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Shallow Geothermal Energy for existing buildings – overview and status of project GEO4CIVHIC

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ABSTRACT

A major obstacle to decarbonisation in the building sector is the comparably low share of new construction, and the specific problems encountered when supplying heat and/or cold from renewable energies (RES) to existing and in particular older/historical, buildings.

Without a solution to the problem of RES in refurbishment, however, the decarbonisation of the building stock will simply take too long. Shallow geothermal technologies have contributed substantially to decarbonisation in new construction. However, for a wider deployment in existing buildings, particularly in historical ones, the technologies need further development and innovative ideas must be tested and brought to the market.

Within the EU-funded project GEO4CIVHIC a survey was done to identify and understand all other possible barriers to install Borehole Heat Exchangers (BHE) in existing building environment, be they technical or socio-economic, and the project partners work on suggestions for suitable solutions.

Based upon this survey, the further work addressed two principal barriers, which are construction of ground heat exchangers under constrained site conditions, and adaption of heat pumps and other components to older heating/cooling systems.

A specific emphasis is given to historic buildings, i.e. those dating from before the mid of the 20th century, including listed buildings, where the constraints are even more severe.

Development work is done to provide technical solutions for overcoming these barriers, e.g. with novel drilling tools and enhanced heat pumps. Several demonstration cases are undertaken to test the solutions found (4 real sites in Belgium, Ireland, Italy and Malta,

and 12 “virtual” sites, where theoretical case studies for renovation with borehole heat exchangers are performed on real, existing buildings). The COVID 19 pandemic hampered drastically the project timeline, resulting in delays of more than one and a half years.

At the time of writing this abstract, two real demonstration cases are finished and started operation (Belgium and Italy), while the other two are scheduled to be operational by July 2022.

This paper gives an overview of the project, the rationale behind it, and the findings of the initial survey of barriers. It presents the experiences with less invasive, less costly and quicker drilling and installation methods for borehole heat exchangers (BHE), as developed within the project and tested both in the real demonstration sites and in dedicated test fields at some of the project partners.

First results of monitoring and results from the "virtual" sites are presented. Other papers within the project also submitted to EGC 2022 address specific aspect in more detail, and are referenced in this overview paper.

1. INTRODUCTION

A major obstacle to decarbonisation in the building sector is the comparably low share of new construction, and the specific problems encountered when supplying heat and/or cold from renewable energies (RES) to existing and in particular older/historical, buildings.

Without a solution to the problem of RES in refurbishment, however, the decarbonisation of the building stock will simply take too long. Shallow geothermal technologies have contributed substantially to decarbonisation in new construction. However, for a wider deployment in existing buildings, particularly in historical ones, the technologies need to be further developed and innovative ideas must be tested and brought to the market.

The H2020-project GEO4CIVHIC is contributing to that issue. It started in April 2018 and it is still in progress. The project timeline suffered drastically the effects of the COVID 19 pandemic and the Commission approved an extension of 20 months. The end is foreseen in November 2023.

The GEO4CIVHIC’s target is to accelerate the deployment of shallow geothermal systems for heating and cooling in retrofitting existing buildings in built environment, including historical buildings.

The innovations are focused on resolving the shortcomings in the drilling method, developing the second generation of heat pumps and co-axial heat exchangers, introducing the adaptations required in the built environment, specifically in narrow spaces typical of centres in the towns or small gardens. Starting partly from results of previous projects like Cheap-GSHPs (http://cheap-gshp.eu/), and developing new ideas, the project provides the tools for a larger implementation of shallow geothermal in the built environment. A specific emphasis is given to historic buildings, i.e. those dating from before the mid of the 20th century, including listed buildings.

A preliminary survey was done to identify and understand all other possible barriers to Borehole Heat Exchangers (BHEs) in existing building environment, be they technical or socio-economic, and the project partners worked on suggestions for suitable solutions. Based upon this survey, the further work addressed two principal barriers, which are construction of ground heat exchangers under constrained site conditions, and adaption of heat pumps and other components to older heating/cooling systems, especially historic buildings where the constraints are even more severe.

Ground heat exchangers under constrained site conditions (like drilling in courtyards, gardens, basements etc.) are installed using novel drilling methodologies and a compact drilling rig. Heat pumps were constructed or adapted to supply the temperatures needed for older heating and cooling systems that cannot be easily replaced.

