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Review

A Review of Groundwater Heat Pump Systems in the Italian Framework: Technological Potential and Environmental Limits

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Abstract: For new buildings in densely urbanised cities, groundwater heat pump systems (GWHPs) represent a concrete, effective solution for decarbonising existing energy systems. Environmental factors must be considered to limit the GWHP system's impact on the subsurface. Particular attention must be given to the long-term sustainability of groundwater abstraction modalities and the development of a thermally affected zone around re-injection wells. Simplified solutions and numerical models have been applied to predict subsurface heat transport mechanisms; these simulations allow researchers to consider site-specific geological conditions, transient heat and groundwater flow regimes, and anisotropies in the subsurface media. This paper presents a comprehensive overview of the current research on GWHPs and discusses the benefits and limitations of their diffusion in Italy. The sources used provide information on and examples of the correct methodological approaches for depicting the induced variations while avoiding the overestimation or underestimation of the impact that GWHPs have on exploited aquifers.

Keywords: geothermal energy system; groundwater heat pump system; urban energy policy; Italy

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1. Introduction

Many technical solutions have been developed to fight climate change (CC), such as various forms of renewable energy (RE), heat storage, carbon dioxide removal approaches, and solar geoengineering approaches. Specifically, RE sources have been investigated as a solution because of their potential for the substitution of fossil fuels with low-carbon alternatives. This focus on CC is evident in the literature; Ref. [1] reports that CC has been used as a keyword in a significant amount of sustainability research over the last three decades.

Since the beginning of 2020, EU Member States were forced to take restrictive actions to slow the spread of COVID-19. In [2], the usage of three petroleum-based fuels was evaluated before and after COVID-19 restrictions were put in place. The authors underlined how those fuel types would provide the best examples of the influence of COVID-19 on the energy supply chain. The initial restrictive measures in 2020 had a significant impact on the use of motor gasoline, kerosene, gas, and diesel in the Member States. During the first half of 2022, energy markets, especially those in Europe, continued to experience higher prices due to uncertainties around fossil fuel supply and economic prospects. Furthermore, there was a strong increase in the second half of 2021, and the Russian invasion of Ukraine has broken all hopes of a fall in energy prices in the short term. In Europe, the situation prompted governments to scale up their ambitions and strengthen existing policies to advance clean-energy transitions and reduce dependence on fuel imports [3].

Despite the described historical and political context, theoretically favourable to the spread of RE sources, only 22% of the energy consumed in the EU was generated from renewables in 2021, according to IEA estimates [3]. The total gross production of derived heat in 2020 was 599 TWh, 4.0% less than in 2019. The highest share of heat was produced from natural gas and manufactured gases (38.2%), followed by RE (31.6%) and solid fossil fuels (19.6%) [2]. In this context, medium- and long-term projections may not meet the current renewable energy sources (RES) target of 32% for 2030. Achieving the newly proposed target of 40% RESs in the EU's energy mix by 2030 requires a fundamental transformation of the European energy system.

As reported by [4], residential and commercial buildings in the EU are responsible for 40% of the overall energy consumption. Low-enthalpy geothermal energy systems represent a promising RE option for meeting buildings' energy needs because of space heating. Among those, ground-source heat pumps (GSHPs) are one of the main technologies used in the building temperature sector. GSHPs are divided into closed- and open-loop plats. The first, also known as ground-coupled heat pumps (GCHPs), is characterised by a heat carrier fluid that flows through a pipe circuit buried in the ground. Conversely, the open-loop ones are also defined as groundwater heat pump systems (GWHPs). The thermal exchange takes place directly with the extracted groundwater [5,6]. These systems were designed to take advantage of the available heat in the shallow subsurface by extracting water from a well or surface water source [7–9]. Closed-loop systems (e.g., borehole heat exchangers (BHEs), energy piles) take advantage of the subsurface resource, defined by a specific local geothermal gradient value. They are based mainly on conductive heat exchange with the surrounding ground, with advection and dispersion involved on a smaller scale. The thermal exchange in GWHPs is mostly advective [10,11]. Because water is reinjected after any heat exchange processes with the evaporator/condenser, a plume of thermally affected groundwater is generated around the plant's injection well. As a consequence, if the construction distance between the abstraction and reinjection wells was not properly designed, a portion of the warmed water can return to the abstraction well, gradually worsening the system's performance. The above-described aspect represents the main environmental limitation to be considered during the open-loop plant design phase.

