GEO4CIVHIC

MOST EASY, EFFICIENT AND LOW COST
GEOTHERMAL SYSTEMS FOR RETROFITTING
CIVIL AND HISTORICAL BUILDINGS

2018 - 2023

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Energy needs and technical solutions for efficient buildings

Authors: GEO4CIVHIC Consortium
Project Coordinator: Adriana BERNARDI
Volume Coordinator: Laura CARNIELETTO

www.geo4civhic.eu

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EDITORS:
Adriana Bernardi
Doinița - Iuliana Cucuețeanu

PREAMBLE

Shallow geothermal energy is a stable and reliable renewable energy source that is always available everywhere. Shallow geothermal energy and it's coupling with other renewable energy sources has very large potential but remains underexploited in some countries and requires further dissemination. The objective of the seven volumes created is the further dissemination of shallow geothermal energy.

The seven volumes:

VOLUME 1 – Energy needs and technical solutions for efficient buildings

VOLUME 2 – Geology and mapping

VOLUME 3 – Drilling methodology, machines and heat exchangers

VOLUME 4 – Geothermal heat pumps technology

VOLUME 5 – Sizing GSHP and hybrid technologies

VOLUME 6 – Environment and standards

VOLUME 7 – Historical and World Heritage Buildings

These volumes describe and summarize research activities from innovation to their implementation and the lessons learned from 2015 to 2023 in the context of 2 European 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)**.

They are a valuable source of information intended to support and strengthen the skills of professionals, students and other important targeted stakeholders (e.g. public policies deciders, end users, investors, etc.) in the application of geothermal systems for heating and cooling of buildings in the field of energy saving.

The seven volumes describe the main results starting with basic principles, barriers, approaches, methodologies, innovations, as well as the legislation underlying the application of surface geothermal energy to all types of buildings. The application of shallow geothermal to historic buildings has many barriers and very stringent regulations, these issues were successfully solved during GEO4CIVHIC. This is a major breakthrough on the issue of heating/cooling and energy saving in these particular buildings.

These volumes were created to support national training around Europe. In particular, the lessons within the four new "European Centres of Excellence for Shallow Geothermal Application in Civil and Historic Buildings" created during GEO4CIVHIC in the Universities of Italy, Germany, Spain and Romania. A high-level training plan is envisaged to train new experts who will consequently guarantee new skills and jobs.

Furthermore, these four European Centres of Excellence could become a dynamic instrument not only for training but also for initiating regulatory improvement across Europe, a way to stimulate communication between specialists and ultimately improve the long-term progress of the shallow geothermal domain.

Each volume is dedicated to specific targets including energy needs and technical solutions for efficient buildings, the geological aspects of European soils, innovative solutions regarding heat exchangers, drilling machines, heat pumps and finally addressing legislative, environmental and economic aspects.

The contents of the volumes are the result of demanding scientific research, technological development, site experiments and demonstrations carried out by the partners of the two H2020 European research projects during eight years of collaboration, discussions and commitments.

The period in which the GEO4CIVHIC project developed was very difficult (pandemic, post pandemic, etc.). This significantly hindered both the research activity and the implementation and management of the project. In particular, the activities at the demo-sites throughout Europe (Italy, Belgium, Malta, Ireland), weighed heavily on the team members, but in the end these challenges were successfully overcome.

The difficulties of the project brought together a strong team of researchers from all over Europe. These specialists will continue to have an important role in the science of shallow geothermal, beyond the strong friendships that formed during the years of the two projects.

As coordinator of both projects, I would like to thank everyone for their efforts and for having deeply believed in shallow geothermal, which will be of great help in the field of energy saving in all Europe detached from fossil fuels.

Finally, a heartfelt thanks to the European Commission, which by financing these two projects has allowed a great step forward in the study of more efficient and less expensive technologies in the field of shallow geothermal.