After practical demonstrations in three pilot sites, the solutions are applied in four real buildings. In addition, 12 virtual demonstrations (simulation) using real buildings as a basis show if the solutions found can fulfil the desired objectives and will help in further optimising the technologies.

Finally, a middleware (BEMS) and a software track (decision support, engineering tools, app’s, and controls) are also part of the project and their development in progress.

2. NOVEL DRILLING TOOL AND HEAT PUMPS

Work is ongoing to provide and demonstrate how the technical solutions overcome the identified barriers. In the following a quick description on the results and the experiences in progress with less invasive, cheaper and quicker drilling and installation methods for innovative borehole heat exchangers (BHE) is presented, as well as the prototypes of the innovative heat pumps already installed or in phase of development.

2.1 Novel heat exchangers and drilling machines

The drilling method for unconsolidated soils, already developed in Cheap-GSHPs (http://cheap-gshp.eu/) and patented in Italy, is improved during the project by de-coupling the rotating drill bit from the external tube of the heat exchanger. This allows increasing the external diameter of the heat exchanger and hence the efficiency (Emmi et al, 2020).

A powerful and efficient rotation-vibration drilling head was also developed to be able to install the BHE’s in consolidated ground. This means that we will be able to drill in all types of unconsolidated soil and even consolidated ones. The new vibration-rotation drilling head uses much lower quantities of compressed air and causes less drill bit wear compared to downhole hammer drilling in consolidated soil.

The drilling rig design reflects the needs of compactness, weight, flexibility and contributes in the reduction of non-productive times. The latter will be done by semi-automated operator support equipment for fast mounting/dismounting of shafts/casings.

The efficiency and cost of co-axial heat exchangers are also improved including the use of innovative developments realized in GEOCOND (https://geocond-project.eu/) using new tube materials (plastics) and grouts (enhanced for high thermal conductivity). The potentially negative implications of larger diameters on drilling speed and depth are in a phase of testing because they need to be verified as well as the impact in thermal performance (laminar vs turbulent fluid flow within the BHE) and of pump size/consumptions (Badenes et al, 2020).

2.2 Innovative heat pumps

Three second generation HPs and one new HP were developed through control and component optimizations supplying high and low temperature terminals with one (geothermal) or two (geothermal/air) sources.

Another HP responds to the trend in the market to move to easy to install, smaller-size heat pumps suitable for retrofitted buildings with low energy demand. Finally, a compact, low temperature geothermal heat pump with mid-term low GWP (Global Warming Potential) fluid anticipates the upcoming legislation in refrigerants.

In GEO4CIVHIC prototypes of the following heat pumps were built:

1 Dual source low temperature HP: based on the GEOTeCH (https://www.geotech-project.eu/) heat pump, the machine has been improved optimizing the operating conditions between functioning on air and geothermal sources. This prototype is installed in the demonstration site of Malta (warm climate).
2 Single source - water to water - high temperature HP: the Cheap-GSHPs solution (Emmi et al. 2020) has been further developed optimizing the cycle for low GWP fluids and simplifying the circuit. This prototype is installed in the real demonstration site in Ireland (cold climate).
3 Single source - water to water - heat pump with two levels of temperature distribution: based on the original Cheap-GSHPs solution, the heat pump has been developed for working at different levels of temperatures (e.g. buildings with part of terminals at high temperature and part of terminals at medium/low temperature). This prototype is installed in the real demonstration site of Belgium (mild cold climate).
4 Dual source (water to water and air to water) high temperature HP: this solution uses a natural refrigerant fluid (CO_2) operating with high temperature terminal units in heating and with usual temperatures in cooling. This prototype is installed in the real demonstration site in the North of Italy (mild cold climate).

Tests were performed in the laboratory of GALLETTI /HIREF to check the performance of each heat pump type.

The expected performance of the heat pumps was demonstrated and their installation in the different pilot and real sites is in progress.

3. PILOT AND REAL DEMONSTRATION CASES

Fig 1 and 2 show the pilot sites and the real demonstration sites with their respective innovations.