In March 2022, the European Commission announced its new REPowerEU plan, which aims to install 10 million heat pumps between 2023 and 2028 to reduce EU reliance on Russian gas supplies [12]. Updates to building codes and regulations are intended to improve heat pump diffusion. In Italy, Law 34/2022 introduced urgent measures to control natural gas and energy costs, develop RES, and relaunch industrial and energy policies. As such, there is a clear endorsement for the development of GSHPs supported by both closed-loop and open-loop heat exchangers [13,14]. Policies that support the diffusion of such geothermal technologies must be accompanied by environmental aspect analyses that aim to reduce the effect of GSHP systems on the subsurface. The continued increase of GWHPs implementation and their reinjection of warmer water could have a significant environmental impact on the subsurface, even in the short term, due to local variations in groundwater temperature within the thermally affected zone (TAZ). As thermal plumes can affect adjacent geothermal systems, the TAZ extension must be constantly checked to ensure sustainable use of the systems. In addition, potential chemical and bacteriological impacts on groundwater ecosystems must be evaluated given the geothermal activity in such systems [15–17]. Many numerical models have been developed over the past 20 years to properly simulate the dimensions of the TAZ. These simulations allowed for a better understanding and forecasting of the mechanisms of underground flow and heat transport [18]. However, to perform simulations, the use of expensive, and time-consuming numerical calculation tools and software is required. Therefore, alternative advantageous analytical methods have been proposed to examine heat transport modalities for small plants in simplified systems [19–21].

This article proposes a synthesis of the recent literature on low-enthalpy geothermal energy systems, especially GWHPs, used for heating and cooling buildings in urban areas. For energy statistics, this review relied mainly on the annual global energy statistics available from the Energy Information Agency (EIA), EUROSTAT and Italian GSE, and EurObserv'ER. For scientific results, this work focused on studies conducted by Italian research groups and institutions over the last two decades. The papers considered are articles that were released in recent years or have been widely cited in the field. Among the selected literature, only 23% of the reviewed articles were published in the past 3 years (from 2019 to the end of 2022) and 38% were from the past 5 years (2017–2022).

2. Shallow Geothermal Energy Systems: European and Italian Frameworks

As [22] reports, a significant portion of building energy consumption in the EU, approximately 60–80%, is attributed to space heating. This may be because 64% of EU buildings are more than 40 years old [4]. As such, buildings have significant energy-saving potential [23]. European governments and organizations have recognised the importance of an energy-efficient building sector when facing climate issues; they have become involved in producing a new legislative framework for improving the energy performance of buildings, reducing their consumption, and mitigating greenhouse gas emissions.

Shallow geothermal energy is generally located less than 200 m deep for temperatures less than 30 degrees. The harvested resource can be considered associated with the geological subsurface and/or unconfined aquifers, depending on the use of closed or open-loop geothermal systems. Such energy can be exploited almost everywhere in Europe and has great potential, although it currently provides only 3% renewable heat. Ref. [24] provides data on underground temperature across Europe. The measures reported range up to a depth of 10 km, with a vertical resolution of 1 km. Starting from these data, reference [25] determined the total heat in place, by performing a calculation of the heat contained in the volume of each cell. In addition, by applying the so-named TIAM-ECN model, the increase in the use of geothermal energy in Europe until 2050 was estimated. They also looked at how its expansion could be stimulated by climate policy and cost reductions achieved as a result of technological progress. They completed this analysis for both geothermal power production and heat extraction: for the latter, they forecasted a magnitude of 880–1050 $TWh \cdot yr^{-1}$ by 2050, mainly to provide heat in residential and commercial sectors. Likewise, recent investigations attempted to estimate the geothermal potentials, modelling heat by analysing deep geothermal resources in various Italian regions and reconstructing heat-flow maps for different Italian regions [26–30]. Some of this research was carried out as part of the VIGOR project. The VIGOR project represents a three-year program dedicated to an assessment of geothermal energy potentials and applications in Puglia, Calabria, Campania, and Sicily (Southern Italy). Specifically, the purpose of the VIGOR project was to study a wide range of geothermal applications, from low to high enthalpy. The results reported by [26] highlight how regional maps of deep reservoirs, temperature data, petrophysical parameters, and flow properties from hydrocarbon industry data can provide a significant base of geothermal energy for direct heat and power production. An estimated $4 \cdot 10^7$ PJ of total thermal energy was found to be available up to 5 km deep in the studied areas (total area 60,500 km^2).

Ref. [31] mapped the shallow geothermal potential in the province of Cuneo, a territory in northwest Italy with an area of 6900 km^2. Estimates were calculated for different types of closed-loop installation (BHEs) and GWHPs systems, and the most suitable areas for different technologies were identified. Ref. [32] performed a regional scale assessment of the potential for a shallow alluvial aquifer in the Po plain (northern Italy) to host low-enthalpy geothermal systems. Ref. [33] proposed a study of the geological, hydrogeological, and thermophysical properties of the subsoil in the lower Metauro sedimentary valley to highlight the area's thermal exchange potential; the study was carried out using only publicly available data. Four main zones were identified based on geothermal potential, which is mainly controlled by the bedrock lithotype and the saturated conditions of the sedimentary infill. A better knowledge concerning the potential use of shallow geothermal energy may come from consulting the bibliographical tools and the map of geothermal potential developed by the different Italian Regions.