Adriana Bernardi
Coordinator of GEO4CIVHIC and Cheap-GSHPs EU projects
Research Director at CNR-ISAC

Volume
1

GEO4CIVHIC Project

Training Manual

Energy needs and technical solutions for efficient buildings

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ABSTRACT

According to the recent policies regarding energy use in buildings and the need for retrofit strategies to move toward zero (or nearly-zero or plus) energy buildings. The aim of the GEO4CIVHIC project is to foster the retrofitting of civil and historical buildings by facilitating the installation, reducing costs and increasing efficiency of the different components through shallow geothermal systems. In particular, policies concerning the reduction of buildings' energy needs should be supported by proposing strategies that integrate ground source heat exchangers with other renewable energy sources. The main goal is to raise awareness on the potential energy saving achievable with optimal sizing and limited impact on the urban environment.

The definition of building archetypes is fundamental to replicate the case studies in other climates and locations, potentially extending the analysis at urban scale. Archetypes have been developed distinguishing among existing and historic buildings and focusing on single-family terrace houses which are the typical residential buildings in European historic centres.

The potential coupling of GSHP with other RES has been explored (i.e., solar thermal collectors with storage tanks, wind energy, photovoltaic (PV) systems, hybrid PV-thermal solutions and air to water heat pumps), and optimal solutions for the different building types and climates have been defined as examples of application.

A methodology for the optimal sizing of ground-source heat pumps has been developed, eventually considering dual-source systems or air systems. Results for archetype buildings have been presented combining simulations of a photovoltaic system to estimate the self-sufficiency and self-consumption for five orientations of the building.

Extreme results have been obtained for warm climates, with negligible heating energy demand and possibly free cooling systems rather than traditional cooling systems needed in wintertime. With proper inclination, photovoltaic systems could provide up to 40% of self-sufficiency share also in northern climates.

AUTHORS/PARTNERS

UNIPD – Laura Carnieletto, Michele De Carli, Angelo Zarrella, Giuseppe Emmi, Davide Menegazzo

SUPSI – Marco Belliardi

CRES – Dimitris Mendrinos

NOMENCLATURE

Abbreviations

AWHP	Air to Water heat pump
BEM	Building energy model
BREEAM	Building Research Establishment Environmental Assessment Method
DHW	Domestic hot water
EPBD	Energy performance of building directive
EPC	Energy performance certificate
ESPC	Energy saving performance contracting
EU	European Union
GHE	Ground heat exchanger
GHG	Greenhouse gas
GSHP	Ground source heat pump
HGSHP	Hybrid GSHP
HVAC	Heating ventilation and air conditioning
IAQ	Indoor air quality
IEQ	Indoor environmental quality
LEED	Leadership in Energy and Environmental Design
NEEAP	National Energy Efficiency Action Plan
NEPC	National Energy Performance Certificates
NGO	Non-governmental organization
NPO	Non-profit organization
nZEB	nearly Zero energy building
PCM	Phase change material
PEH	Positive energy house
PV	Photovoltaic
RES	Renewable energy sources
SNBS	Sustainable Building Standard Switzerland
ZEB	Zero energy building

Symbols

λ	Thermal conductivity [W/(m K)]
CO2	Carbon dioxide [-]
COP	Coefficient of performance [W/W]
EER	Energy Efficiency Ratio [W/W]
Lc	(Probe) Length for space cooling [m]
Lh	(Probe) Length for space heating [m]
Lmax	Maximum Probe Length [m]
SCOP	Seasonal coefficient of performance [W/W]
SEER	Seasonal Energy Efficiency Ratio [W/W]
PBT	Pay back time [y]
SC	Self consumption [%]
SS	Self sufficiency [%]

