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Ground Source Heat Pump Systems Applied To Historical Buildings To Improve Their Energy Efficiency

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ABSTRACT

The H2020 EU-funded projects “Most Easy, Efficient and Low Cost Geothermal Systems for Retrofitting Civil and Historical Buildings (GEO4CIVHIC) and Cheap and Efficient application of Reliable Ground Source Heat Exchangers and Pumps (Cheap-GSHPs) developed innovative ground source heat exchangers (GSHEs) and drilling machine components to accelerate the deployment of shallow geothermal systems for heating and cooling for retrofitting existing buildings and in particular the historical ones.

The innovations are focused on resolving the shortcomings in the drilling methods and heat exchangers, introducing the adaptations required in the built environment, including working in narrow spaces that are typical of historical centers, in towns or small gardens by using novel drilling methodology and compact drilling rigs.

In this article the basic principles, barriers, approaches and procedures, as well as the legislation at the base of the geothermal application to historical buildings, including UNESCO World Heritage sites, are described. Some examples (both real and virtual) of geothermal installation in historical buildings are presented, illustrating how the use of geothermal energy systems facilitates the balancing effort between heritage significance and energy conservation.

The results demonstrated that the ground sources heat pumps (GSHPs) are often among the best solutions to match the requirements of sustainable energy with the integrity and authenticity of the Cultural Heritage and its buildings, both in their interior and exterior features. In addition, the GSHP solutions applied during the two projects, as they include a large portion of underground elements (i.e. the borehole heat exchanger field), have minimal visual impact, especially when compared to air source heat pumps and gas boilers, which include external elements (outer units or chimneys), that alter the appearance of the building envelope.

1. INTRODUCTION

Europe has the world's greatest concentration of cultural heritage, including at today 440 cultural sites inscribed in the UNESCO World Heritage List, encompassing monumental buildings, districts of towns and cities and even whole EU member states 'capitals' (https://whc.unesco.org/en/list/&order=region).

Many renewable technology solutions are not always directly applicable in these contexts (i.e., photovoltaic panels, envelope thermal insulation may not be installed). Shallow geothermal can be proposed in some cases (Perry &Jay 2009), and some European projects (www.cheap-gshp.eu, http://www.geo4civhic.eu) are trying to enlarge the target of historic buildings that can apply such technology.

Using the shallow geothermal energy for retrofitting not only existing civil buildings but also historical buildings forming part of our cultural heritage has great potential, making these sites good practices of sustainability by applying innovative sustainable energy technologies. Historical buildings are the material manifestations of immovable tangible cultural heritage. These are considered of heritage significance to current and future generations, based on a different combination of heritage values, including: aesthetic, historical, scientific, cultural, social or of spiritual nature, which can include architectural, artistic, economic, social, symbolic and technological aspects.

Historical buildings differ from other building types by the fact that their envelope, including glazing of openings, has a cultural value, that must be preserved. This implies that no interventions on their building envelope other than restoration works are permitted, thus placing limitations on the energy saving measures that can be applied. As a result, historical buildings are characterized by higher heating and cooling demands, which makes imperative the use of energy efficient heating/cooling systems such as the ground source heat pump systems introduced by the Cheap-GSHPs and GEO4CIVHIC projects.

Historical buildings often require high energy use due to large exhibition spaces that require heating and cooling in order to provide both comfortable conditions for the visitors and employees and at the same time to assure the proper conservation of the housed artefacts and heritage collections (Bernardi, 2008). However, a vast majority of historical buildings are currently equipped with obsolete, inefficient, and sometimes dangerous heating systems, for instance hanging on the walls and operated through electric resistance.

Retrofitting historical buildings bridges the importance of protecting the cultural, artistic, historical value of heritage with the protection of our environment using low impact geothermal systems.

2 LEGISLATIVE FRAMEWORK, RISK AND BARRIERS OF HISTORICAL BUILDINGS

2.1 Legislative framework and permission process

The specific needs and standards related to cultural heritage protection pose many constraints and requirements for the application of mainstream sustainable energy solutions.

The standard EN 16883: "Conservation of Cultural Heritage - Guidelines for improving the energy performance of historic buildings" (EN 16883:2017) is the only guideline at European level currently applicable to historical buildings. This standard, however, refers to the energy improvement of the historical building without a specific reference to ground source heat pumps, describing and providing a systematic procedure for identifying and selecting appropriate measures to improve the energy performance of buildings that match the requirements for built heritage conservation.