The installations in the Pilot sites were completed and tests are in progress. Regarding the real case studies, the installations in Italy and Belgium were started-up and performance testing is ongoing. Drilling in Ireland was completed whilst drilling in Malta is in progress. Preliminary evaluation about the local suitability of each test site in term of heat exchange with the underground and time and cost of the drilling operation were completed and were verified for the case study in Belgium (Galgaro et al, 2022; Dalla Santa et al., 2020; Di Sipio and Bertermann, 2018).

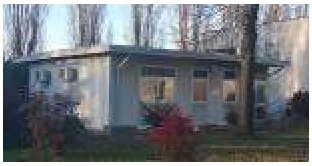		
Pilot facility n. 1 (CNR-Padova, Italy)	Pilot facility n. 2 (TECNALIA, Derio, Spain)	Pilot facility n. 3 (UPV-Valencia, Spain)
Two Plug & play HPs with respectively on/off and inverter driven compressors, one low GWP refrigerant HP; Co-axial BHEs with modified well point technique, steel and plastic	Plug & play HP + RES and controls optimization via BEMS	Facility to test very shallow heat exchangers with and without PCM. Advanced control and testing facility to perform precise TRTs.

Figure 1: GEO4VICHIC pilot sites.

			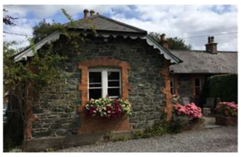
Demonstration site n.1 Msida Bastion Historic Garden, Valletta, Malta (warm)	Demonstration site n.2 Porta degli Angeli, Ferrara, Italy (mild warm)	Demonstration site n.3 Private house, Battel, Belgium (mild cold)	Demonstration site n.4 Private historical house, Wicklow, Ireland (cold)
Co-axial BHE in consolidated soil low temperature dual source HP	Co-axial BHE in unconsolidated soil high temperature dual source and CO_2 driven HP	Co-axial BHE in unconsolidated soil high and low temperature levels, single source and CO_2 driven HP	Co-axial BHE in unconsolidated soil high temperature single source HP

Figure 2: GEO4VICHIC real demonstration sites.

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A monitoring system is or will be following the performance of the borehole heat exchangers and the heat pump throughout the seasons relevant for the site location.

3.1 Pilot sites

Research area of CNR, Padova (Italy)

The testing on this site is the most advanced. The installation of different BHEs includes the testing of different experimental grouts. These grouts need to seal the borehole or the water injection openings of well points or co-axial heat exchanger, demanding to be waterproof, of good plasticity, adequate viscosity, thermally conductive, easily injectable and low cost (Mascarin L. et al., 2022).

The innovative BHEs are:

a) Well point techniques
b) Coaxial steel and plastic heat exchangers

Well points are traditionally used to lower surface aquifers keeping excavations for underground works dry. Such well points were installed in this Pilot. The developed grout subsequently closed the water injection openings of the well points, transforming these devices into shallow closed loop ground heat exchangers upon inserting an internal tube and head. This concept could lead to very fast and cheap installations by using small machines to complete this type of ground heat exchanger. The depth of these BHE is generally limited (down to about 15 m). In the pilot site the installed depth was 8 m. The goal is to check the potential benefits in cost and efficiency compared to the conventional BHEs and other very shallow heat exchangers.

Co-axial heat exchangers with diameters of 60.3 mm and 88.9 mm, respectively, were installed using the piling drilling methods developed in GEO4CIVHIC.

Plastic technologies applied to co-axial heat exchangers have several advantages over the metal ones, but direct insertion via piling is difficult due to the low mechanical strength. A borehole was drilled with the conventional rotary drilling method to insert the improved plastic co-axial BHE from the GEOCOND project.

The performance of the different types of co-axial borehole heat exchangers are being monitored following the TRT tests.

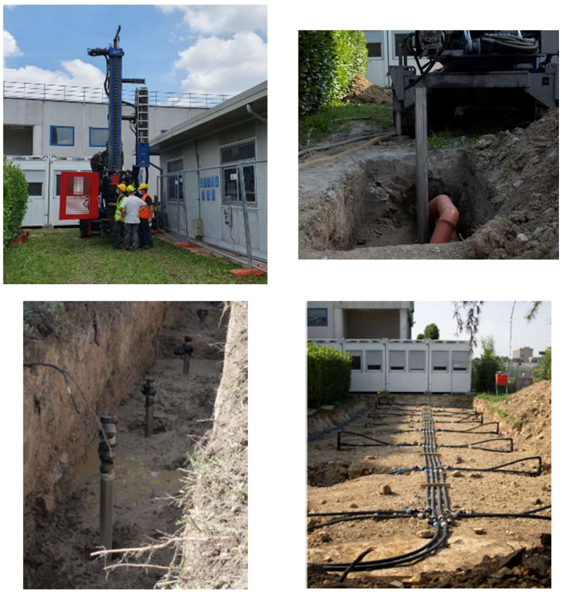

Figure 3: Pictures from BHE field at CNR pilot site in Padova.

