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Feasibility and environmental benefits of an open loop shallow geothermal system for heating and cooling an industrial building: The YKK Mediterraneo S.P.A. Case Study (Marche Region, Italy)

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Lastly, my deepest gratitude goes to my mother, who remains ever-present in my heart and thoughts. Everything I am and all that I have achieved is thanks to her. It is because of her incredible strength and struggles that I learned to fight for what I want. Her motto has become mine: "One day, I will get there!"

Contents

Introduction

The largest energy end use in the world, accounting for about half of the total final energy consumption, is related to heating, being also responsible for 38% of energy-related CO_2 emissions in 2022. About 53% of the total energy produced for heating is spent for industrial activities, while 44% is used in buildings for space and water heating as well as, at reduced level, cooking. The remainder is primarily used in agriculture to heat greenhouses.

Annual heat consumption expanded by 6% globally over 2017-2022. Renewable energy, excluding traditional uses of biomass, met only half of this increase, with its share in global heat consumption rising by only 2 percentage points to 13% in 2022. More than two-thirds of global growth in renewable heat use was in the form of bioenergy (especially in industry) and renewable electricity (mainly in buildings).

Renewable heat consumption is predicted to climb modestly and rise more than 40% (+12 EJ) globally between 2023 and 2028 as shown in Figure 1. However, this development only accounts for 70% of the anticipated increase in world heat demand overall, which means that annual emissions of CO_2 would rise due to increased use of fossil fuels for heating (+5%/+0.6 Gt CO_2) (IEA, 2023).

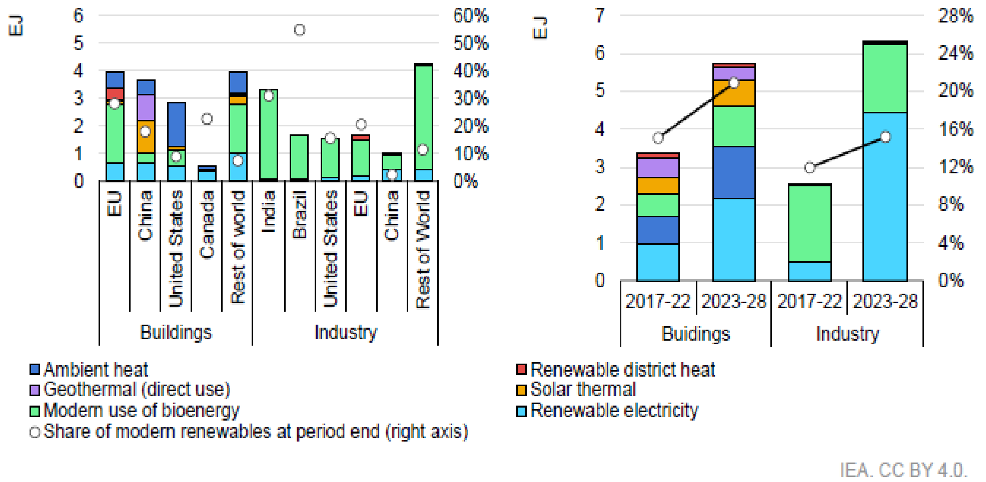


Figure 1 - Renewable energy consumption and shares of heat demand in selected regions 2022 (left) and global increases in renewable energy consumption 2027-2028 (right) (IEA, 2023)

The REPowerEU plan, released in May 2022, suggests increasing the EU objective for renewables in total final consumption from 40% to 45% by 2030 to lessen the EU's reliance on Russian gas. In addition to a solar PV strategy, it includes provisions for the decarbonization of the industrial sector by electrification, doubling the rate of use of heat pumps, integrating geothermal and solar thermal energy in modernized district heating system, and hydrogen derived from renewable sources (European-Commission, 2022).

Therefore, increasing the use of renewable heat sources and accelerating the development of energy and material efficiency are both necessary for decarbonizing industry, especially in sectors hard-to-abate.

Low-temperature geothermal energy, also called shallow or low-enthalpy geothermal energy, is thermal energy extracted from the uppermost part of the lithosphere. The low enthalpy energy in shallow levels of the Earth's crust, typically below 100-150 m in depth, indicates an energy resource in which the temperature is below 30°C (Allen, et al., 2003; Banks, 2012). This geothermal energy is mostly derived from solar radiation as only a minor proportion of the thermal stored energy in shallow levels or aquifers originates from the Earth's internal heat or from heat produced by plate tectonics (Teppo, et al., 2014) and can be efficiently extracted with the use of the ground-coupled heat pump systems (GHPs) installations.

It is then easy to understand how low temperature geothermal system can contribute to reduce the energy needs for heat and cooling in buildings, industries and greenhouses, and can be a significant component to achieving this goal and contribute to reduce by 55% green gas emissions by 2030 and the Carbon neutrality by 2050.

This thesis focuses on analyzing the feasibility and benefits of implementing an open-loop shallow geothermal system at YKK Mediterraneo S.P.A., an industrial facility located in Ascoli Piceno, central Italy. Data collected from geological and hydrogeological surveys, sensors installed both on wells and in the heat pumps were utilized to estimate the operational setting, assess system’s efficiency, and evaluate the associated environmental benefits of the project.

Chapter 1 – Geothermal Energy

Heat held in the Earth's crust is known as geothermal energy. Geothermal resources are usually related to hot water reservoirs that exist at different temperatures and depths beneath the earth's surface. A geothermal system traps meteoric waters in a reservoir, heats them, and activates natural convection circulation, which drives the heat to the surface.

A conventional high temperature geothermal system, as shown in Figure 2, is composed by four main components:

1. a heat source: hot rocks or magma with high temperatures and low depths 5-10 km;
2. a reservoir: permeable rocks containing the geothermal fluid, connected to a recharge area;
3. a geothermal fluid: water, often meteoric, in liquid or vapor phase depending on pressure and temperature;
4. impermeable rocks (cap-rock or clay-cap) that keep the fluid warm at depth and pressure.

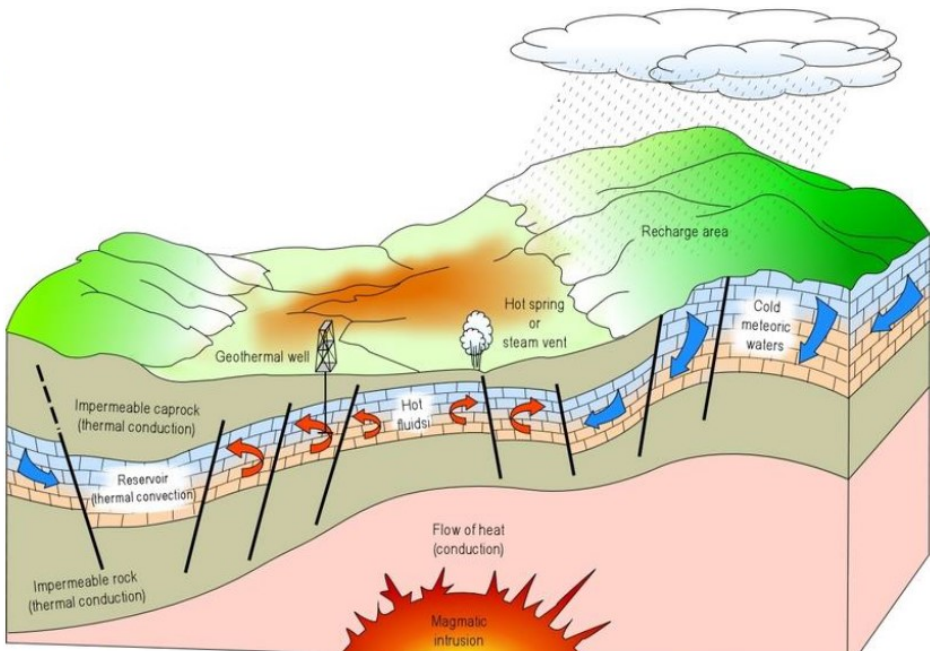


Figure 2 - Schematic sketch of a conventional geothermal system (Source: www.unionegeotermica.it)

The primary method of extracting this energy is by drilling the first kms of the Earth's crust, at different temperatures and depths, and fluids are then used to bring the energy to the surface. The energy is extracted at the surface and used to produce electricity and/or thermal energy. As shown in Figure 3, based on the fluid temperature, the geothermal resources can be classified into three categories:

- high enthalpy geothermal: geothermal fluid temperature above 150°C;
- medium enthalpy geothermal: fluid temperature in the range 90-150°C;
- low enthalpy geothermal: fluid temperature lower than 90°C.

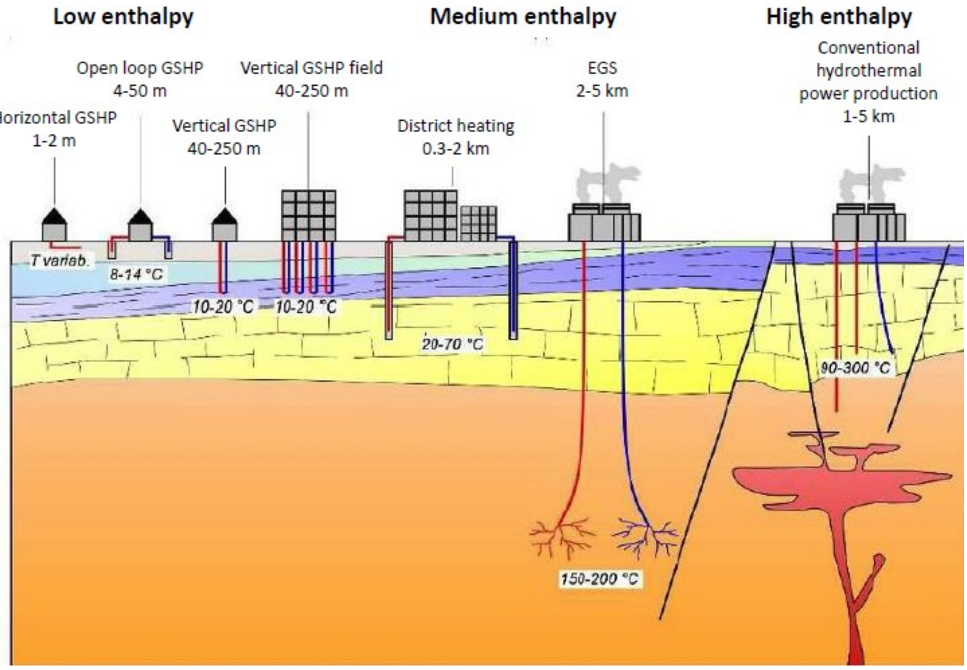


Figure 3 – Conceptual model of the geothermal systems' categories based on depths and temperatures of the resources (Source: www.igg.cnr.it)

1.1 Shallow low temperature geothermal system

The stable, low-temperature conditions in the shallow sub-surface are widely used through ground-coupled heat pump systems (GHPs) to provide efficient space heating and cooling. Temperature in the ground has a daily (up to few cm) and seasonal (up to few meters) fluctuations, becoming essentially constant and similar to the annual average of outdoor air temperatures at about 10-15 m of depth, and up to about 100 m, where, below this depth, it starts to increase based on the local geothermal gradient, which average value is globally of ~3°C/100 m (i.e., 30 °C/km) (Figure 4) (Manzella, 2014).

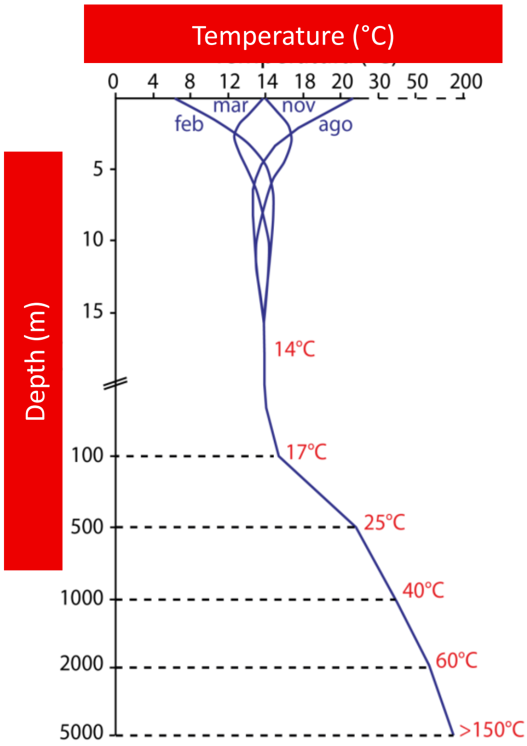


Figure 4 – Geothermal Temperature profile

In a shallow low temperature system, the GSHP exploit the physical property of fluids to absorb and release heat when they vaporize or condense, respectively, and remove heat from a space (to keep it cool) discharging heat at higher temperature (heating mode) in another place. There are two main type of shallow low temperature systems (Manzella, 2014):

• Closed Loop: these systems exploit the shallow ground heat content without directly exchanging water, either vertically or horizontally (Figure 5). Closed-loop Borehole Heat Exchangers (BHE) systems mainly consist of a closed loop U-shaped series of probes inserted into the ground, down to 80–120 m of depth or more, where a heat carrier fluid flows into the probes, thus allowing the heat exchange between the ground and the building at the surface by using a geothermal heat pump (GHP) to meet the building's thermal needs (Di Pierdomenico, et al., 2024).

Vertical systems are more efficient and require less installation area. A water plus, in case, additional antifreeze solution circulates through the pipes, collecting heat from the ground in the winter and reinjecting heat into the ground in the summer. Thermally enhanced grout fills the gap between pipes and well's wall, allowing for efficient heat transfer between fluid and surrounding surface (soil or rock).

Backfilling boreholes prevents surface water from entering and potentially contaminating subsurface spaces. Heat transport relies strongly on the borehole's thermal resistance, influenced by the architecture of the pipe and the thermal properties of the used grout. The most popular grout formulations are cement- or bentonite-based with enhanced thermal conductivity (Saša Kovačević, et al., 2012).

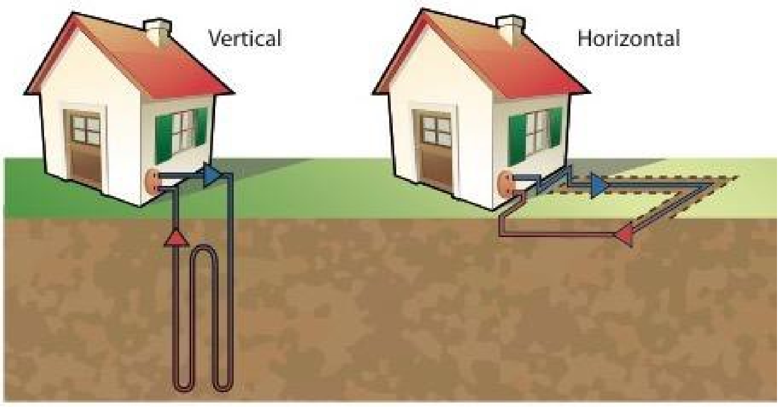


Figure 5 - Typologies of Closed loop system with vertical (left) or horizontal (right) probes.

• Open Loop System: these systems extract water directly from an aquifer or a pond and exchange thermal energy with a building using a heat exchanger and a Groundwater Heat Pump (GWHP). Water is extracted from a well, goes through the heat exchanger, and is then reinjected into the reinjection well (Figure 6). This process helps to avoid depletion, depressurization, and induced ground settlements.

When buildings are built above aquifers, the most cost-effective way to install heat pumps in a large building is typically through an open loop ground source system. Above a heating or cooling capacity of 100 kW, closed loop solutions require a significant number of boreholes and are progressively uneconomical to develop (Herbert, et al., 2013).