EN 16883 highlights that constraints on interventions should respect the building's existing spatial configurations, appearance and exterior building fabric and that any measures that could cause damage to the structural elements should be avoided. Furthermore, interventions should be additive, non-invasive and reversible, in order to minimize their impact on heritage significance and integrity. Both the extent and depth of any interventions should also be minimized following this standard.

The regulation of geothermal system in the retrofit scenarios and in the case of historical buildings is also considered in the context of the regulatory frameworks that include the implementation of the Energy Performance in Buildings Directive 2002/91/EC (EPBD, 2003) and subsequent amendments in different Member States and how these are implemented though local legislation and regulations in the building sector.

Requirements with regard to the refurbishment of historical buildings are mostly in line with existing planning and construction laws and regulations, but in some cases additional laws and permits, including the use of expert advice, are required from government departments responsible for the preservation of cultural heritage. This is especially true when buildings are listed as protected.

Each country or region have different rules when Cultural Heritage is involved.

Given the innovative characteristics of the Cheap-GSHPs and GEO4CIVHIC technologies to deliver on low impact retrofit solutions for heating and cooling, the historical buildings subject to the inclusion of the project technologies, could benefit from reduced permitting requirements.

2.2 Risk and Barriers with respect to historical buildings

In the case of historical buildings, it is very important not only to preserve the architectural aspect of the building but also the archaeological aspect of the whole "site" where the building is located, including gardens and squares close to the building. Therefore, the installation of Cheap-GSHPs and GEO4CIVIC technologies in historical buildings has to be based on detailed studies allowing decision making based on the suitability of the project on a case by case basis, in order to overcome the special barriers characterizing such historic sites.

Deep refurbishment of an existing building faces constraints given by the properties of the given building structure, site and space limitations, and in particular economic feasibility.

The barriers might be grouped into two main types, technical and non-technical barriers, plus the specific problems posed by historic buildings.

Technical barriers are deemed to be overcome more easily, with development work ongoing from many years and new solutions found constantly (see for instance (Vella, 2020) and (Wang, 2020)).

Dealing with the non-technical barriers is less straightforward and needs to address a large number of different aspects, ranging from individual perception of shallow geothermal exchangers (SGE) to the economic viability and environmental impacts. Changing negative perception of an SGE-based energy refurbishment in terms of feasibility, reliability and affordability can be a difficult task.

Many issues are similar to those in newer buildings, however, often exacerbated by the historical nature of the buildings considered, by the surroundings they usually are found in, and often also by specific regulations securing their historic integrity. So, historical buildings are interesting examples in the field of energy management in the built environment. They have a high energy use due also to the frequent presence of large exhibition rooms and spaces. They additionally often have specific and/or different heating and cooling requirements associated with specific artefacts and collections they house that need to be taken in consideration for their conservation.

Historical buildings are well suited also to test the performance of the proposed geothermal system in delivering innovative renewable energy solutions whilst retaining their heritage significance. In most historical buildings, it is impossible to intervene in the external façade, and sometimes even impossible to change the heating terminals or install radiant thermal panels or floor heating. Innovative heat pumps were developed during Cheap-GSHPs and GEO4CIVHIC to overcome these barriers.

In the case of historical buildings, it is very important to preserve the architectural aspect of the building, but also the archaeological aspect of the whole "site" where the building is located, including gardens and squares close to the building. In the case of drilling in historical building areas, existence of underground infrastructure might include objects of archaeological interest, and the use of technologies such as Ground Penetrating Radar - Geo-radar (GPR) may be appropriate to avoid incidents and perturbations.

Moreover, a significant barrier that could be encountered, in particular in historical centres, is the presence of narrow and difficult to reach external spaces. GEO4CIVHIC found special solutions to overcome this aspect by means of an innovative compact and modular drilling machine able to perform drilling in very narrow spaces.

Beside these barriers, lack of knowledge (and even misinformation) about new technologies like SGE can be identified as a main barrier to the increased uptake of GSHP technologies in these applications.

3 METHODOLOGICAL APPROACH

In general, the integration of geothermal technologies in any type of building strongly relies on analysis of the ground conditions and building fabric. The former is characterized by the site-specific thermal properties of the ground, whilst the latter depends on the specific characteristics of the building itself and its thermal energy requirements. Therefore, the installation of Cheap-GSHPs and GEO4CIVHIC innovative technologies in historical buildings is based on detailed studies to assess the suitability of the project on a case-by-case basis, as recommended also by the abovementioned EN 16883.

