitura e posa dell'eventuale reticella di contenimento dello strato interno	4.404	m^3	€ 158.49	€ 697.99
18	Piemonte	22.P03.A85.005	Impermeabilizzazione dell'intercapedine eseguita con argilla di cava posta in opera per gravità	0.777	m^3	€ 152.39	€ 118.41
19	Piemonte	22.P03.A90.005	Impermeabilizzazione dell'intercapedine eseguita con calcestruzzo posto in opera per gravità	0.259	m^3	€ 152.39	€ 78.94
20	Piemonte	22.P03.A95.010	Allestimento del sistema di spurgo ed esecuzione dello sviluppo del pozzo mediante motocompressore d'aria a doppia colonna o pistone e sonda, per un minimo di 15 ore effettive di spurgo Per ogni ora	24	h	€ 91.44	€ 2,194.56
21	Piemonte	22.P06.A05.005	Allestimento del sistema di pompaggio e degli strumenti di misura per esecuzione prova di portata	1	cad	€ 1,036.26	€ 1,036.26
22	Piemonte	22.P06.A10.005	Esecuzione di prova di portata per la determinazione dei parametri idrodinamici dell'acquifero, compresa la fornitura dell'energia elettrica, la registrazione, l'elaborazione e l'interpretazione dei dati Per ogni ora, con pompa da 25 kW	24	h	€ 60.98	€ 2,927.04
23		-	TOTALE POZZI RESTITUZIONE	2	cad	€ 16,928.56	€ 33,857.12

OGHP : Open loop Geothermal Heat Pump							
N.	**Price list**	**Code**	**Description**	**Number of unit**	**unit**	**Unit value**	**Total value**
24	Piemonte	05.P59. C30.010	Scambiatore di calore a piastre in acciaio inox Oltre kW 240	500	kW	€ 6.10	€ 3,050.00
25	Piemonte	05.P59. C30.010	Scambiatore di calore a piastre in acciaio inox Oltre kW 240	500	kW	€ 6.10	€ 3,050.00
26	Piemonte	05.P69. B00.005	Posa in opera di scambiatore di calore come agli articoli 59.C10 - 59.C20 - 59.C30, per acqua calda e fredda Aumento sui prezzi di detti articoli	€ 6,100.00	%	25.00	€ 1,525.00
27	Milano	1M.02.0 70.0020. n	Pompa di calore acqua/acqua (720kWt/650kWf)	2	cad	€ 61,953.22	€ 123,906.44

*** Due to the impossibility to find costs for so high power Methane Absorption Chillers, it is necessary to adopt an assumption. A proportion is computed between prices of smaller Air-Cooled Chiller (1M.02.010.0160.k) and Methane Absorption one (1M.02.080.0010.e) with the price of an Air-Cooled Chiller of the required power (1M.02.010.0200.j).*

Note:

1. Dimensions and characteristics of well construction are related to the information collected from Geostudio, 2013

2. In OGHP piezometer well cost is not reported for absence of the construction dimension. Its cost it will be considered equal to a reinjection well, even if it has certainly a minor diameter and relative minor cost.

At this point, to evaluate lifespan and annual maintenance costs of components, it is possible to use the table below with relative value.

Table 25 Considered lifespan and annual maintenance percentage cost of main components

Component	Lifespan	Annual maintenance % of initial investment cost
Boilers - condensing *	20	2
Heat pumps *	20	2
Pipes composite *	50	1
Heat exchanger	20	2
Water Well	25	0

* Proposed by EN 15459, 2007

Values for Heat exchanger are assumed according to the Heat pumps ones. Instead, lifespan for water well is assumed according to [11] and maintenance value from information of the operator of the structure. Heat pumps values are used for all devices characterized by an inverse cycle (also Methane Absorption Chiller) and Pipe composite values for the Closed loop geothermal heat exchanger.

The following tables report calculation of the Global cost for each scenario and for the reference case.

Table 26 (MTB.ACC) Condensing Methane Boiler & Air-Cooled Chiller Global Cost calculation

MTB.ACC : Condensing Methane Boiler & Air-Cooled Chiller				
Investment cost				
Description	**Total value**			
Condensing Methane Boiler	€ 73,909.08			
Air-Cooled Chiller	€ 200,520.08			
Investment cost	**€ 274,429.16**			
Specific Investment cost (€/m^3)	**5.05**			
Replacement cost				
Description	**Total value**	**Replacement year**	**Rd**	**Total value (discounted)**
Condensing Methane Boiler	€ 76,553.26	20	0.456	€ 34,937.91
Air-Cooled Chiller	€ 200,520.08	20	0.456	€ 91,514.75
Condensing Methane Boiler	€ 76,553.26	40	0.208	€ 15,945.21
Air-Cooled Chiller	€ 200,520.08	40	0.208	€ 41,766.14
			Replacement cost	**€ 184,164.00**
			Specific Replacement cost (€/m^3)	**3.39**
Maintenance cost				
Description	**Total value**	**Calculation period**	**fpv**	**Total value (discounted)**
Condensing Methane Boiler	€ 1,478.18	50	21.482	€ 31,754.57
Air-Cooled Chiller	€ 4,010.40	50	21.482	€ 86,152.19
			Maintenance cost	**€ 117,906.76**
			Specific Maintenance cost (€/m^3)	**2.17**
Energy cost				
Description	**Total value**	**Calculation period**	**fpv**	**Total value (discounted)**
Heating and Cooling	€ 51,967.23	50	21.482	€ 1,116,369.68
			Energy cost	**€ 1,116,369.68**
			Specific Energy cost (€/m^3)	**20.55**
Final value				
Description	**Final value**	**Calculation period**	**Rd**	**Final value (discounted)**
Condensing Methane Boiler	€ 23,228.57	50	0.141	€ 3,268.55
Air-Cooled Chiller	€ 63,020.60	50	0.141	€ 8,867.79
			Final Value	**€ 12,136.35**
			Specific Final Value (€/m^3)	**0.22**
			GLOBAL COST	**€ 1,680,733.24**
			SPECIFIC GLOBAL COST (€/m^3)	**30.94**

Table 27 (MTB.MAC) Condensing Methane Boiler & Methane Absorption Chiller Global Cost calculation

MTB.MAC : Condensing Methane Boiler & Methane Absorption Chiller

Investment cost

Description	Total value
Condensing Methane Boiler	€ 73,909.08
Methane Absorption Chiller	€ 477,697.72
Investment cost	**€ 551,606.80**
Specific Investment cost (€/m^3)	**10.15**

Replacement cost

Description	Total value	Replacement year	Rd	Total value (discounted)
Condensing Methane Boiler	€ 76,553.26	20	0.456	€ 34,937.91
Methane Absorption Chiller	€ 477,697.72	20	0.456	€ 218,015.00
Condensing Methane Boiler	€ 76,553.26	40	0.208	€ 15,945.21
Methane Absorption Chiller	€ 477,697.72	40	0.208	€ 99,499.20
			Replacement cost	**€ 368,397.32**
			Specific Replacement cost (€/m^3)	**6.78**

Maintenance cost

Description	Total value	Calculation period	fpv	Total value (discounted)
Condensing Methane Boiler	€ 1,478.18	50	21.482	€ 31,754.57
Methane Absorption Chiller	€ 9,553.95	50	21.482	€ 205,239.81
			Maintenance cost	**€ 236,994.38**
			Specific Maintenance cost (€/m^3)	**4.36**

Energy cost

Description	Total value	Calculation period	fpv	Total value (discounted)
Heating and Cooling	€ 37,627.94	50	21.482	€ 808,330.42
			Energy cost	**€ 808,330.42**
			Specific Energy cost (€/m^3)	**14.88**

Final value

Description	Final value	Calculation period	Rd	Final value (discounted)
Condensing Methane Boiler	€ 23,228.57	50	0.141	€ 3,268.55
Methane Absorption Chiller	€ 150,133.57	50	0.141	€ 21,125.69
			Final Value	**€ 24,394.24**
			Specific Final Value (€/m^3)	**0.45**

GLOBAL COST	**€ 1,940,934.67**
SPECIFIC GLOBAL COST (€/m^3)	**35.73**

Table 28 (DSH.ACC) District Heating & Air-Cooled Chiller Global Cost calculation

DSH.ACC : District Heating & Air-Cooled Chiller

Investment cost

Description	Total value
District heating substation	€ 43,475.35
Air-Cooled Chiller	€ 200,520.08
Investment cost	**€ 243,995.43**
Specific Investment cost (€/m^3)	**4.49**