A GSHPs comprises three basic elements: a ground heat exchange loop (i.e., closed and/or open-loop), the heat pump, and a heat distribution system. The European heat pump market has expanded significantly in the last 5 years: despite negative consequences due to COVID-19, 1.6 million heat pumps were installed in EU countries in 2020, a 5% increase from 2019, with Italy, France, and Spain leading in this sector. Heat pumps can be differentiated based on their energy source: air, water, or ground. Air-source heat pumps dominate the European market. In 2021, the top three European markets were France, Italy, and Germany, which recorded an increase of 28% for the year. Other countries with significant market growth included Italy (+64%), Poland (+60%, mostly due to coal phase-out), France (+36%), and Switzerland (+20%). GSHPs have the second-largest market share worldwide after air-source units [12].

Around 100,000 ground-source units were sold in 2020 in Europe [34] (Figure 1A). Figure 1B shows the split of RE production from heat pumps at a country level. France produces the most RE, followed by Sweden, Germany, and Italy. Within Italy, the air/air heat pump market is the most dominant.

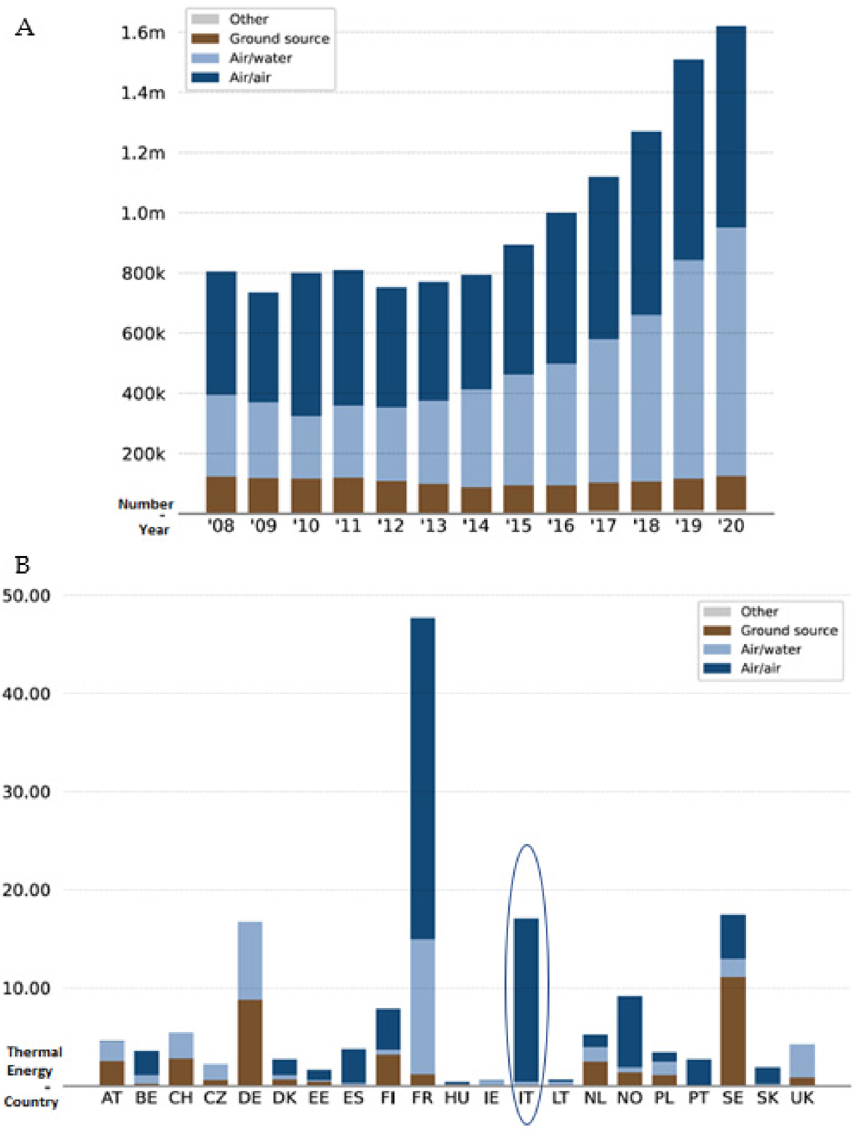

Figure 1. (**A**). Heat-pump market by type (2008–2020); (**B**). Thermal energy provided per type per country in 2020 (in TWh) (modified from [34]).