To minimize short-circuiting between wells, which occurs when some of the reintroduced water with a higher temperature is withdrawn again, the extraction and reinjection wells must be placed at an appropriate distance depending on the hydrogeological setting of the area. Short-circuiting not only reduces system efficiency but can also cause an anomalous increase in underground temperature (Galgaro, et al., 2013; Perego, et al., 2022).

Figure 6 - Typologies of Open loop system exploiting groundwater (left) and surface water (right).

1.2 Uses of geothermal energy

Geothermal resources with medium to high temperatures are more effective for producing electricity. Commercial-scale energy generation requires a minimum resource temperature of 150-180°C (depending on technology), however small-scale applications can generate electricity at temperatures as low as 70°C if coupled with an Organic Rankine Cycle in Binary cycle plants (ThinkGeoEnergy, 2021).

Medium temperature geothermal resources are used for a variety of uses, including space heating and cooling, industrial activities, and agriculture. Combined Heat and Power can be used for heating, cooling, and electricity generation. Cascaded utilization maximizes geothermal resources by using the outlet stream from the first application, such as hot water collected after electricity generation, for lower-temperature applications like district heating (IRENA and IGA, 2023).

In low temperature geothermal systems, the geothermal fluid can be used directly as a heat source for bathing or district heating or coupled with a geothermal heat pump (GHP) which boost the heat content of low-temperature resources, meeting energy needs for varied applications including providing efficient space heating and cooling for buildings, greenhouses, aquaculture and many other applications in industrial process heat as shown in Figure 7 (Lund, and Toth, 2021).

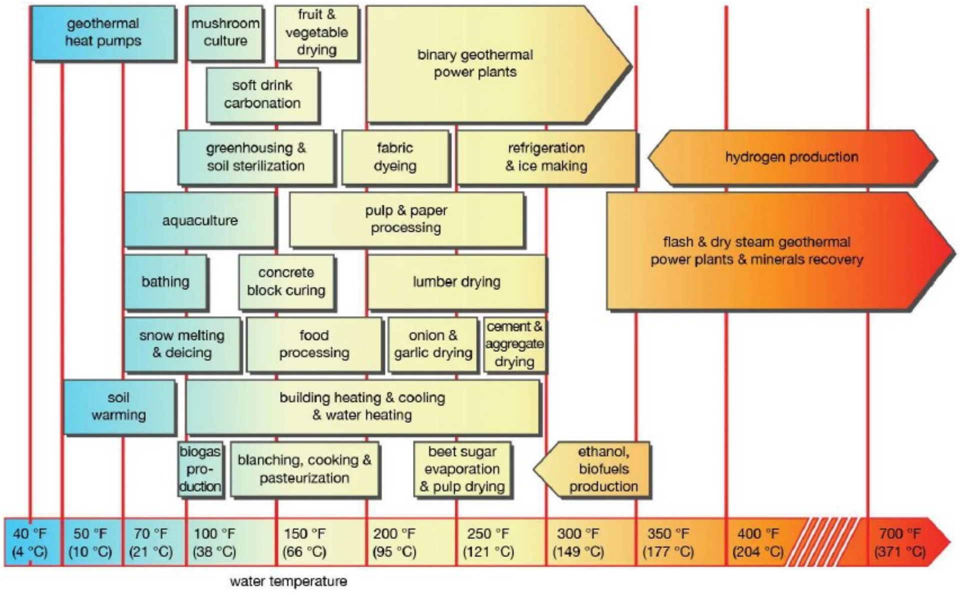


Figure 7 - Uses of geothermal energy (https://www.britannica.com/science/geothermal-energy)

1.3 Heat pump efficiency

The efficiency of a heat pump, commonly referred to as COP (Coefficient of Performance) for winter heating and EER (Energy Efficiency Ratio) for summer cooling, represents the ratio between the thermal power output (kW) and the electrical power input (kW), which is due to the work of the electric compressors on the refrigerant (Centi, et al., 2017).

For a vapor compression machine, the most used type, the refrigeration cycle can be divided into four main phases, as shown in Figure 8:

1 - Compression: The refrigerant in a vapor state is compressed and heats up, absorbing heat (high pressure).

2 - Condensation: The refrigerant, coming from the compressor, changes from a superheated vapor state to a liquid state, releasing heat to the environment.

3 - Expansion: As it passes through the expansion valve, the refrigerant, in liquid state, partially turns into vapor, cooling down.

3 - Evaporation: The refrigerant absorbs heat from the environment and completely evaporates (low pressure).

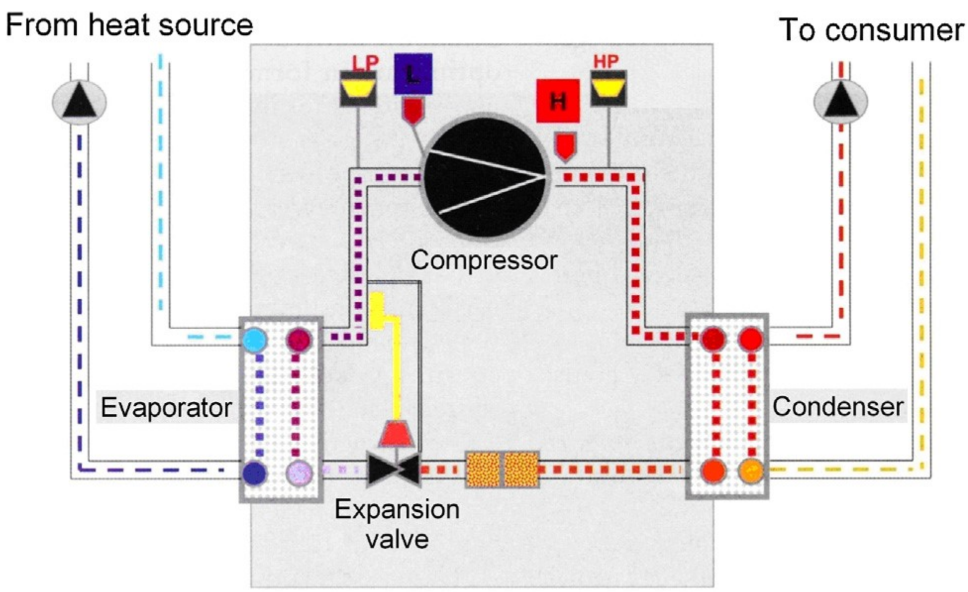


Figure 8 – Principle diagram of a heat pump (Source: https://doi.org/10.1016/j.enbuild.2013.11.068)

In an ideal cycle (Carnot cycle), efficiency would be influenced exclusively by the temperatures of the heat sources.

The formula for the Carnot efficiency of a heat pump in heating mode is:

$$COP = \frac{Q_H}{Le} = \frac{Tu}{Tu - Ts}$$

And in colling mode:

$$EER = \frac{Q_H}{Le} = \frac{Ts}{Tu - Ts}$$

Where:

Q_H refers to the thermal energy supplied to the conditioned environment. In the case of a heat pump in heating mode, Q_H is the amount of heat transferred from the heat source to the inside of the building, Tu and Ts are the absolute temperatures of hot (condensation) and cold (evaporation) sources, respectively.

In both circumstances, as temperature differences in the heat exchange process increase, so does the amount of compression effort required by the refrigerant. Furthermore, the power generated by the compressor is proportional to the mass of refrigerant being compressed and the enthalpy difference between the heat exchange sources. When the evaporation temperature drops, this reduces the refrigerant's vapor density, resulting in a lower power output.

In real cycles, such as those used in building HVAC (heating, ventilation, and air conditioning) applications, the efficiency of the various components results in energy losses during the many thermodynamic transformations that the refrigerant goes through.

Apart from the climatic conditions of the individual area (sink temperature), there are various other elements that influence heat pump efficiency. These include groundwater temperature and level, compressor type, refrigerant used, compression ratio, system component parameters as well as control strategy (Centi, et al., 2017; Halilovic, et al., 2022)

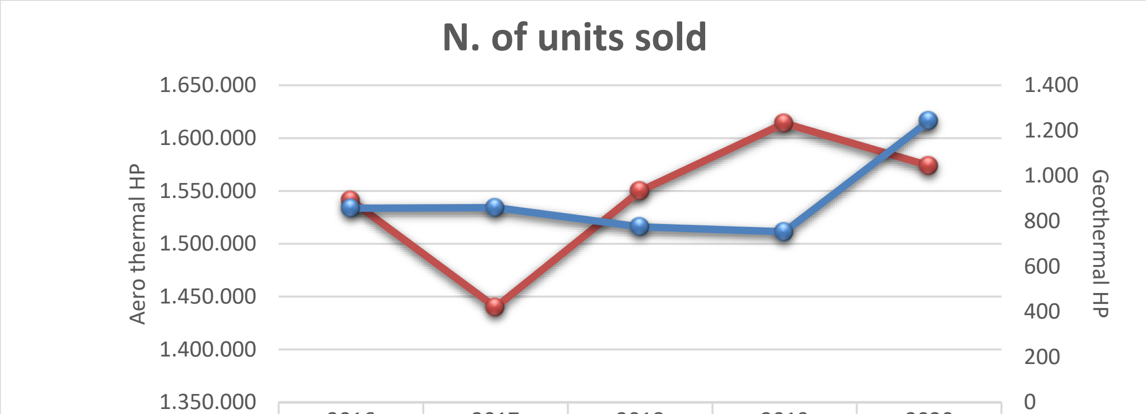
Chapter 2 - Shallow low temperature geothermal system in Italy

2.1 Diffusion of shallow low temperature geothermal system

Geothermal systems constitute some of the most efficient technologies currently available for producing thermal and cooling energy. Despite significant potential, market development faces significant challenges and limitations.

To better understand the diffusion of shallow low-temperature geothermal systems in Italy, it's essential to consider both the ground source heat pump (GSHP) market and the growth of geothermal heat produced for indoor climatization. This is because the lack of a national census for geothermal systems with heat pumps significantly limits the available data. Only a few local and regional authorities, such as the Lombardy Region, maintain a register of these installations. Furthermore, the absence of a unified regulatory framework results in highly fragmented dataset that is difficult to compare, as it often pertains to different contexts and types of systems. In some instances, the data refer to GWHPs in general, while in others, they only cover closed-loop systems.

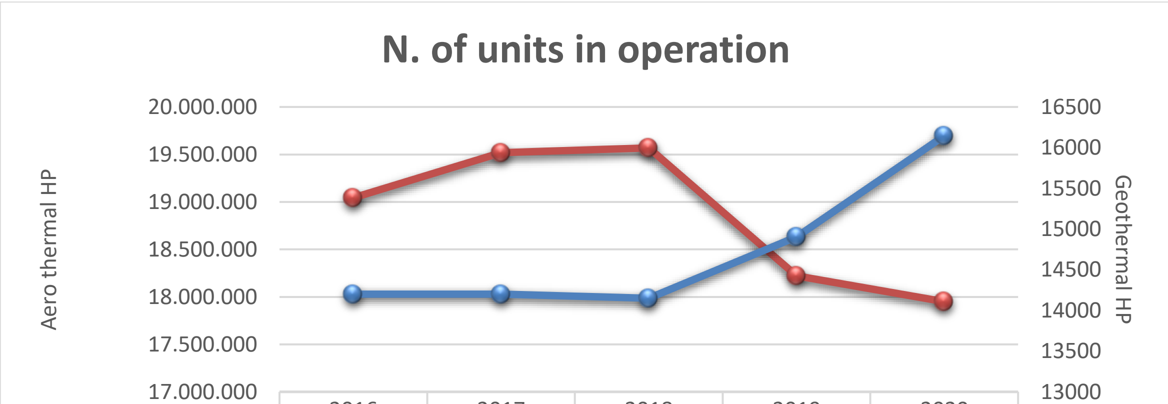
According to Eurobserv'ER heat pump publications (EurObserv'ER, 2018 ; 2019), the sales of geothermal heat pumps, that include both closed-loop and open-loop for residential sector has growth in Italy by 65% from 2019 to 2020 probably influenced by the energetic crisis in the Covid period (Chart 1).



	2016	2017	2018	2019	2020
Aero thermal HP	1.541.200	1.440.000	1.550.000	1.614.016	1.574.000
Geothermal HP	857	860	775	753	1.242

Chart 1 – Number of aero- and geothermal- heat pump units sold in Italy from 2016 to 2020 (EurObser'ER, 2021)

In Italy, the latest data (EurObserv'ER, 2021) reports a total of 16.145 geothermal heat pumps (HP) in operation, accounting for just 0,1% of all installed heat pumps (Chart 2).



	2016	2017	2018	2019	2020
Aero thermal HP	19.045.000	19.520.000	19.569.000	18.222.141	17.949.738
Geothermal HP	14200	14.200	14.150	14.903	16.145

Chart 2 - Number of aero- and geothermal- heat pump units in operation in Italy from 2016 to 2020 (EurObser'ER, 2021)

However, by analyzing data from the official national renewable energy report (Table 1) (GSE, 2023), it becomes evident that geothermal heat pumps contribute only a small portion to indoor climatization. In 2021, they accounted for just 3,3% (82 ktep) of the total heat produced by heat pumps (2.485 ktep) and 1,1% of the total final heat consumption as reported in Chart 3. The increase in energy production from GHP increased by 1% from 2019 to 2022, double compared to production from air sources heat pump.

Table 1 - Ambient heating from Heat Pump in Italy (GSE, 2023)

	2016	2017	2018	2019	2020	2021	Variazione % 2021/2020
Apparecchi installati a fine anno (milioni di pezzi)	19,1	19,5	19,6	19,2	19,4	20,3	4,31%
Potenza termica installata (GW)	124,7	126,4	123,8	119,4	118,1	120,3	1,88%
Energia rinnovabile da pompe di calore (*Eres*) (TJ)	**109.219**	**110.949**	**108.684**	**104.595**	**103.627**	**104.059**	**0,42%**
Energia rinnovabile da pompe di calore (*Eres*) (ktep)	**2.609**	**2.650**	**2.596**	**2.498**	**2.475**	**2.485**	**0,42%**
– di cui aerotermiche (ktep)	*2.523*	*2.563*	*2.507*	*2.408*	*2.385*	*2.394*	*0,39%*
– di cui idrotermiche (ktep)	*9*	*9*	*9*	*9*	*9*	*9*	*1,00%*
– di cui geotermiche (ktep)	*77*	*78*	*80*	*81*	*81*	*82*	*1,00%*
Calore utile prodotto (*Qusable*) (ktep)	4.211	4.278	4.190	4.031	3.993	4.010	**0,41%**
Seasonal Performance Factor (SPF) medio generale	2,6	2,6	2,6	2,6	2,6	2,6	0,02%
Consumo energetico delle pompe di calore (ktep)	1.602	1.628	1.594	1.533	1.518	1.524	0,39%

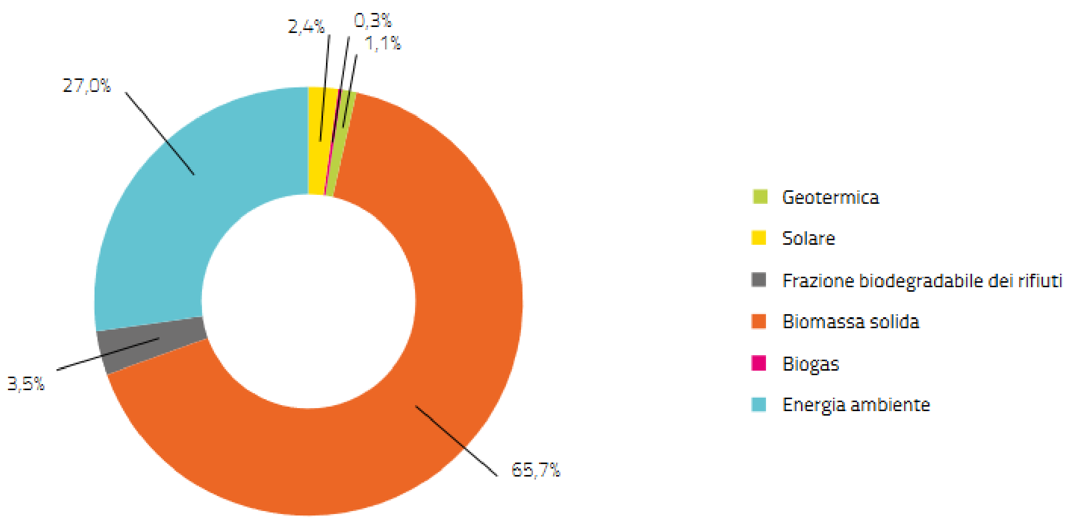


Chart 3 - Total final heat consumption in 2021 (GSE, 2023)

2.2 Legislation

Geothermal energy has been identified as a key resource for Italy, with the potential to greatly speed up the country's energy transition. Despite some progress, there are still gaps in legislation that need to be addressed.