Replacement cost

Description	Total value	Replacement year	Rd	Total value (discounted)
District heating substation	€ 46,119.53	20	0.456	€ 21,048.35
Air-Cooled Chiller	€ 200,520.08	20	0.456	€ 91,514.75
District heating substation	€ 46,119.53	40	0.208	€ 9,606.19
Air-Cooled Chiller	€ 200,520.08	40	0.208	€ 41,766.14
			Replacement cost	**€ 163,935.43**
			Specific Replacement cost (€/m^3)	**3.02**

Maintenance cost

Description	Total value	Calculation period	fpv	Total value (discounted)
District heating substation	€ 869.51	50	21.482	€ 18,678.91
Air-Cooled Chiller	€ 4,010.40	50	21.482	€ 86,152.19
			Maintenance cost	**€ 104,831.10**
			Specific Maintenance cost (€/m^3)	**1.93**

Energy cost

Description	Total value	Calculation period	fpv	Total value (discounted)
Heating and Cooling	€ 76,288.52	50	21.482	€ 1,638,843.99
			Energy cost	**€ 1,638,843.99**
			Specific Energy cost (€/m^3)	**30.17**

Final value

Description	Final value	Calculation period	Rd	Final value (discounted)
District heating substation	€ 13,663.68	50	0.141	€ 1,922.65
Air-Cooled Chiller	€ 63,020.60	50	0.141	€ 8,867.79
			Final Value	**€ 10,790.45**
			Specific Final Value (€/m^3)	**0.20**

GLOBAL COST	**€ 2,140,815.50**
SPECIFIC GLOBAL COST (€/m^3)	**39.41**

Table 29 (DSH.MAC) District Heating & Methane Absorption Chiller Global Cost calculation

DSH.MAC : District Heating & Methane Absorption Chiller				
Investment cost				
Description	**Total value**			
District heating substation	€ 43,475.35			
Methane Absorption Chiller	€ 477,697.72			
Investment cost	**€ 521,173.07**			
Specific Investment cost (€/m^3)	**9.59**			
Replacement cost				
Description	**Total value**	**Replacement year**	**Rd**	**Total value (discounted)**
District heating substation	€ 46,119.53	20	0.456	€ 21,048.35
Methane Absorption Chiller	€ 477,697.72	20	0.456	€ 218,015.00
District heating substation	€ 46,119.53	40	0.208	€ 9,606.19
Methane Absorption Chiller	€ 477,697.72	40	0.208	€ 99,499.20
			Replacement cost	**€ 348,168.75**
			Specific Replacement cost (€/m^3)	**6.41**
Maintenance cost				
Description	**Total value**	**Calculation period**	**fpv**	**Total value (discounted)**
District heating substation	€ 869.51	50	21.482	€ 18,678.91
Methane Absorption Chiller	€ 9,553.95	50	21.482	€ 205,239.81
			Maintenance cost	**€ 223,918.72**
			Specific Maintenance cost (€/m^3)	**4.12**
Energy cost				
Description	**Total value**	**Calculation period**	**fpv**	**Total value (discounted)**
Heating and Cooling	€ 66,397.57	50	21.482	€ 1,426,364.81
			Energy cost	**€ 1,426,364.81**
			Specific Energy cost (€/m^3)	**26.26**
Final value				
Description	**Final value**	**Calculation period**	**Rd**	**Final value (discounted)**
District heating substation	€ 13,663.68	50	0.141	€ 1,922.65
Methane Absorption Chiller	€ 150,133.57	50	0.141	€ 21,125.69
			Final Value	**€ 23,048.34**
			Specific Final Value (€/m^3)	**0.42**
			GLOBAL COST	**€ 2,496,577.01**
			SPECIFIC GLOBAL COST (€/m^3)	**45.96**

Table 30 (AHP) Air Heat Pump Global Cost calculation

AHP : Air Heat Pump				
Investment cost				
Description	**Total value**			
Air Heat Pump	€ 210,096.08			
Investment cost	**€ 210,096.08**			
Specific Investment cost (€/m^3)	**3.87**			
Replacement cost				
Description	**Total value**	**Replacement year**	**Rd**	**Total value (discounted)**
Air Heat Pump	€ 210,096.08	20	0.456	€ 95,885.11
Air Heat Pump	€ 210,096.08	40	0.208	€ 43,760.71
			Replacement cost	**€ 139,645.82**
			Specific Replacement cost (€/m^3)	**2.57**
Maintenance cost				
Description	**Total value**	**Calculation period**	**fpv**	**Total value (discounted)**
Air Heat Pump	€ 4,201.92	50	21.482	€ 90,266.46
			Maintenance cost	**€ 90,266.46**
			Specific Maintenance cost (€/m^3)	**1.66**
Energy cost				
Description	**Total value**	**Calculation period**	**fpv**	**Total value (discounted)**
Heating and Cooling	€ 37,034.82	50	21.482	€ 795,588.84
			Energy cost	**€ 795,588.84**
			Specific Energy cost (€/m^3)	**14.64**
Final value				
Description	**Final value**	**Calculation period**	**Rd**	**Final value (discounted)**
Air Heat Pump	€ 66,030.20	50	0.141	€ 9,291.28
			Final Value	**€ 9,291.28**
			Specific Final Value (€/m^3)	**0.17**
			GLOBAL COST	**€ 1,226,305.91**
			SPECIFIC GLOBAL COST (€/m^3)	**22.57**

Table 31 (CGHP) Closed Loop Geothermal Heat Pump System Global Cost calculation

CGHP : Closed loop Geothermal Heat Pump				
Investment cost				
Description	**Total value**			
Geothermal heat exchanger	€ 923,125.00			
Water Heat Pump	€ 123,906.44			
Investment cost	**€ 923,125.00**			
Specific Investment cost (€/m^3)	**16.99**			
Replacement cost				
Description	**Total value**	**Replacement year**	**Rd**	**Total value (discounted)**
Water Heat Pump	€ 123,906.44	20	0.456	€ 56,549.28
Water Heat Pump	€ 123,906.44	40	0.208	€ 25,808.35
			Replacement cost	**€ 82,357.64**
			Specific Replacement cost (€/m^3)	**1.52**
Maintenance cost				
Description	**Total value**	**Calculation period**	**fpv**	**Total value (discounted)**
Geothermal heat exchanger	€ 9,231.25	50	21.482	€ 198,307.42
Water Heat Pump	€ 4,201.92	50	21.482	€ 90,266.46
			Maintenance cost	**€ 288,573.87**
			Specific Maintenance cost (€/m^3)	**5.31**
Energy cost				
Description	**Total value**	**Calculation period**	**fpv**	**Total value (discounted)**
Heating and Cooling	€ 25,179.79	50	21.482	€ 540,916.97
			Energy cost	**€ 540,916.97**
			Specific Energy cost (€/m^3)	**9.96**
Final value				
Description	**Final value**	**Calculation period**	**Rd**	**Final value (discounted)**
Geothermal heat exchanger	€ 0.00	50	0.141	€ 0.00
Water Heat Pump	€ 38,942.02	50	0.141	€ 5,479.63
			Final Value	**€ 5,479.63**
			Specific Final Value (€/m^3)	**0.10**
			GLOBAL COST	**€ 1,829,493.84**
			SPECIFIC GLOBAL COST (€/m^3)	**33.68**

