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Original Research Article

Shallow geothermal energy for industrial applications: A case study

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ABSTRACT

Shallow geothermal energy is of great interest for HVAC (heating, ventilation and air conditioning) designers. While increasingly popular in the residential and commercial sectors, shallow applications are still little used in the industrial sector and unfamiliar to policy makers, designers and stakeholders [1]. Despite this, geothermal applications are feasible for industrial plant for several reasons: operating at high load factors and supplying energy to a single location, geothermal systems would cut energy costs, a large slice of overall industrial production costs. This paper presents the results of a feasibility study carried out for an industrial shallow geothermal project, where the required preheating to the innovative Expanding-Gas-Power-Transformation (EGPT) process was supplied through a Hybrid Geothermal-Air Transcritical Heat Pump. Focus was given to modeling the geothermal component to comply with the heat pump working temperature requirements, integrating this with geostatistics and numerical simulation of heat/water flows.

Introduction

A shallow geothermal system (commonly closed loop/open loop geoexchange system) allows thermal energy exchange with the first 100–200 m of the underground within a specified volume [2]. Shallow geothermal systems are designed to allow operational repeatability during the year, thereby avoiding thermal depletion of the soil.

A so-called geoexchanger, whose temperature level (<100 °C) falls within the range of low enthalpy geothermal systems [3,4], is connected to a heat pump in a system that can be used for different purposes: heating and cooling of buildings, subsurface energy storage, production of domestic hot water, de-icing and snow melting, conservation and reuse of waste heat from industrial processes [5].

Heat pumps exploit heat from ambient sources. The warmer the source, the higher their efficiency. Given the virtual absence of any seasonal temperature variability, underground sources enhance heat pump capability [6]. Examples of use include:

- Winter heating of buildings. In winter, underground temperatures are higher than the average temperature of air and superficial water [7].
- Summer cooling of buildings. In summer, underground temperatures are lower than the average temperature of air and superficial water [8].
- Underground thermal energy storage (UTES). Underground temperatures are lower than the circulating fluid, causing heat transfer to the surrounding underground area [9–11].

Low enthalpy geothermal applications in the industrial sector are still infrequent, temperatures exploited falling mainly into the medium enthalpy range (90 °C < T < 150 °C) [1].

The reason for the poor industrial uptake has to do with the high temperature requirements of most industrial processes, in contrast to the low-temperature requirements of domestic hot water production. Despite this, certain industrial processes do present conditions conducive to geothermal applications. These include high load factor operations, single-location load concentration requirements, and industrial operations where energy is a major production cost item [12].

The main recent applications of medium enthalpy reservoirs for industrial purposes have been the Organic Rankine Cycle (ORC) production of electrical energy [13,14], the production of heat and cold distributed to final users through pipeline networks (district heating and cooling) [15] and thermal energy storage applications [16].

An application of medium enthalpy geothermal resources with binary Organic Rankine power cycle is described by Hettiarachchi et al. [17]. Geothermal water is passed through the evaporator that

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heats a secondary fluid, typically an organic working fluid with a low boiling point. Vapor generated at the evaporator is used to drive a turbine. On leaving the turbine, the working fluid is condensed and pumped back to the evaporator, passing through a series of devices forming a closed loop. By modeling each device, a complete cycle simulation is achieved.

Kalina cycles have been used to generate electricity from geothermal sources. A notable example is the 2 MW_e power plant in Husavik, Iceland [18]. Started in 2000, the plant utilizes a 124 °C hot water geothermal source, which cools down to 80 °C, to generate electricity. The geothermal water leaving the plant at 80 °C is used for urban district heating. Medium enthalpy geothermal energy has huge potential as a source of district heating and cooling and its use is expected to increase [19,20]. Examples in Europe include the district heating schemes of Ferrara [21], Southampton [22], Munich [23] and the Pannonian basin [24]. Many other plants under construction or recently completed will also increase the deployment of ORC-based combined heat and power systems [25,26]. In the case of district heating alone, there are many examples of shallow low-enthalpy resource schemes linked to heat pumps. In Paris [27] and Milan [28] water stored in the first aquifer below the city is used to feed several high-temperature heat pumps linked to the network. In other cases, the heat pump uses seawater to provide district heating in Stockholm [29,30], Helsinki [31] and Tallinn [32].