The legislation concerning low temperature geothermal energy descended from the regulations on water wells, and in general on the exploitation of water resources.

The starting point comes from the Legislative Decree 11 February 2010, n. 22, containing Reorganization of research regulations e cultivation of geothermal resources, in compliance of article 27, paragraph 28, of law 23 July 2009, n. 99, where we can identify the definition of geothermal system as reported in art. 2:

a) high enthalpy geothermal resources are those characterized by a temperature of the fluid obtained above 150 °C;

b) medium enthalpy geothermal resources are those characterized by a temperature of the fluid obtained between 90 °C and 150 °C;

c) low enthalpy geothermal resources are those characterized by a temperature of the fluid found below 90 °C.

The art. 10 of the Decree 11 February 2010, n. 22 also identify, the small-scale local uses of geothermal heat, for open-loop and closed-loop system, in those for which the following conditions are jointly satisfied:

a) allow the construction of plants with a thermal power of less than 2 MW, obtainable from the geothermal fluid at the conventional wastewater temperature of 15°C;

b) obtained by drilling wells up to 400 meters deep for research, extraction and use of geothermal fluids or hot waters, including those flowing from sources for a total thermal power not exceeding 2 MW, also for possible production of electricity with zero-emission binary cycle systems.

c) Closed-loop (point 2 of art.10): Small local uses of geothermal heat are also those carried out through the installation of geothermal probes which exchange heat with the subsoil without the withdrawal and reintroduction into the subsoil of hot water or geothermal fluids;

and identify the Regions as the competent authorities for administrative functions, including supervisory functions, regarding small local uses of geothermal heat.

Furthermore, the Decree establishes that:

a) the small-scale local uses in open-loop system are granted by the region with territorial jurisdiction, in accordance with the procedures set out in the Consolidated Law on Water and Electrical Installations, as established by Royal Decree of December 11, 1933, No. 1775.

b) plants with a power of less than 1 MW obtainable from geothermal fluid at a conventional wastewater temperature of 15°C geothermal and uses through geothermal probes are excluded from the regional procedures for verifying environmental suitability.

For the open-loop system we also need to refer to the withdrawal well legislation. The withdrawal and use of public waters are regulated by laws of the State (Royal Decree n.1775 of 11/12/1933 and subsequent amendments) and in Marche Region by the Regional Law n. 5 of 09/06/2006 “Discipline of public water diversions and occupations of state water property” that concern:

- issuing concessions for the diversion of public surface water;
- issuing research authorizations and concessions for the use of groundwater;
- issuing of annual drawing licenses;

In addition to:

- Control, supervision and verification of water uses;
- Management of the integrated information system on water resources and related Water Utilities Registry;
- Authorization procedures for the recognition of use of existing utilities (wells);
- and discharging law.

Regarding the reinjection well, particularly the reinjection into the subsoil, attention must be paid to the Legislative Decree 3 April 2006, n. 152 “Environmental regulations”, especially on those Italian Regions without a specific regulation for open-loop geothermal system. The art. 104 “Discharges into the subsoil and groundwater” specifies that discharge into groundwater and the subsoil is prohibited but, in some cases, the competent authority may, after a preliminary investigation, authorize the discharge into the *same aquifer* of water used for geothermal purposes, including those from thermal exchange systems.

Moreover, while referring to the Legislative Decree 152/2006, also the water quality to be reinjected must be in compliancy with the limits of Table 2 of Annex 5 Title V of Part IV for those Regions without specific regulations, even if in an open-loop system there is only a thermal heat exchange between the water and heat pump, without any change in the chemical composition.

These weaknesses in national legislation have prompted the various Provinces and Basin Authorities to pursue diverse interpretations of the law and, in just a few cases, to develop their own rules.

For example, Lombardy Region with their own geothermal legislation (DGR 6203/2017) prescribes the technical elements necessary for the competent Authority to carry out the preparatory investigation for the authorization to reintroduce water into the aquifer, pursuant to art. 104 paragraph 2 of the legislative decree 152/2006, including some other prescriptions such as:

- the geological unit into which the water is re-injected is the same one from which the water is extracted; furthermore, this unit is confined to the first aquifer;

- it must be ensured that the chemical composition of the reinjected water remains consistent with that of the extracted water, meaning that the reinjected water must not have worse qualitative characteristics than the extracted water. Exceptions to this rule, applied for all systems indifferently of the amount of extracted water, include cases where water is extracted from areas of widespread contamination or where plumes are present and by the regional Plan for diffuse pollution. Another exception is the reinjection of water extracted for geothermal purposes from sites undergoing remediation procedures;

- the reintroduction temperature of the water used in the heat pump system: the temperature of the reinjected water must not exceed a maximum increase of 5°C above the annual average temperature T of the aquifer, as determined during the design phase. In any case, the temperature of the reinjected water should not generally exceed 21°C.

All these limitations and gaps in the Italian Legislation have a consequence on the development of open-loop circuit.

Regarding the closed-loop system there is a clear endorsement for the development of it in the recent Decree 30 September 2022 "*Regulations for the installation of heat production systems using geothermal resources for heating and cooling buildings, and simplification measures for the installation of these systems.*". The decree applies to small-scale local uses of geothermal heat as outlined in Article 10, paragraph 2 of Legislative Decree No. 22 of 2010, which are achieved by installing systems with a capacity of less than 2 MW that only exchange thermal energy with the ground, using a carrier fluid circulating in specific systems in contact with the ground, without extracting or injecting fluids into the subsoil. It additionally specifies the regulations for the installation and identifies circumstances where the installation of such systems, up to a thermal capacity of 100 kW, falls under the category of free construction or is subject to the simplified authorization procedure.

Chapter 3 – YKK Mediterraneo SPA

The chapter describes the activities carried out within an industrial facility, named YKK Mediterraneo SPA, highlighting the various production processes and their energy consumption, which require different forms of energy, including electricity and natural gas. The chapter also examines the continuous improvements of the facility's energy efficiency to reduce overall consumption and reduce greenhouse gas emissions according to European Fit 55.

3.1 YKK Mediterraneo SPA - Site description

The YKK Mediterraneo SPA is part of a Japanese multinational group YKK which operates on a large scale worldwide. In the case of the facility under consideration, various types of clothing accessories are manufactured, including zipper sliders, buttons, rivets and other metal accessories.

The plant is located in the industrial area “Campolungo” of Ascoli Piceno in the Marche Region, Italy, and cover an area of about 25.000 m^2 (Figure 9). The production activities mainly take place over 3 working shifts and mainly 5 days a week.

The production area includes the activities strictly related to the general intended use of the company, in practice the activities that represent the company's "core business", and is identified in 9 functional areas:

- Galvanic department
- Die casting department

- Stamping department
- Painting department
- Assembly department 1;
- Assembly department 2;
- Button Assembly Department;
- Flow Department;
- Packaging Department.

3.2 Geographic location

The site is located at an elevation of approximately 61,5 meters above sea level on a slightly sloping towards the south-southeast terrain, near the Tronto River, which flows about 100 meters south of the YKK Mediterraneo property boundary.

The geographical localization, in Monte Mario coordinates (EPSG:3003), are Nord: 4755014.90 m, Est: 1883676.39 m.

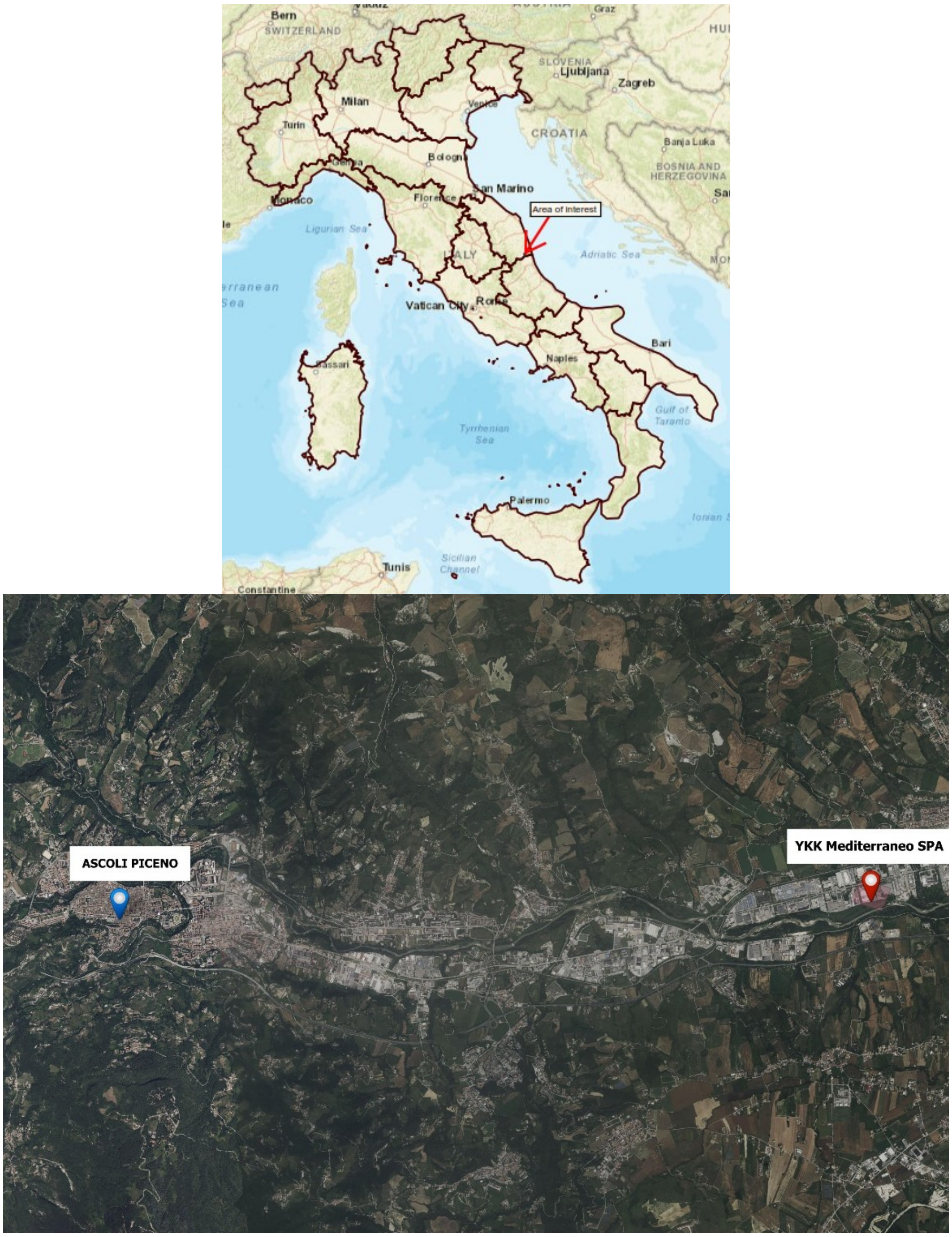


Figure 9 - Geographical location. YKK Mediterraneo S.P.A.

3.3 Energy requirements

YKK Mediterraneo SPA purchases exclusively electricity and natural gas from the public network. From a thermal point of view, it is an energy-intensive industry and was also electric energy-intensive until 2023.

Primary energy is utilized for industrial processes, as well as for auxiliary services such as compressed air systems, thermal cooling processes, and wastewater treatment and general services, including office operations, canteen, lighting, and ambient heating and cooling.

The natural gas purchased, in addition to being used directly for industrial purposes and ambient heating, is also used to power the trigeneration plant which came into operation at the end of 2018 and was fully operational in January 2019.

The electrical energy consumed by the plant comes from three different sources: the power-grid, the on-site 1,5 MWe trigeneration plant and 1,2 MW photovoltaic plant installed on the rooftop.

In 2023 the factory has purchased from the grid 1.421.415 kWh and 22.479 MWh of natural gas. Natural gas accounts for 94% of the energy consumption due to the trigenerator, while electricity makes up the remaining 6% as reported in Chart 4.

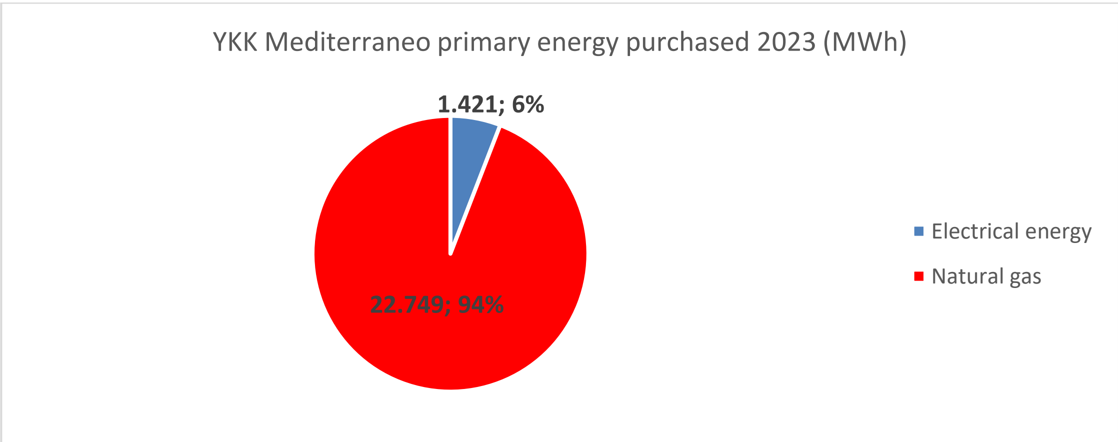


Chart 4 - Purchased primary energy (MWh)

In terms of energy demand for the entire industrial plant, meaning not considering the primary energy used to power the trigenerator while accounting for the electricity produced both by it and the photovoltaic plant and self-consumed by the facility, 34% of primary energy is for thermal needs and 66% is for electrical needs from witch 45% comes from the cogeneration, 11% from photovoltaic and just 10% from the national grid and as shown in Chart 5.