Table 32 (OGHP) Open Loop Geothermal Heat Pump System Global Cost calculation

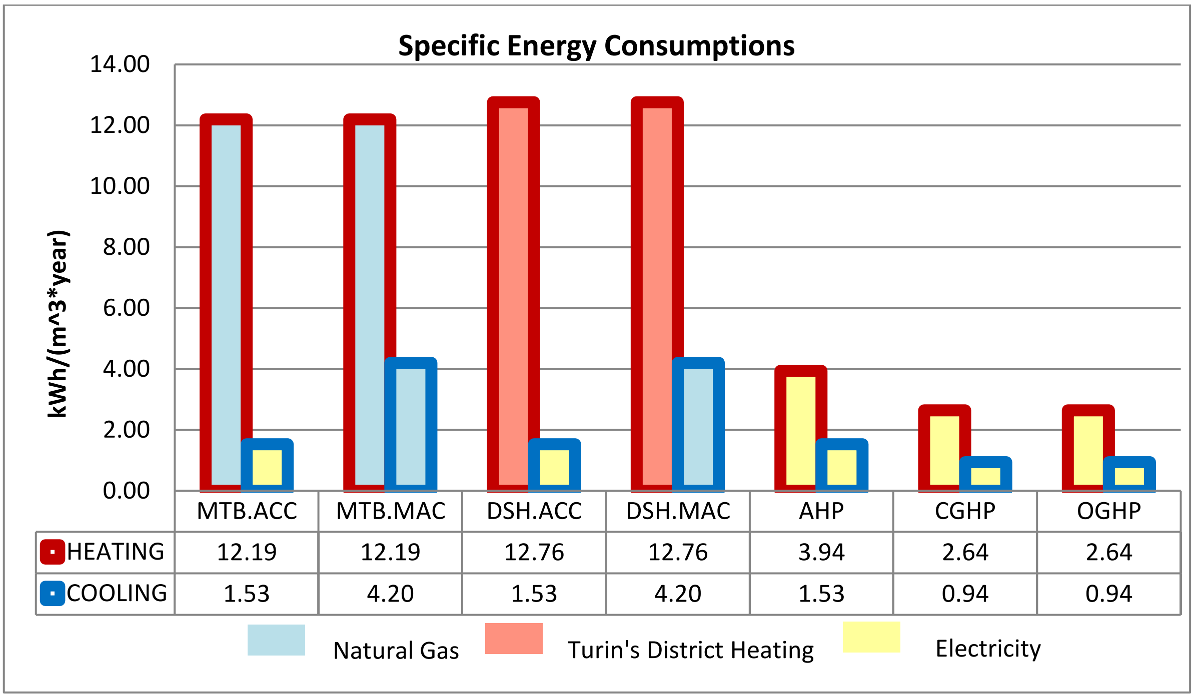
OGHP : Open loop Geothermal Heat Pump				
Investment cost				
Description	**Total value**			
Well doublet system	€ 94,356.12			
Disjunction heat exchangers	€ 7,625.00			
Water Heat Pump	€ 123,906.44			
Investment cost	**€ 225,887.56**			
Specific Investment cost (€/m^3)	**4.16**			
Replacement cost				
Description	**Total value**	**Replacement year**	**Rd**	**Total value (discounted)**
Water Heat Pump	€ 123,906.44	20	0.456	€ 56,549.28
Disjunction heat exchangers	€ 10,269.18	20	0.456	€ 4,686.72
Well doublet system	€ 94,356.12	25	0.375	€ 35,394.57
Water Heat Pump	€ 123,906.44	40	0.208	€ 25,808.35
Disjunction heat exchangers	€ 10,269.18	40	0.208	€ 2,138.96
			Replacement cost	**€ 122,438.92**
			Specific Replacement cost (€/m^3)	**2.25**
Maintenance cost				
Description	**Total value**	**Calculation period**	**fpv**	**Total value (discounted)**
Water Heat Pump	€ 2,478.13	50	21.482	€ 53,235.62
Disjunction heat exchangers	€ 152.50	50	21.482	€ 3,276.03
			Maintenance cost	**€ 56,511.65**
			Specific Maintenance cost (€/m^3)	**1.04**
Energy cost				
Description	**Total value**	**Calculation period**	**fpv**	**Total value (discounted)**
Heating and Cooling	€ 25,179.79	50	21.482	€ 540,916.97
			Energy cost	**€ 540,916.97**
			Specific Energy cost (€/m^3)	**9.96**
Final value				
Description	**Final value**	**Calculation period**	**Rd**	**Final value (discounted)**
Well doublet system	€ 0.00	50	0.141	€ 0.00
Water Heat Pump	€ 38,942.02	50	0.141	€ 5,479.63
			Final Value	**€ 5,479.63**
			Specific Final Value (€/m^3)	**0.10**
			GLOBAL COST	**€ 940,275.47**
			SPECIFIC GLOBAL COST (€/m^3)	**17.31**

4.4. Results

This last subchapter will be used to show the results obtained from the previous ones; graphs will be added in order to clarify differences between the analysed cases.

Following the calculation, here below are proposed different graphs derived from 4.2. Subchapter, which focus on specific results. For all cases, parameters are reported both for heating and cooling production to enhance the comparison; when it is possible, a total value is pointed out.

Graph. 11 Specific Energy consumptions

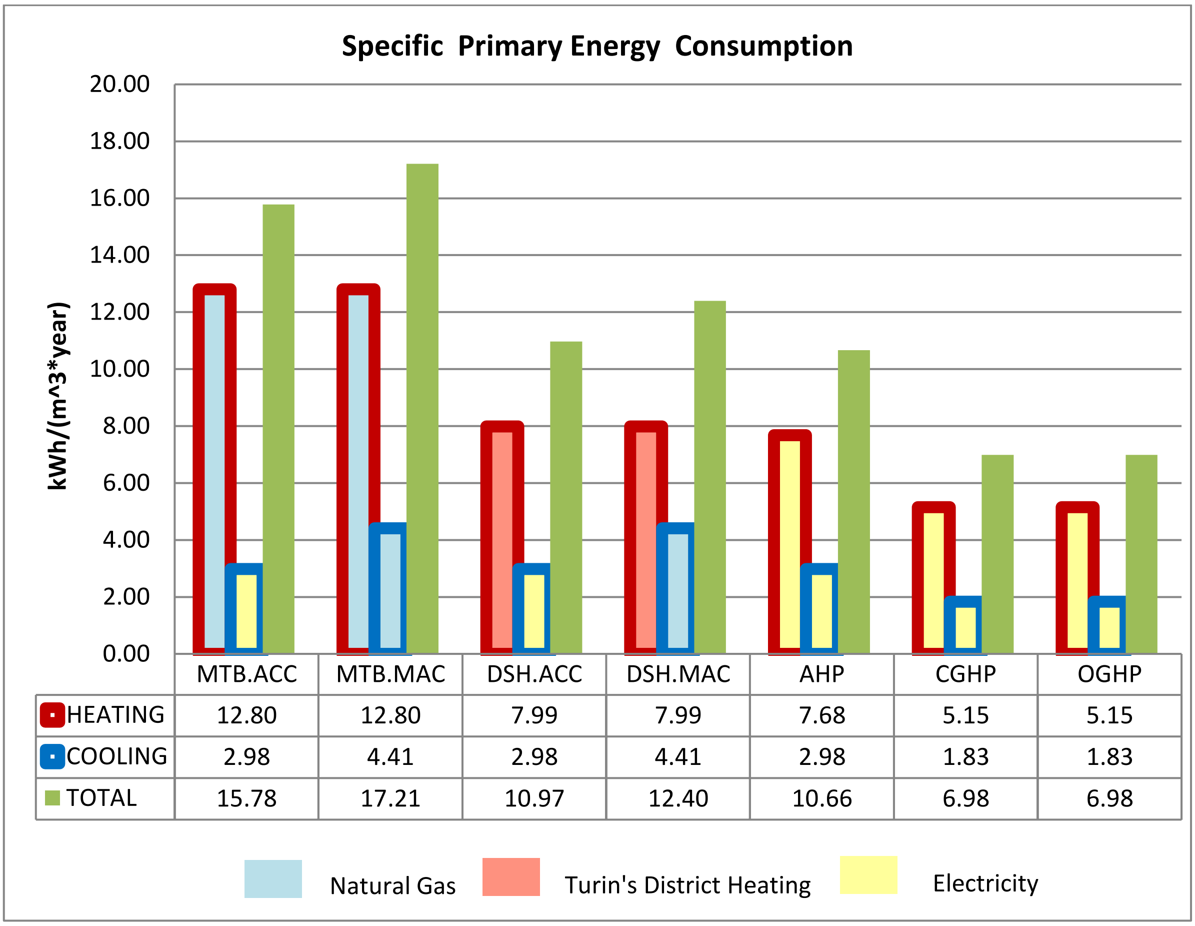


	MTB.ACC	MTB.MAC	DSH.ACC	DSH.MAC	AHP	CGHP	OGHP
HEATING	12.19	12.19	12.76	12.76	3.94	2.64	2.64
COOLING	1.53	4.20	1.53	4.20	1.53	0.94	0.94

In the previous graph, the specific energy consumption is showed. First of all, it is important to underline that different generators can utilize different energy vectors, therefore these results can have different natures. A proper legend is proposed at the bottom of the graph to remember the used energy vectors.

