Ecological and Energetic Transition towards industrial Sustainability: feasibility study of a low enthalpy ground source heat pump for heating and cooling systems

Bianchini A.*, Bigazzi E.*, Pellegrini M.*, Rossi J.*

** Dipartimento di Ingegneria Industriale, University of Bologna, Via Fontanelle, 40 47121 – Forlì – Italy (augusto.bianchini@unibo.it, elena.bigazzi@studio.unibo.it, marco.pellegrini3@unibo.it, jessica.rossi12@unibo.it)*

Abstract: Low enthalpy geothermal sources in Italy are spread all over the territory thanks to its geological conformation. Water at a constant temperature, from 15°C to 30 °C, can be found at relatively short depths and extracted through wells and submersible pumps, and high fractions of renewable thermal energy (over 80%) can be produced. Applications are growing, but, looking at the overall potential, they are still not enough due to the lack of investment policies in this field and legislative, technical, and economic barriers. Since Paris Conference of December 2015 till the recent European Green Deal presented in December 2019, international and European guidelines concerning emissions have become increasingly challenging and industries must gradually but concretely adapt their energy plants. The paper shows a feasibility study of a ground source heat pump (GSHP) system for the air conditioning of a manufacturing company's canteen building. The paper compares the GSHP system and the existing trigenerative centralised system: the whole plant's energy structure modelling is introduced through a process flow diagram to spot all potential actions given the initial conditions. The GSHP feasibility study aims to be part of a more comprehensive strategy for gradual transition to renewables and energy efficiency improvement, representing an innovative choice that a company can make to become more sustainable.

Keywords: transition to renewable energies, sustainability, ground source heat pump, energy efficiency.

1. Introduction

Nowadays, energy sustainability has become a goal to be reached in many contexts. Making sustainable the way we interact with nature is the only way we can delete our heavy carbon footprint on the planet. Paris Agreement (2015) has raised some key points to keep average temperature's increase strictly under 2°C, with a solid effort to remain under the safety target of 1.5°C. Markets and stakeholders must do everything possible to get more and more independent from fossil fuels, starting a "green" transition and, above all, implementing reliable business models based on renewables, energy efficiency, circular economy. The Agreement includes some goals defined in 2014 European Council, such as a reduction of 40% of greenhouse gases (GHG) emissions and 25% of energy efficiency targets from 1990 to 2030. Besides, the recent European Green Deal (December 2019) added, by 2050, three more goals: reaching net-zero GHG emissions, getting economic growth dissociated from natural sources exploitation and, socially speaking, do not neglect any human being or any place. European Union (EU) has a central role in climate change's policies and, on top of Paris directives, it has identified its own goals. The Directive 2009/28/CE assigned to EU an overall replacement target of primary energy consumption with renewable sources that is 20% by 2020, while for Italy the target is 17%. In 2018, Italy was the only Country that achieved this goal taking third place among EU Countries for renewable share on the overall energy consumption. Besides EU goals, at the end of 2019, Italy sent to Brusselles the final release of the Integrated National Plan for Environment and Climate (PNIEC), where some more ambitious targets are defined. Table 1 shows the European climate goals in comparison to Italian ones.

Table 1: Italian 2030 targets vs European 2030 targets

TARGETS	EU	Italy
Renewable share on gross final energy consumption	32%	30%
Primary energy consumption reduction compared to PRIMES 2007** scenario	-32%	-43%
GHG reduction vs 2005 for ETS* regulated sectors	-43%	
GHG reduction vs 2005 for non ETS* sectors	-30%	-33%
Global GHG reduction vs 1990	-40%	