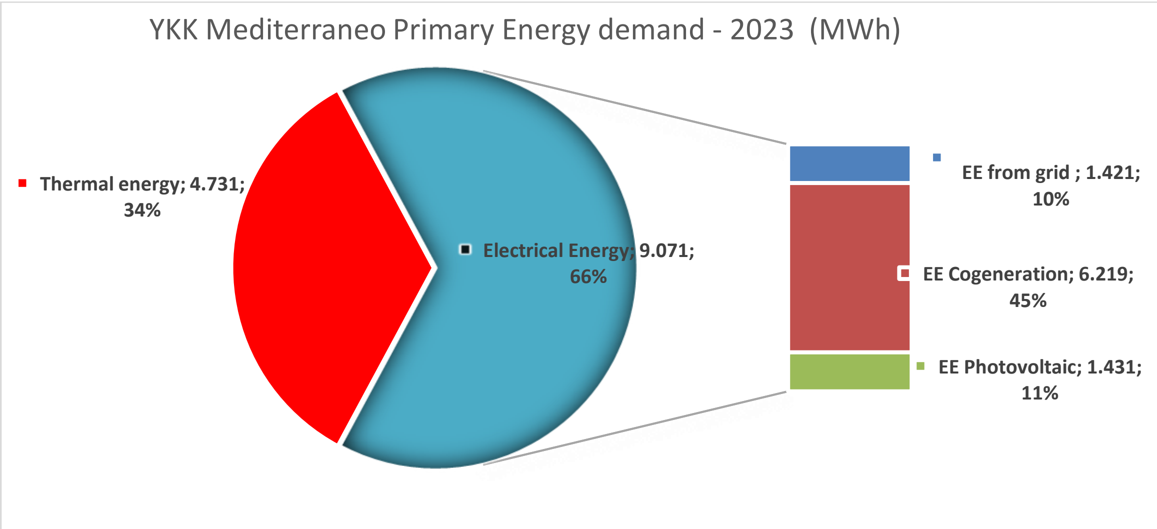


Chart 5 - Primary Energy demand - 2023 electrical demand

The thermal energy needs in turn can be divided based on use into i) ambient heating, ii) die casting, iii) galvanic, iv) canteen/hot water as reported in Chart 6.

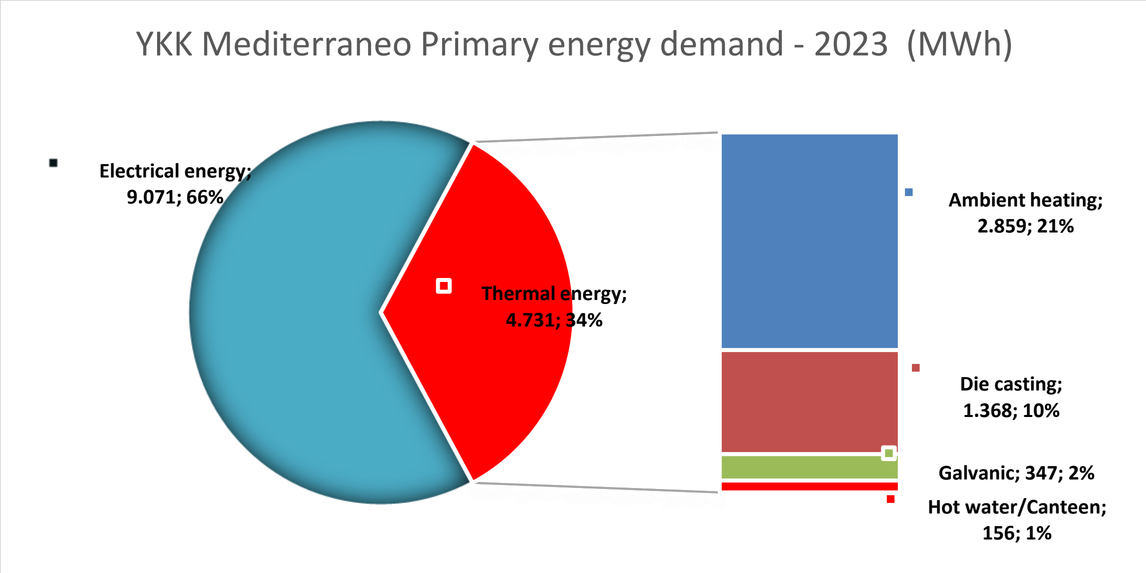


Chart 6 - Primary energy demand – 2023 thermal demand

As observed from Chart 4, the ambient heat is the most significant thermal energy user area, reason why the YKK Mediterraneo has chosen to electrify part of the thermal needs for ambient heating using a Geothermal open-loop system improving even more it's continuously improvement in energy efficiency. In specific, the geothermal energy system is used to replace the old gas heat generator of the Assembly department since other departments are heated by the cogeneration system and by recovery thermal system installed in Die-casting department as showed in Figure 10.

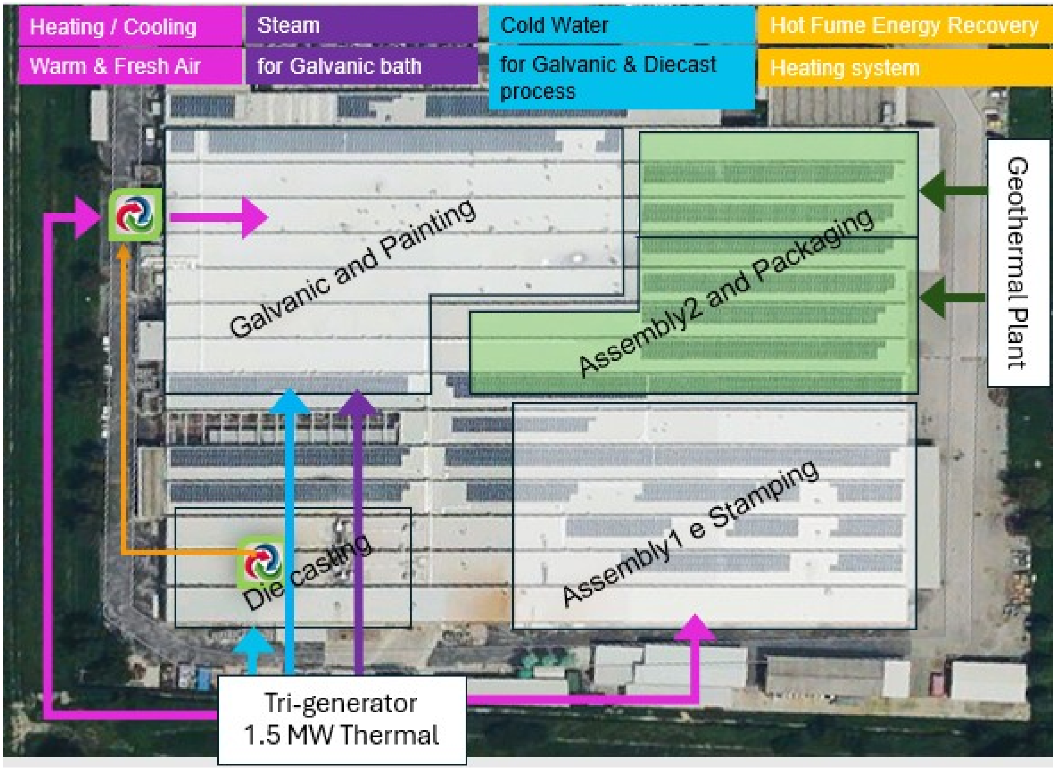


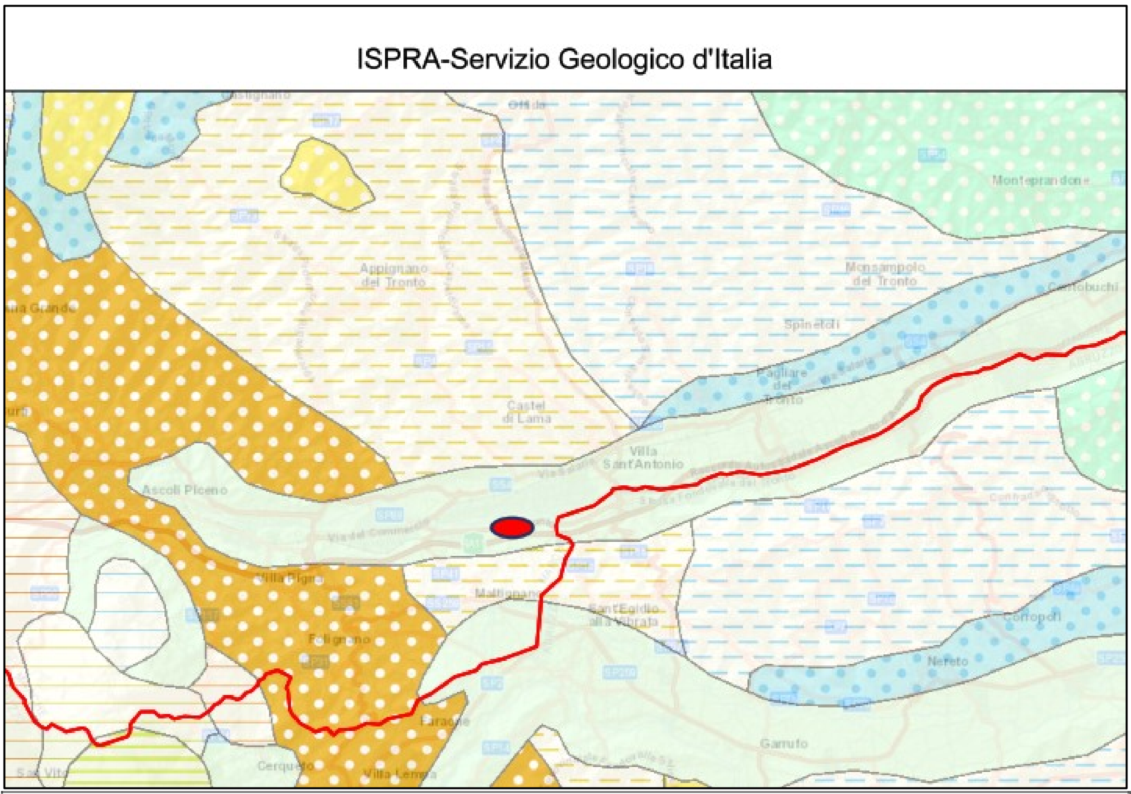
Figure 10 – Flow distribution of thermal energy produced by different sources

Chapter 4 – Open-loop geothermal system: Preliminary evaluation

4.1 Study area and geological background

The YKK Mediterraneo S.P.A. plant, and therefore the area within its property designated for the construction of the exploratory wells, is located on a fourth-order alluvial plain formed by the erosional and sedimentary activities of the Tronto River which flow about 280 meters from the area designated for the wells.

Lithologies of the area pertain to the geological history of the Umbria-Marche Apennines, characterized by sedimentation of pelagic carbonates (limestones and marly limestones) since the Jurassic and continuing until the Paleogene, as the result of extensional processes (Carmignani, et al., 2020). These latter were firstly induced by the opening of the Ligurian Ocean (Neo-Tethys domain) and, later, by both thermal subsidence and tectonic thinning of the paleo-margin (Cello, et al., 1995; Tavarnelli, 1997). From the Miocene, this succession of the African-Adriatic continental margin was involved in the structuring of the Apennine thrust system, which, in the study area, began at the Miocene-Pliocene transition (Calamita Fernando, 1994; Ricci Lucchi, 1986)) with continuous reorganization of the foreland areas dominated by turbiditic successions (Bigi, et al., 1999; Marcheggiani, et al., 1999). (Figure 11)



Legend:

- Sandstones and clays- sometimes with evaporitic rocks (Upper Miocene)
- Clays (Pleistocene)
- Clays and marls sometimes with olisthostromes (Pliocene)
- Limestones and marly limestones in pelagic facies (Palaeogene -Upper cretaceous)
- Colluvial, terraced alluvial, fluviolacustrine and fluvioglacial deposits (Pleistocene)
- Colluvial, alluvial, fluviolacustrine and young beach deposits (Holocene)
- Marls and calcareous marls of pelagic facies (Palaeogene)
- Marls sometimes with chert of pelagic facies (Middle-lower Miocene)
- Sand and conglomerates (Pleistocene)
- Travertines (Pleistocene and Holocene p.p.)

Figure 11 - Geological map of the area of interest (https://sgi2.isprambiente.it/viewersgi2/)

The surface water circulation in the area is regulated by the Tronto River, the main drainage channel in the region, which flows approximately 100 meters south of the property boundary and about 280 meters from the area designated for the exploratory wells. The industrial plant is located on the current fourth-order alluvial terrace of the Tronto River, which, together with a minor hydrographic network, regulates the surface water circulation in the area.

Due to its location, the site is influenced by direct rainfall and runoff from the Northern slopes, part of which is channeled into the industrial area's drainage system, while another part (where the topographic surface is not affected by urbanization) infiltrates the moderately permeable alluvial cover deposits. Regarding groundwater, it develops within the alluvial deposits, where an aquifer is located, fed by runoff from the slopes, infiltration on the alluvial plain, and the Tronto River.

4.2 Site activities

The methodological approach consisted first in drilling two wells to confirm the geological setting and hydrogeological conditions of the investigated site, as well as for conducting step-drawdown tests. After this first step, a third well was built to increase the quantity of water to be withdrawn and the thermal yield.

The three wells were finally completed in date 03/11/2022 (PW1, PW2) and 9/12/2022 (PW3), as shown in Figure 12, and were realized as follow:

- Drilling method: rotary drilling
- Depth of excavation: 12 m from the surface level
- Excavation diameter: 800 mm
- Type of cladding : non-toxic PVC, 400 mm

• Excavation/coating saturation: siliceous gravel 3-4 mm

• Cementation: from the ground level up to deep -1 m

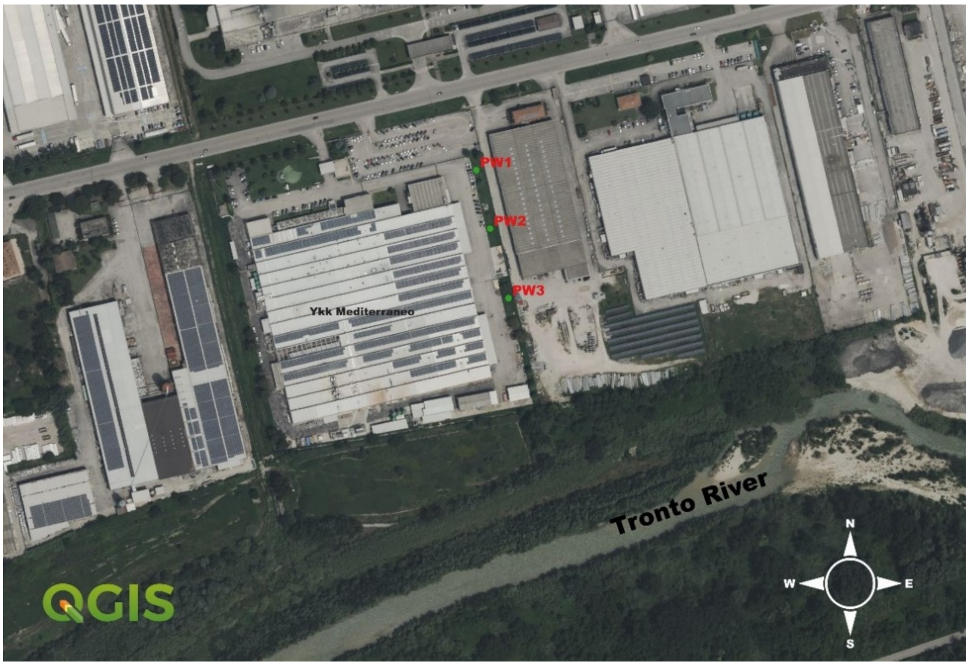


Figure 12 – Localization of the three drilling wells.

The wells' locations were determined based on the available surface area near the departments to be conditioned. The wells are in the eastern part of the industrial plant, with approximately 47 meters between PW1 and PW2, and 56 meters between PW2 and PW3.