For each scenario and for the reference case, cooling energy consumption is lower than the heating one. This is clearly due to the lower energy requirements during the cooling season and, secondly, to the higher generation efficiency of cooling power generators. As expected, OGHP and CGHP have equal energy consumptions for the same adopted efficiencies, and they have the lowest energy consumption both in heating and in cooling operation. Then, AHP shows a slightly higher consumption compared to the first ones. Cooling energy consumption of AHP is the same compared to the scenarios where ACC was designed (MTB.ACC and DSH.ACC) for the fact that they are the same machines, but in the ACC configuration is not reversed. For the last cooling machine, MAC, highest value is associate, even if it is relatively moderated. MTB and DSH are relatively at first and second positions for highest energy consumption during heating season for the lowest generation performances.

Graph. 12 Specific Primary Energy Consumptions

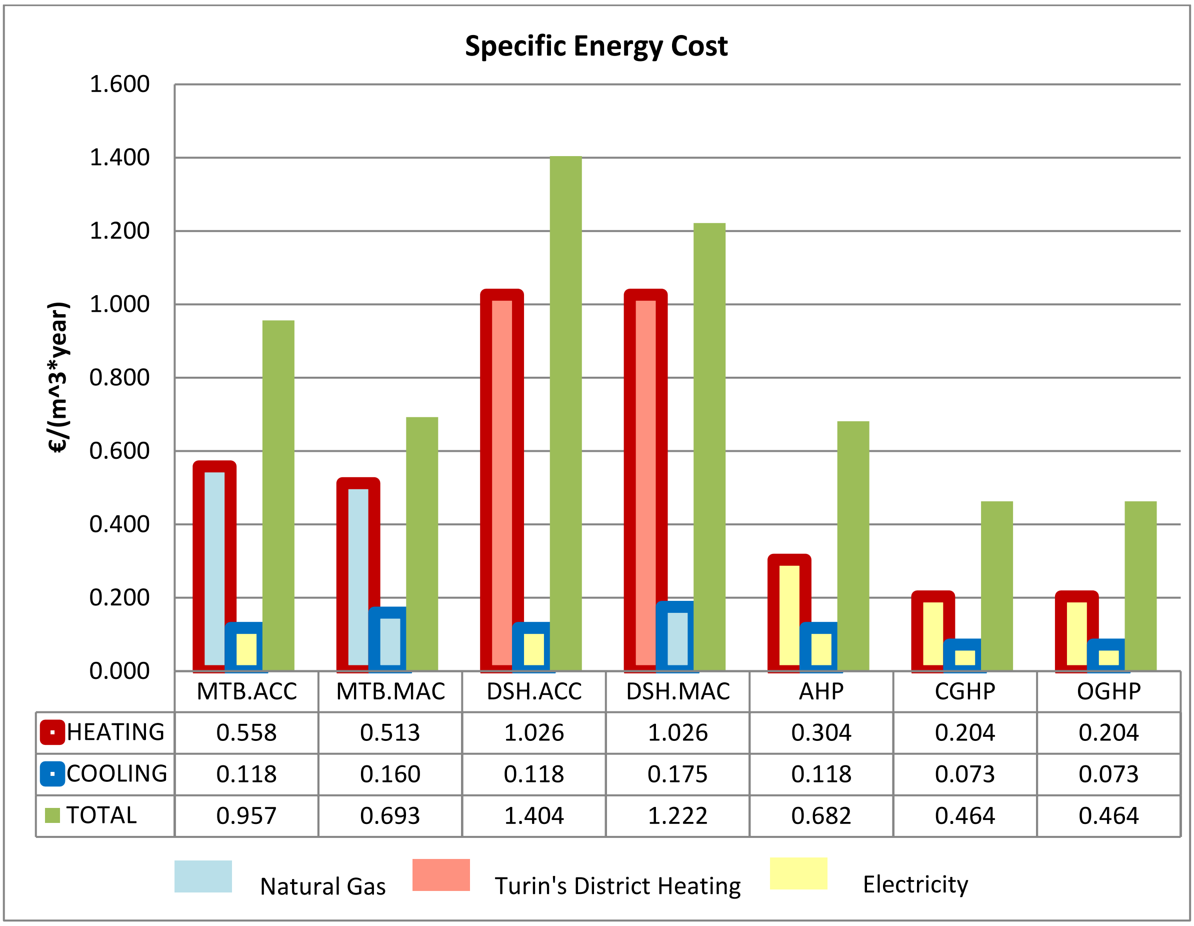


	MTB.ACC	MTB.MAC	DSH.ACC	DSH.MAC	AHP	CGHP	OGHP
HEATING	12.80	12.80	7.99	7.99	7.68	5.15	5.15
COOLING	2.98	4.41	2.98	4.41	2.98	1.83	1.83
TOTAL	15.78	17.21	10.97	12.40	10.66	6.98	6.98

In the previous graph, the specific primary energy consumption is showed. Differently from the Energy Consumption Graph, a total value for each scenario and for the reference case is computed with the sum of relative primary energy consumptions of two conditioning seasons. A proper legend is proposed at the bottom of the graph to remember the used energy vectors.

Once again, OGHP and CGHP have equal values, for the same reason mentioned before; they remain the lowest primary energy users both in heating and in cooling operation. Then, in increasing order, AHP and DSH.ACC show an almost equal total primary energy consumption. This is due to the almost equal primary energy consumption of heating production and, in second place, to the same cooling generators. Turin's district heating has a relatively low primary energy factor due to the presence of cogenerative cycle that feed this district heating. For this reason, DSH consumes less primary energy than MTB. Now, MAC reduces the distance from ACC because Natural gas owns lower primary energy factor compared to the electricity one. Composing single consumptions, MTB.MAC and MTB.ACC are relatively at first and second positions for highest total primary energy, followed by DSH.MAC.

Graph. 13 Specific Energy Cost

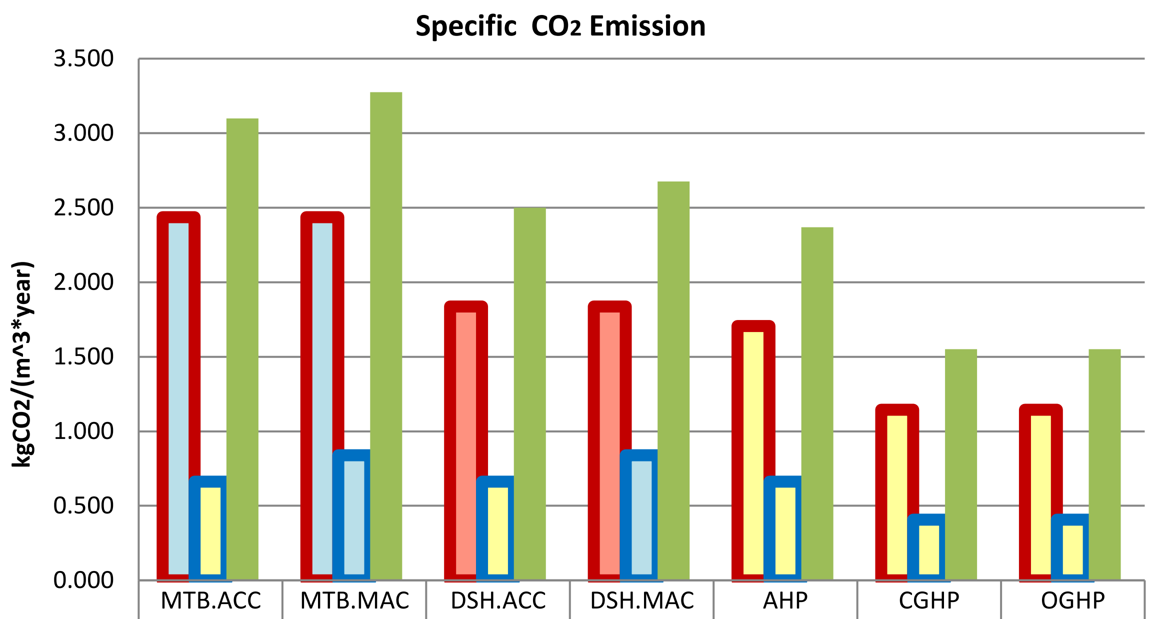


	MTB.ACC	MTB.MAC	DSH.ACC	DSH.MAC	AHP	CGHP	OGHP
HEATING	0.558	0.513	1.026	1.026	0.304	0.204	0.204
COOLING	0.118	0.160	0.118	0.175	0.118	0.073	0.073
TOTAL	0.957	0.693	1.404	1.222	0.682	0.464	0.464

In the previous graph, the specific energy cost is showed. Specific Energy Cost for heating and cooling is referred only to the direct cost of the energy vector, without considering possible fixed costs. Instead, Total Specific Energy Cost includes the direct cost of the energy vector and all fixed costs due to the dispatching for both heating and cooling case.