Based on the official national report [35], the share of geothermal heat production in the total thermal sector in Italy is 2%. At the end of 2020, the installed capacity of geothermal energy for thermal use exceeded 1300 MWh. The main sector utilising this energy was space heating for buildings, which accounted for 41% and 49% of installed capacity and energy use, respectively. GSHPs accounted for 43% of the total installed capacity and about 36% of the total energy [14].

Despite the above-mentioned data availability, to date, the absence of a national census of geothermal systems with heat pumps constitutes a limitation to the diffusion of shallow geothermal systems. Only a very few local and regional authorities have a plant register. In addition, the absence of a univocal regulatory framework means that the few data available are highly fragmented and are difficult to compare because they refer to different contexts and plant types. In some cases, the data refer to GWHPs in general, while in other cases, they refer only to closed-loop systems. The work proposed by [36] is a guidance tool for consulting existing policy issues and legislative instruments in the field of geothermal surface energy at the European level. The authors proposed in [36] a concise and helpful review, analysing fourteen countries: Croatia, Cyprus, France, Greece, Italy, Latvia, Lithuania, Poland, Portugal, Serbia, Slovenia, Spain, Sweden, and Turkey. Considering the Italian legislative framework, competencies have been divided between central and local authorities, depending on several factors, mainly exploited resources, type, and size of the installation. Unlike closed-loop schemes [37], open-loop installations are subject to authorization for drilling, groundwater extraction, and groundwater reinjection, as are any other groundwater wells (D.Lgs. 152/2006) [38]. In addition, GWHPs cannot be installed in water protection areas (e.g., drinking-water extraction areas) and must be restricted to shallow unconfined aquifers. On the contrary, the recommendations are found only in a few regional guidelines. In the Piedmont Region (north-western Italy), local authorities in charge of the authorization process for GWHP systems usually allow a maximum temperature difference in the well-doublets of 7 °C. Competent offices also require the prediction of thermal plume evolution after the first year or season of plant operation by performing numerical simulation models. Some technical standards are available at the national level [39–42] for the design, installation, and environmental aspects of geothermal heat-pump systems. In addition, a monitoring system consisting of at least four piezometers (four different monitoring points) is required in the Piedmont Region for large BHE fields. A yearly report on the monitored data must be produced by the owners and delivered to the permitted authorities.

3. GWHP Systems: Technological Potential and Environmental Limits

GWHPs have the potential to be one of the most suitable technologies used for the heating and cooling of residential buildings and for being implemented in new-generation district heating networks in urbanised areas. They were designed to extract the heat available in a shallow aquifer by abstracting water from a well, passing it through a heat exchanger, and discharging water into an injection well or nearby river [43]. In GWHPs, the heat-pump system connects the shallow aquifer through a production well which is composed of a column of slotted screens. A submersible pump is installed above the top of the well-screen. As [44] reports, the performance of GWHPs depends strongly on the thermal loads required for the building's heating and cooling, the heat pump design characteristics (e.g., compressor efficiency and heat exchanger configuration), and aquifer characteristics (e.g., the undisturbed temperature of the aquifer, thermal and hydraulic conductivity of geological formations). Large flow rates, of the order of tens or even hundreds of L/s, can be subtracted to supply a large quantity of thermal power (MW). Water must generally be reinjected into the same aquifer to avoid depletion, depressurization, and induced settlements into the ground. Fouling and clogging are two of the major water-quality problems that can occur with open-loop GWHPs [45].

In GWHPs, the main environmental limitation is represented by the development of a TAZ in aquifers, even in the short term. The ambient aquifer temperature is continuously disturbed as cold or warm plumes develop during the operations of the geothermal plant. TAZ plumes represent a potential anthropogenic source of pollution; they pose a risk to groundwater down-gradient users, and they also affect the sustainability of geothermal well systems. In addition, reinjected water has a different temperature than the undisturbed aquifer (i.e., colder when the plant operates in heating mode, and hotter when it operates in cooling mode), and returning that water to the abstraction well can present a major technical and design issue (i.e., the thermal feedback phenomenon) [7]. Avoiding adverse effects on adjacent geothermal systems through a TAZ produced in the subsurface prediction is required. As previously reported in Chapter 2, correct estimations of thermal plume evolution and dimensions associated with a new open-loop plant are required by the competent offices of different Italian authorities.