*ETS: EU Emission Trading System

** PRIMES: Price-Induced Market Equilibrium System

In Italy, the most critical sectors concerning GHG emissions are transports (34%), residential heating and cooling (28%) and industry (23%) (ISPRA, 2018). The transport sector is going towards electric mobility while, starting from 2021, all new buildings would have to respect the nZEB (nearly zero energy building) definition (Directive 2010/31/EU). Manufacturing industries are willing to follow a new green deal manifesto in the following years. However, there are still not solid strategies to implement gradual decarbonisation and transition to renewables. It is often difficult to find reliable and economically sustainable alternative solutions to traditional fossil fuel-based technologies. Companies would have to redesign their energy structures and processes and invest in renewable energies less environmentally impactful. That is not only related to targets but also competitiveness. Consumers have recently acquired a strong sensitivity to environmental issues, and they are driven to support companies involved in "green" actions (and that can communicate this). To give an example of these actions, many companies have recently decided to buy electricity through the Guarantee of Origin (GO) system. This financial tool, as well as ETS, was created to incentivise renewable production: industries pay a slight surplus to power companies to have a 100% renewable electricity usage certification. However, the global demand for those GO certificates is growing faster than the actual production of renewables globally, so more specific action plans are vital for industries to follow the energy scenario's changes (Ragwitz et al., 2019).

This paper focuses on shallow geothermal energy use. In particular, the paper shows how groundwater can be a resource for a manufacturing company to produce renewable thermal energy and get a more efficient heating/cooling system. The research is included in a more complex sustainability strategy that involves different issues such as solar energy, power-to-gas, and other types of energy efficiency improvements. Through the construction and analysis of the process flow diagram (PFD) of energy sources and users in the manufacturing company, the points of interest in energy transition or energy recovery were spotted, and a specific action plan was developed. Having a global action plan allows companies to take more forward-looking choices and investments, and the more the best practices and the related know-how will be shared, the more the industrial sector could take advantage of this.

At this level, it is essential to underline that a faster reduction of GHG emissions can be reached both with a decrease of the overall consumption through energy efficiency and with new investments in renewable energy production. A geothermal plant unifies these two aspects: it involves renewable energy and it brings an energy efficiency improvement thanks to high coefficients of performance of water-water reversible heat pumps. There is also a third aspect: consumption electrification, which means reducing emissions and potential integration with renewable electricity.

Low enthalpy geothermal energy involves resources at temperatures below 25°C and, as well as other more exploited renewables, and it represents an opportunity within the energy sustainability issue. Yet, geothermal energy, differently from intermittent low-carbon solutions such as solar photovoltaic and wind power, is a continuous source when designed and used correctly. Italy is a country with a high geothermal potential which, according to the most conservative estimations, is around 500 Mtep, for 1/3 electric and 2/3 thermal. That means that, in a reference period of 50 years and supposing continuous running, the thermal capacity is around 6,6 Mtep/year. According to GSE, the Italian energy service provider, in 2017, only 0,131 Mtep of geothermal energy were used, which is 2% of the overall potential. If we consider the annual primary energy need around 155 Mtep, and the annual amount of energy from renewable sources, 22 Mtep, geothermal heat from direct uses covers respectively 0,08% and 1%. Direct uses growth's projections to 2030, based on PNIEC, are very weak, from 0,131 Mtep in 2017 to 0,16 Mtep in 2030. In 2019, only 2% of the whole incentives for renewables (100M€), different from solar, went to geothermal sources. A tiny slice considering that financial subsidies for fossil fuel amounted to about 19.000 M€.

Despite its benefits, such as long-term base-load energy providing and GHG emissions reduction with minimum environmental risks, geothermal applications in Italy currently have only modest growth per year concerning solar or wind technologies. However, some economic, technical and legislative barriers have been identified (Bianchini et al., 2017; Pellizzone et al., 2017). For example, relatively high costs of ground drillings could represent a deterrent at the beginning; besides, extraction and reinjection of warmer and colder water could generate thermal aquifer instability. To reduce this second unwanted effect, temperature's variation is bounded above, but legislation isn't uniform all over the Italian territory. The Italian decree law n.22 of 2010 classified geothermal plants in function of their size and enthalpy; as for Ground Source Heat Pump GSHP systems under 2 MW of thermal power, legislation is up to regional administration and changes from region to region.