Subscripts

h or H	Heating
c or C	Cooling
max	Maximum

1. INTRODUCTION ON ENERGY EFFICIENT BUILDINGS

1.1. Retrofit of the existing building stock

The Horizon 2020 European Project GEO4CIVHIC[1] (Most Easy, Efficient and Low-Cost Geothermal Systems for Retrofitting Civil and Historical Buildings) aims to accelerate the deployment of shallow geothermal systems for heating and cooling through retrofitting existing and historic buildings located in urban city centers and by overcoming barriers such as space availability and law limitations related to the architectural and cultural importance of the buildings. It is based on innovative solutions for ground heat exchangers (GHE) and ground source heat pumps (GSHPs). Shallow geothermal energy is a very promising solution shown by the interest of the European Commission with the Energy Performance of Building Directive (EPBD) and its recast versions (The European Parliament and the Council of the European Union 2010 and 2018). More recently, Europe developed a plan to fast forward the green transition, named REPowerEU[2], poposing several actions to support energy saving policies and promote the diversification of supplies to replace fossil fuels with emerging renewable energy sources. The EU Solar Strategy aims to triple the geothermal capacity by 2030. The legislation will be improved to create a solid market for geothermal heating and cooling through ground source heat exchangers, and to support the decarbonisation of buildings and the industry. Under the “Fit for 55” package of European Green Deal legislation[3], the EU Commission proposed the enhancement of long-term energy efficiency measures, including an increase from 9% to 13% of the mandatory Energy Efficiency Target.

Several approaches in literature aimed to provide strategies to increase the sustainability of the urban environment, involving environmental, economic, and social perspectives (Directive 2010/31/EU) as well as cultural and institutional aspects (Directive 2012/27/EU, Directive 2018/844). However, the generation and optimization of energy in buildings should be one of the main foci for implementing the process of cities’ decarbonization. Space heating and cooling in buildings is one of the most energy-consuming end-uses that must be reduced to achieve the European Union’s 2050 energy efficiency and greenhouse gas emissions (GHG) goals. Several studies have focused on detailed individual building energy modelling (BEM), by optimizing internal loads and envelope insulation and heating, ventilation, and air conditioning (HVAC) system operation. However, retrofit strategies should be studied to be replicable on a wide scale; thus, building datasets should be representative of European or national building stocks to help dealing with such a large number of buildings and support urban-scale simulation tools.

The energy demand of existing buildings around Europe ranges from 150 kWh/(m^2 year) to 300 kWh/(m^2 year) based on recent studies (Ballarini and Corgnati, 2014). Hence, there is big potential in Europe estimated at about 25,000 km^2 of floor area. However, most of the buildings which need to be renovated are in urban areas, where the space availability for installing the borehole field for a GSHP is an important issue and has to be overcome according to law limitations. The space availability depends both on the real free space available (gardens, parking lots, etc.), and on the refurbishment level applied, because deep retrofitting of the envelope and of the system will reduce the energy need and thus the probes’ length and the space needed. The application of GSHP to historic buildings has been investigated by Emmi et al. (2017), who showed the impact of an optimal sizing despite the peculiar urban development of two case studies in Venice and Florence. Comparing the results with an air to water heat pump (AWHP), GSHP had the best performance. Similarly, Zarrella et al. (2019) showed the coupling between GSHP and AWHP when the thermal load is unbalanced by defining a switch air temperature to take advantage of the highest efficiency of the system. Another application of GSHP has been studied by Emmi et al. (2020), which provided space cooling and space heating to a residential building with a GHSP that was able to assist a solar field in the production of domestic hot water.

Although several papers worked on the efficient integration of GSHP as generation systems for space heating and cooling, each analysis has been done at single building level. On the contrary, research is moving towards a wider perspective at district or city scale, to optimize the energy sharing and exploiting renewable energy sources. The existing available information concerning archetypes already developed for the European context, such as TABULA and EPISCOPE[4], excluded information concerning hourly energy demand, peak loads, and data to simulate the potential integration with renewable energy sources were missing. Therefore, a complete database for thermal and electrical profiles would be useful to define the energy demand of stocks of buildings thus, allowing urban planners and policy makers to state a priority list of districts or cities that need urgent support towards energy use reduction. Integrated results concerning both envelope and plant refurbishment provide a new perspective of urban modelling, including the possibility of sharing both thermal and electric energy through the development of energy communities.