From the total energy cost point of view, OGHP and CGHP remain the cheapest, followed by MTB.MAC and AHP at almost the same value. Then MTB.ACC before most expensive cases of DSH.MAC and DSH.ACC. It is interesting to notice that scenarios with electricity supply only are the most affected from the difference of costs between heating/cooling and total cost for the presence of relatively high fixed costs. With minor effects, it is possible to see this aspect for natural gas supply only case MTB.MAC. As it is possible to know from the previous chapter, Turin district heating doesn't have any fixed cost, but it is related to the highest specific energy cost. Noteworthy, it is also the different costs for Natural gas supplied generators; installing together MTB and MAC, the total consumption of natural gas increases and it makes possible a reduction of the price of a unit of volume of Natural gas.

Graph. 14 Specific CO_2 Emission



	MTB.ACC	MTB.MAC	DSH.ACC	DSH.MAC	AHP	CGHP	OGHP
HEATING	2.436	2.436	1.837	1.837	1.706	1.145	1.145
COOLING	0.662	0.839	0.662	0.839	0.662	0.407	0.407
TOTAL	3.098	3.276	2.499	2.676	2.368	1.552	1.552

In the previous graph, the specific CO_2 emission is showed. A total value for each scenario and for the reference case is computed with the sum of relative specific CO_2 emission of two conditioning seasons.

OGHP and CGHP have the lowest specific CO_2 emission both for heating and for cooling, therefore also total value is the lowest one. They are followed by AHP, DSH.ACC and DSH.MAC with not much different CO_2 emissions. Scenarios characterized by MTB presence, turns out to be the main CO_2 emitters. Talking about heating production only, it is interesting to underline that DSH and AHP have almost similar emissions. This is due to the extremely low CO_2 emissions for a unit of heat from Turin's District Heating.

After these graphs, it is possible to sum up that the reference case OGHP, together with the CGHP scenario, are the best options for what concern energy consumption, primary energy consumption, energy cost and CO_2 emissions.

For 4.3. Subchapter, it is interesting to report Global Cost and Specific Global cost composition, reported below in form of table.

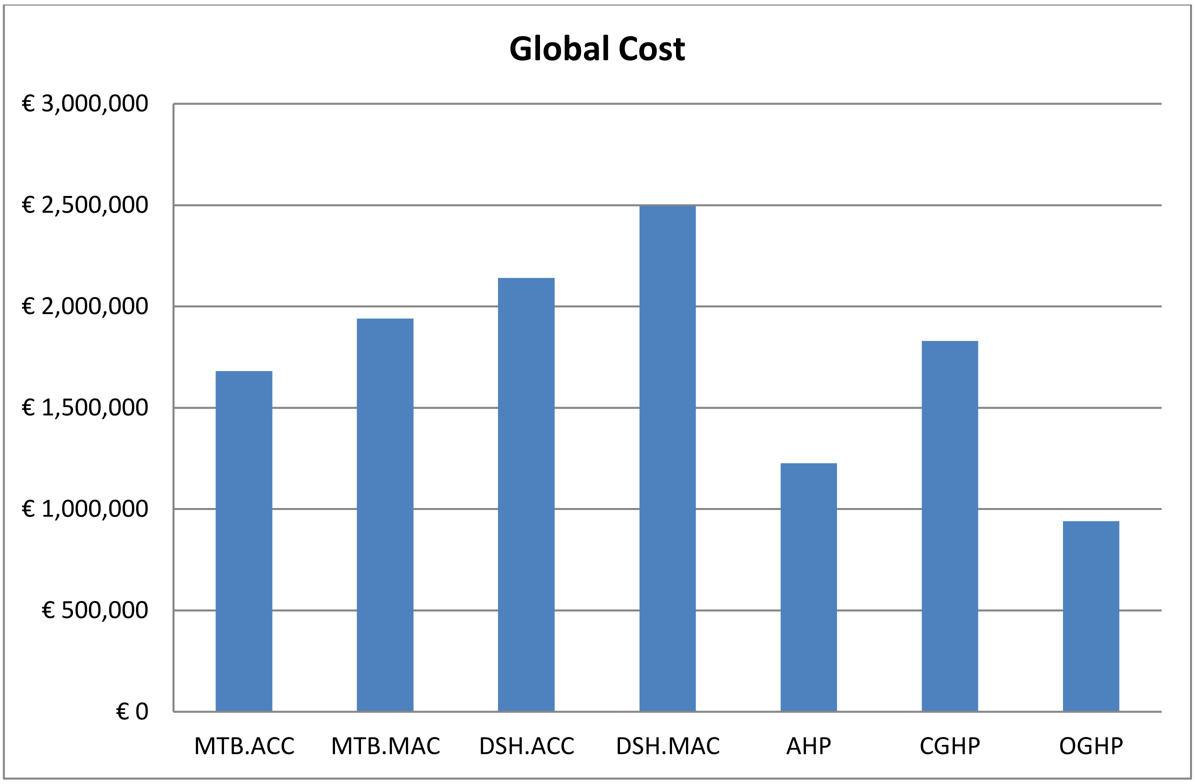
Table 33 Global cost composition (up) and Specific Global cost composition (down)

CODE	Investment cost	Replacement cost	Maintenance cost	Energy cost	Final value	Global cost
MTB.ACC	€ 274,429.16	€ 184,164.00	€ 117,906.76	€ 1,116,369.68	€ 12,136.35	**€ 1,680,733.24**
MTB.MAC	€ 551,606.80	€ 368,397.32	€ 236,994.38	€ 808,330.42	€ 24,394.24	**€ 1,940,934.67**
DSH.ACC	€ 243,995.43	€ 163,935.43	€ 104,831.10	€ 1,638,843.99	€ 10,790.45	**€ 2,140,815.50**
DSH.MAC	€ 521,173.07	€ 348,168.75	€ 223,918.72	€ 1,426,364.81	€ 23,048.34	**€ 2,496,577.01**
AHP	€ 210,096.08	€ 139,645.82	€ 90,266.46	€ 795,588.84	€ 9,291.28	**€ 1,226,305.91**
CGHP	€ 923,125.00	€ 82,357.64	€ 288,573.87	€ 540,916.97	€ 5,479.63	**€ 1,829,493.84**
OGHP	€ 225,887.56	€ 122,438.92	€ 56,511.65	€ 540,916.97	€ 5,479.63	**€ 940,275.47**

CODE	Specific Investment cost (€/m^3)	Specific Replacement cost (€/m^3)	Specific Maintenance cost (€/m^3)	Specific Energy cost (€/m^3)	Specific final value (€/m^3)	Specific Global cost (€/m^3)
MTB.ACC	5.05	3.39	2.17	20.55	0.22	**30.94**
MTB.MAC	10.15	6.78	4.36	14.88	0.45	**35.73**
DSH.ACC	4.49	3.02	1.93	30.17	0.20	**39.41**
DSH.MAC	9.59	6.41	4.12	26.26	0.42	**45.96**
AHP	3.87	2.57	1.66	14.64	0.17	**22.57**
CGHP	16.99	1.52	5.31	9.96	0.10	**33.68**
OGHP	4.16	2.25	1.04	9.96	0.10	**17.31**

Graphical representations are more indicated to compare and discuss different results.

