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Geothermal Technologies: Progress Through Examples of Sustainable Applications in an Urban Context / Gizzi, M.; Berta, A.; Vagnon, F.; Taddia, G.. - In: GEAM. GEOINGEGNERIA AMBIENTALE E MINERARIA. - ISSN 1121-9041. - ELETTRONICO. - 171(2024), pp. 51-57. [10.19199/2024.171.1121-9041.051]

Availability:
This version is available at: 11583/2998213 since: 2025-03-10T18:21:36Z

Publisher:
Patron Editore S.r.l.

Published
DOI:10.19199/2024.171.1121-9041.051

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22 May 2025

DX.DOI.ORG//10.19199/2024.171.1121-9041.051

Geothermal Technologies: Progress Through Examples of Sustainable Applications in an Urban Context

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Geothermal energy, sourced from the geological subsurface and/or unconfined aquifers, plays a crucial role in addressing the energy and environmental challenges of urban areas. By leveraging closed-loop and open-loop geothermal systems, cities can reduce greenhouse gas emissions and enhance energy sustainability. As urban energy demands grow, geothermal systems offer a promising solution, seamlessly integrating into existing infrastructures. Open-loop systems, with their ability to manage large water volumes and provide continuous heating and cooling, are particularly suited for high-demand buildings. While retrofitting existing structures poses challenges, the long-term benefits include energy efficiency, cost savings, and reduced emissions. Although regulatory frameworks in Italy have advanced to facilitate geothermal installations, particularly for closed-loop systems, complexities remain for open-loop systems due to specific regional administrative procedures. Raising awareness among policymakers and the public, along with fostering collaboration between the public sector, private enterprises, and research institutions, is essential to promoting geothermal adoption. Case studies exemplify the potential of geothermal systems to mitigate urban environmental impacts and support sustainable urban energy futures. Investing in these technologies is vital for fostering greener, more resilient cities and contributing to a global shift toward renewable energy.

Keywords: *renewable energy, geothermal energy system, ground source heat pump (GSHP), groundwater heat pump (GWHP).*

1. Introduction

The urgent need to reduce CO_2 emissions in urban areas is driven by the rapid pace of urbanization and the growing impact of climate change. Cities are major contributors to global carbon emissions, primarily due to transportation, industry, and energy consumption. Reducing these emissions is crucial for improving air quality, mitigating global warming, and enhancing public health. In this context, the importance of renewable energy sources cannot be overstated. By transitioning to clean energy – such as solar and geothermal – urban areas can significantly lower their carbon footprint while fostering a sustainable future. At a regional scale, the Climate Plan of the City of Torino is a key initiative to address the climate crisis and promote sustainable development at the local level (Comune di Torino, 2022). Like many other large cities, Torino is particularly vulnerable to the impacts of climate change, such as heat waves, air pollution, and water resource scarcity. The plan aims to reduce greenhouse gas emissions, improve energy efficiency, and promote renewable energy, contributing to the transition toward a more resilient and sustainable city. Torino has set ambitious goals for reducing carbon emissions in line with European directives, aiming for significant emission cuts by 2030 and achieving carbon neutrality by 2050. The plan aims to improve energy efficiency in public and private buildings, encouraging the adoption of more energy-efficient technologies, such as low-emission heating and cooling systems. Additionally, it seeks to increase the use of renewable energy sources like solar, wind, and geothermal energy. Both a program aimed at making the city more resilient to the effects of climate change through integrated management of land and natural resources and projects to improve energy management efficiency and promote the intelligent use of resources using data and digital technologies are specific initiatives of the Climate Plan of the City of Torino. Identifying the role that geothermal energy can play in this context is not straightforward. Although it is available, it is often difficult to harness effectively. High population density makes it difficult to find space for geothermal wells and may limit access to the land required for installing infrastructure. Existing infrastructure, such as water and sewage systems, as well as historical or architecturally significant buildings, can further complicate the integration of geothermal systems. Additionally, local geology does not always favour the exploitation of underground heat, as the depth or quality of geothermal resources can vary significantly from one area to another. This necessita-

If there are references to colour figures in the text, the articles are available in open-access mode on the site www.geam-journal.org tes thorough geological studies and advanced technologies to ensure efficiency. Berta *et al.*, 2024 and Berta & Taddia, 2024 proposed a preliminary examination of the geological and hydrogeological contexts, at urban and site-specific levels respectively, to define their attitude toward installing open-loop groundwater heat pumps (GWHPs) with a limited environmental impact. The stable aquifer temperatures of 13-15 °C, independent of external climate, make it a valuable resource for this application (Taddia *et al.*, 2019; Barbero *et al.*, 2020). Besides, based on the G.POT method, geothermal energy potential was described by Casasso *et al.*, 2016 for the Piedmont Region. The evaluation was based on a spatial distribution of thermal and hydrogeological parameters. After, Baralis *et al.*, 2024 demonstrated the great potential of exploiting locally available geothermal energy in the Torino central districts by proposing a new combined approach called rOGER (acronym for Opti mising GEothermal Resources in urban areas).