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[1] Available at: https://ec.europa.eu/inea/en/horizon-2020/projects

[2] Communication on REPowerEU: Joint European Action for more affordable, secure and sustainable energy, COM (2022) 108 final. Available at: https://eur-lex.europa.eu

[3] Available at: https://www.consilium.europa.eu

[4] Available at: https://episcope.eu/welcome/

1.2. New buildings (ZEB, nZEB, PEH)

Highly energy-efficient buildings are designed and constructed to consume less energy for heating, cooling and lighting than conventional buildings. New buildings in particular, have the opportunity to integrate energy-saving features from the beginning, affecting aspects that would otherwise be more difficult to change (structures, installations, spaces, esthetics, etc.). Examples of energy-efficient design strategies for new buildings include optimizing natural light, controlled mechanical ventilation, using better insulated walls, roofs and windows, selecting energy-efficient appliances and lighting, using renewable energy sources such as sun and wind, and highly efficient technologies such as heat pumps. By lowering energy consumption, these buildings can economically reduce energy bill costs and environmental impact and create healthier and more comfortable living or working environments.

European Union directives establish legislation on the energy efficiency of buildings. The most recent is Directive 2018/844/EU, known as the Energy Performance of Buildings Directive (EPBD), which sets targets for the energy efficiency of existing and new buildings in the EU. The directive requires member countries to take measures to achieve a high level of energy performance of buildings and promotes the use of renewable sources for heating and cooling in buildings.

More specifically, the directive states:

- Building Energy Performance Certificates (EPCs) - Member States must ensure that EPCs are issued for all buildings when they are constructed, sold, or leased.
- Nearly Zero-Energy Buildings (nZEBs) - Member States must ensure that all new buildings occupied and owned by public authorities are nZEBs from the 31st of December 2018, and all new buildings are nZEBs from the 31st of December 2020. A building with this concept has a very high energy efficiency standard, using only a small amount of energy from renewable sources.
- The renovation of existing buildings - Member States must adopt a long-term strategy to increase the rate of renovation of existing buildings, with the aim of reaching a significant level of energy renovation by 2050.
- Smart readiness indicator - Member States must ensure that new buildings, as well as buildings undergoing major renovations, are designed and built to be “smart ready”.
- Energy Saving Performance Contracting (ESPCs) - Member States must encourage the use of ESPCs, which are a way to finance building energy efficiency retrofits through savings on energy bills.
- National Energy Performance Certificates (NEPCs) - Member States must ensure that NEPCs are issued for all buildings when they are constructed, sold or leased.
- National Energy Efficiency Action Plan (NEEAP) - Member States must establish and implement a NEEAP every five years to establish the measures they will take to improve the energy performance of buildings.

Building planners, designers and developers are required to use materials and technologies that have a high thermal insulation value and a lower environmental impact. This includes the use of insulated walls, roofs, and floors, as well as high-efficiency windows and doors, to minimize heat loss. Additionally, the use of renewable energy systems such as solar thermal and photovoltaic systems, heat pumps, and thermal energy storage systems must be used to supply a significant proportion of the energy required for heating and cooling the building. The EPBD also promotes the use of smart technologies to monitor and control the energy consumption of buildings and to make it easier for building occupants to adjust their energy usage.

The selection of materials and technologies will depend on the context, availability, cost and other specific factors of each building and country, but the directive encourages the use of the most energy-efficient solutions.

The individual member countries have adopted different measures to comply with European legislation on energy efficiency in buildings. Each European country has its own specific legislation, but all are required to follow the EU Directive. For example, in Germany there is a "Federal Law on Energy Efficiency in Buildings" (2020) which sets minimum requirements for the energy efficiency of existing and new buildings and promotes the use of renewable energy sources.