Heat pump-based district heating exploits low-enthalpy geothermal energy through water extraction, i.e. open loop circuits. Reservoirs like aquifers, lakes or even seas are widely preferred for these applications on account of their favorable flow rates.

Non-residential applications using geo-exchangers are found in the agricultural and winery sector. There are many examples around Europe of greenhouses [33–36] and wine cellars [37] operating on closed loop geothermal energy systems. In greenhouses, gas-fired low-temperature heat pumps provide both heating and cooling and CO_2 controlled injection [38]. Dedicated production processes in the wine-making sector, such as grape cooling and fermentation cooling, use low-enthalpy geothermal energy [39]. This energy source is also appearing in innovative processes such as freshwater production and desalination [40].

Finally, other frequent non-residential applications are the heating and cooling of industrial sheds and office buildings to ensure comfort-zone temperatures for occupants. Eicker and Vorschulze provide several examples along with the related energy data [41].

As regards thermal energy storage applications, shallow geothermal energy systems have been successfully integrated with solar thermal energy applications for higher storage efficiency [42]. Several recent central solar heating pilot plants with seasonal heat storage in Central and Northern Europe have proved the suitability of these systems and confirmed their high energy efficiency potential [43,44]. Moreover, recent studies have also shown their applicability in Southern Europe climates as well. The excess energy produced by solar thermal panels in climates with high irradiation is injected into the ground and then recovered through GSHP, providing a solution to the overheating problems of solar thermal systems [45,46].

Our case study presents an innovative non-residential application of low-enthalpy geothermal energy. It is a pre-feasibility study of a closed loop shallow geothermal system entirely slaved to a new industrial application, the Expanding Gas Power Transformation (EGPT) process that considerably reduces CO_2 emissions in the natural gas pressure reduction stations. EGPT is an innovative technique harnessing gas expansion by means of a turboexpander generator, extracting motive power from the gas flow, whilst the required preheat is provided by a connected Transcritical Heat Pump [47]. To produce exportable electrical power, the COP of the heat pump must be higher than 2.0, which depends entirely on the ambient temperature available and the gas preheating temperature required. The minimum ambient temperature threshold for system applicability is 0 °C. By exploiting geothermal energy alone or with a combination of aerothermal and geothermal energy, the power produced by the system is always higher than the power absorbed by the Transcritical Heat Pump, giving rise to zero-consumption or even a positive-production process [47].

The pre-feasibility study carried out on a viable application investigated the potential integration of EGPT and shallow geothermal energy, and identified preliminary guidelines for the correct analysis and design of such a system in different climatic conditions.

Materials and methods

The following interdependent components must be taken into account when designing a borehole heat exchanger field [48,49]:

- System energy demand (peak power, functioning temperature and timing).
- Heat pump appropriate to the energy requirement.
- Underground providing the thermal energy.
- Possible GSHP systems providing ambient energy to the heat pump and building.

For relatively small residential applications (generally up to 30 kW) technical norms allow the use of simplified design methods, based prevalently on peak heat pump power, the type of underground and average yearly working hours. For more complex and powerful industrial systems, these simplifications are not feasible and a detailed analysis must be conducted [50–52].

For the design of a large borehole field with more than 100 BHEs, as in the case of industrial projects, the methodology must:

(a) Assess the hydrogeological site: lithologies, permeability, aquifer condition and flow velocity.
(b) Assess the underground thermal parameters: thermal conductivity of the different layers, geothermal flow, natural temperature gradient.
(c) Evaluate the technical feasibility of the various design alternatives for the geoexchangers and their configurations/disposal in the ground.

As regards the detailed analytical design of borehole heat exchanger fields, the ASHRAE American method is one of the most commonly used (see Italian technical norm UNI 11466:2012 [52] and ASHRAE Transactions [48]). The methodology is iterative with the following phases:

1. Identification of the energy to be extracted from the underground, based on the equivalent monthly/yearly hours and on the heat pump load factor.
2. Choice of the geoexchanger and the connection configuration.
3. Calculation, on the basis of the soil's thermal properties, of the total length of geoexchangers required to meet thermal needs.
4. Iterative analysis to verify the system's working temperature based on the hypothesis made for the chosen geoexchange system, both on an annual and decennial basis.

It should be noted that the particular heating requirements of the EGPT process follow seasonality only in part and involve energy consumption mainly by the preheater boiler: higher gas consumption during winter, but almost zero take-up during