Graph 15 Global cost

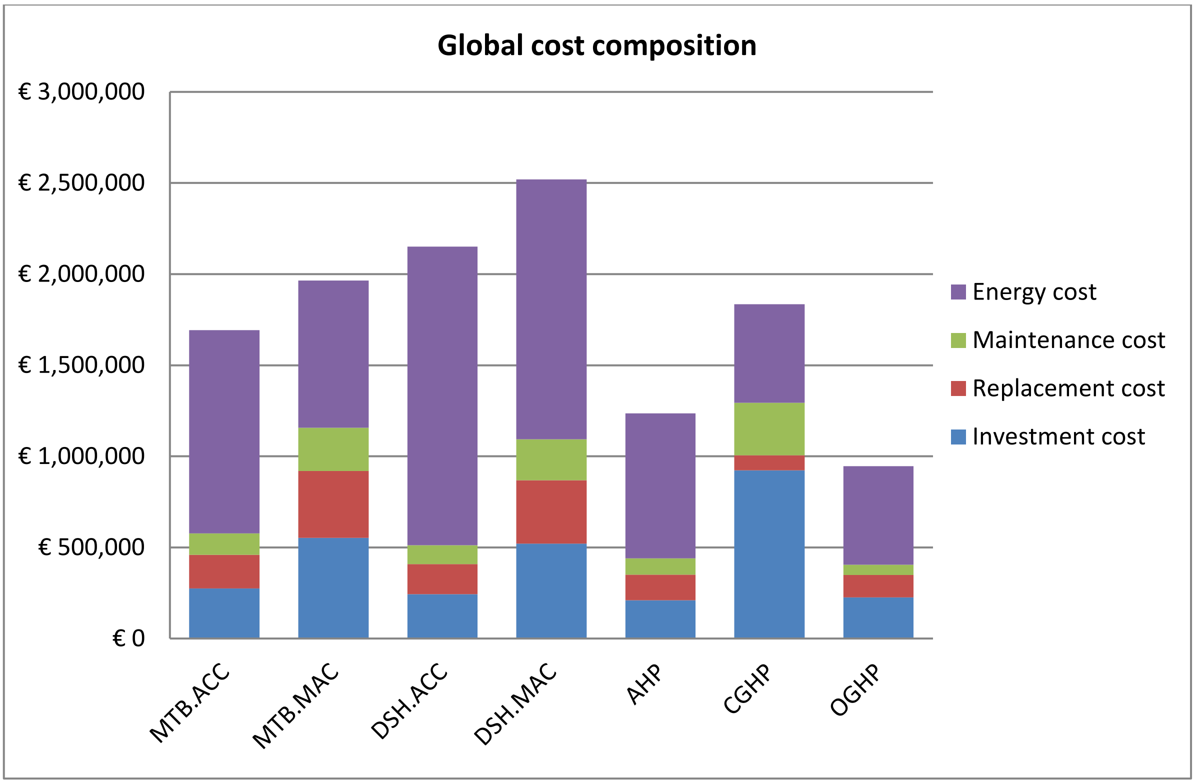


Thanks to this representation, it is more clear to evaluate a Global cost classification of the different cases.

The graph represents the Global cost obtained from the sum of: investment, replacement, maintenance, energy discounted costs, subtracting the discounted final value contribute.

How it is possible to understand from the relative tables, residual values are much smaller than other. Over the linear depreciation, this is especially due to the discount rate contribute, which present a very low value for 50 years. Therefore, in order to have a clear view on the Global cost composition, only positive contribute are reported in the following graphs.

Graph 16 Global cost composition



First of all, it is interesting to notice differences between the same discounted cost of different cases.

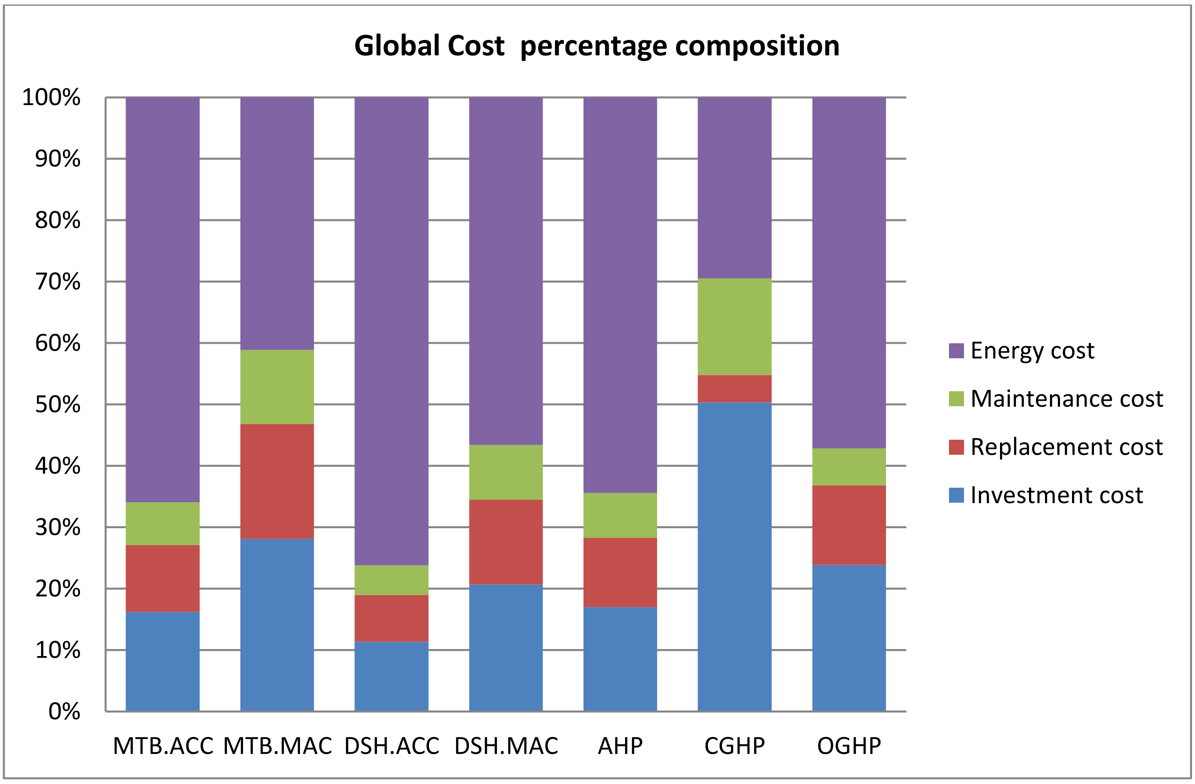
For what concern investment cost, the highest value is related to the Closed loop Geothermal Heat Pump system (CGHP), due to the high expenditure for the geothermal heat exchanger. Then, it is clear that Methane Absorption Chiller increases the total initial investment cost of scenarios in which it is included. For other cases, investment cost is almost comparable. An advantage of AHP, CGHP and OGHP is that it is possible to use the same device in order to produce cooling and heating power; this can bring a reduction in term of investment cost.

As said before, replacement cost is strictly related to the cost of components that will be substituted and from their lifespan. In most cases, this cost is proportional to the investment one, and this is due to the fact that most components have the same lifespan. In the other hand, CGHP is characterized by a smaller discounted replacement cost, because useful life of pipes that compose the geothermal heat exchanger is 50 years, longer than other components. In summary, the geothermal heat exchanger is very expensive, but durable in time.

Also, maintenance cost is directly proportional to the investment one; this aspect is clearly visible in the graph. Due to the long period of calculation, even if maintenance cost for each year is relatively low, it gives a noteworthy contribute at the Global cost calculation like replacement one.

At the end, it is possible to say that the most important contribute to the Global cost calculation, is imputed to the discounted energy cost. As maintenance cost, energy one is an annual expenditure, but considering its present value factor during all years of the calculation period, the discounted cost turns out to be conspicuous. As it is showed in a previous graph, the costs of energy is very different from the analyzed cases. The high cost of heat from district heating increases, over the others, the global cost of cases which contain it. A moderate discounted energy cost for MTB.MAC is not enough to reach a low Global cost, but it approaches to the CGHP one. The lowest Global cost is the OGHP one, thanks to the lowest discounted energy expenditure. AHP and MTB.ACC are located relatively at the second and third position; in this case too, thanks to a relative low discounted energy cost contribution.