In Italy, Legislative Decree of 26 June 2015 "Application of energy performance calculation methodologies and definition of minimum prescriptions and requirements for buildings" the methodology for calculating the energy performance of buildings, including the use of renewable sources, as well as minimum requirements on the energy performance of buildings and units properties, in compliance with the general criteria referred to in Legislative Decree No.192 of 19 August 2005.

In France, the "Grenelle 1" law of 2007 sets targets for energy efficiency in existing and new buildings and promotes the use of renewable energy sources. France has adopted a building energy efficiency labeling system, similar to those used in other European countries, to provide easily understandable information to consumers about the energy efficiency of buildings.

In Switzerland, the national regulations for energy-efficient building include the Energy Performance of Buildings Directive (EPBD) and the Swiss Federal Energy Ordinance (EnO, 2017). The EPBD sets minimum requirements for the energy performance of new and existing buildings and promotes the use of renewable energy sources. The EnO sets energy efficiency standards for buildings and requires regular inspections to ensure compliance. Switzerland has also adopted a building energy labeling system similar to those used in other European countries.

In Spain, the national regulations for energy-efficient buildings include the Documento Básico Ahorro de la Energía (updated in 2022), part of the Código Técnico de la Edificación (CTE), that provides guidelines for the limitation of energy consumption by setting minimum requirements for the control of energy demand (HE1), the installation of appliances (HE2, HE3) and the minimum contributions of renewable energy sources (HE4, HE5). The Real Decreto 390/2021, which replaced the Real Decreto 47/2007, approved the guidelines for the energy efficiency standards for buildings. It established the technical and administrative procedures that must govern the performance of efficiency certifications and the methodology for calculating the energy efficiency rating, to adopt a building energy labeling system similar to those used in other European countries.

In addition to the previous national requirements, the concept of a PEH (Positive Energy Home) is becoming increasingly popular as more and more countries strive to reduce their carbon footprint and become more sustainable. A PEH is a building that produces more energy than it consumes, thus contributing to the grid. The goal of a PEH is to be energy self-sufficient or even energy positive. It is achieved by using energy-efficient design and technology, combined with renewable energy sources such as solar panels.

1.3. Energy and sustainable labelling

A building energy efficiency certification system is an instrument used to evaluate and label buildings based on their energy performance. The goal of these systems is to provide transparent and comparable information on the energy performance of buildings, allowing building owners and occupants to make informed decisions about energy use and costs. Building energy certification systems typically evaluate a building's energy use and efficiency in areas such as heating, cooling, lighting, and hot water and assign a rating or label based on this evaluation. These labels can then be used to compare the energy performance of different buildings.

Different European countries use different names for their energy performance certificates. Here are a few examples:

- In Germany, the certificate is called the "Energy Performance Certificate" or "Energieausweis"
- In France, the certificate is called the "Certificat de Performance Énergétique" or "CPE"
- In Italy, the certificate is called the "Attestato di Certificazione Energetica" or "ACE"
- In Spain, the certificate is called the "Certificado de Eficiencia Energética" or "CEE"
- In Switzerland, the certificate is called GEAK “Gebäudeenergieausweis der Kantone” or “Building energy certificate of the Cantons”
- In the UK, the certificate is called the "Energy Performance Certificate" or "EPC"

It is worth noting that the certificate format and the information provided vary slightly from country to country.

On the other hand, there are voluntary certification systems that set higher standards for energy efficiency and comfort. Buildings that meet these standards are usually more energy-efficient, healthier, and more comfortable to live in than buildings that only meet the minimum requirements set by each “Energy Performance Certificate”. Voluntary national certifications aim to promote energy efficiency and sustainability in buildings and provide additional information to consumers and building owners.