In the pilot site, two geothermal heat pumps have been installed, one with ON/OFF controller and the other one with an inverter-driven compressor. These two systems are connected to the aforementioned geothermal field and to a unique manifold serving the heating/cooling terminals installed in the rooms.

The two heat pumps will work alternatively to compare the performance of the two control systems. Except for the compressor control systems, the heat pumps are identical, with R454B as refrigerant (GWP=466) and 10 kW of heating power. Both heat pumps are fully equipped with pressure and temperature sensors between each component of the refrigeration circuit in order to analyse in detail the systems performance.

At a later stage, one heat pump will be replaced with another heat pump with an even lower GWP.

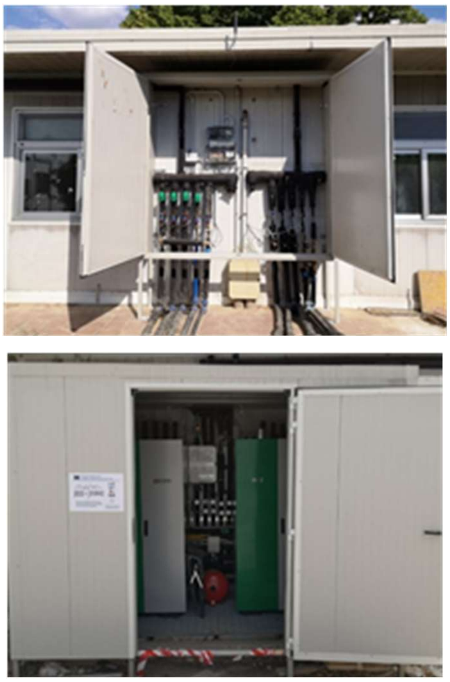

Figure 4: Heat pumps at CNR pilot site in Padova.

Pilot Site of UPV, Valencia (Spain)

The pilot site at UPV (Mateo Pla M. A. et al, 2019) is equipped with advanced appliances to test any possible BHE configuration with high precision and to determine ground and grout properties.

Two plastic flat horizontal heat exchangers with forty-two temperature probes were installed in parallel, one with and one without a PCM-enhanced grout to test and evaluate the ability of such materials to add heat storage capacity to the ground. In parallel, an ambitious numerical modelling effort was started to ensure a proper understanding of the underlying thermodynamics of the process (see Figure 5).

Although a high difference in the variation of the dissipated power has been shown in the experiments, the numerical results demonstrate that the presence of PCM in the backfill material has a positive effect.