GSHP systems can be closed or open-loop (Bianchini et al., 2017). Closed-loop systems use geothermal probes and work with ground temperature's gradient. Open-loop systems, instead, exchange heat with groundwater at a constant temperature between 10°C and 20°C. Both of them, through reversible heat pumps, produce heating and cooling energy. Geothermal (water-water) reversible heat pumps take heat from water or release it to increase or decrease the output water temperature (up to 50°C in winter and 7°C in summer). If reversible heat pumps are involved, though, the output energy is not entirely renewable because of the national electricity production system, which enters about 39% of renewable energy on the overall input primary energy and has an efficiency factor of about 40%. If renewable electricity is used, for example, electricity from solar energy, then a 100% renewable energy factor could be obtained. In any case, with coefficients of performance (COP) from 4.3 and 5.1 (higher than standard air-water heat pumps that are around 3), a small amount of electricity is used compared to thermal output energy, so good fractions of renewable energy could be obtained (over 80%). This case of study was developed by a big manufacturing company in Forlì (Emilia-Romagna Region – Italy) and concerned a free-standing canteen building separated from the production plant. After the characterisation of a 40 m aquifer, a feasibility study of an open-loop GSHP system was carried out. The aim was to compare the GSHP system to the present trigenerative central system in terms of technical and economic aspects.

2. Methods

2.1 Process Flow Diagram of energy flows

The chart of the plant's energy flows was developed taking into consideration three main aspects: i) typologies of primary energy utilities including energy vectors such as water; ii) energy inputs and outputs of the main elements of the factory, qualitatively; iii) energy inputs and outputs of the main elements of the factory, quantitatively. The chart also allowed us to understand the energetic starting conditions of the factory in terms of renewables usage and thermal and electric need. Fig.1 shows the process flow diagram (PFD): triangular blocks are the primary sources, rectangular ones are the principal departments, and rhomboidal ones represent the main equipment.

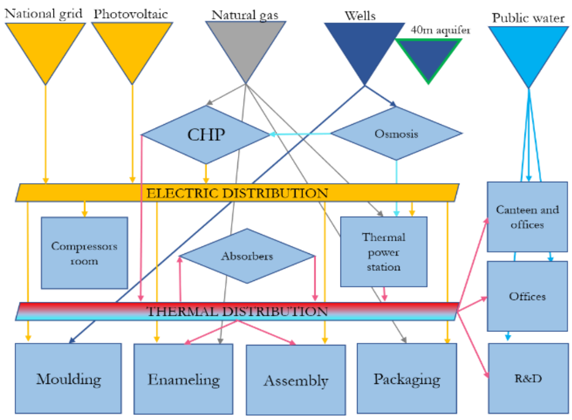

Figure 1: PFD of the factory

Firstly, the energy map helped to understand the industrial site energy dynamics better and draft an action-plan diagram. Fig.2 shows in a more synthetic way energy blocks and flows and, in addition, shows the short to long term actions that could be done in the plant. The energy map is crucial to give a clear direction to future choices and investments. For example, if new reversible heat pumps will be introduced, there would be the electrification of the consumptions, and growth of the electrical capability if a new photovoltaic system will be installed. Besides, in the long term, power-to-gas technology could be used to store synthetic CH_4 starting from CO_2 and H_2O recovery, reducing emissions and natural gas purchase's costs.