The focus of this work will be centered on emerging geothermal technologies, e.g., open and closed loop systems as well as energy geostructures, with a particular emphasis on innovative applications and their potential to contribute to urban sustainability. Indeed, cutting-edge geothermal technologies could play a key role in achieving sustainable urban development are proposed. Examples of application concerning the specific geological and hydrogeological context are also analyzed.

2. Geothermal technologies: from closed to open-loop systems

Geothermal energy, traditionally used for heating and power generation, is now being explored in new ways, such as through closed-loop systems, open-loop systems, energy geostructures, enhanced geothermal systems (EGS), and hybrid systems (García-Gil *et al.*, 2018; Budiono *et al.*, 2022; Liu *et al.*, 2023; Gizzi *et al.*, 2023; Dokmak *et al.*, 2024; Sadeghi *et al.*, 2024). Many geothermal solutions documented in the literature are not well-suited for the unique challenges of urban environments, especially those located in alluvial plain geological context, such as Torino plain. Closed-loop geothermal systems are at the forefront of geothermal technology, offering innovative and sustainable solutions. Their versatility and numerous benefits have made them a popular choice for a wide range of applications, accelerating the shift towards a cleaner and more sustainable energy future (Beckers *et al.*, 2022). Closed-loop groundsource heat pump (GSHP) systems exchange heat with the subsoil through one, or multiple borehole heat exchangers (BHEs). They are widely used for residential and commercial space heating, cooling, and domestic hot water production. During the winter, the fluid extracts heat from the ground and transfers it to the building for heating. In the summer, the process reverses, with the fluid absorbing heat from the building and releasing it into the ground to provide cooling. This is possible because the ground maintains a fairly constant temperature at a certain depth, allowing for efficient heat transfer all year round.

Open-loop geothermal systems are a type of geothermal system that directly interacts with groundwater. In this system, groundwater is extracted from an aquifer, circulated through a heat exchanger to extract or release heat, and then returned to the aquifer. This process allows for the transfer of heat between the ground and the building or process being heated or cooled. Water is pumped from a suitable aquifer. The extracted groundwater passes through a heat exchanger where it either absorbs or releases heat, depending on the desired application (heating or cooling). Thus, the modified water is then returned to the aquifer, completing the cycle. Therefore, they enquire a reliable and sufficient groundwater source. Geological bodies and groundwater in the Piemonte plain could represent an important source of clean geothermal energy and seemed particularly suitable for a wide implementation of groundwater heat pump (GWHP) systems (Berta *et al.*, 2024; Gizzi *et al.*, 2024).

Together with the use of ground source heat pump (GSHP) and groundwater heat pump (GWHP) systems, underground geotechnical structures, such as deep and shallow foundations, diaphragm walls, tunnel linings, and anchors, have recently started to serve as energy geostructures. This is achieved by integrating absorber pipes directly into these structures, allowing them to harness geothermal energy (Laloui *et al.*, 2011). Energy geostructures both provide structural support while also functioning as heat exchangers with the ground, enabling the heating and cooling of buildings and infrastructure using low-enthalpy geothermal systems. The primary advantage of these geostructures compared to standard geothermal systems is the significant reduction in installation costs and construction time. This is mainly due to the dual use of structural elements that would have been built regardless, such as foundations, diaphragm walls, and tunnel linings. However, the design and implementation of energy geostructures require additional considerations, such as thermal interactions with the soil and long-term performance. Over the past decade, several research projects and real-world case studies have focused on these aspects, monitoring and analyzing the performance of energy geostructures to optimize their efficiency and durability. The key differences with respect to conventional shallow geothermal systems are mainly due to the geometry, which is imposed by the geotechnical project, and the need for ensuring that the primary structural role is always guaranteed (Aresti *et al.*, 2024).