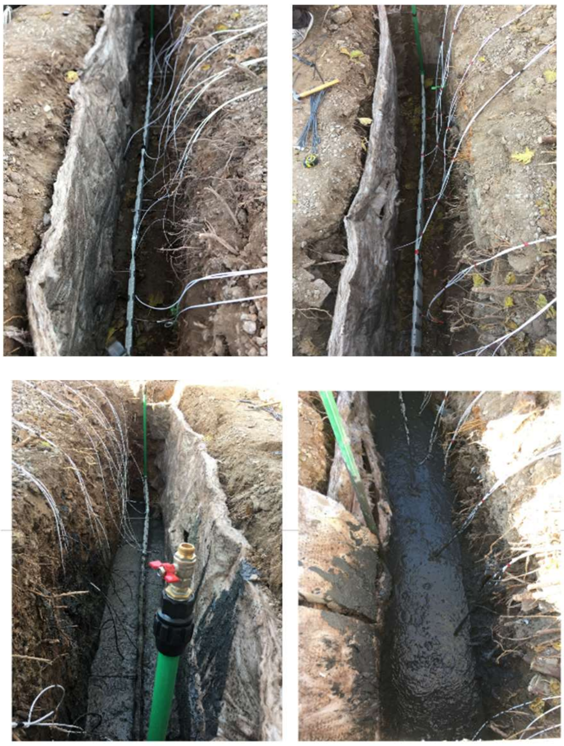

Figure 5: Flat heat exchangers with sensors and grout material

After the heat injection, during the thermal recovery, the trench with PCM had a more significant temperature reduction and, therefore, a better recovery than the other trench. This was due to the fact that some of the phase change materials that melted started to solidify because of the temperature reduction to which it was subjected, absorbing more heat than the other trench dissipation. This variation has been around 0.6 ºC.

Thus, the use of PCM has certain advantages, which causes a higher thermal efficiency, and in the recovery, a better temperature reduction for the same period.

The test site in Valencia has also served, due to its flexibility, to give support to other areas of development of GEO4CIVHIC, such as plastic coaxial development tasks.

Pilot Site of TECNALIA, Bilbao (Spain)

The pilot site in TECNALIA's facilities in Derio is placed at the experimental KUBIK building (https://www.tecnalia.com/en/infrastructure/kubik-experimental-building). This is a R+D+i installation designed for the development of new concepts, products and services for the improvement of building energy efficiency. The building is equipped with a monitoring and control system that provides the necessary information for the development of R+D+i activities.

The geothermal installation is composed of a Canadian well that was already installed at the site, and the plug & play heat pump developed in GEO4CIVHIC. The installation will be used for the demonstration of the management system, under development, that will optimize the integration of geothermal energy with other RES.

Figure 6: KUBIK building and representation of the installed heat pump in the Building Information Model

3.2 Private house, Battel (Mechelen), Belgium

The two-story semi-detached building was completely refurbished with external wall insulation, new insulated roof, new windows, radiant floor panels at ground level, fan coils at the first floor.

Hence, the geothermal heat pump of 12 kW supplies a heating and cooling installation with two levels of heating temperatures. The high temperature heating system with the fan coils at 60 °C connects in series with the radiant panels at 35 °C. In such a way, the CO_2 driven heat pump always faces a temperature gradient of at least 30 K. The heat pump should achieve a COP of 3.3.

The source side of the system consists of 4 stainless steel coaxial BHE for a total of 340 m. The innovative piling method was used for the installation of the newly developed co-axial heat exchangers. A crane has lifted the drill rig and all drilling accessories in the garden which is not accessible from the street.

The plant is up and running whilst performance monitoring of heat pump and geothermal field is ongoing.

3.3 Private historical house, Wicklow, Ireland

The historical house from the 1860s is the location where three of the GEO4CIVHIC project technologies are being tested. The objective of this case study is to demonstrate the potential integration of ground source heat pump technology in historical buildings where minimal building fabric intervention is possible.

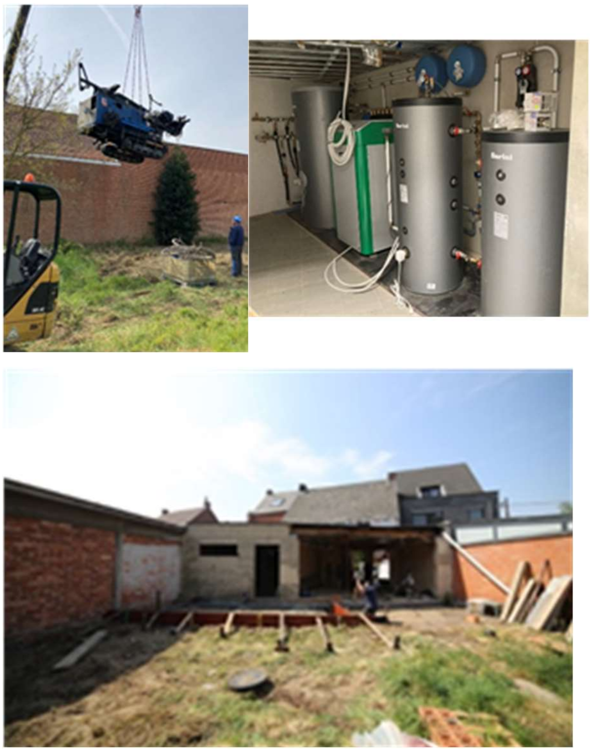

Figure 7: Real demonstration project in Battle, Belgium.