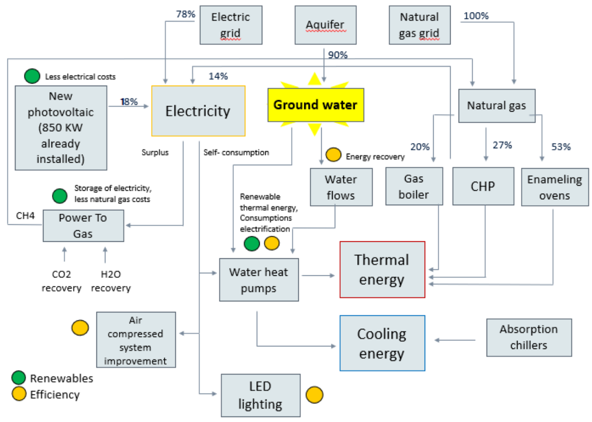

Figure 2: Example of energy action plan of the factory

2.2 Characterisation of the aquifer

The factory already includes two wells to extract water to be used in industrial processes at depths of 80 m and 300 m. A third unused aquifer was found at a depth of 40 m and short term and long term tests were carried out as shown in figure 3.

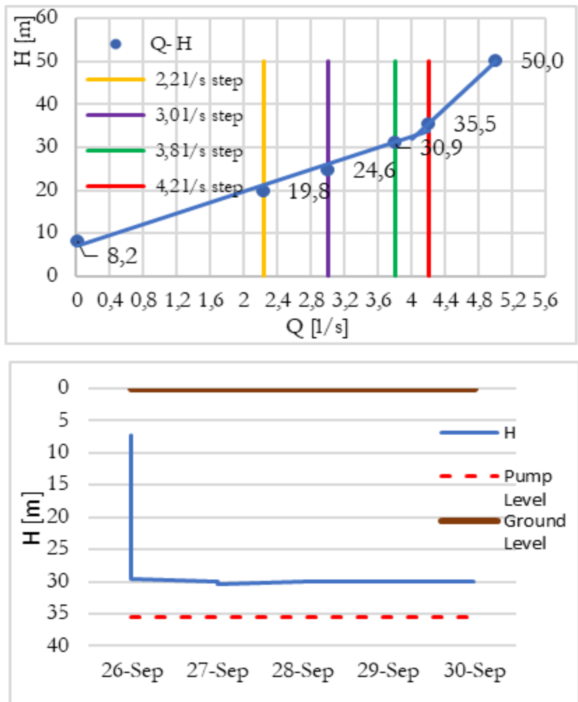

Figure 3: Short term test (above); Long term test (below)

A piezometer was then installed in proximity of the 300 m well. Once spotted the new aquifer, the characterisation tests were carried on to determine the balance extraction flowrate value (flowrate above which an aquifer emptying would occur). Short term tests, called step tests, allowed to identify balance flowrate (Q=4,2 l/s). Long term tests, that must last more than 72 hours, allowed to verify that, for a fixed flowrate, below the maximum value (3,7 l/s), the piezometric high kept constant and above the pump priming point (fig.3). This value was then considered as design maximum flowrate for each well.

2.3 Legislative constraints

Since the case study is located in Forlì, legislative issues involve legislation of Emilia-Romagna region and can refer to both bureaucratic and technical aspects. As for open-loop systems, local authorities have to approve drilling operations and extraction of public groundwater (Regional Regulation n.41/2001) and the consequent reinjection into the aquifer, released by the province of Forlì-Cesena (D.lgs 152/2006). Then a preliminary geological report has to be released by the competent company.

The thermal gap between extracted and injected groundwater cannot be too high not to have a ground thermal unbalancing. Regional authorities generally fix this gap; in Emilia-Romagna it is set to 6°C (Landonio et al., 2014). In this case of study, it was lowered to 5°C to have a safety margin. Besides, local authorities often require an adequate number of monitoring piezometers based on the size of the plant and the morphology of the interested area. Proper measuring devices must be foreseen to monitor the right temperature discriminant and the overall water extraction (and reinjection) during the year. The maximum extraction flowrate sets the potential power of the plant. Second drilling falls outside the first well's influence range at a certain distance from the extraction point. So, as well as will happen in this case, it is possible to place a second drilling at a sufficient distance (Dupuit relation) to extract a doubled flowrate if the thermal need requests that. In this case, about 30 m were considered. Another constraint is represented by groundwater quality, both in terms of contamination and protection of the water heat pump. As for the protection of equipment, an intermediate plate heat exchanger allows having less restrictive chemical values. In fact, without the heat exchanger, groundwater should have a hardly reachable purity (BS EN 15450 fixes some chemical ranges). In the case of exchanger usage, often, a plate model is chosen. Chemical tests were requested to have water quality feedback. Despite the chemical tests results being lower than the maximum suggested values, the heat exchanger must be periodically cleaned, and filters must be foreseen in 2° and 3° loop to preserve equipment.