A site-specific analysis focusses on the integration of shallow geothermal systems in historical buildings based on the availability of free surface where those underground systems could be installed. In rare cases, even drilling from within a basement room might be considered (cf. GEO4CIVHIC D2.1, 2018, chapter 3.3). Internal spaces need to be able to accommodate a plant room big enough to install the ground source heat pump, which is not always present or suitable.

The ground and underground conditions in historic areas needs special attention. A verification of the presence of historic remains needs to be performed and if these are evidenced, the recovery of artefacts etc. may have to precede any mechanical digging and drilling. The impacts of the construction operations on the ground and hydrogeological conditions also require careful planning with the necessity for adequate borehole design, the selection of adequate drilling methodologies and drilling fluids that minimize the impacts relating to possible subsidence in nearby ground as well as the preventing the penetration of important aquifers or the cross contamination between these. The assessment of the most suitable drilling technology for a given geological context was developed during the two European projects through the publication of a 'Drillability map' at European scale, and thematic 'Drillability maps' at detailed municipal scale. These maps could support both the administrators and the end users such as designers and drillers, identifying the most suitable or unsuitable zones for the installation of geothermal systems.

Moreover, the Drillability application for mobile devices (APP), developed during GEO4CIVHIC project, provides an initial assessment tool for the sites where the historical buildings are located based on simple inputs provided by the user. These give a rough estimate of the energy demands of the building, the climatic zone, that is retrieved via geo-localization, and the size of the building itself. This estimate makes it possible to size the ground heat exchangers as a first approximation and allows for qualitative analysis of the feasibility of installing the geothermal plant. This APP also contains a 'Drillability map' at European scale which suggests the most suitable drilling methods based on the type of ground on which the building is located. However, the determination of the underground typology must subsequently be confirmed by the use of a more detailed map at the local level, together with other soil inspection and testing techniques.

A second step is performing a preliminary feasibility study of the building and its energy requirements. similar to non-historical building, the exact heating and cooling solutions have to be selected and tuned on case specific basis to each historical site by evaluating climatic conditions and related energy loads: climatic conditions to define the energy demand and the peak power for heating and cooling, detailed analysis of the building fabric, different levels of insulation, etc.

Once energy demands and peak loads are defined, the ground source heat pump system will be sized based on the available space for the collector, ground conductivity and location (i.e. undisturbed ground temperature). Based on the layout of the city, different hypotheses can be considered, thus leading to different options either with GSHPs or hybrid solutions, including innovative heat pumps developed in the two European projects. This process can be facilitated with the help of the Decision Support System (DSS) realized during GEO4CIVHIC. This tool assesses the most suitable technologies for the given building and location, evaluates their feasibility and provides a pre-engineering cost and impact analysis. The result is a preliminary, nevertheless detailed technical, economic and environmental analysis of the solutions.

4 DEMONSTRATION CASE STUDIES

During the two projects, several real and virtual case studies where performed. These are considered exemplars of "good practice" and demonstration of the applicability and performance geothermal and heat pump installations in historical buildings.

In this article a summary of the application of geothermal solutions in two of the real demo sites is described. Examples of the studies performed for the numerous virtual cases to demonstrate the applicability of the systems in the historical building, their performance and an evaluation of the energy saving is also provided.

4.1 Real demonstration site: Technical Museum Nikola Tesla of Zagreb, Croatia

The Technical Museum Nikola Tesla in Zagreb (Figure 1) is one of the most visited museums in Croatia.

The entire complex is listed within the National Register of Cultural Property, by decision of the Ministry of Culture of the Republic of Croatia (class UP-I-612-08 / 05-06 / 896, no. 532-04-01-1 / 4-05-2 of 28 April 2005) and located in the Historic Urban Areas of the City of Zagreb, an urban zone abiding to a special regime of conservation and heritage protection.

The Cheap-GHSPs installation (Cadelano et al., 2019) is a central attraction at the museum and acts as an educational tool, creating awareness in particular on the role of science and technology to enhance sustainable energy.

Figure 1: Nikola Tesla Technical Museum in Zagreb (left) and technical room devoted to the geothermal plant (right)

The underground conditions are characterized by floodplain and alluvial deposits comprising silty clays and sandy layers; some gravel sediments in the upper part of the alluvial sedimentary sequence.