Graph 17 Global cost percentage composition



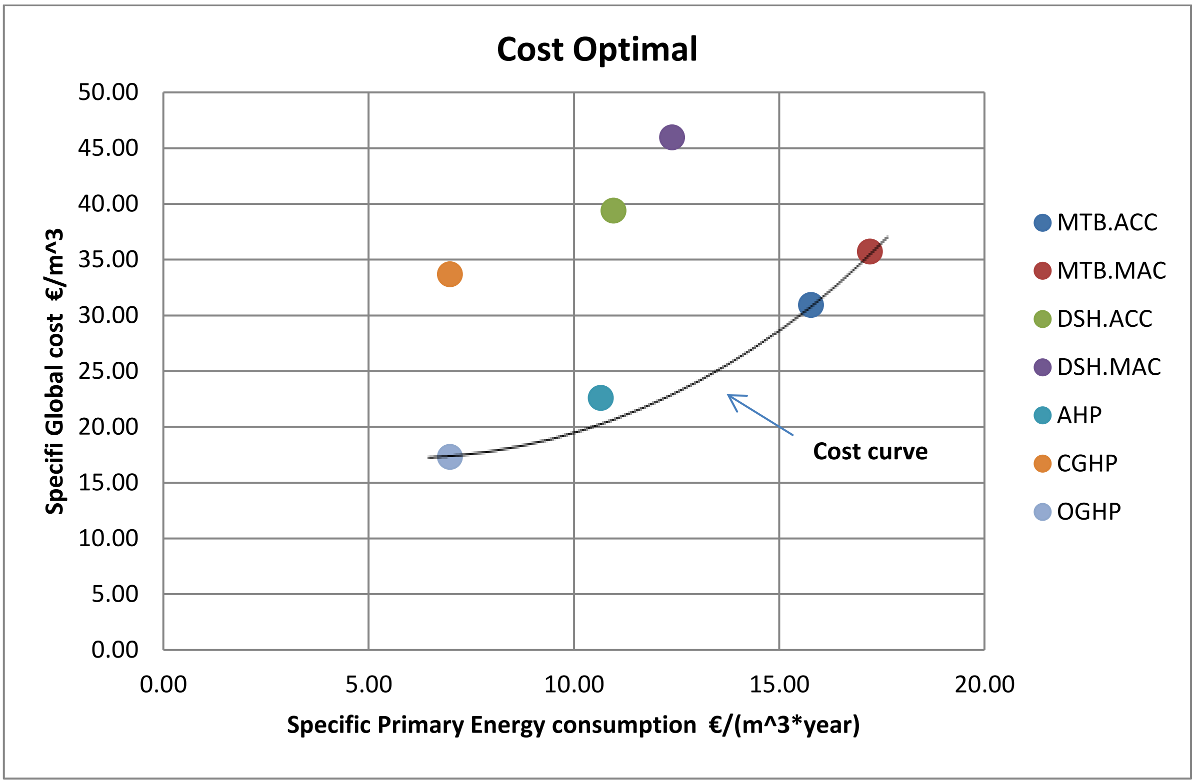
In addition, with the previous graph it is possible to appreciate the percentage composition of Global cost for each scenario and for the Reference case.

Finally, Specific Primary energy consumption and specific Global cost can be reported together as final results of the thesis.

Table 34 Specific Primary energy consumption and Specific Global cost

CODE	Specific Primary energy Consumption (kWh/m^3)	Specific Global cost (€/m^3)
MTB.ACC	15.78	30.94
MTB.MAC	17.21	35.73
DSH.ACC	10.97	39.41
DSH.MAC	12.40	45.96
AHP	10.66	22.57
CGHP	6.98	33.68
OGHP	6.98	17.31

Graph 18 Cost Optimal



With this last graph the Cost-optimal analysis can be considered concluded. In this graph, each indicator is related to a single scenario or to the reference case (OGHP). The Specific Primary energy consumption is reported on x-axis, while the Specific Global cost is noted on y-axis. The aim of this graph is to represent for each scenario Specific Global cost in function of its Specific primary energy consumption. Some points, which can be found on or near the represented Cost curve, declare what scenarios have the minor Specific Global cost, for a Specific Primary Energy consumption. It is interesting to notice that the reference case, Open loop Geothermal Heat Pump system (OGHP) is the cheapest and, with CGHP, it represents the best option in terms of Primary energy consumption. Carry on with Cost curve, in increasing order, it is possible to find AHP, MTB.ACC and MTB.MAC that represents the highest primary energy consumption case. On the top of the graph, DSH.ACC and DSH.MAC are present with the highest Specific Global costs, but also with an intermediate primary energy consumption.

Chapter 5: Conclusion and future development

The proposed thesis has been carried out with the goal of comparing heating and cooling production scenarios different from the reference case: an Open Loop Geothermal Heat Pump system. It is proved that the realization of this type of system can be considered as the best practicable choice among those analyzed for “RSA Il Trifoglio”, both for costs and environmental impact.

Generally, people consider Geothermal Heat Pump Systems as a new and not diffused technology, but it is not. Simply, a Geothermal system has null visual impact, therefore it is impossible to understand if a building is supplied by this type of system. Capilongo, 2018 refers that only in the Municipality of Turin, 36 approved Open loop Geothermal Systems are present, and, in addition, in some cases with relative big dimensions. To report only some example from the Turin context: Polytechnic of Turin, Intesa Sanpaolo skyscraper, Turin Metropolitan Palace and Egyptian Museum have to disposal an Open loop Geothermal Heat Pump system. Nowadays, other similar plants are under construction, and the growth of this kind of systems will probably increase in the next future. Of course, aquifer has to be relatively easy to reach, and there must be available area for realization of wells at correct distance. On the other hand, the increase of Geothermal System installations, relatively close to each other, can partially reduces their overall performances; this is mainly because of interactions between reinjection and abstraction well of different plants. This aspect could be treated in possible future works with the aim to establish how much performances are reduced.

From the energy and economic point of view, Cost optimal analysis can be implemented with other production technologies, also including hybridization of already considered systems. To extend possible scenarios and to put in evidence the heat pump behaviour, a Cost optimal analysis can be computed varying the manifold temperature of water of distribution circuit. To do this, it will be necessary to consider also final user devices.

References

Baietto et al., 2010 Baietto A., Pochettino M., Salvatici E.
Progettazione di impianti geotermici. Sonde verticali e pozzi d'acqua
Palermo, Dario Flaccovio Editore, 2010

Bayer et al., 2014 Bayer P., de Paly M., Beck M.
Strategic optimization of borehole heat exchanger field for seasonal geothermal heating and cooling
Applied Energy, 136 (2014) pp. 445-453

Benazza et al., 2011 Benazza A., Blancob E., Aichouba M., Río J. L., Laouedj S.
Numerical Investigation of Horizontal Ground Coupled Heat Exchanger
Energy Procedia, 6 (2011), pp. 29-35

Boughanmi et al., 2015 Boughanmi H., Lazaar M., Bouadila S., Farhat A.
Thermal performance of a conic basket heat exchanger coupled to a geothermal heat pump for greenhouse cooling under Tunisian climate
Energy and Buildings, 104 (2015) pp. 87-96

Capilongo, 2018 Capilongo L.
Gestione amministrativa ed autorizzativa degli scarichi idrici degli impianti geotermici
Presentation for Città Metropolitana di Torino, Torino, 11 maggio 2018

Casasso and Sethi, 2014 Casasso A., Sethi R.
Efficiency of closed loop geothermal heat pumps: A sensitivity analysis
Renewable Energy, 62 (2014), pp. 737-746

Comune Milano, 2018 Comune di Milano
Listino Prezzi per l'esecuzione di opere pubbliche e manutenzioni Edizione 2018: Opere Compiute Impianti elettrici e meccanici, Volume 1.2
Area opere pubbliche e coordinamento tecnico (2018)

Adjustable Speed Pumping Applications, 2010
Adjustable Speed Pumping Applications
World Pumps, 2 (2010), pp. 40-41

Dickson and Fanelli, 2004 Dickson M. H., Fanelli M.
What is Geothermal energy?
Istituto di Geoscienze e Georisorse, CNR , Pisa, Italy, (2004)

Erdélyi et al., 2014 Erdélyi B., Tóth A.
Geothermal method
Advanced Geophisics, 2 (2014)

Fridleifsson et al., 2008 Fridleifsson I. B., Bertani R., Huenges E., Lund J. W., Ragnarsson A.,Rybach L.O. Hohmeyer and T. Trittin, ed.
The possible role and contribution of geothermal energy to the mitigation of climate change
Luebeck, Germany: 59–80. Retrieved 2013-11-03.