2.4 Functional model

The canteen building is currently heated and cooled by a trigenerative central system with CHP (Combined Heat and Power) machines and absorption chiller as main producers and AHU (Air Handling Unit) and aerotherms ad enders whose technical specifications are known. AHU and unit heaters (UH) nominal thermal power was then calculated to understand the total monthly thermal need. The two most critical monthly values, for winter and summer, were considered the final thermal need. It changes from one month to another and has four possible ranges:100%, 75%, 50%, 25%. Running time was set to 10 hours per day for 22 monthly working days. The GSHP plant (fig.4) is made of a first loop that involves extraction and injection wells that brings thermal energy to the plate heat exchanger.

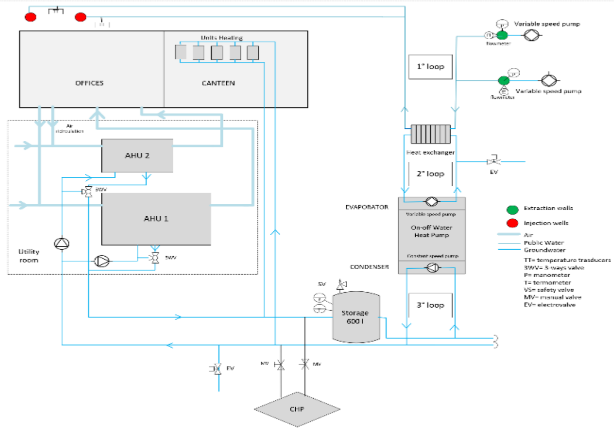

Figure 4 : Functional scheme of the geothermal plant

The second loop, instead, goes from the heat exchanger to the reversible heat pump, and it is a closed-loop filled with public water (or, even better, with demineralised water from osmosis central). The third loop is the utility loop, filled with public or demineralised water, and it goes from the reversible heat pump to the air units. In this part of the circuit, on the water return side, a water tank is located. A storage of water, in fact, is necessary to have a thermal flywheel and limit the number of on/off transition of the reversible heat pump (maximum 6 switches per hour). The reversible heat pump has an external circuit and manual valves for the seasonal running mode's switch. This way, the evaporator side, always keeps this function, as well as the condenser side, so that they both can be correctly sized by the constructors. On the evaporator side, a variable speed circulation pump could be foreseen. In fact, if during summer the thermal load decreases, a lower flowrate of utility water is necessary to guarantee the wanted temperature. If there wasn't a regulation on the flowrate, temperatures at the condenser could decrease and there could be a freezing risk.

A reference machine has been chosen on the base of the thermal need previously calculated. Then, looking at its technical sheet and with some more precise running simulations functional parameters were determined. Known the nominal electric power and the nominal thermal power (heating and cooling), COP and EER (Energy Efficiency Ratio) were calculated.

Output fixed temperatures are 50°C in winter and 7°C in summer. Temperature gap at the aquifer side is set to 5°C (from 13°C to 8°C in winter and from 17°C to 22°C in summer at downstream of heat exchanger), while water flow must be under 7,4 l/s (the maximum available flowrate having two extraction wells).