Recent studies have also provided new insights into EGS in Italy, including an assessment of super-hot (>450°C) EGS potential at Larderello (Feng *et al.*, 2017). These studies highlight the importance of temperature modeling and understanding fluid dynamics for effective EGS exploration and development.

Starting from the consideration that drilling costs account for the majority of geothermal project costs, authors have started to work on the reuse of hydrocarbon well for geothermal energy production Alimonti *et al.*, 2016; Alimonti *et al.*, 2018; Lo Russo *et al.*, 2020; Gizzi *et al.*, 2021). Recent numerical investigations have been proposed about the comparison between open and closed geothermal systems advantages for that purpose (Nassan *et al.*, 2024). Italy has substantial potential, with 847 active onshore wells in various operational states (Alimonti *et al.*, 2024). In Gizzi, 2021 both the site-specific geological and thermo-physical properties of a selected case study, i.e., Trecate 4 disused hydrocarbon well, were properly considered for analysing its conversion by means of closed-loop configurations (Coaxial and U-tube wellbore heat exchangers). Even for variable flow rate values, an ever-higher output working fluid's temperature and thermal power for the coaxial configuration is recorded. Besides, Alimonti *et al.*, 2024 following an assessment of the geothermal resources of case studies located in the province of Novara and Viterbo, demonstrated how reusing depleted hydrocarbon wells for geothermal district heating can be a sustainable opportunity in Italy. Geothermal data, including bottom hole temperature (BHT), play a crucial role in understanding the thermal state of the subsurface, thus the possibility to be employed an already existing well in the exploration of geothermal resources (Barrera Acosta *et al.*, 2024).

3. Geothermal technologies: results from practical applications in Torino City

As of today, within the urban area of the City of Torino, there are 44 open-loop geothermal systems (GWHPS) (Berta *et al.*, 2024). Information regarding the operation of these systems, particularly the flow rates re-injected into the aquifer via injection wells, can be obtained by reviewing the specific documentation that authorizes the discharge of water volumes into the aquifer (Unified Environmental Authorization – AUA) (Figure 1). Among these open-loop geothermal systems, some are used to provide heating and cooling for key university buildings at the Politecnico di Torino. The open-loop geothermal systems at Politecnico di Torino main building include three 35-meter deep control piezometers located downstream of the injection wells (S2, S3, S4), as well as five abstraction and three injection wells with similar technical characteristics. All components of these geothermal systems interact with the shallow unconfined aquifer of Torino, which has an average temperature of 15°C. The average monthly flow rates extracted from the corresponding abstraction wells range between 3.5 and 9.5 l/s. Since these systems are used solely for summer cooling purposes, these average values pertain to the months from May to October.

Along with the main campus of the Politecnico di Torino, both the Valentino Castle and the Energy Center are equipped with open-lo-

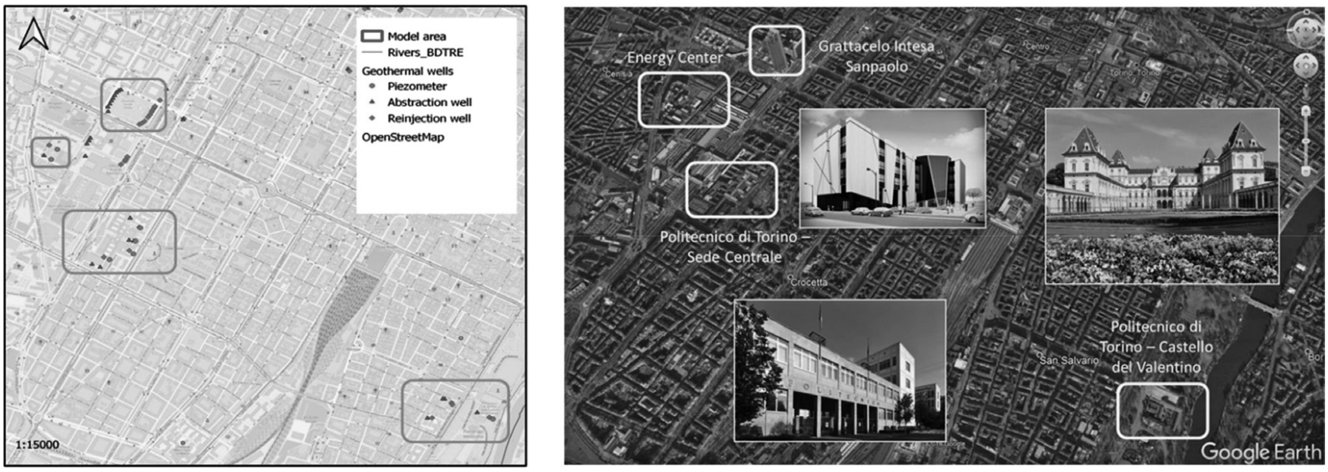

Fig. 1 – Overview of the GWHPs installed in the Politecnico di Torino university buildings (Torino city).