Some examples include Germany’s “Passive house” (or “Passivhaus”), Switzerland's “Minergie”, Sweden's “Miljöbyggnad”, Italy’s “CasaClima”, and France’s “Effinergie”.

There may be specific constraints concerning voluntary certificates within countries, e.g., in Switzerland new constructions or renovations of public buildings must comply with at least the Minergie certification (but this is not compulsory for private buildings).

All these systems, in some way, are trying to achieve the same goal, which is to provide a simple and understandable way for consumers to access the energy efficiency of buildings and to help governments and building owners to monitor and improve the energy performance of buildings.

1.4. Environmental and sustainability performance of a building

Green building certification systems are a set of assessment systems and instruments used to evaluate the performance of a building or construction project from a sustainability and environmental aspect. These assessments aim to improve the overall performance of buildings and infrastructure, to integrate a life-cycle approach into their design and construction and to promote the construction industry's achievement of the United Nations Sustainable Development Goals. Buildings that are assessed and considered capable of satisfying a certain level of performance and quality receive a certificate attesting to this accomplishment.

These systems are typically developed by organizations or groups of experts in the field of sustainable building and are intended to be used globally. They are designed to provide a consistent and transparent method for assessing the environmental and sustainability performance of buildings, so that building owners, developers, and other stakeholders can make informed decisions about the design, construction, and operation of buildings.

Examples of international sustainable building certification systems include LEED[5] (Leadership in Energy and Environmental Design) and BREEAM[6] (Building Research Establishment Environmental Assessment Method), which are both widely recognized and respected systems.

BREEAM is a sustainability assessment method for buildings developed by the Building Research Establishment (BRE) in the UK, whereas LEED is a rating system developed by the U.S. Green Building Council (USGBC).

These certifications have a set of criteria that a building must meet to be certified, such as energy and water efficiency, indoor environmental quality, materials and resources, and more. They also have different levels of certifications such as Gold, Silver, and Bronze. Buildings that meet these criteria and achieve a certification can demonstrate to the public, tenants, and regulators that the building is environmentally responsible and has a lower environmental impact.

LEED (Leadership in Energy and Environmental Design) and BREEAM (Building Research Establishment Environmental Assessment Method) are examples of international sustainable building certification systems that are used in many countries worldwide, including Europe.

Both LEED and BREEAM are often used in addition to the national systems previously mentioned. These certifications can be a useful tool for building owners and developers who want to demonstrate the environmental and sustainability performance of their buildings.

International sustainable building certification systems, such as LEED and BREEAM, are typically developed by organizations or groups of experts in the field of sustainable building and are intended to be used globally. They are intended to be rigorous and comprehensive, covering a wide range of environmental and sustainability aspects of building design, construction, commissioning and operation.

These systems are unbound by any specific national or regional rules and regulations, but they are designed to be aligned with, and sometimes even be incorporated into, the local building codes and regulations.

International certification systems do not replace the national or local regulations but can be used as a tool to comply with them. They can also be used as a way to demonstrate compliance with local regulations and codes, and to provide additional information about the building's environmental and sustainability performance.

Additionally, many countries have their own green building rating systems, which are sometimes aligned with the international rating systems such as LEED or BREEAM. This allows buildings to get certified by both the national and international systems.

International sustainable building certification systems such as LEED and BREEAM have some similarities with, for example, the Swiss SNBS (Swiss National Standard for Sustainable Buildings) in terms of their focus on evaluating the environmental and sustainability performance of buildings.

The Sustainable Building Standard Switzerland (SNBS) 2.1 is the overall standard for sustainable building in Switzerland. It integrates existing instruments and tools such as the SIA Recommendation 112/1 "Sustainable Construction - Building Work", the goals of the 2000-Watt Society or the Minergie criteria and is oriented toward the steps of the SIA Performance Model. According to the SNBS office/administrative, residential, and educational buildings can be certified. This applies to both new constructions, and renovation of buildings.