The space hosting Cheap-GSHPs solution is the exhibition room (Figure 1, on the right), with a total surface area of 380 m^2 and a volume of 1.463 m^3. The external walls are made of brick and mortar without any insulation. Double glazed, aluminum-framed windows from the ceiling to floor level cover the north wall almost completely. The ceilings and the floors are composed of wooden floors and concrete.

A large exhibition room of the museum has been energy refurbished using the geothermal solutions developed in Cheap-GSHPs. The room was originally heated by six electrical heaters with no cooling system present. This had a serious impact on the thermal comfort of both visitors and workers; moreover, it used to represent a possible threat to the fire safety to wooden components both in the interior and exterior structure of the building.

Both heating and cooling loads of the room were calculated by means of TRNSYS software. The results are reported in Table 1.

Table 1: Yearly energy demand of the museum

	Summer	Winter
Sensible Energy [kWh]	1768.42	16460.87
Specific Sensible Energy [kWh/m^2]	4.65	43.32
Latent Energy [kWh]	505.44	-
Specific Latent Energy [kWh/m^2]	1.33	-
Total Energy [kWh]	2273.87	16460.87

Total Specific Energy [kWh]	5.98	43.32

Six boreholes with a depth of 100 m each were drilled and fitted with three double-U BHEs (Borehole Heat Exchanger) and three coaxial BHEs, respectively (Figure 2).

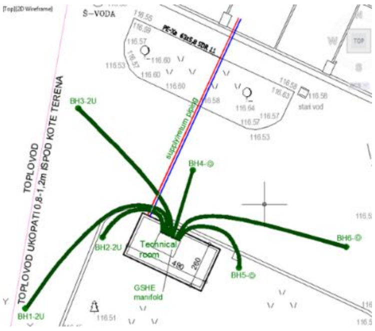

Figure 2: Layout of the boreholes in Technical Museum yard

A prototype heat pump developed during the first phase of Cheap-GSHPs project was installed. This heat pump is equipped with two refrigerants (CO_2 and R1234ze) and operates with a double cascade cycle designed to supply high temperature water (up to 65-70°C) with high efficiency.

The performance analysis of the newly installed system took into consideration a one-month period both in the heating and cooling seasons.

The system succeeded in maintaining a constant air temperature inside the exhibition room during the cooling season; very low variations (about ±1°C) around the set-point temperature (23°C) were observed.

The main parameters in terms of energy performance of the innovative heat pump in one summer month (period from 26th of June to 26th of July 2018) are indicated in Table 2.

Table 2: Energy performance of the heat pump in summer operation (26th of June - 26th of July 2018)

Energy delivered by the BHEs [kWh]	4311
Energy supplied to the building [kWh]	3345
Electricity consumption – compressor [kWh]	1016
Electricity consumption – pumps [kWh]	225
Heat Pump average COP [-]	3.29
Energy costs [€/kWh]	0.0483

The results showed that the system modulates and fulfils the demand load correctly and the internal conditions showed a constant behavior and therefore successfully achieving the conservation rules required for the building.

Figure 3 shows an example of the air temperature trend outside and inside the exhibition room during winter conditions. The system succeeded in maintaining a rather constant air temperature inside the exhibition room, with daily variations of about ±1°C. A set point temperature equal to 26°C (quite high in normal conditions) was set in such a way as to perform a stress test of the heat pump to evaluate the behavior of the system during a period when neither exhibitions nor sensitive collections were present inside the room.

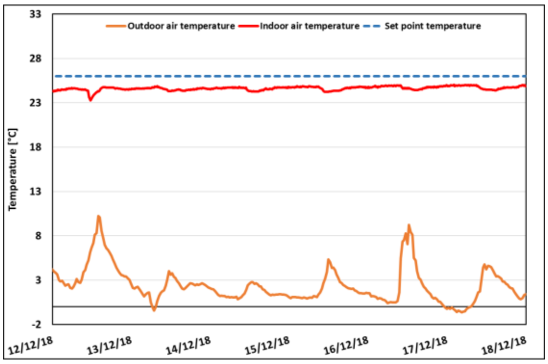

Figure 3: Outdoor and indoor air temperature - Winter operation

The energy performances and parameters of the innovative heat pump in winter (period from 15th November to 31st December 2018) are indicated in Table 3.

Table 3: Energy performance of the heat pump in winter operation (period from 15th of November to 31st of December 2018)

Energy delivered by the BHEs [kWh]	8715
Energy supplied to the building [kWh]	15720
Electricity consumption – compressor [kWh]	7254
Electricity consumption – pumps [kWh]	491
Heat Pump average COP [-]	2.17
Energy costs [€/kWh]	0.0639

Also in winter operation the heat pump worked successfully with the system modulating to fulfill the demand load correctly. The heat pump worked around 67% of the time during the analyzed period as is expected by this type of pump in such conditions.