op geothermal systems for the climate control of their premises. An urban-scale numerical model was set up and described in Gizzi *et al.*, 2024 to analyse the impacts on the undisturbed flow regime of groundwater and the temperature field, resulting from the operating modalities of the existing geothermal abstraction wells. In detail, a simulation impact scenario around the main university complex of the Politecnico di Torino is described, considering average extraction flow rates. Findings from the scenario, fixing values for the temperature of water re-injected into the aquifer of 8°C and 21°C respectively for the winter season (6 months) and the summer season (6 months), demonstrated the absence of relevant hydraulic and thermal disturbances (Figure 2). Given a negligible impact, this geothermal solution is currently capable of meeting part of the energy demand related to the buildings' cooling needs.

Berta & Taddia (2024) explored the potential for integrating new open-loop geothermal plants into the district heating network of IREN S.p.A., specifically the IREN Energia section in Torino, Italy. Two case studies were analyzed for this purpose: the Torino Nord area and the Moncalieri area. Data were collected and examined from various sources, including geotechnical surveys and permeability tests. In particular, they analyzed data from 11 geognostic boreholes drilled in 2006 in the Torino Nord area (Case Study 1) for IREN S.p.A., and from 2 boreholes drilled in 2022 in the Moncalieri area (Case Study 2) (Figure 3). Both case studies demonstrated promising conditions for accommodating open-loop geothermal installations, showing geological and hydrogeological suitability while minimizing the risk of interference with nearby systems.

Examples of a virtuous application of geothermal systems for buildings in urban areas is represented by the 166 m high Intesa Sanpaolo Tower and Piedmont Region Headquarters Tower. In the case of Intesa Sanpaolo Tower, groundwater is extracted from the aquifer at a temperature of 14 °C using a network of wells. Throughout the year, this water is utilized for the building's air conditioning, and afterward, it is returned to the aquifer at approximately 20-21 °C (Barla, 2017).

4. Discussion and Conclusions

Geothermal energy can be linked to the geological subsurface or unconfined aquifers, depending on