Many authors have addressed the thermal feedback issue mainly by considering homogeneous and porous media or developing methods to analyse heat transport for small plants in simplified systems characterised by conduction–advection-dominated processes [46,47]. According to [20], the TAZ length (L_{pl}) can be approximated by Equation (1), while the maximum down-gradient width (W_{pl}) is defined by Equation (2) (Figure 2):

$$L_{pl} = v_d \frac{S_{VC_{wat}}}{S_{VC_{aq}}} t \tag{1}$$

$$W_{pl} = \frac{Q_{pl}}{m v_d} \tag{2}$$

where Q_{pl} is the fraction of the maximum injected flow rate ($m^3 \cdot day^{-1}$) which is not recirculated to the abstraction wells; $S_{VC_{wat}}$ and $S_{VC_{aq}}$ are the volumetric heat capacity of the water and the saturated aquifer, respectively (measured in J/km^3); v_d is the groundwater flow velocity (in m/s); t is the simulation time; and m is the aquifer thicknesses (in m).

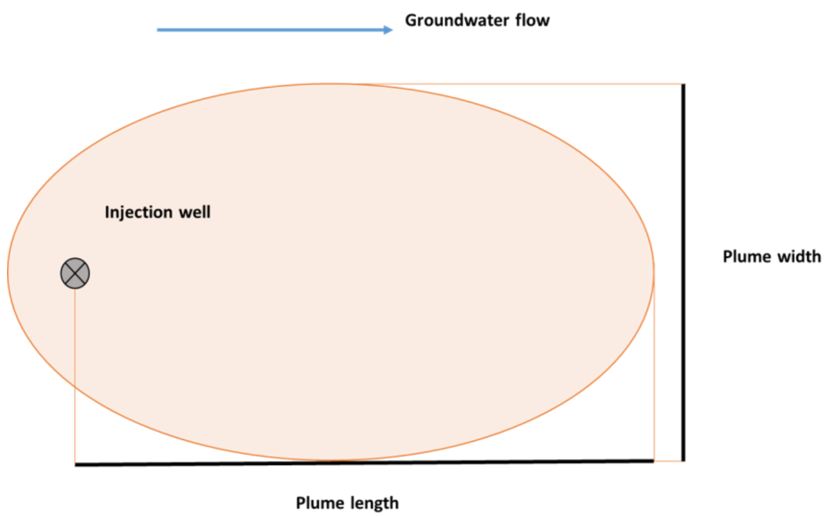

Figure 2. Simplified representation of the TAZ plan view (modified from [44]).

Analytical solutions, like that proposed by [20], have several advantages, particularly for geothermal installations with limited dimensions. Namely, it reduces the computing time and technical complexity required for the plant design. Conversely, the applicability of such solutions to complex plants must be properly verified. To allow the application of an analytical solution, indeed, there are many assumptions concerning site-specific characteristics that should be validated. Moreover, analytical solutions turn out to be valid and have been defined for steady abstraction and reinjection flow conditions in terms of discharge rate, temperature variation in the heat pump, and temperature of the reinjected groundwater. The described constraints can limit their applicability because steady operating arrangements are usually unrealistic. The ordinary functioning conditions of open-loop GWHPs are time-variable. As described in [44], in modern plants, installed technologies are continuously able to modify the operating conditions of the specific components, matching the real energy demand of the building. Cycles in outdoor air temperature on a daily and weekly scale usually induce dynamic functioning in the systems using the heat pump, abstraction wells, and reinjection wells. As a result, the pumping rate in the abstraction wells (with the corresponding reinjection rate) and the temperature of the reinjected groundwater are time variables. Figure 3A,B, as an example, describes the variation in pumping rate and reinjected water temperature during the 2016 summer operation period of the Politecnico di Torino GWHP (Piedmont Region, north-western Italy). The reported values were recorded in correspondence with the Politecnico di Torino GWHP injection well (P4) using a multiparametric probe which records hourly values for both injection rate (Q) and water temperature variation (T). Q and T parameters fluctuate weekly (with a Monday-to-Saturday weekly cycle) and daily (with a 7 a.m. to 6 p.m. daily cycle) depending on energy demand during each summer-operation period. As shown in Figure 3A, the maximum extracted flow values are approximately 0.028 m^3/s. For the reliable modelling of complex geothermal systems, such as the one described, transient flow conditions should be considered for both discharge rate and reinjection temperature.