The drilling of the wells permitted to reconstruct the stratigraphic characters of the area as follow:

a) the substrate composed of grey-blue clays (Argille Azzurre Formation) is covered by colluvial-alluvial deposits mainly consisting of silty-sands and sandy-silts, with heterometric and heteroclastic alluvial gravels in a silty-sandy matrix, generally characterized by an average thickness of about 7,8 to 8,3 meters from the ground level as reported in Table 2:

Table 2 - PW1, PW2 and PW3 stratigraph*ic and hydrogeological characters*

	Well 1 (PW1) and Well 2 (PW2)		
	Depth from ground level (m)	**Geological characteristics**	**Permeability K (cm/s)**
Layer 1	0,00 - 0,40	Paving and subgrade with arid material or topsoil	-
Layer 2	0,40 - 1,20	Lightly silty sands of hazelnut color, dry and moderately consistent with scattered gravel	Medium permeability: 10^{-4} - 10^{-5}
Layer 3	1,20 - 7,80	Heterometric and heteroclastic gravel, moderately compacted, with a silty-sandy matrix of hazelnut color in the upper part and gray in the lower part	Medium - High permeability: 10^{-3} - 10^{-4}
Layer 4	> 7,80	Grey-blue clay, stratified, compact and dry, altered in the upper part	No permeable (Aquiclude) K > 10^{-8}

	Well 3 (PW3)		
	Depth from ground level (m)	**Geological characteristics**	**Range Permeability K (cm/s)**
Layer 1	0,00 - 0,40	Topsoil	-
Layer 2	0,40 - 1,80	Lightly silty sands of hazelnut color, dry and moderately consistent with scattered gravel	Medium permeability: 10^{-4} - 10^{-5}
Layer 3	1,80 - 8,30	Heterometric and heteroclastic gravel, moderately compacted, with a silty-sandy matrix of hazelnut color in the upper part and gray in the lower part	Medium - High permeability: 10^{-3} - 10^{-4}
Layer 4	>8,30	Grey-blue clay, stratified, compact and dry, altered in the upper part	No permeable (Aquiclude) K > 10^{-8}

b) the presence of the aquifer at an average depth of 4,1 m (PW1) to 4,6 m (PW3) from the surface (i.e. from 4,6 to 5,10 m from the well cap). This depth is higher than those measured during a previous environmental characterization carried out in 2015, when the groundwater was located at generally lower depths (2,8 ÷ 4,6 m from the surface).

   This underlines that the water table can have seasonal fluctuations, and during the last piezometric survey the meteorological conditions were characterized by a long critical period of rainfall, as reported by the meteorological station of the Protezione Civile delle Marche located in Brecciarolo (AP), 3,5 km far from the YKK Mediterraneo site (Chart 7).

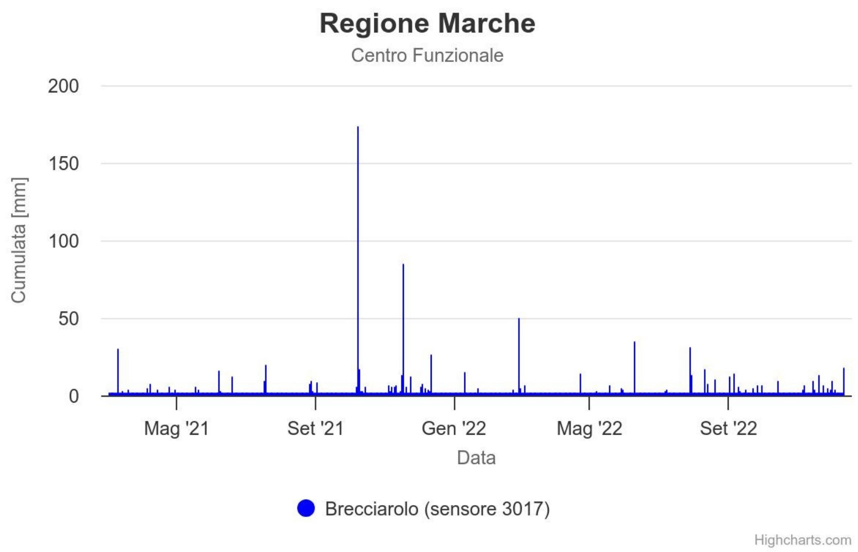


Chart 7 – Cumulated rainfall from Genuary-2021 to December 2022 – Sensor located area: Brecciarolo (AP) (Source: http://app.protezionecivile.marche.it)

c) the groundwater temperature was between 15 and 16,5°C.

During well activities, also physicochemical analyses were measured on the water extracted from the piezometers during the environmental study, which provided quality parameters that comply with those specified in Table 2, Attachment 5, Title IV, Part Four of Legislative Decree 152/2006.

The detailed stratigraphy obtained from the three wells are reported in Figure 13:

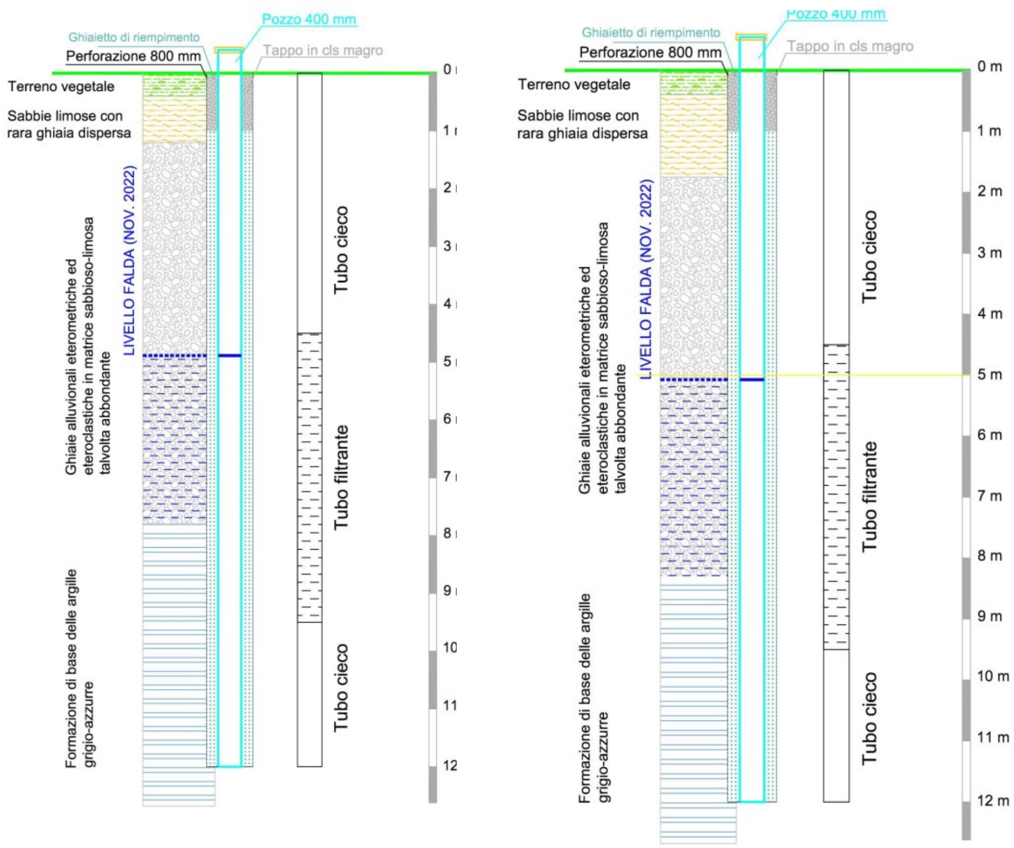


Figure 13- PW1 and PW2 stratigraphy (left) and PW3 stratigraphy (right)

4.3 Step-drawdown test

The step-drawdown test is performed to estimate aquifer parameters and well losses in a single well pumping test (Clark, 1977; Jacob, 1946; Kawecki, 1995). Step-drawdown tests typically involve the pumping of a well at a constant rate until a quasi-steady state (QSS) is observed in the drawdown response. The well is then pumped at a higher constant rate until a new quasi-steady state is achieved. The process is repeated for additional flow rates. Analysis involves plotting the QSS drawdowns against their corresponding abstraction rates and fitting a nonlinear empirical expression as the so-called Jacob method (Todman, et al., 2010).

For the flow rate tests, the well was equipped with a Pedrollo 6SR 44/6 three-phase submersible pump with a power of 9,2 kW and flow rate up to 6 l/sec, complete with a cable and a Pedrollo E1 TRI/2 control panel, including level control.

A polyethylene pipe Picenumplast code 21310 PN10 DN90 was installed on the pump, on which a gate valve (to regulate flow rates during the tests) and a flow meter consisting of a "Woltmann axial turbine meter OMEGA SDC UNI PN16 DN 80" were positioned.

Additionally, appropriate monitoring equipment for the water table level and water temperature was installed inside the wells, connected to a datalogger that allows remote data reading.

The investigation plan included the forecast of a step-drawdown test on each of the three wells, with the measurement of the water table drawdown as a result of different flow rates, after a predetermined period of time, set at 30 minutes.

Different steps with increasing flow rates were planned, with an interruption period following each step of equal duration (30 minutes) to allow the water to rise in the well and to measure the residual drawdown before performing the next step with a higher flow rate.

The first step flow rate was set at the minimum flow rate provided by the pump (1 l/s), then increased up to 5 l/s, in order to exceed the critical flow rate value.

The tests were programmed to determine the efficiency of the wells, meaning their correct construction and operation, and to obtain the well's critical flow rate, as well as some hydrodynamic parameters of the aquifer.

On 25/11/2022, the first step-drawdown test was performed on well PW2, located south of PW1. This well, as inferred from the hydrogeological study conducted, taps into the aquifer between 4,4-7,8 meters from the ground level.

Five steps flow rate (1 l/s, 2l/s, 3l/s, 4 l/s and 5 l/s) were set during the test as reported in Chart 8. From the data below it’s possible to observe that around 5 minutes are necessary to reach the same level as before the pumping start, and almost 20 minutes to reach the steady state.

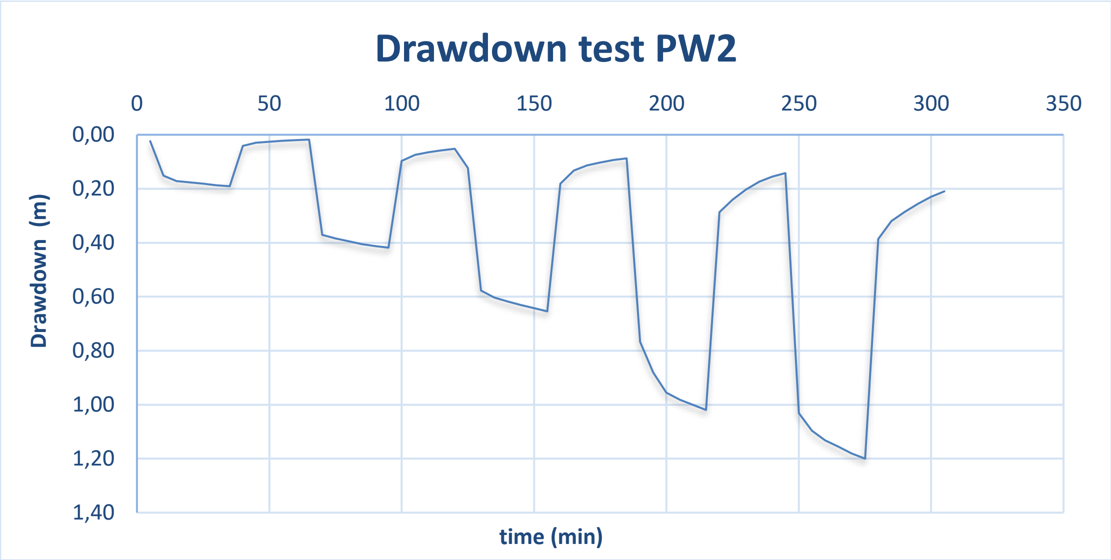


Chart 8 - Drawdown test during five steps pumping rate in PW2

In Chart 9 is reported the variation in the ground water level (ΔH) at increasing pumping flow rate, determining that the well's critical flow rate exceeds 0,005 m^3/s (5 l/s), as no significant drawdowns were recorded compared to the linear drawdown line proportional to the increase in flow rate.

The critical flow rate was obtained through graphical interpolation of the drawdown/flow rate curve. This value corresponds to the intersection point between the line representing the linear drawdown as a function of the flow rate increase and the line representing the quadratic drawdown.

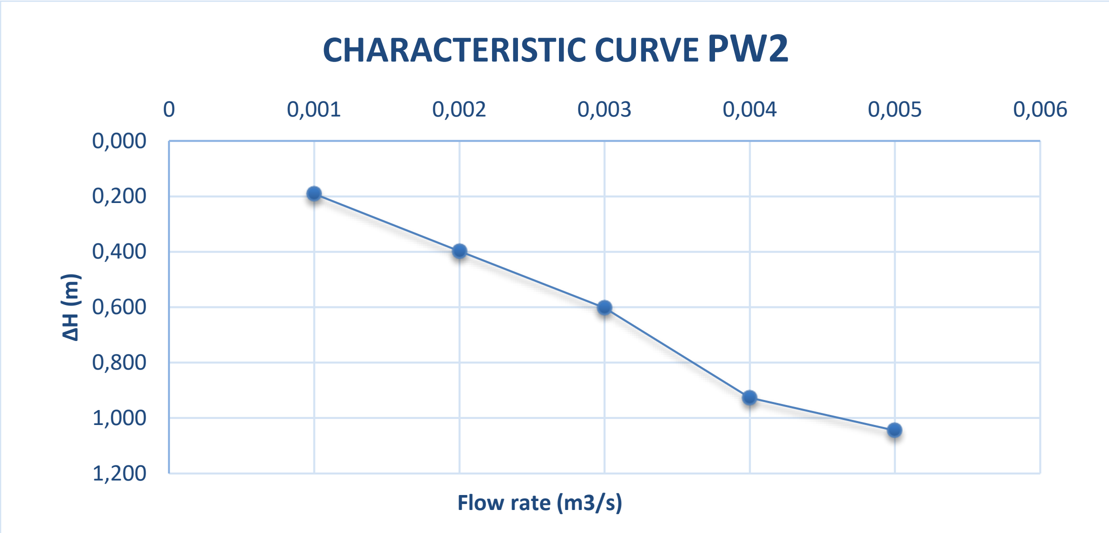


Chart 9 - Changes on groundwater level during five steps pumping rate in PW2

On 13/12/2022, the first step-drawdown test was performed on well PW3, located further south of PW1 and PW2. This well taps into the aquifer between 4,6-8,3 meters from the ground level.

Three steps flow rate were set during the test (1 l/s, 2,0 l/s and 3,0 l/s) as reported in Chart 10.

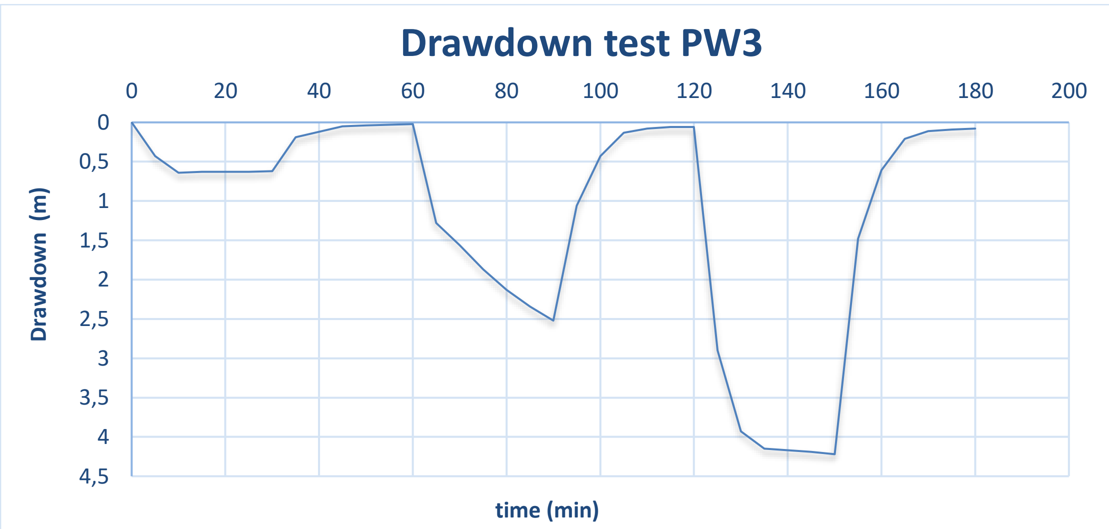


Chart 10 - Drawdown test during five steps pumping rate in PW3

The test conducted on well PW3 determined the well's critical flow rate to be approximately 0,0016 m^3/s, or 1,6 l/s (Chart 11).