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[5] Available at: https://www.usgbc.org/

[6] Available at: https://bregroup.com/

All of these systems are designed to help building owners and developers to design, construct and operate buildings that have a lower environmental impact. They can be used together, although meeting the requirements of one of them does not guarantee the compliance with the other.

2. POTENTIAL RETROFIT SCENARIOS

There is a great debate on the refurbishment of buildings which may be of two types: shallow or deep renovation. Shallow retrofit is the most widespread and focuses on low-risk energy conservation measures with short payback time (PBT) such as partial lighting retrofits, HVAC replacement and retro-commissioning, or renewable energy sources (RES) installation due to actual favorable costs or incentives. On the other hand, a deep renovation reduces energy consumption compared to pre-renovation levels, typically by more than 60%. These interventions often include building envelope retrofit (façade and/or roof insulation, replacement of windows, and significant improvements in building air tightness) with the refurbishment of the HVAC system.

Today the interventions are mainly of shallow nature, due to the higher upfront investment costs of deep retrofit: on average a shallow retrofit may cost ca. 650 €/m^2 (referred to net floor area), while a usual deep retrofit costs about 830 €/m^2. Moreover, the timing required for deep retrofit works is 25% higher than shallow refurbishment. There are other problems: difficulties in access to many buildings, potential disruption to occupants and neighborhoods, low level of awareness, reluctance to risks and/or lack of experience amongst the operators (architects, installers, building owners) and few integrated solutions that may help solve different problems in one time, e.g. structural repairs coupled with energy efficient measures.

Since the EU aims to move toward 100% RES in buildings by 2050, deep retrofit should be applied when possible to meet this goal. Reducing the time needed to provide deep retrofit and reduced installation costs are two of the most important issues to tackle. Prefabrication could be an interesting solution since it reduces variation in product quality and process timing, reduces cycle times for production and installation and supports various tracking technologies that help make the process visible.

Internal smaller modular solutions can be more efficient and can be applied in different types of buildings: historical buildings where it is impossible to change the outer façade, multi-story buildings where the outer insulation can be complicated, buildings in city centres where the external scaffold may represent a problem and buildings that have been already partially refurbished (second step retrofit), e.g. roof and/or external painting. Internal insulation can be hence a very interesting solution that might allow a wider diffusion of deep retrofit interventions. However, it is still poorly adopted. Inner modular solutions are therefore very attractive and not investigated as deeply as outer insulation, and hence present a potential solution for the deep retrofit of buildings. A crucial point is how to design, build and manage modular solutions and at the same time how to industrialize the work site in order to increase the efficiency of the workers and speed up the process of the deep retrofit of the building. An important issue to solve is the possibility of reinforcing structures and make the building anti-seismic.

A crucial issue is Indoor Environmental Quality (IEQ, temperature and humidity control, acoustic, IAQ, solar shading), which must be carefully considered and may represent part of high costs and timing of works in the refurbishment. Suitable integrated solutions with easy-to-use technologies and maintenance, help in providing good IEQ and maintain the predicted comfortable solutions in the design phase.

Much of the effort has to be directed to civil buildings that are both residential and non-residential types. A particular effort should be made for buildings with high intrinsic value either because they are historical or because they have a social role, i.e. council housing, public buildings, non-profit organizations (NPOs), non-governmental organizations (NGOs) and churches. These buildings may represent leading good practices and the leverage can be obtained by the amplification that public companies/bodies and churches, NGOs and NPOs. In fact, on one hand, they own a wide portfolio of stock buildings; on the other hand, they have a consistent network. Hence, thanks to communication and information activity, citizens can be more aware of the deep retrofit solutions. Moreover, they are present in wide areas/regions allowing wide geographical replicability.

Particular effort has to be made to check the cost-benefit analysis to allow the use of easy to install systems (plug and play solutions) along with different local renewable energy sources such as solar PVs and ground source heat pumps. As demonstrated in the literature, the combination of PV and GSHP solutions is a good driver to meet nZEB solutions with reasonable pay back times (PBT).