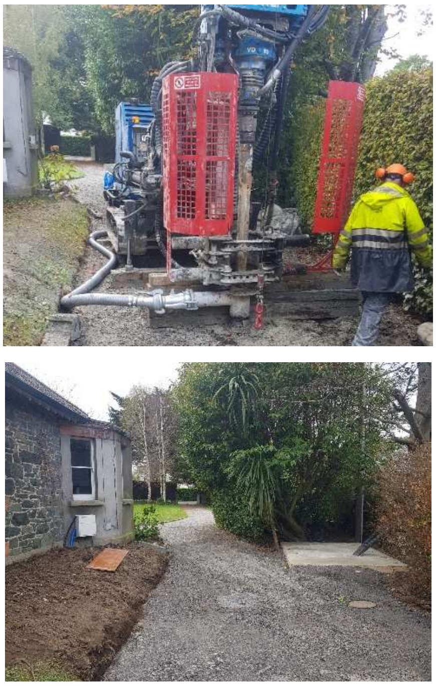

Figure 8: Drilling at the Greystones demonstration site and location of the new plant room to accommodate the dual cycle heat pump.

The new compact drill rig with the rotating vibrating head was used to complete three borehole heat exchangers in the Palaeozoic greywackes and siltstones. A total length of 280 m of 60.3 mm stainless steel coaxial heat exchanger was installed. The probes will act as the source for a dual cycle, transcritical CO_2, water to water heat pump (HTHP) with an installed capacity of 15 kW and operating at 60 – 70 °C. The new HTHP heat will displace up to 80 % usage of the existing gas fired central heating system. The boiler remains as a backup and peaking option and to facilitate the DHW supply. The prototype HTHP should achieve a COP of 2.26 and will be integrated, in a newly designed and installed plant room adjacent to the house. The plant room will also house new buffer vessels for both the hot water and the heating system. Pre-insulated pipework has been installed to connect the new system to the existing radiators and domestic hot water pipework in the house.

3.4 Porta degli Angeli in Ferrara, Italy

The case study regards the renovation of the heating system of a historic building replacing the existing gas boiler and fan coils with a heat pump and new fan coils.

The new geothermal heating and cooling system was designed to secure the coexistence between heritage-significant conservation in interior/exterior features of built heritage and affordable geothermal infrastructure.

The new system consists out of four boreholes with co-axial heat exchangers drilled at 96 m depth, a geothermal hybrid dual source high temperature heat pump, a new technical room hosting the heat pump and new terminals. All probes were installed with the traditional rotary drilling method with water, using a double rotating head as requested by the ARPAE Italian authorities.

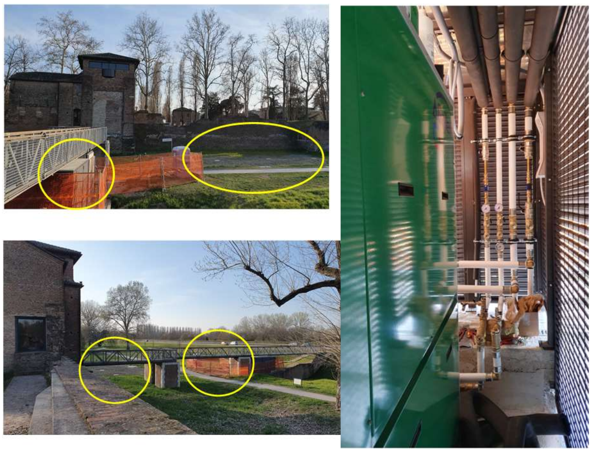

Figure 9: Location of BHEs and piping at Ferrara demonstration project.

The innovative heat pump uses geothermal and air as sources and CO_2 as refrigerant. The heat pump has a total power about 35 kW and operates as follows: geothermal and air-water in alternating operation in winter mode based on the atmospheric conditions and in series in summer mode.

The use of the two heat sources, the air and the ground, allows to reduce the size of the geothermal field while assuring good efficiencies, even when producing high-temperature heat. The use of CO_2, moreover, is more environmentally sustainable, in comparison to the traditional synthetic fluids.

Simulations of the GSHP system were also carried out to identify the optimal design of the machine.