Starting from the heat pump technical sheets, annual production and consumption were estimated. Knowing the overall seasonal consumes it's possible to calculate the SPFs (seasonal performance factors). SCOP (Seasonal-COP) is defined as overall thermal energy produced by heat pump divided by overall electrical energy consumed during the utility season. EER is the same value but concerning cooling energy. Given the SPF [kJ/kJ] and the thermal power needed, then produced, (Pth [kJ]), it is possible to calculate the renewable energy amount (Ren.En. [kJ]), from D.lgs n.28 of 2011:

$$Ren.En. = Pth \times \left(1 - \frac{1}{SPF}\right)$$

Beside the reversible heat pump consumption, in the overall consumption calculation, the electrical pumping consumption to withdraw water from the aquifer is also a relevant parameter, about 20% of the total consumption.

To compare the present system, a consumption estimation was also done for the trigenerative conditioning. Known the overall annual natural gas consumption of CHPs and their EER, and by assuming that they have to generate the same thermal energy of the geothermal plant, a proportional calculation was used to find out canteen's annual consumptions, separated from the other utilities. The coefficient of transformation from Sm^3 to kWh was assumed equal to 9,33 which is the value conventionally considered by the company's national and international plants. Then, knowing the average energy's specific costs, it was possible to make also a cost calculation.

2.5 Economic feasibility of the project

A comparative payback model was chosen to make economic evaluations. Consequently, the present annual financial resources and payments (revenue, costs - such as i) drilling costs, ii) reversible heat pump and other equipment costs, iii) installation costs - taxes, ecc…) in the fixed service life of the geothermal plant (25 years) has been considered and calculated based on consumption models discussed in the functional model.

The investment for the plant becomes economically profitable when the cash flow starts to be positive. The payback evaluation method considers the year such that the cash flow becomes zero. The higher the value, the riskier the investment. Costs are represented by the running costs of the geothermal plant (electric energy). In contrast, the revenues are represented by the company's non-costs by implementing the geothermal system and decommissioning the trigenerative one, including maintenance savings (CHP machines are old and often involved in extraordinary maintenance) and incentives. This kind of actions can benefit from an Italian energetic incentive called "Conto Termico", managed by GSE.

3. Results

3.1 Technical results

Technical evaluation attested that two extraction wells are necessary to cover the heating and cooling need of about 115 kW. As for injection wells, usually, geologists confirmed that there are conditions to realise only one perforation (that consists of a meaningful saving of money) in the same number of extraction wells. In the consume model described at 2.5, several parameters were put to light based on the difference between geothermal and trigenerative system. Table 2 and 3 and show these values.

Table 2: Trigenerative system parameters

	UoM	Value/year
Energy production	kWh	240.000
Gas consumption	Sm3	37.000
Electric consumption	kWh	38.000
Energy consumption	kWh	386.000
Running cost	Euro	20.000
CO_2 emissions	kg	65.000
Renewable fraction	-	7%

Table 3: Open-loop GSHP system parameters

	UoM	Value/year	Δ/year
Energy production	kWh	240.000	**-**
Gas consumption	Sm3	0	**-100%**
Electric consumption	kWh	63.000	**-**
Energy comsumption	kWh	63.000	**- 83%**
Running cost	Euro	8.500	**- 60%**
CO_2 emissions	kg	6.000	**- 90%**
Renewable fraction	-	86%	**+79%**

*considering that the national renewable electricity fraction is 39% and that the factory has an electricity self-production of about 7% .

The 86% of the overall energy exploited in geothermal system is renewable. This renewable amount is 74% made of energy taken from ground, 10% of the national electric distribution renewable ratio, and 2% of the self-production of the factory. Besides, the fact that all the input energy is of the electric kind, leads to a consistent CO_2 saving (less 90%) in relation to trigenerative system which uses natural gas. In terms of overall energetic consumption (calculated as the sum of natural gas and electric consumption) there is a significant saving (less 83%) because a large part of energy is "freely" taken from the ground, allowing also a cost reduction (less 60%).

3.2 Economic results

The economic evaluation includes two commercial offers: the first one is for drilling costs, while the second one is a "turnkey" offer made by a single company specialised in geothermal installations. Both offers include incentives from Conto Termico calculated by suppliers (7.800 € for 5 years).