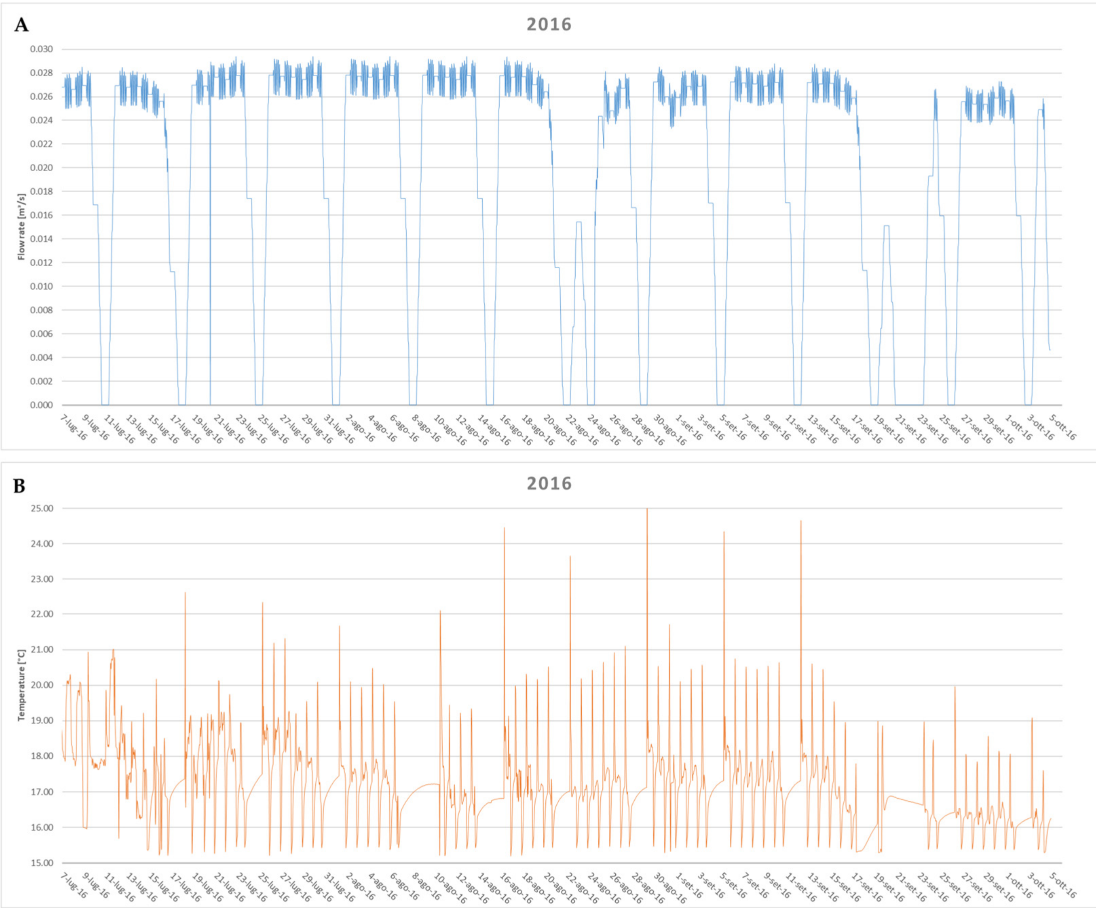

Figure 3. Politecnico di Torino (Turin plain, northwest Italy) 2016 plant-functioning season: (**A**) Pumping rate variations; and (**B**) reinjected water-temperature variations.

Transient flow conditions have been successfully modelled through numerical simulation tools and applied to shallow aquifers in different geological and hydrogeological contexts.

Findings described by several Italian scientists concerning the modelling work of the induced variations that GWHPs have on the aquifers are presented below.

Ref. [48] presents a study on the feasibility of providing heating and cooling using an open-loop GWHP for a commercial building in Rovigo, located in the Po River Plain (Italy). The differential temperatures generated in the exploited aquifer of the Eastern Po alluvial plain (Rovigo City) were modelled through the numerical code FEFLOW. In addition, the consequences of this induced variation on the GSHP system, as well as ways to reduce these consequences, were analysed. Ref. [49] performed different subsurface simulations of the shallow aquifer in the Turin plain, calculating the TAZ using hourly discharge flow and temperature data (i.e., real plant-functioning functions) and then recalculating the TAZ using average daily, monthly, and seasonal energetic equivalents. In their work, the authors describe how the quality of the simulations was satisfactory only when hourly, daily, or monthly flow rate and injection temperature data were used. The seasonal averages were not suitable for reliably assessing TAZ development. Ref. [50] considered the similarity between solutes and heat transport within aquifers. They simulated scenarios for heat-pump operation in the Canavese power station, which has a maximum water withdrawal rate of 0.3 m^3/s. The developed MT3DMS code was compared with a groundwater flow model built on a regional scale (Lombardy Region) with the MODFLOW code. Their results confirmed the impossibility of reinjecting the entire flow drawn from the wells due to the significant thermal interference produced. In addition, ref. [51] developed a useful open-source numerical code, which solves the hydraulic and thermal transport problem of a well-doublet in the presence of a subsurface flow. The code, called the Thermal Recycling Simulator, is based on a finite-difference approximation of the potential flow theory. The validated method was implemented in MATLAB software and allows for the calculation of the time series of the extracted and injected water temperature in a GWHP with a constant flow rate and temperature. Ref. [52] described the results obtained from a comprehensive sensitivity analysis, performed to assess the influence of hydrodynamic, thermal subsurface properties, and the plant setup on the size of the TAZ. The authors focused the analysis on the length and width of thermal plumes and on their time evolution: among the hydraulic and thermal subsurface parameters, the most influential for both plume length and width is the Darcy velocity (v_d). As such, estimating the hydraulic conductivity values employing reliable in situ tests is essential to perform realistic simulations, avoiding major errors in plume size estimations. Ref. [53] explored the possibility of a development project with a geothermal well-doublet in the Pisa plain, Italy. Variations in temperature and pressure conditions in the aquifer under different exploitation scenarios were evaluated. For doing that, a 3D numerical model was performed, defining the coupled thermal-hydraulic evolution of the local, deep carbonate aquifer exploited with a single geothermal doublet.