4.2 Real demonstration site: Angel's Gate, the UNESCO World Heritage Site of Ferrara

Angel's Gate (Fig. 4) is a former watchtower, designed by the architect Biagio Rossetti at the end of the 1400s and built around 1525. Ferrara, the city of the Renaissance (northwest Italy, Emilia Romagna region), where another real demonstration site is located, is a UNESCO World Heritage Site since 1995. The site is protected under national cultural heritage legislation: the "Codice dei Beni Culturali e del Paesaggio" (Legislative Decree 42/2004). The World Heritage Site is comprised of the city centre of Ferrara, as well as the adjoining agricultural lands within the ancient and vast Po River delta.

Figure 4: Angel's Gate: watchtower on the left and lower building on the right (A), view of Angel's Gate (B), the walkway and the ravelin (C) (UNESCO copyrights)

The demo site area is located in the Po Valley at a regional scale, a tectonic depression formed between the Alps and Apennines when these mountainous ranges rose and emerged from the sea, following orogenic processes, and subsequently filled with loose materials deposits of marine and fluvial-delta origins.

Angel's Gate was equipped with an old and inadequate 23 kW, natural gas boiler heating system installed on a basement wall and feeding a manifold that serves a series of fan coils. The internal distribution system comprised copper pipes, partly exposed and partly embedded in the floor or wall.

To identify the best GEO4CIVHIC geothermal retrofitting option for the building, load calculations were performed to define the heating and cooling demand of the building using the Edilclima – EC700 calculation software. The simulations identified the design capacity requirement for the heat pump to be 35 kW in winter and 33 kW in summer, with the most suitable heat pump being a dual-source heat pump (air and ground source).

The retrofit measures included the installation of new terminals in the three rooms inside the building and the replacement of the existing gas boiler with the new prototype of hybrid dual-source heat pump developed in the project.

Four Borehole Heat Exchangers (BHE) at a 7 m spacing were installed.

Two types of innovative BHEs developed and studied during GEO4CIVHIC project were installed (Figure 5):

- TKI BHE;
- Hydra-Red BHE.

Figure 5: Aerial view of the geothermal field of Angel's Gate (Georicerche srl copyrights)

A technical room was installed in the garden under the footbridge (figure 5), as the heat pump and the buffer tank could not be placed inside the building for conservation reasons.

The hybrid heat pump operates with air and/or water as a heat source in alternating operation in summer and in series in winter, according to climatic conditions (Figure 6). The heat pump is using CO_2 as refrigerant.

The installed system clearly demonstrated the usefulness of such a hybrid solution in an urban context and historical centers, where the space devoted to BHE installation is typically rather limited.

Figure 6: Fan coil (A) and technical room (B) (Finotti copyrights)

New fan-coil units were installed to exploit the energy saving potentials of the new hybrid heat pump. These terminal units work based on high temperature difference of the heat carrier fluid, allowing the flow rate at each unit to be lower than usual. In each exhibition hall two fan-coil units were installed.

The recently installed system will run for one year and will be monitored to measure the performance of the system, the energy saving and the comfort.

4.3 Virtual demonstration site: the Ex Ospedale Geriatrico (Padova, Italy)

Several case studies of historical buildings have been investigated (Emmi et al, 2017; Cadelano et al. 2022). both in the Cheap-GSHPs and in the GEO4CIVHIC projects to demonstrate good practice and promote the integration of ground source heat pumps as main generation system for historic buildings. These showcase the ability of newly developed heat pump solutions to increase the temperature at the supply side of the condenser and provide space heating at higher temperatures. This is compatible with most historic buildings, that are commonly heated by high temperature radiators or similar units and have poor building envelope properties fo resulting in high thermal losses.

Among the different case studies, the Ex Ospedale Geriatrico (Padova, Italy) (Figure 7) demonstrates the application of a deep retrofit case with a cooling dominated energy demand.

The new humanistic pole of the University of Padua (Italy) is a historical complex of the late 1800 located in the city center that has been analyzed during the GEO4CIVHIC project. The building ensemble hosted a former Geriatric Hospital as a result of several transformations of the old “Beato Pellegrino” convent to a retirement home for the elderly. The first phase of enlargement dates from 1882, while two other phases took place: in the 30’s and 50’s of last century. After the recent intervention in 2019, the buildings have been partly retrofitted and partly demolished or rebuilt, for an overall area of 16’667 m^2 and a volume of 104’672 m^3.