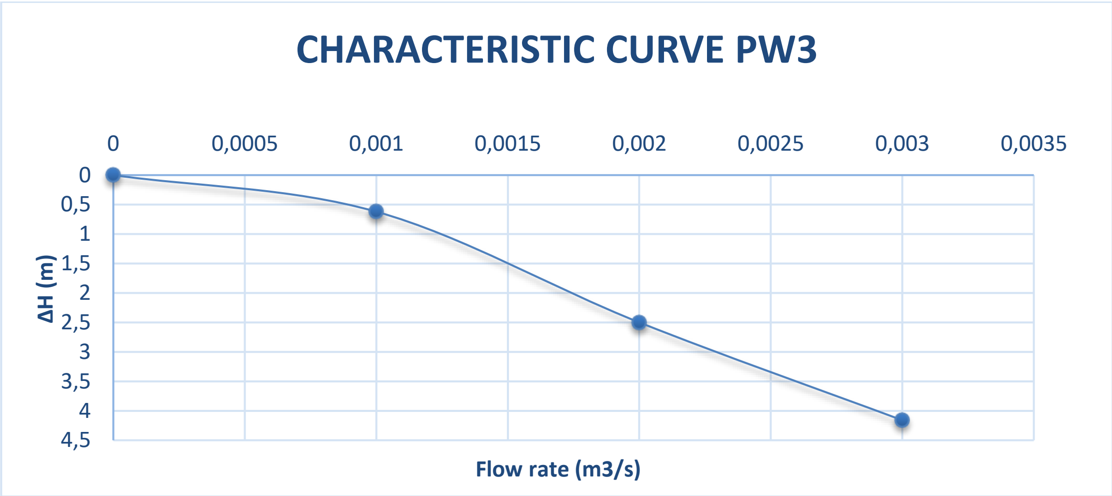


Chart 11 - Changes on groundwater level during three steps pumping rate in PW3

On 16/12/2022, the first step-drawdown test was performed on well PW1, located northern than the others. This well taps into the aquifer between 4,4-7,8 meters from the ground level.

Four steps flow rate were set during (1 l/s, 1,6 l/s, 3,2 l/s and 4,7 l/s). Chart 12 shows the drawdown measured during the changing in pumping flow rate.

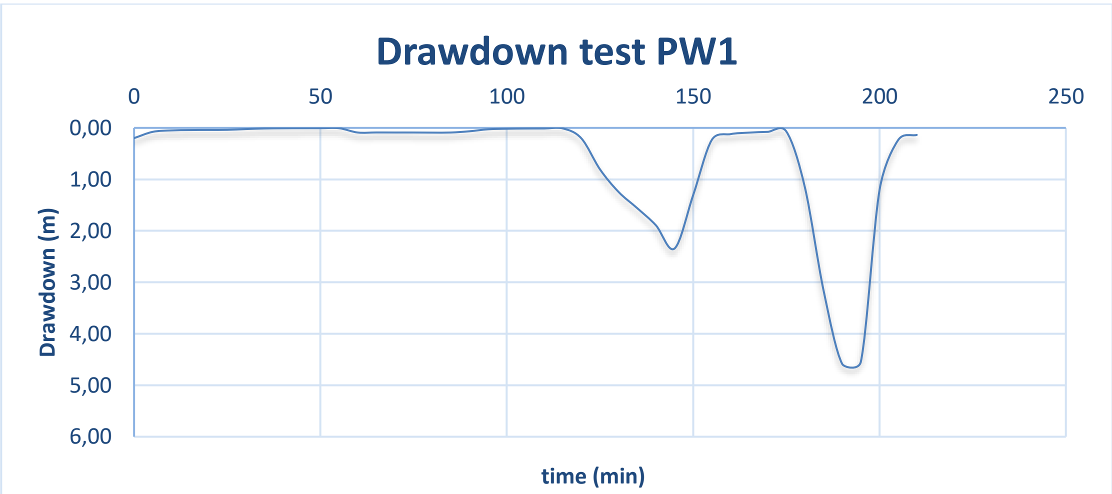


Chart 12 - Drawdown test during four steps pumping rate in PW1

The test carried out on well PW1 allowed for the determination of the well's critical flow rate which is approximately 0,002 m/s (2,0 l/s) (Chart 13).

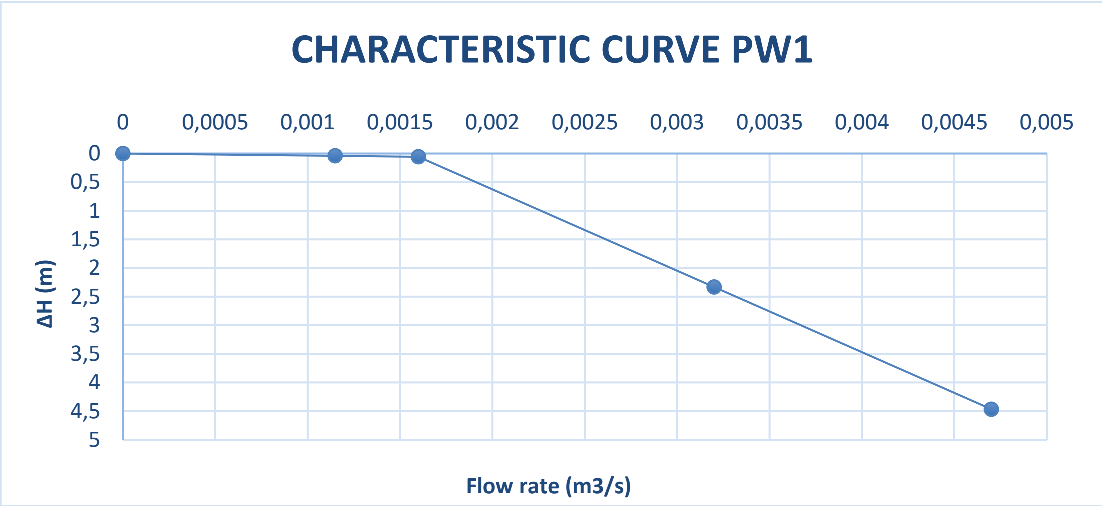


Chart 13 - Changes on groundwater level during four steps pumping rate in PW1

Chapter 5 – System design

Through the data obtained from the geological surveys and step drawdown test and based on an average 350 kW maximum of thermal request for heating and cooling the Assembly-2 department, the geothermal system has been defined.

5.2 Geothermal heat pump

A ground-water heat pump TEON, model TINA 350, was chosen according to the thermal needs, coupled with a safety dry-cooler. From its technical characteristics, as shown in Table 3, the amount of water request during winter, at 15°C, is around 12,2 l/s with an outlet water temperature to plant set at 60°C. In cooling mode, around 13,2 l/s are needed, at 15°C, to obtain 276,5 kW.

The energy performance in heating mode has a range from 2,7 to 6,13 depending on water source characteristics and in cooling mode about 4,9.

Table 3 - Geothermal heat pump Teon TINA 350 technical data

PERFORMANCE	**U.M.**		**Tina T350**	
HEATING (T models)				
Thermal Power	[kW]	345,7	334,7	286,6
Electric Power	[kW]	56,4	79,6	106,2
COP	[-]	6,13	4,21	2,7
Inlet water temperature from source	[°C]	10	15	15
Outlet water temperature to source	[°C]	7	10	10
Inlet water temperature from plant	[°C]	30	50	70
Outlet water temperature to plant	[°C]	35	60	80
Water flow on the source side	[l/s]	23,04	12,19	8,62
Water flow on the plant side	[l/s]	16,52	8	6,85
Refrigerant charge (R600a)	[kg]		24	

COOLING (RT models)		
Refrigeration Power	[kW]	276,4
Electric Power	[kW]	56,4
EER	[-]	4,9
Outlet water temperature to source	[°C]	20
Inlet water temperature from source	[°C]	15
Outlet water temperature to plant	[°C]	7
Inlet water temperature from plant	[°C]	12
Water flow on the source side	[l/s]	13,2
Water flow on the plant side	[l/s]	15,9
Refrigerant charge (R600a)	[kg]	24

The GWHP has a continuous monitoring of electrical energy consumed, water flow rate and water temperature to and from plant.

5.1 Water demand and injection well

To satisfy the 350 kW thermal power supply, roughly 12 l/s of withdrawal water at a temperature of 15°C is required, and hence all three wells must be used as extraction wells..

Assuming an operating time of the heating system during winter of approximately 10 hours/day and from 90 to 100 working days, and during the summer for about 70/80 working days, the annual water demand is estimated to be approximately 70.000 cubic meters.

The withdrawal water is completely reinjected into the aquifer through three injection wells (IW) located downstream of the extraction wells, and identified as IW1, IW2 and IW2 in Figure 14, to minimize environmental impact and ensures the sustainable and efficient management of groundwater resources. The direction of the groundwater flow, calculated from the piezometric level obtained during the step-drawdown test is represented by the orange arrow in Figure 14. The three injection wells were realized as follow:

- Drilling method: rotary drilling
- Depth of excavation: 11 m from the surface level
- Excavation diameter: 1000 mm
- Concrete ring diameter: 800 mm (perforated throughout the thickness of the gravel deposit)
- Excavation/coating saturation: fine siliceous gravel

The injection wells are spaced 25 meters apart and IW3 is located approximately 30 meters from the nearest production well (PW3). Injection well IW1 is situated at approximately 100 meters from the Tronto River.

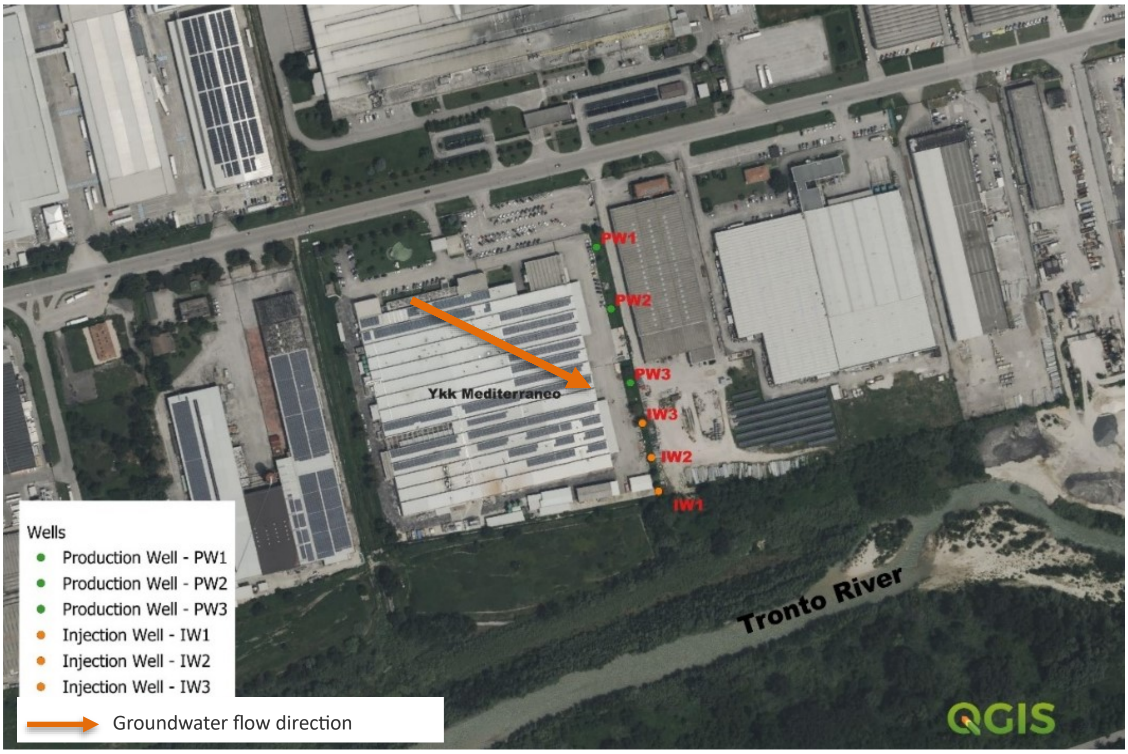


Figure 14 – Geographical localization of three production wells and three injection wells

Both production and injection wells are continuously monitored in temperature and water level by a sensor STS model DL.WMS.BT.4G.LTC.

Figures 15 and 16 illustrate the layout of the entire system in heating and cooling mode, respectively. The electropumps inside the wells are connected to an inverter which can regulate the water flow according to the thermal demand. One of the two heat pumps reported in the layout, the one connected to the dry cooler, is part of the second phase project and is necessary to cover the entire thermal need for Assembly2 and Packaging department.