In summer mode, the unit uses the two sources in series and this reduces the drift of the ground temperature and increases the efficiency of heat pump, in comparison to the traditional cooling units operating with CO_2. This concept allows operating with high efficiency in all climates, also in warm condition typical of central and south part of Europe.

In winter mode, the unit operates with the sources in parallel. On the basis of the external air temperature and on the predicted performance compared to the water source, the unit switches in order to operate with the most convenient source. This strategy allows to increase the seasonal performance by the choice of the best source and has the big indirect advantage to avoid the losses of energy due to the defrost cycle in comparison to the air source heat pumps.

The plant is up and running whilst performance monitoring of heat pump and geothermal field is ongoing.

3.5 Msida Bastion Historic Garden, Valletta, Malta

This historic building is used as a tourist centre given the historical cemetery located just adjacent to the building.

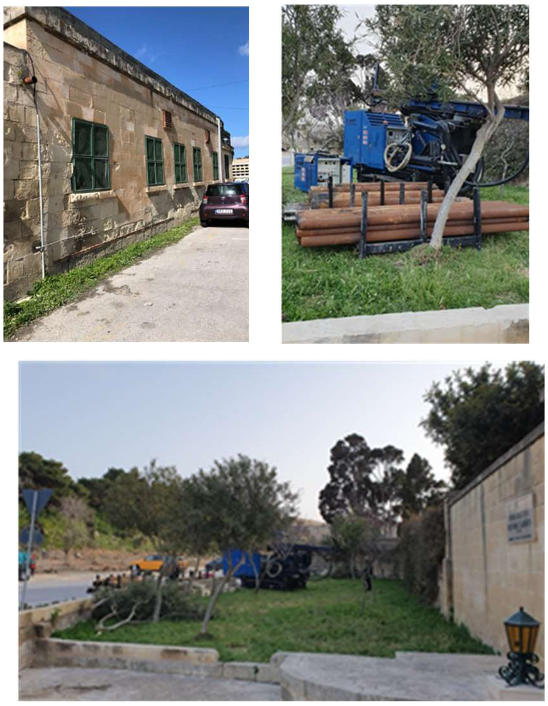

Figure 10: Site and drilling for BHE in Valetta demonstration project.

A number of retrofit solutions of the building are planned in the future following the drilling of geothermal heat exchangers and the installation of the dual source (geothermal and air source) heat pump and fan coils. The demo case will demonstrate how ground source heat pumps can be installed in an agile and efficient manner in compact spaces and around historical buildings.

The renovation consists of the drilling of four boreholes connected to a dual source heat pump, in turn supplying cold or hot water to new fan coil units. The innovative rotating and vibrating drilling head, developed in the project has been used for all boreholes.

The dual source heat pump is particularly suited for the high cooling demand of the Maltese climate, which is classified as a Mediterranean climate according to the Köppen climate classification, with very mild winters and hot summers.

The installations are in progress whilst the boreholes were drilled.

VIRTUAL DEMONSTRATION SITES

The installation of the GEO4CIVHIC technologies (i.e. GSHE field + the HP) have been modelled for 12 virtual cases, proposing different solutions, including cost estimates.

The BHE fields have been designed using the simulation tool based on the ASHRAE model. Specifically, two different coaxial heat exchangers have been modelled, both for consolidated soil and for non-consolidated soil.

In the following development of the project when an economic evaluation will be performed, all these virtual cases will facilitate the comparison in terms of economic feasibility. This will be performed by comparing real data about the economic costs and performance of the installation and infer the costs that may be derived by a new installation with the developed new type of heat exchangers, drilling machines and HP solutions.

In all virtual and real case studies, life cycle cost analysis (LCCA) is under way, also considering the cost of carbon emissions. Main assumptions are 5 % discount rates, 25 years time span, local natural gas and electricity prices prevailing during past year (2021), national electricity emission factors and projected CO_2 ICE market price of 76,92 €/ton. Until now, 5 cases have been analysed covering different GEO4CIVHIC solutions and gas-fired systems. They are retrofitting existing air-to-air heat pump system for heating and cooling in Alexandroupolis, Greece, and gas heating system in Erlangen, Germany, comparing GEO4CIVHIC with new gas-chiller systems for heating and cooling in Lugano, Switzerland, and with new gas heating systems in Clondakin and Wicklow, Ireland. The results showed that GEO4CIVHIC ground source systems provide heating and cooling with LCOE 0,100-0,187 €/kWh_{th} and 0,109-0,196 €/kWh_{th} when carbon emissions value is considered. The corresponding LCOE of replaced gas fired systems is 0,075-0,220 €/kWh_{th} without and 0,091-0,229 €/kWh_{th} with carbon emission costs.