Below, for each case, the net present value trend during the geothermal plant's lifetime is shown. At the end of 25 years, the total income would be about 20% more than the initial investment. To visualise the effect of the interest ratio was put to evidence also the line with i=0 (blue line).

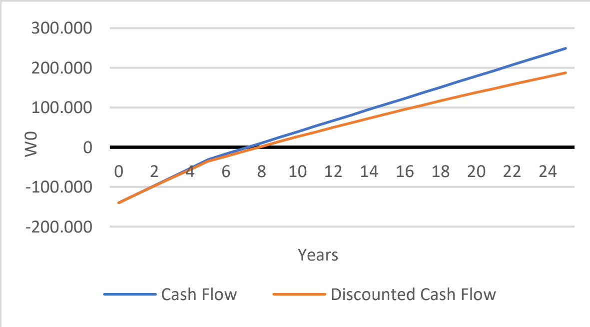

Figure 5 : First offer, payback 7,5 years

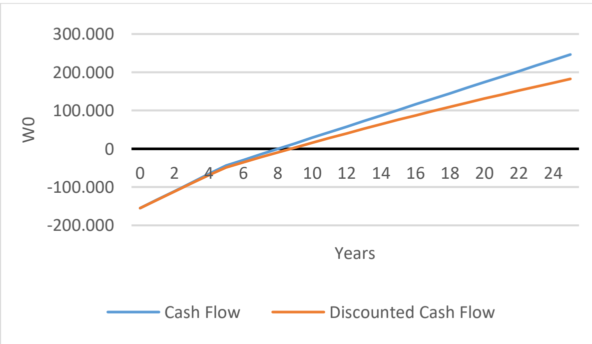

Figure 6: Second offer, payback 8,5 years

First offer (fig.5):

I_0 = 140.000 €; Payback = 7,5 years

Second offer (fig.6):

I_0 = 155.000 €; Payback = 8,5 years

In conclusion, the paper showed that it is technically possible to replace the existing trigeneration heating and cooling system with an open-loop GSHP system for the canteen building, program a relatively safe investment, and use part of the existing equipment. In future, to get higher efficiency, a new AHU could be provided. The company will then decide if this level of risk can or cannot be acceptable for its internal policies. The company already has the extraction license from the local authorities to exploit groundwater for industrial. The new application would be still under the allowed flowrate limit. Nevertheless, local authorities could request monitoring piezometers to be installed in the area. Although the described installation impacts only a small fraction of the overall industrial site thermal need (about 1,5%), it is essential to have guidelines to implement best practices, define a transition action plan, and increase internal know-how. Besides, a gradual transition moving towards consumption electrification becomes crucial to reduce natural gas purchasing and stimulate renewable on-site production through new photovoltaic installations.

4. Conclusions

The paper describes the techno-economic assessment of an open-loop GSHP system for application in a production site. The economic feasibility study showed that almost 25% of the overall investment involves drilling operations. To overcome this limit, it could be beneficial to check all the water flows within the factory (for example, with the help of PFD diagram) to understand if other waste heat sources can be available. As a further step, the opportunity to extract more water from the existing wells could be considered since the present extraction rate is far below the authorised value. Groundwater could be used for direct cooling circuits (if the temperature gap remains under 6°C) or sent to reversible heat pumps. Moreover, high-temperature heat pumps could replace the natural gas boiler, reducing natural gas consumption. Another topic to be deepened is the choice of the heat pump. In fact, the first commercial offer includes a traditional water-water heat pump that is a f-gas machine with a maximum water output temperature of 50°C. Instead, the second offer consists of a high-performance water-water heat pump designed ad hoc for geothermal applications and can reach 80°C of water output temperature. Unfortunately, this machine has a doubled cost compared to the traditional one in the face of running costs very similar (in the same running conditions).

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