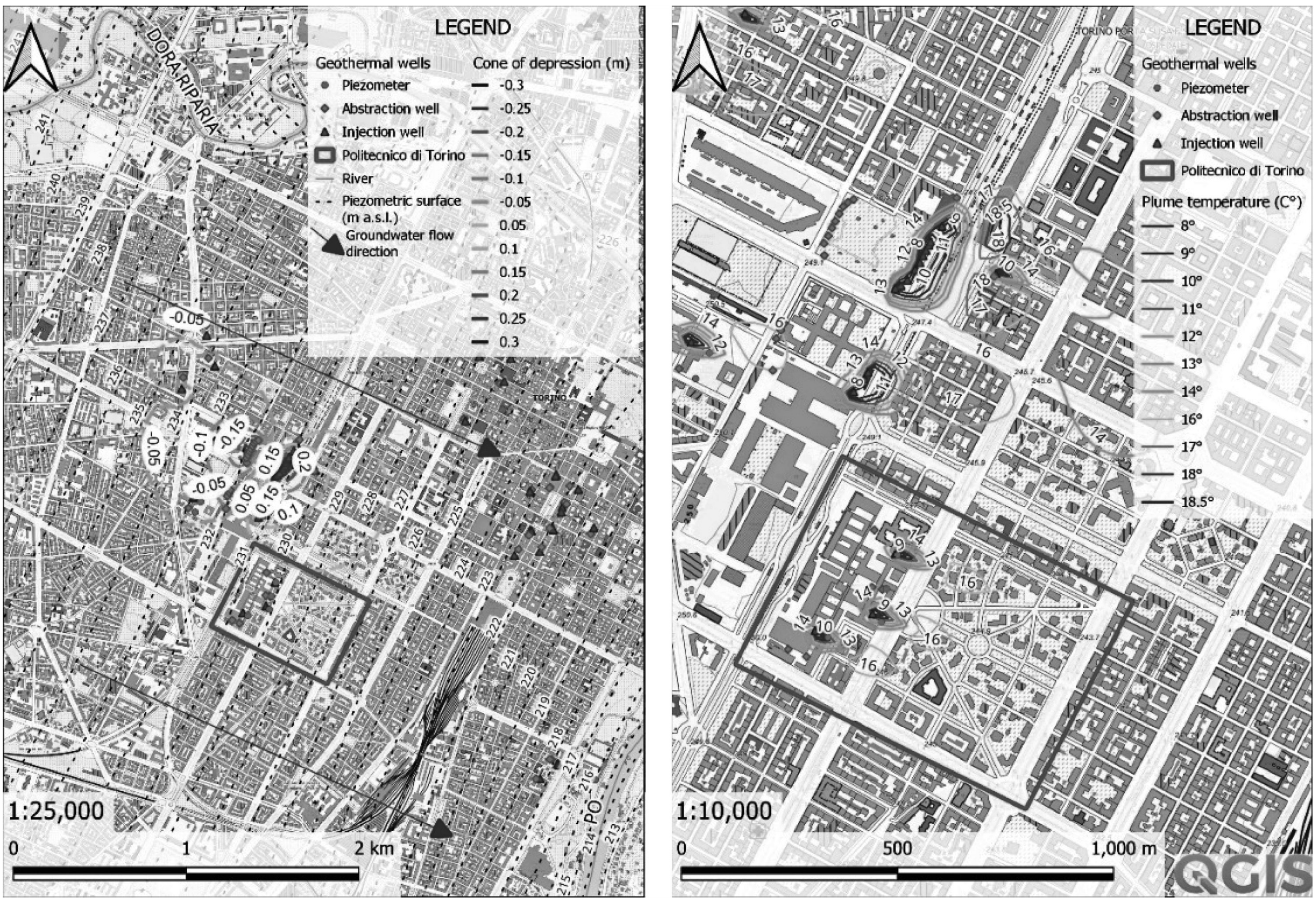

Fig. 2 – Average flow rate (Qmean) scenario's results with cooling/heating operating seasons mode for 6 months/year: a. groundwater flow field disturbances; b. temperature field disturbances (from Gizzi *et al.*, 2024).