Geostudio, 2013 Accattino G., Biolatti G., Dosio P.
Relazione Finale sui pozzi di emungimento e restituzione in falda a servizio degli impianti di climatizzazione presso una casa di cura sita in Torino, Via Mongrando
(2013)

Iren Energia, 2017 Iren Energia S.p.a.
Fattori di conversione in energia primaria dell'energia termica fornita ai punti di consegna della rete di teleriscaldamento della rete di Torino
Torino, 21 marzo 2017
Jun et al., 2009 Jun L., Xu Z., Jun G., Jie Y.
Evaluation of heat exchange rate of GHE in geothermal heat pump systems
Renewable Energy, 34 (2009), pp. 2898-2904
Kurevija and Strpić, 2018 Kurevija T., Strpić
Hydraulic and thermogeological design differences between two-loop vertical and inclined coaxial borehole heat exchangers
Renewable Energy, 117 (2018), pp. 314-323
Lindal, 1973 Lindal B.
Industrial and other applications of geothermal energy
In:
Dickson M. H., Fanelli M.
What is Geothermal energy?
Istituto di Geoscienze e Georisorse, CNR , Pisa, Italy, (2004)
Lo Russo, 2018 Lo Russo S.
Slides of Geothermal Energy course
Corso di Laurea Magistrale in Ingegneria Energetica e Nucleare, A.A. 2017-2018
Makasis et al., 2018 Makasis N., Narsilio G. A., Bidarmaghz A.
A machine learning approach to energy pile design
Computers and Geotechnics, 97 (2018), pp. 189-203
Mediapolis, 2013 Mediapolis engineering s.r.l.
Progetto Esecutivo
Progetto di una residenza sanitaria assistenziale sita in via Mongrando, (2013)
Pu et al., 2018 Pu L., Xu L., Qi D., Li Y.
Structure optimization for horizontal ground heat exchanger
Applied Thermal Engineering, 136 (2018), pp. 131-140
Raymond et al., 2015 Raymond J., Mercier S., Nguyen L.
Designing coaxial ground heat exchangers with a thermally enhanced outer pipe
Geothermal Energy, 3:7 (2015), pp. 12-13
Regione Piemonte, 2018 Regione piemonte
Prezzario opere pubbliche Regione Piemonte 2018
Regione Piemonte (2018)
Song et al., 2017 Song X., Shi Y., Li G., Yang R., Xu Z., Zheng R., Wang G., Lyu Z.
Heat extraction performance simulation for various configurations of a downhole heat exchanger geothermal system
Energy, 141 (2017), pp. 1489-1503
Stauffer et al., 2017 Stauffer F., Bayer P., Blum P., Molina-Giraldo N., Kinzelbach W.
Thermal Use of Shallow Groundwater
CRC Press, Taylor & Francis Group, (2014)
The KamLAND Collaboration, 2011 The KamLAND Collaboration
Partial radiogenic heat model for Earth revealed by geoneutrino measurements
Nature Geoscience, 4 (2011), pp. 647–651

Tinti et al., 2017 Tinti F., Boldini D., Ferrari M., Lanconelli M., Kasmaee S., Bruno R., Eggerb H., Vozab A., Zurlo R.
Exploitation of geothermal energy using tunnel lining technology in a mountain environment. A feasibility study for the Brenner Base tunnel – BBT
Tunnelling and Underground Space Technology, 70 (2017), pp. 182-203

Toth et al., 2017 Toth A., Bobok E.
What is Geothermal Energy?
Flow and Heat Transfer in Geothermal Systems - Basic Equations for Describing and Modeling Geothermal Phenomena and Technologies, 1 (2017), pp. 2-9

Vergerio et al., 2018 Vergerio G., Becchio C., Delmastro C., Lanzini A., Corgnati S. P., Borchiellini R.
A decision-making process to support public administrations in defining local energy policies
Thermal Science and Engineering Progress, 6 (2018), pp.498-409

Wu et al., 2010 Wu Y., Gan G., Verhoef A., Vidale P.L., Gonzalez R.G.
Experimental measurement and numerical simulation of horizontal-coupled slinky ground source heat exchangers
Applied Thermal Engineering, 30 (2010), pp.2574-2583

Zhang et al., 2015 Zhang W., Yang H., Lu L., Fang Z.
Investigation on influential factors of engineering design of geothermal heat exchangers
Applied Thermal Engineering, 84 (2015), pp. 310-319

Sitography

[1] http://viessmann.com.ua/novost-179/Klasternoe_geotermalnoe_pole.html

[2] https://geoflow.com.au/geothermal/#Water-Loop-Heat-Exchanger

[3] https://www.energyplus.net/sites/default/files/docs/site_v8.3.0/InputOutputReference/01c-InputOutputReference/index.html#groundheatexchangerpond

[4] https://www.ksb.com/centrifugal-pump-lexicon/closed-loop-control/191338/

[5] http://www.linde-gas.com/en/legacy/attachment?files=tcm:Ps17-111483,tcm:s17-111483,tcm:17-111483

[6] https://it.wikipedia.org/wiki/Protocollo_di_Montr%C3%A9al

[7] https://www.areabios.com/trifoglio-torino/

[8] https://www.gruppoiren.it/teleriscaldamento-informazioni-commerciali

[9] http://www.sistemapiemonte.it/siceefree/base/ace/cpRisultatoRicercaAce.do

[10] https://www.arera.it/it/dati/condec.htm

[11] http://spazioinwind.libero.it/geopiu/servizi4.htm

Legislation

DD. 3 marzo 2016, n. 66, regarding: "Linee guida regionali per l'installazione e la gestione delle sonde geotermiche"

DM. 26 giugno 2009, regarding: "Linee guida nazionali per la certificazione energetica degli edifici"

DM. 26 giugno 2015, regarding: "Applicazione delle metodologie di calcolo delle prestazioni energetiche e definizione delle prescrizioni e dei requisiti minimi degli edifici"

EN 15459, 2007, regarding: "Energy performance of buildings - Economic evaluation procedure for energy systems in buildings"

D.P.G.R. 29 luglio 2003, n. 10/R, regarding: "Disciplina dei procedimenti di concessione di derivazione di acqua pubblica (Legge regionale 29 dicembre 2000, n. 61)"

UNI/TS 11300-2, regarding: "Prestazioni energetiche degli edifici. Parte 2: Determinazione del fabbisogno di energia primaria e dei rendimenti per la climatizzazione invernale, per la produzione di acqua calda sanitaria, per la ventilazione e per l'illuminazione in edifici non residenziali"

UNI/TS 11300-4, regarding: "Prestazioni energetiche degli edifici. Parte 2: Utilizzo di energie rinnovabili e di altri metodi di generazione per la climatizzazione invernale e per la produzione di acqua calda sanitaria"

Acknowledgements *Ringraziamenti*

Il primo ringraziamento è per i miei relatori: Professor Andrea Lanzini, Professoressa Cristina Becchio, Professoressa Glenda Taddia, Professor Stefano Lo Russo e il Professor Stefano Paolo Corgnati. Grazie per avermi pazientemente condotto nello sviluppo della tesi. Volevo inoltre ringraziare Città Metropolitana di Torino, in particolare l'Ingegner Luigi Capilongo e la Geometra Monica Cartello per aver accolto la mia proposta di tesi in un ambito in cui provo molto interesse. Ringrazio la Cooperativa Sociale Bios e l'Ingegner Francesco Torsello per aver acconsentito allo studio dettagliato dell'impianto geotermico trattato nella tesi.

Il mio più profondo ringraziamento spetta a tutta la mia famiglia per non aver mai smesso di credere in me. In particolare a mia Madre e a mio Padre, che mi hanno permesso di raggiungere questo grande obiettivo. Grazie a loro sono potuto diventare la persona che sono oggi. Sono fiero di essere vostro figlio. Grazie a Daniele, per ogni momento passato insieme, alla sua capacità di farmi pensare ad altro e la voglia di starmi vicino nel momento del bisogno. Con lui, ho potuto imparare tutto ciò che di arricchente ci può essere nella condivisione. Sono orgoglioso di essere suo fratello.

Voglio ringraziare di cuore tutti gli amici di sempre: Riccardo, Davide, Giulio, Gabriele, Beatrice, Laura e Verdiana; con cui ho potuto vivere più di un decennio di esperienze, con alcuni quasi due. Da voi ho imparato il confronto e l'immensa importanza di avere un amicizia sincera.

Grazie ai compagni ed amici scout, presenti e passati, per aver vissuto con me la più grande avventura che abbia mai avuto il piacere di intraprendere. La frase che si sente spesso "Scout ti cambia la vita" non è totalmente vera, semplicemente ti permette di viverla appieno e al meglio di come avresti potuto viverla diversamente. Grazie a loro ho imparato a non arrendermi e credere sempre nei miei obiettivi, oltre al giudizio altrui e oltre le condizioni al contorno.

Un sincero ringraziamento va agli amici del poli: Tommaso, Paolo, Daniele, Flavio, Umberto e Davide; con i quali ho potuto condividere e concludere questo importante cammino. In questi anni di studio, non si sono mai tirati indietro nel darmi un aiuto o semplicemente un consiglio quando che avevo bisogno.

Il mio ultimo e più sentito ringraziamento va a Noemi, che con la sua dolcezza mi da la forza di credere e puntare in alto. La ringrazio per avermi sostenuto durante la tesi, ma ancor più per aver colorato la mia vita.

Grazie a tutte le persone che ho incontrato lungo la mia strada. Grazie a loro ho imparato che è si importante raggiungere la propria meta, ma lo è ancor di più il modo in cui viene percorsa la strada per raggiungerla.