Figure 7: The University center "Ex Ospedale Geriatrico in Padova (Italy)

The various thermal zones in the building have been designed with two configurations of the emission system: fan-coils and air diffusers or radiant surfaces and air diffusers. Emitters provide both space heating and cooling. Since the envelope has been insulated and renewed in some parts, in this particular case the thermal load is not balanced and it appears a cooling dominant as shown by Figure 8.

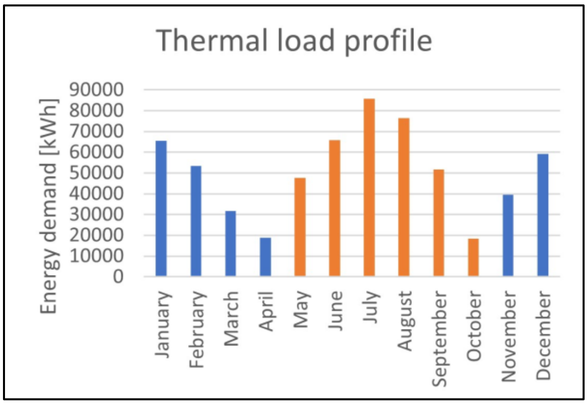

Figure 8: Thermal load profile of the building

The estimated total BHE length leads to a compact matrix for the geothermal collector array, minimizing the land required. However, due to the space constraints, this results in minimum distance between the BHE and accordingly increases the risk of mutual thermal influence between the BHEs. The unbalanced building energy demand loads lead to very different BHE lengths which may increase the temperatures over the time (Bernier et al. 2004). The constrained space available for the collector in a cooling dominated application can result in the risk of overheating the ground. Based on results from other case studies, this does not occur when the difference between the cooling energy demand of the building is greater than 30% heating energy demand on average. This is related to the operation of the GSHP: while the heat extracted from the ground during the heating season is lower compared to the load of the building, since part of the thermal load is covered by the compressor work of the heat pump, the heat injected into the ground is higher than the building load because the work of the heat pump compressor turns into heat. As a consequence, the effect of the thermal drift of the ground is less evident since the ground temperature is maintained at about the same temperature during long term operation of the system, which in turn results in an almost constant energy performance of the heat pump.

In this case study the cooling demand is much greater than 30% of the heating demand. Even an increase of the borehole spacing would not be sufficient to mitigate the effects of ground overheating. Therefore, the installation of a hybrid system is strongly recommended in such a way to preserve the heat balance of the ground. In this case study, the smallest among the total BHE length to satisfy either the space heating or the space cooling demand was chosen as the most convenient strategy. In order to increase and maximize the efficiency of the system and to control the temperature drift of the soil, the combined operation of an air-to-water heat pump and two ground-coupled heat pumps have been assumed. A preliminary study (Zarrella et al 2004) shows the estimation of an optimal switch temperature between the GSHP and the air-to-water heat pump (AWHP); the results obtained may help to improve the operation of the system depending on the outdoor air temperature, thus reducing the operating costs. This example shows a different hybrid solution compared the Ferrara “Angel’s Gate” case. As a matter of fact the power of the heat pump of Ferrara is small so as to provide a unique system with a double source (air and water). In large plants as the one of the case study of Padova “Ex Ospedale Geriatrico” the optimal solution is to work with different heat pumps: an air-to-water heat pump and a GSHP solution.

CONCLUSIONS

The GEO4CIVHIC and Cheap-GSHPs projects have demonstrated the potential for integration of GSHP technologies to meet the heating and cooling demand of historical buildings.

However, critical strategies to project design and at the implementation stages need to be adopted in order to successfully integrate such solutions. A detailed design process that considers the fabric of historical buildings and the specific requirements in the context of energy demand to determine heating and cooling loads of such systems needs to be implemented. This is achieved through considering the importance of assessing the building energy demands and performance and the temperature requirement of historical buildings in advance of proposing a possible solution.

We do hope that the narratives using examples of application and recommendations included in this article, will be instrumental in inspiring both professionals and the general public in considering use of ground source heat pump systems in the context of historically, architecturally or culturally-valuable buildings where special provisions are necessary to ensure the optimum balance between indoor comfort, energy performance and conservation requirements.

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