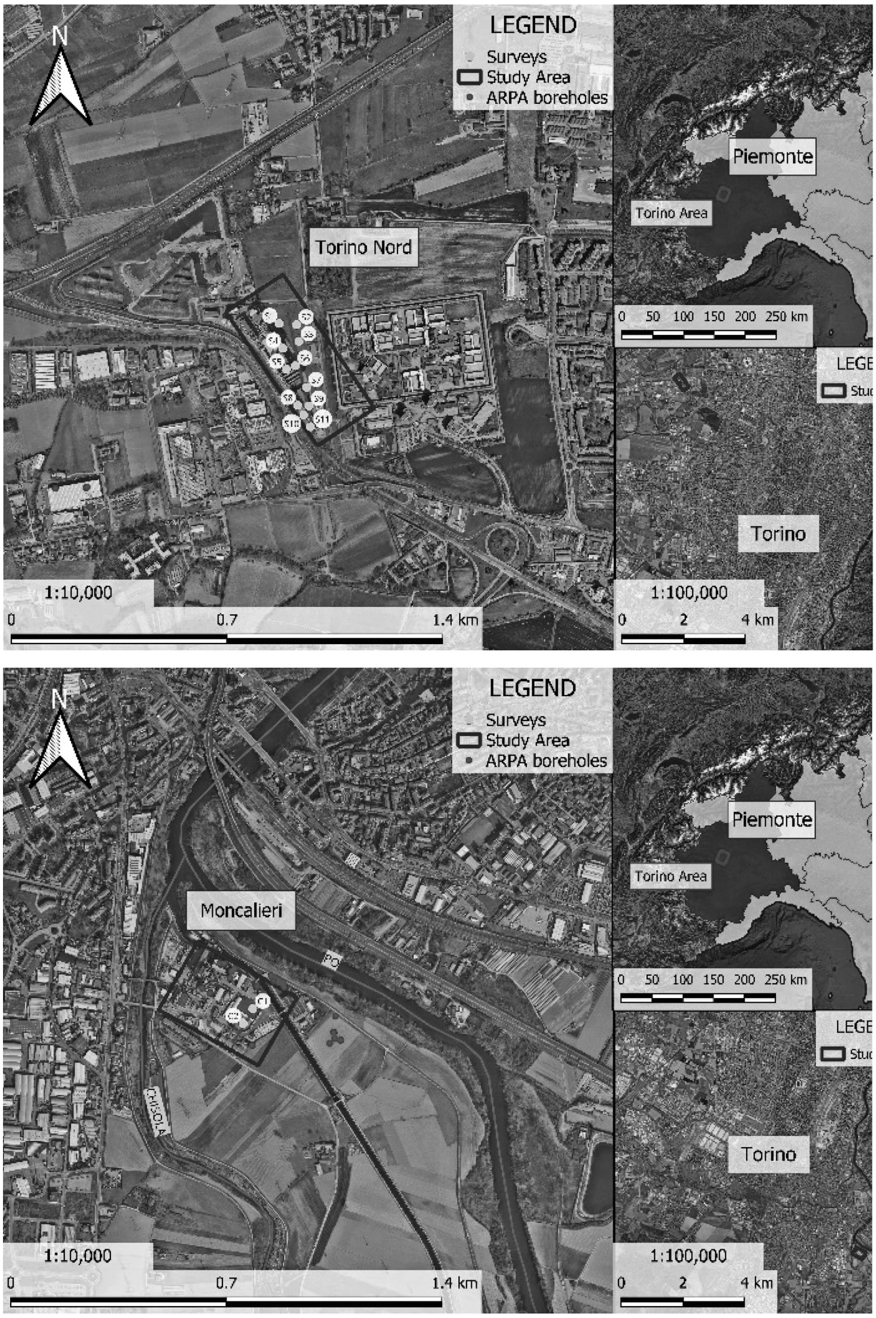

Fig. 3 – Torino Nord and Moncalieri study areas and analysed boreholes location (from Berta & Taddia, 2024).

whether closed- or open-loop geothermal systems are employed. In urban settings, geothermal solutions offer a crucial resource to help tackle modern energy and environmental challenges. Utilizing geothermal energy provides several key benefits, such as lowering greenhouse gas emissions and improving energy sustainability. As cities expand, energy demands rise, making it essential to adopt renewable and innovative technologies. Geothermal systems, like closed- and open-loop configurations can easily integrate with existing urban infrastructure, as discussed in Chapter 3. Open-loop geothermal systems are particularly well-suited for new buildings with high energy demands, such as the Intesa Sanpaolo Tower and the Piedmont Region Headquarters Tower, due to their capacity to handle large water volumes and provide consistent heating and cooling. Additionally, these systems can be adapted to new technologies and regulations, which is vital for large buildings where energy needs may shift over time and regulatory compliance becomes more critical. Retrofitting existing buildings, like the old main building of the Politecnico di Torino, to geothermal systems is more complex. However, switching from conventional cooling systems to geothermal offers several advantages. Geothermal systems are highly efficient, reducing both energy use and utility costs. Since they utilize renewable energy, they also help decrease greenhouse gas emissions, aiding climate change mitigation efforts. Although initial installation costs can be higher, operational expenses are generally lower in the long run due to increased efficiency and low maintenance needs. Moreover, geothermal systems provide a stable and reliable energy source, decreasing reliance on non-renewable energy.

As mentioned by Berta *et al.* (2024), while Italian building codes and regulations regarding the installation of closed-loop geothermal systems (Law 34/2022; DL 30 September 2022) have been adapted to simplify the installation processes, issues persist concerning incentives for the installation of open-loop systems. The current national legislation regarding withdrawals and discharges into aquifers (Article 124 of Legislative Decree No. 152/06) provides a suitable framework for groundwater protection and allows for the optimal configuration of each system. However, it also makes the related regional administrative procedures quite complex. In some regions, such as Piedmont, the technical documentation requirements vary depending on the discharge capacity of the project (Article 29 of the PTA Plan Regulations). The support of a responsible professional is essential at every stage of the process of submitting the request for discharge and withdrawal. Indeed, the timelines for obtaining permits are not always aligned with the timelines for building construction. Working toward harmonizing and simplifying regulations, without neglecting the monitoring and control of the impact on aquifers, is essential.

It is essential to increase awareness among policymakers and the public about the advantages of geothermal energy solutions, while also promoting pilot projects and feasibility studies. The evaluation of results from the geothermal systems installed in the aforementioned case studies can provide valuable insights into their benefits. Cooperation between the public sector, academic institutions, and private companies is vital for developing geothermal district heating networks and introducing large-scale geothermal systems in existing industrial facilities. The adoption of geothermal technologies not only helps reduce the environmental footprint of urban areas but also supports a more sustainable energy future. Investing in these systems is a key step toward building greener, more resilient cities, and driving a positive transformation in the global energy landscape.

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