Conversely, ref. [54] performed a hydrogeological characterization of the city of Milan (Lombardy, northern Italy) by developing a proper 3D model of the aquifer. The conceptual model was implemented in the numerical model MODFLOW-2000 [55], a well-known modular code able to simulate groundwater flow in a 3D heterogeneous domain. Their study discussed the hydrogeological hazards for existing underground structures and infrastructures (i.e., metro tunnels and stations) that arose from the upward trend in the water table observed in the urban area of Milan (northern Italy). Ref. [56] performed a preliminary investigation of the interactions at the city scale for Turin (Italy). Data from existing installations were collected and thermo-hydro finite element analyses were conducted to establish the actual ground thermal conditions and forecast their evolution. This allowed the researchers to identify the areas of the city where temperature anomalies could be expected due to thermal exploitation. Ref. [57] developed and validated a hydrogeological model of the shallow aquifer system in Villaverla (northeast Italy) using version 7.1 of the FEFLOW numerical code, which allows users to also define thermal plume and aquifer parameterization. This is a useful methodology that could be applied to properly check and define aquifer parameters, which are a prerequisite for effective water-resource management and environmental protection. Ref. [58] presented a holistic city-scale 3D FEM model to introduce possible thermal management applications in the Milan metropolitan area, such as: (1) understanding the hydrothermal regime of the urban aquifer by disentangling the thermal contributions of natural and anthropogenic heat sources, (2) quantifying the geothermal potential, and (3) investigating the effects of urbanization and CC scenarios.

4. Results and Discussion

Underground water resources represent a renewable energy source for large cities in urbanised areas. Many factors drive the development of the GWHP market. New subsidies such as grants, loans, or tax credits, as well as national and regional policies, must help offset the upfront costs of a heat pump system by facilitating its spread [59,60]. Despite their potential in terms of energy efficiency, the environmental impact of GWHPs is one factor that limits their development in densely populated neighbourhoods. Thermal interferences among different users are common phenomena in groundwater heat exchange systems, particularly in historical town districts where the distances between wells are necessarily close due to buildings' proximity and the possibility of other group plants in the neighbourhood. The construction of each new open-loop geothermal plant cannot be separated from the development of a model which can forecast a developing TAZ during and at the end of consecutive plant-operating seasons. The use of complex numerical open-loop models is often required from local authorities to allow analyses of thermal perturbations using a case-by-case approach, thereby obtaining the best planning and utilization of geo-exchange plants in complex systems. To date, several numerical codes have been made available to simulate heat transport in groundwater: MODFLOW-2000 [55], FEFLOW [61], HST3D [62], SEAWAT [63,64], and TOUGH2 [65]. Through the analysis of scientific papers published over the last decade (since 2013) relating exclusively to Italian literature, it is possible to state that many authors have been involved in the development of models using the numerical codes FEFLOW [61] and MT3DMS, combined with MODFLOW [66]. Local- and regional-scale hydrogeological system models have been produced, which allows for the definition of strategies that depict the variations in shallow aquifers induced by GWHPs; the models also offer an understanding of how such induced variations may be reduced based on the geological features of each system. As demonstrated, the re-injection of water into an aquifer creates a thermal plume, whose dimensions and geometry depend primarily on the properties of the geological formations of the subsoil and, in particular, on the operating conditions of the system and the cooling/heating demands. Testing different heating/cooling daily timetable schemes can help in reducing the risk of thermal feedback between extraction and injection wells, thereby preventing the GWHP system from becoming uneconomical and energetically inefficient. For good-quality numerical simulation results, thus avoiding overestimation and underestimation of environmental impact, the use of average seasonal temperature and injection rates should be avoided. In addition, the groundwater velocity and the thermal properties of the soil (i.e., horizontal hydraulic conductivity; vertical hydraulic conductivity; effective porosity; volumetric heat capacity of the solid; heat conductivity of the solid; dispersivity) must be clearly defined because they influence both the medium- and the long-term evolution of the plume. Finally, defining new strategies for avoiding reinjecting the entire flow rate drawn from the wells for high-efficiency open-loop heat pump capacity is increasingly required to ensure the diffusion of such plants in urban areas. A practical solution that aims to reduce thermal interference is to discharge part of the water into surface channels or main rivers.