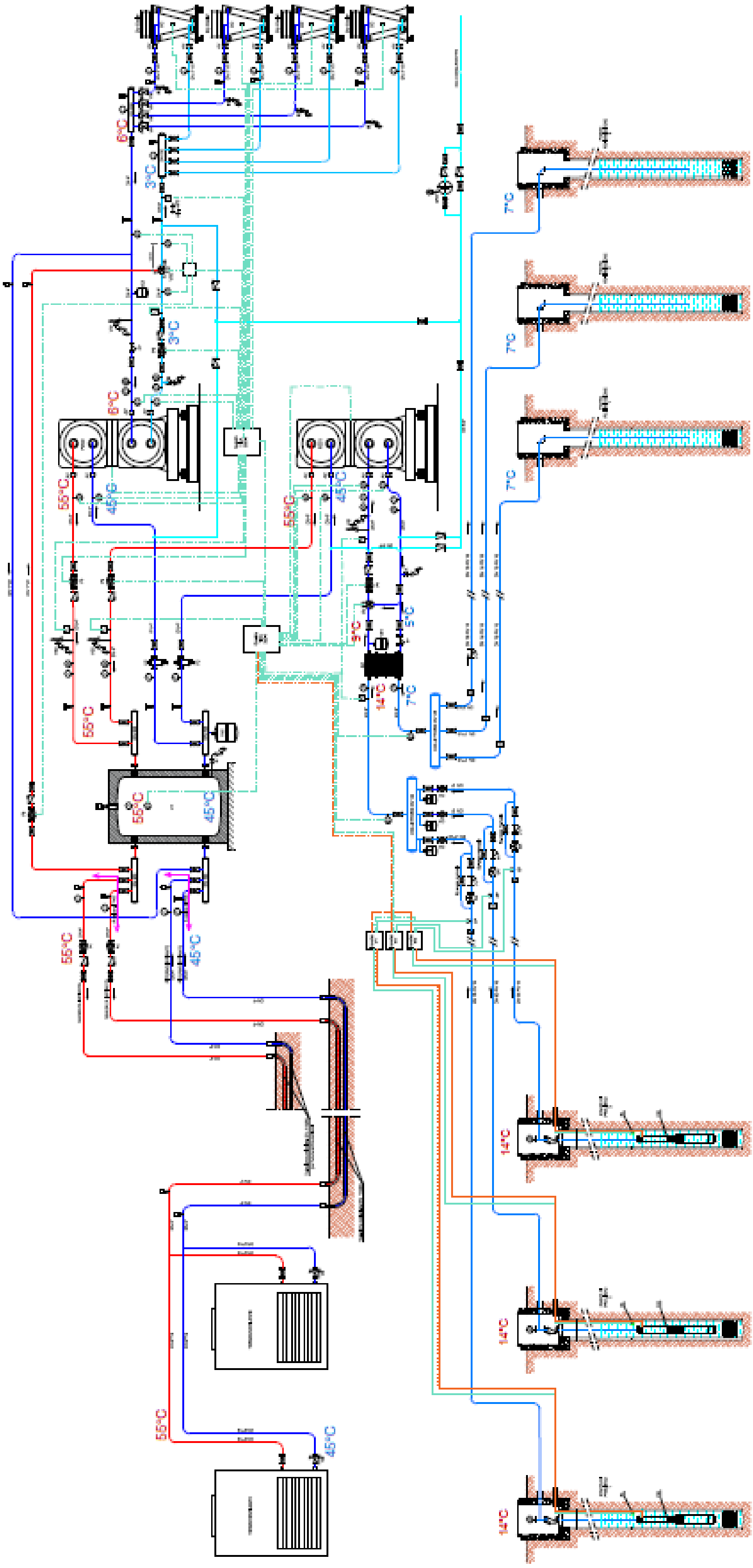


Figure 15 – Geothermal system layout in heating mode

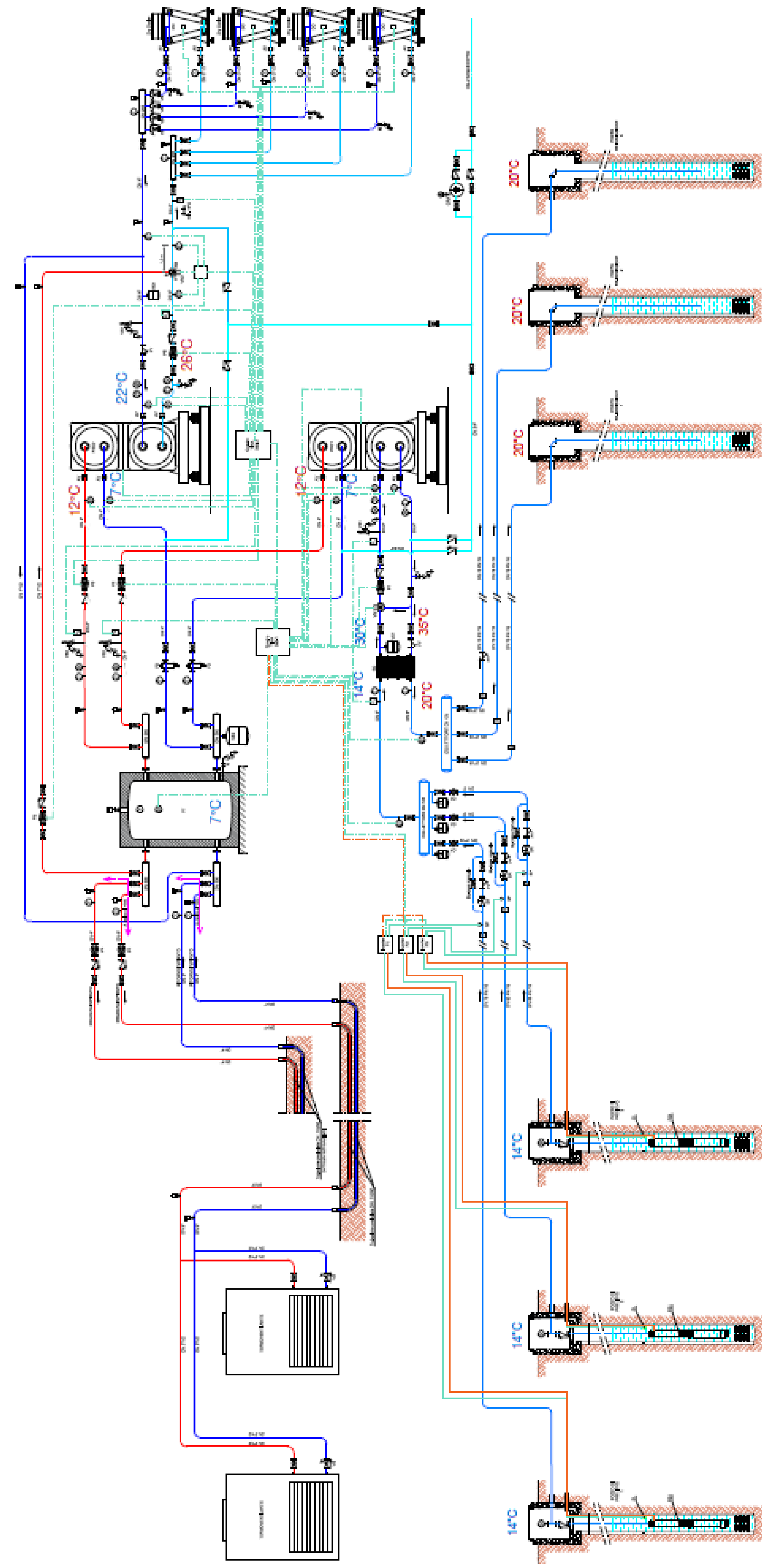


Figure 16 Geothermal system layout in cooling mode

Chapter 6 – Analysis from monitoring data and Project schedule evaluation

In this chapter the data collected from the sensors installed inside the wells and in the heat pump will be analysed starting from 21 February 2024 (monitoring starting program) until the end of the heating period related to the Climatic Zone D (e.g. 15 April 2024).

6.1 Project schedule evaluation

Table 4 shows the project time spent in the key activities and authorization process, from preliminary evaluation to the start of the heating period, with each rectangle representing one week. It is organized into:

- Preliminary activities: from the first project plan meeting to the preliminary evaluation;

- Authorization process: include all authorization procedures and some activities necessary to the authorization process itself like step drawdown test, physical and chemical water analyses;

- Operative Phase 1: from drilling of reinjection wells to the end of heat pump installation;

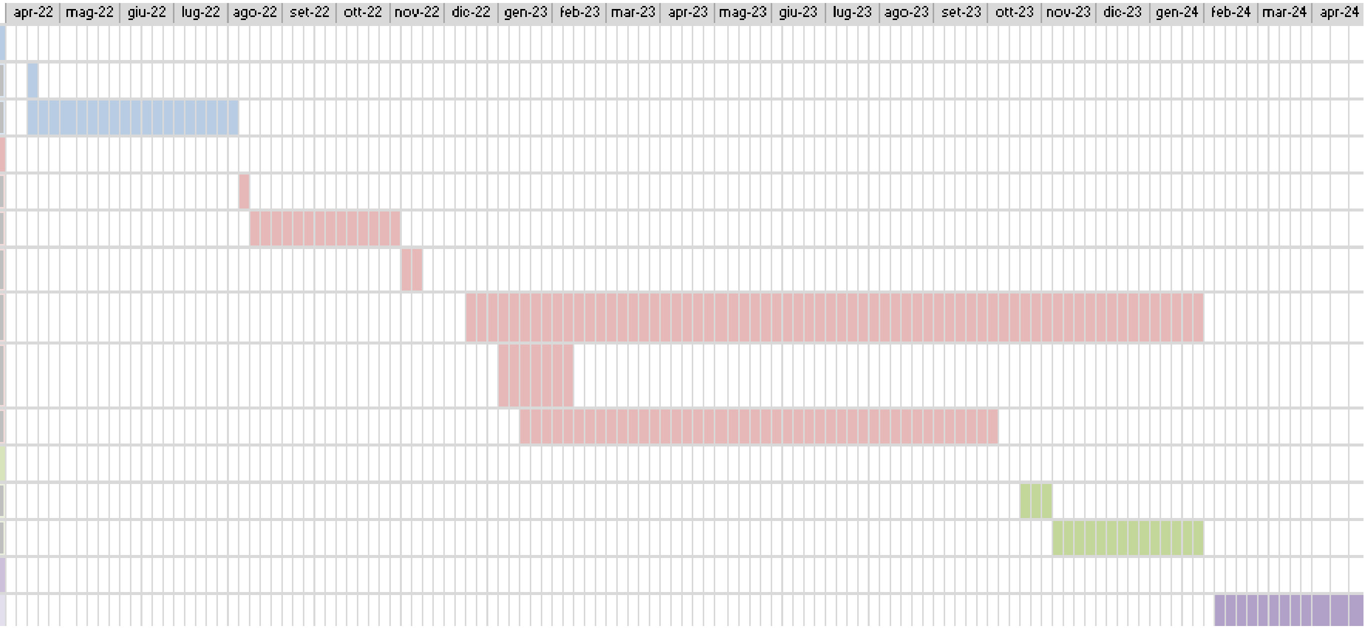
- Operative Phase 2: activities related to the second geothermal heat pump for heating and cooling packaging department.

The overall time required to be fully operational, or to begin heating the Assembly-2 department, which corresponds to phase 1 of the entire geothermal project, was around 108 weeks, with certain tasks performed during the same period.

The time required for preliminary activities was roughly 19 weeks. The time spent in the authorization process was about 89 weeks (504 days), considering that in some cases two permission procedures were performed at the same time and that some operations (drilling production wells and step-drawdown tests) were carried out during this time. Site activities for Phase 1, which included drilling injection wells, building, and GWHP installation, were completed in 17 weeks and Phase 2 was still in progress in April.

Table 4 - Open-loop low temperature geothermal project time - Gantt diagram

PRELIMINARY EVALUATION	PROJECT STATUS
Preliminary meeting	100%
Site inspection and Preliminary evaluation	100%
Authorization process	PROJECT STATUS
Request for authorization to explore water and excavate 2 wells and Authorization	100%
Site activities	100%
Request for authorization to explore water and drill a third well and Authorization	100%
Application for multi-year concession for diversion of public waters (pumping) and Authorization	100%
Application for authorization to drill reinjection wells (Authorization obtained but before drill the reinhection wells authorization process must be completed)	100%
Application for authorization to reinject withdraw all water	100%
Operative activities PHASE 1 - Heating and coolling Assembly-2 Department	PROJECT STATUS
Drill of reinjection wells	100%
GWHP Installation process	100%
Operative activities PHASE 2 - Heating and coolling Packaging Department	PROJECT STATUS
Construction and Installation	80%



6.2 Well data analysis

In the production wells the water temperature during the winter season (Chart 14), varies in the range from 19°C in February to 17°C in April. Temperature in PW1 has dropped around 1,5°C from the beginning to the end of the period. In PW2 the temperature difference is about 0,7°C and in PW3 0,5°C.

These temperature differences are likely due to variations in the water table levels, as indicated by the hydrogeological survey. This is particularly evident for PW3, where the water table is 0,5 m deeper than in PW1 and PW2, resulting in lower thermal energy fluctuation.

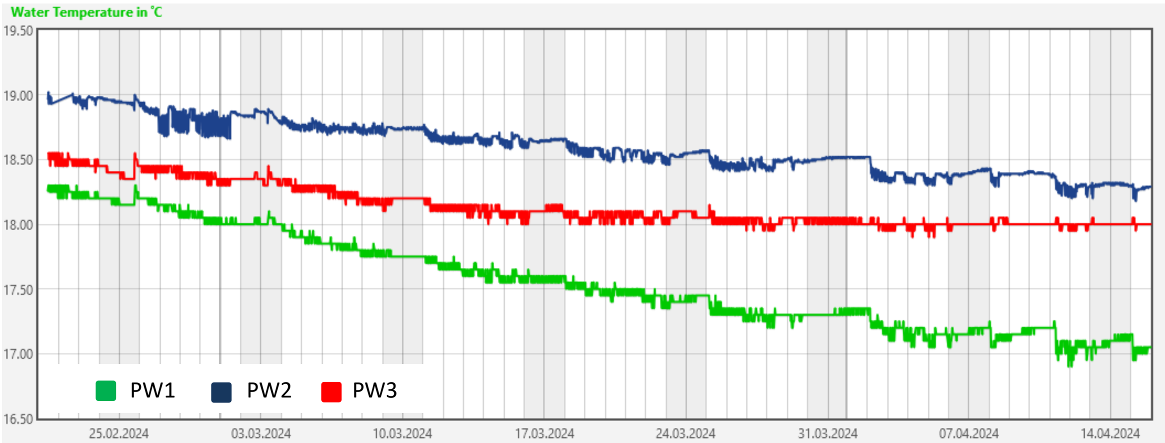


Chart 14 – Monitoring of temperature in production wells PW1, PW2 and PW3 during winter season

In the injection wells, however, the temperature difference inside each of them is more evident, and it is possible to observe a peak of around 1°C during weekends when the heat pump is stopped, as shown in Chart 15.

The water temperature remained relatively constant throughout the entire winter period. In IW1 the temperature rise form 12,85°C to 14°C, in IW2 there was no change and in IW3 from 13,6°C to 14,0°C.

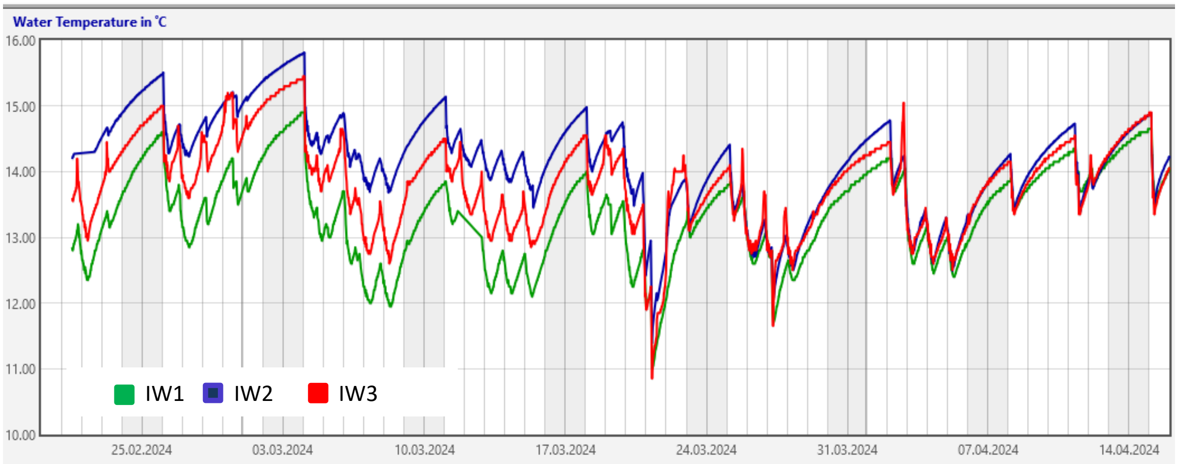
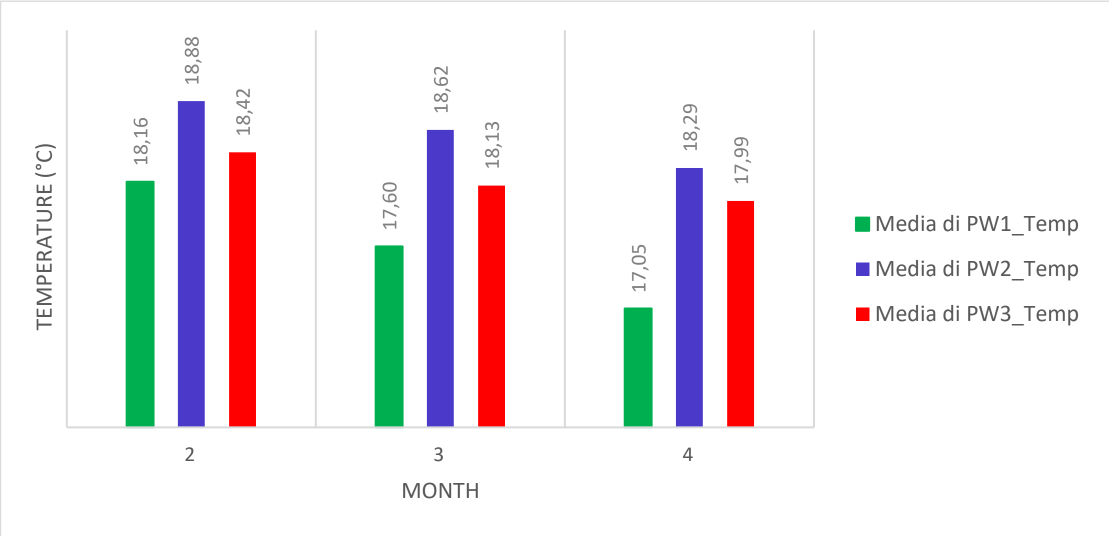


Chart 15 - Monitoring of temperature in injection wells IW1, IW2 and IW3 during winter season

The average temperatures in the PW1, PW2, and PW3 production wells, from February to April are 18,5 °C, 18,1°C and 17,8°C respectively, while in IW1, IW2, and IW3 injection wells are 14,2°C, 13,6°C and 13,7°C. An important information obtained from these data is that the average difference of temperature between withdrawal water and reinjected water remain below 5°C during the entire production period, the limit imposed by authorization process (Chart 16).