The results from these studies showed the applicability of the geothermal solution for the space conditioning of the buildings in different European urban scenarios and the importance of a correct sizing to avoid overheating or undercooling of the ground. In particular, the thermal properties of the ground are a key point for the design of the BHE field, and its behaviour during the years of operation is influenced by the balanced or unbalanced thermal load profile of the building and by the possible effects due to the spacing between the BHEs.

5. NOVEL ICT TOOLS

Several applications and tools that optimise the installation and operation of GSHP technologies (decision support, engineering tools, apps, control system) are in progress.

The Web based Decision Support tool (DSS) and the engineering tools to size the GSHEs and to select HPs all started from the design work done in Cheap-GSHPs. The repository with solutions for drilling, heat exchangers, HPs was built using the knowledge and experience from the partners in each of their areas of expertise.

The main objective of the DSS is to do a rapid pre-project assessment, with an engineering and cost analysis, that facilitates a pre-design discussion around the installation of a GSHP in a retrofit project. It helps understanding the benefit of investing in GSHP and has an educative value for other stakeholders of energy renovation. The tool is based on simple general inputs requested from the user, such as the location, the type of building or the planned level of retrofit. With this information, the system estimates the project's climate conditions and the energy demand of the building. Then, a series of possible solutions are presented to the user, each of them being a combination of Heat Exchanger (HE), Heat Pump (HP) and drilling technologies. These solutions are dimensioned and evaluated, from a technical, environmental, and economical point of view. The results of the calculations and evaluation of the solutions are presented to the user, including a personalised analysis of possible barriers in the installation of the geothermal systems and risk management measures.

The most suitable drilling technology for shallow geothermal applications in a given geological context plays a key role in the techno-economic evaluation of shallow geothermal solutions. The installation costs are one of the main constraints to the wider application of shallow geothermal heat exchangers and are due mainly to the BHE drilling time and fees. In the GEO4CIVHIC project also geothermal drillability maps were produced, as a tool to select the most suitable drilling technique for borehole heat exchanger installations in a given geological and hydrogeological setting. Drillability maps at European and municipal scale are proposed as a guideline for drillers and ground source heat pump designers. The former summarizes the most suitable drilling technology based on lithology and borehole heat exchangers type, whilst the latter provides an insight in the ground thermal properties and the installation timing/costs.

The app helps drillers and designers speed up and facilitate a preliminary geothermal plant feasibility analysis.

The app follows these steps:

- localization of the site to study
- definition of the subsoil structure
- definition of the building structure
- estimation of feasibility and best drilling technique.

The user can define the soil type through the subsequent choice of Environment, Sub-environment and Lithology. The choice of these three sections allows the app to determine the soil thermal conductivity, the method, the time, and the drilling costs. In the definition of the building structure, the information on the type and size of the building is necessary to estimate its thermal needs for cooling and heating to calculate the most appropriate borehole field.

The calculations are different between residential and non-residential buildings. The calculation results include:

- The total length of the BHE field
- The number of BHEs provided and their length
- A rough estimate of the time required for drilling operations
- A rough estimate of the costs associated with drilling operations

Besides, a Building Energy Management System (BEMS) is under development. It aims to facilitate the integration of geothermal energy with other renewable energy sources (RES) by providing a control layer that handles the different technologies installed and optimises their operation. The development considers the analysis of the control strategies for the integration of Control strategies for integration of geothermal energy with other RES carried out in the project. The BEMS will be demonstrated via the pilot case installed in TECNALIA's facilities in Derio, Spain.

6. CONCLUSIONS

The GEO4CIVHIC project is still in progress. The innovative technologies were already realised and all installed recently in the different sites. The collection of data to evaluate the performance of innovative methodologies, BHEs and heat pumps has just started. An evaluation of the costs and the future market will also be performed.

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