The potential of the simplified methods available in the literature for simplified systems characterised by conduction–advection-dominated processes should not be overlooked. The use of such analytical solutions can create several advantages: they can keep costs down during the design phase and reduce the calculation time and technical complexity required for the specific plant design.

Despite the numerous studies conducted and the high level of knowledge in modelling hydrogeological systems, the use of GWHPs in Italy is still limited. This is due to a lack of information on the advantages offered by these systems and their high initial costs. In some cases, these costs may be the result of an oversized design. GWHPs may be erroneously designed, and the payback time could increase due to the system's inefficiencies. Only predicting a plant's hydrogeological sustainability with high accuracy during the design stage of GWHP systems can reduce their initial costs, limiting the payback time. Furthermore, the lack of an Italian national census of geothermal systems equipped with heat pumps and a single national regulatory framework means that the data available are highly fragmented. As reported in Chapter 2, current national legislation related to withdrawals and discharges into aquifers creates a suitable framework for the protection of groundwater and allows for the best configuration of each plant. However, they also make the related regional administrative procedures quite complex. For certain regions (e.g., Piedmont Region), the technical documentation varies according to the discharge capacity of the project. The support of a professional in charge is essential in every making of the process of submission of the request for discharge and withdrawal. In effect, the timing for obtaining permits is not always consistent with the timelines for building construction.

In the European context, the Italian heat-pump market turns out to be one of the largest, with a 13–18% market share in the last 10 years [67]. However, in terms of primary energy sources, air-based heat pumps cover almost all of the market (around 97%), whereas ground-based pumps make up almost 3% of the market. The water-based pumps contribute a negligible amount. In addition to the matter of cost, the low share of GWHP sales is due to the existing space-heating system that needs to be retrofitted, replacing old radiators with new-generation ones. To date, the former represents over 90% of the current domestic equipment in households.

Given the above-described considerations, efforts are needed in different directions. Competent authorities should strive to overcome the limits imposed by existing urban and regional regulations, making them as simple and time-efficient as possible. In addition, it is necessary to pursue the policy of encouragement to deduct expenses related to the purchase and installation of new radiators, radiators, and floor or wall panels (e.g., Italian Conto Termico 2023). Promoting renovation incentives for buildings (i.e., Superbonus 110) is still required.

The political context described in Chapter 1, coupled with the new European REPowerEU plan and the updates in Italian building codes and regulations (Law 34/2022; DL 30 September 2022) can become the main tools for the diffusion of green-energy sources such as GWHPs and lead to remarkable developments in the GSHP market, supported by both closed and open heat exchangers [68,69]. In urban areas, the increase in GSHPs and GWHPs is driven by two of the seven NGEU Flagships (power and renovate) of the Next Generation EU. Improving the energy efficiency of public and private buildings is the only way to achieve the EU's climate goals.

5. Conclusions

The energy crisis that Italy and the rest of Europe have experienced determines the need for immediate changes regarding the more widespread use of RES such as geothermal energy, especially for thermal applications associated with heating and cooling buildings. GSHPs are increasingly playing a leading role in European and national energy policies. Due to their energy efficiency, GWHP systems represent one of the major technologies to encourage diffusion at different scales. Aquifers become a source of renewable energy for large cities in urbanised areas. Among the environmental aspects that must be considered to minimise the impact of a GWHP installation on the subsurface, attention must be given to (1) the long-term sustainability of the groundwater abstraction modalities (i.e., well-doublet configuration) and (2) the development of a TAZ around the reinjection wells. Both analytical solutions and numerical models have been applied in the past several years to appropriately predict and examine subsurface heat-transport mechanisms, determining the portions of the aquifer subjected to thermal alterations. The availability of numerous studies aimed at investigating Italian subsurface hydrogeological systems, in the context of the current socio-economic-political situation, represents a fundamental key tool to be exploited to encourage the diffusion of GWHPs in Italian urban areas, overcoming obstacles to the spread of GWHPs. The mentioned scientific resources provide information and examples of correct methodological approaches for depicting induced variations, as well as avoiding the over- or underestimation of the impact of GWHPs on exploited aquifers.

The current historical context, besides being favourable to the diffusion of GWHPs, offers some hope for a future characterised by increasingly positive trends in shallow geothermal energy solutions. At a national scale, law 34/2022 and the DL 30 September 2022, as well as new simplifications for the installation of geothermal probe systems for local geothermal uses, represent the first confirmation of authorities' intentions to encourage the diffusion of such systems.

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