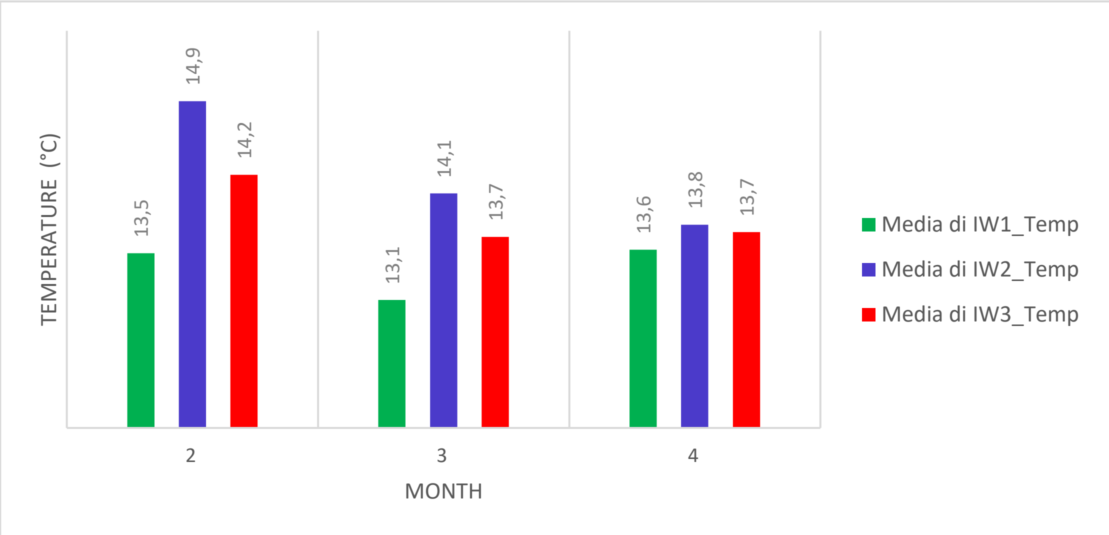


Chart 16 - Average groundwater temperature from March to April in production wells PW1, PW2 and PW3 (above) and in injection wells IW1, IW2 and IW3

In Chart 17, the water levels inside each production well during the winter heating period are reported.

In PW1 the water level drops from 4,5 m to approximately 8,7 m, in PW2 the water level drops from 5,1 m to 5,6 m and in PW3 from around 4,7 m to 9,1 m. Difference in water levels are of 4,2 m, 0,5 m and 4,4 m respectively.

These values indicate, according to the step drawdown test (Charts 9, 11, 13), a flow rate lower than the critical value for PW2, a flow rate over the critical value for PW1 and PW3 as the water level drop around 4 meters, even if the water level changes continuously during the operating time and return to the initial state just the heat pump is stopped.

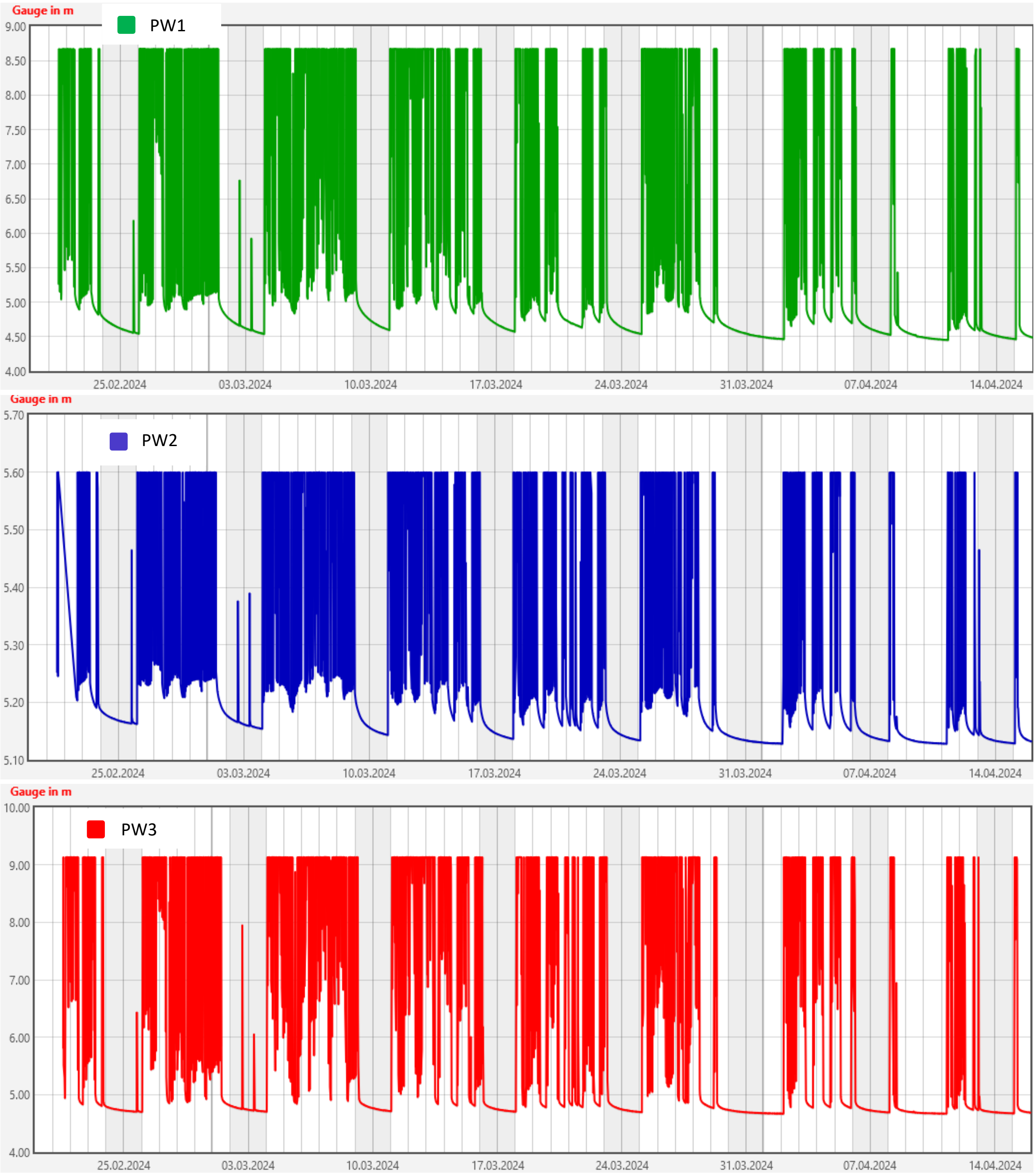


Chart 17 – Water level in production well: PW1 (Upper chart), PW2 (middle chart), PW3 (lower chart)

Water levels in injection wells are shown in Chart 18. It’s possible to observe that the amount of reinjected water level in IW1 has been reduced since March, probably due to the lower thermal request and consequently lower pumping flow rate.

For the three injections wells, during the winter heating season, the water table level remained constant in time, at a 4,9 m for IW1, 4,03 m for IW2 and 4,20 for IW3, reaching the steady state twenty-four hours after the heat pump has been stopped.

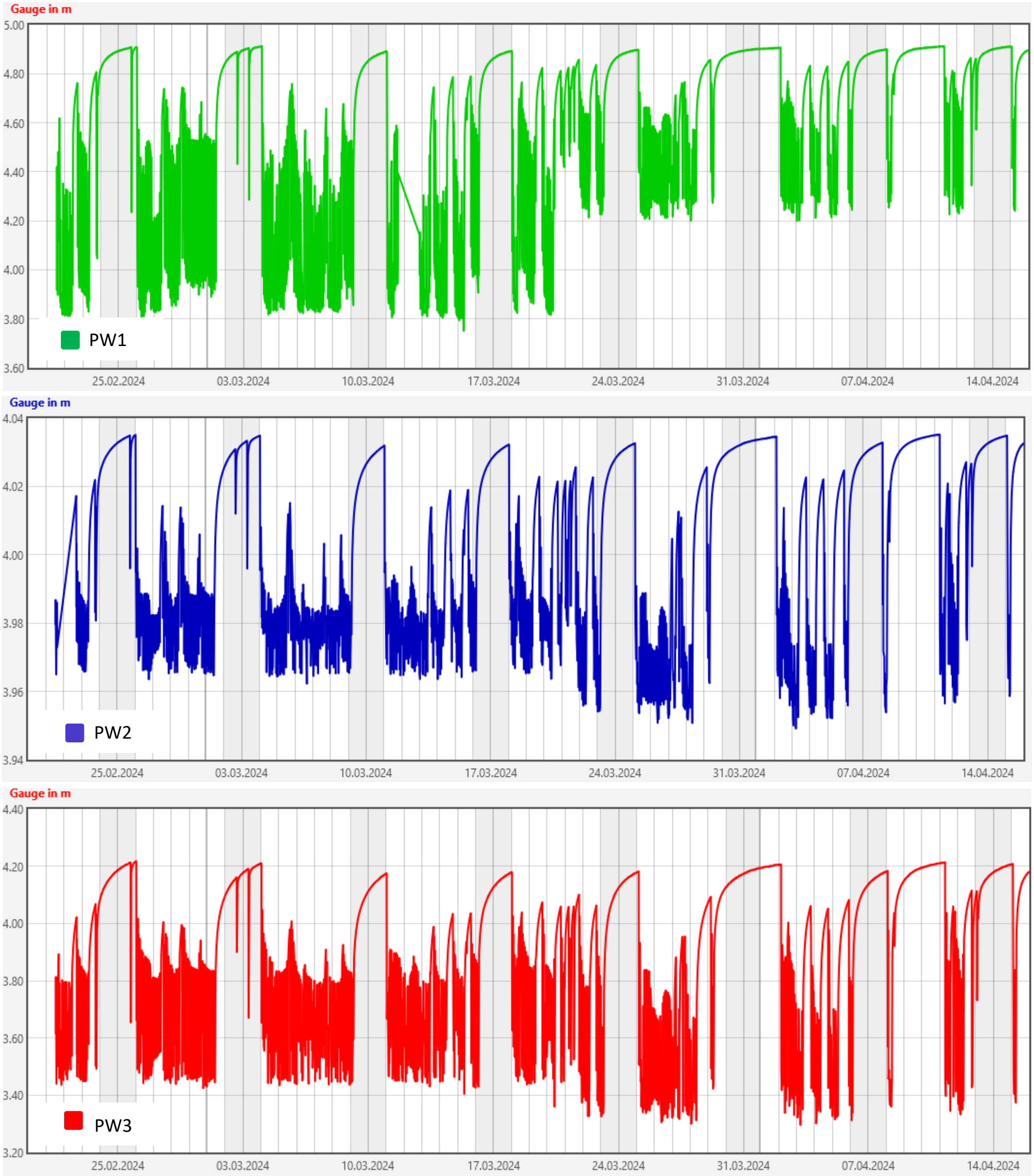


Chart 18 - Water level in injection well: IW1 (Upper chart), IW2 (middle chart), IW3 (lower chart)

6.3 Heat pump energy efficiency and environmental benefits

In this study, thermal energy produced were computed using measurements of water flow rate and water temperature differential to and from the plant, and the COP was calculated using heat pump electrical energy consumption measurements. As a result, it does not account for the electrical consumption of the electro pumps installed in the well.

The results are displayed in Table 5 and are similar to those reported in Ioan & Calin (2013), which report a COP value of about 3,85 under similar environmental conditions.

Table 5 - Groundwater heat pump energy performance

Period	Thermal energy supply (kWh)	Electrical energy consumption (kWh)	COP
feb-24	79.152	23.141	3,42
mar-24	52.554	15.666	3,35
apr-24	29.702	6.899	4,31

From an environmental perspective, an amount of 18.398 Sm^3 of natural gas was avoided, considering the energy efficiency of the previous air heating burners and distribution equal to 0,8. Over a three-month period of space heating, the system achieved significant results, saving 9 tons of oil equivalent (toe) in energy. This represents a 50% reduction in energy consumption compared to the previous system. Additionally, it reduced CO_2 emissions by 85 tons, cutting emissions by around 75%. These savings highlight the efficiency of the system in both energy use and environmental impact and can be considered a Net Zero Emission system taking into account the self-consumption energy from the photovoltaic plant and the green energy purchased from the grid.

Values of toe were calculated using Italy's primary energy conversion factor (MiSe, 2014), while the CO_2 reduction was determined using the latest Italian greenhouse gas inventory coefficient published by (ISPRA, 2023), as reported below in Table 6.

Table 6 - Italian energy primary conversion factor and CO_2 emission factor

Energy vector	Unit of measurement	Conversion factor (toe)	CO_2 conversion factor (t)
Electricity	kWh	$0{,}187 \times 10^{-3}$	0,309
Natural gas	Sm3	8.360×10^{-7}	$2{,}004 \times 10^{-3}$

Chapter 7 – Conclusion

In conclusion, the adoption of low-temperature open-loop geothermal systems for heating and cooling in the industrial sector presents a highly promising solution for reducing carbon emissions and improving energy efficiency. As demonstrated in this thesis, such systems have the potential to significantly reduce reliance on conventional fossil fuels, leading to a substantial decrease in CO_2 emissions, which is crucial for meeting environmental targets and transitioning towards sustainable energy solutions. This case study and data presented clearly indicate that geothermal energy can serve as a reliable and efficient resource for industrial heating and cooling, contributing to the overall reduction of greenhouse gases while also providing long-term cost savings.

However, despite the clear environmental benefits, the feasibility of implementing low-temperature open-loop geothermal systems in Italy faces significant challenges, particularly due to the complexity of the legal and regulatory framework. The current Italian legislation surrounding geothermal energy is fragmented, overly restrictive, and lacks uniformity across regions, creating a significant barrier to widespread adoption. The absence of a clear, streamlined legal framework complicates the planning and approval processes, often resulting in long delays and increased costs for industries attempting to develop geothermal projects.

These legal and bureaucratic obstacles probably affect small and medium-sized industries (SMIs), which may lack the financial and administrative resources to navigate the complex regulatory environment. Larger industries, with their greater capacity to absorb these costs and administrative burdens, are more likely to be able to implement such projects. However, for SMIs, which form a substantial part of Italy's industrial landscape, the current regulatory framework makes it almost prohibitive to invest in open-loop geothermal systems, despite their long-term benefits.

Moreover, the high initial investment required to design and install open loop geothermal systems adds an additional barrier to adoption. Without sufficient economic incentives, such as grants, tax breaks, or government-backed financing options, industries may struggle to justify the upfront costs of transitioning to geothermal energy, despite the long-term savings and environmental benefits. Financial support is crucial to offset these initial expenses to invest in long-term sustainability projects.

Therefore, in addition to legislative reform, it is essential that stronger economic incentives are provided to encourage the adoption of geothermal systems in the industrial sector. Government subsidies, lower interest loans, and increased financial support can make this technology more accessible to businesses of all sizes. Without significant financial incentives, the widespread implementation of geothermal technology will remain out of reach for many industries, despite the clear environmental and economic advantages it offers.

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