The target buildings in urban districts are existing and historical residential and non-residential buildings where the external insulation is only sometimes easily applicable, with particular attention. The definition of strategies at the urban level needs the development of building archetypes to widen the perspective of the single building scale (Carnieletto and Ferrando, 2021), representing the most common typology of buildings for modelling purposes. This approach is important to better define the potential obstacles in the application of a specific retrofit strategy. Archetypes are generally defined as theoretical buildings obtained by statistical analysis of building characteristics grouped based on similarities (Carnieletto and Ferrando, 2021). Building archetypes can also be defined as models that allow the application of simulation tools to evaluate the energy demand of a wide building stock (Ferrando and Causone, 2020). Even though the application of archetype-based modeling requires some simplifications, literature shows that it allows the development of innovative strategies and technologies to increase energy efficiency with acceptable results both at single-building and at urban scale, as presented in the works of Fracastoro and Ferraino (2011), Dall'O' and Galante (2012), Prataviera and Romano (2021) and Teso and Carnieletto (2022). Therefore, the potential reduction in energy consumption can be compared with other parameters for economic management.

2.1. Possible retrofit actions

As already mentioned, the project GEO4CIVHIC looks at the retrofit of existing and historic buildings in urban city centres, applying GSHPs. A typical structure of historic buildings (i.e., built before 1950) consists of external walls with solid bricks (50 cm) eventually separated by an air gap of 5 cm according to the climate of the considered location. Typical roofs of historic buildings have a wooden trussed roof that supports a wooden layer with the tiles. The attic below can be divided from the rooms through a non-walkable attic formed by another wooden layer supported by joists.

Considering existing buildings, a reference construction can be defined as 25 cm perforated blocks or cellular blocks in bricks, eventually separated by an air gap of 5 cm. Roofs should be defined according to the location; in Strasbourg and Helsinki, for example, there are brick-concrete sloped roofs with tiles, while in Athens, horizontal roofs have concrete beams and hollow bricks flat blocks. Since many historic buildings are listed buildings where it is impossible to install insulation, replacing the gas boiler with a high temperature GSHP maintaining the radiators has also been considered. Therefore, solutions should take into account both high temperature terminals and mid and low temperature heating emission systems (i.e., fan-coils and radiant systems).

In case of envelope retrofit, the proposed strategy suggests the insulation on the opaque walls using 12-cm EPS applied on the inner side to consider potential limitations related to the protection of the cultural heritage or the urban layout. This strategy may not allow the use of external insulation in city centres and may reduce the pedestrian zone as a consequence of the pavement area reduction. The thickness of the insulation layer is an average value that does not excessively reduce the inner net floor area available, thus being positively considered from the user. Internal floors should also be slightly insulated to consider the possible installation of radiant systems that can be better coupled with ground source heat pumps due to the lower temperature required (Carnieletto and Kazanci, 2018). The replacement of windows should be included to reduce the overall thermal losses.

Supposing that most of the buildings are supplied by standard gas boilers, the first strategy proposed is the replacement with a more efficient GSHP (Case 0), combined with the replacement of medium or low temperature emission systems (i.e., fan-coil or radiant systems) both for heating and cooling (Case 1), eventually coupled with the thermal insulation of the envelope (Cases 2 and 3).

Hence, overall, four main retrofit potential solutions have been investigated (cs 2-1):

- Case 0: the standard boiler is replaced with a high temperature GSHP and the traditional radiators are maintained.
- Case 1: the standard boiler is replaced with GSHP and the heating and cooling terminal units are replaced either with fan coils (1a) or with radiant system (1b)
- Case 2: the standard boiler is replaced with GSHP, the radiators are maintained, but the insulation of the building is improved.
- Case 3: the standard boiler is replaced with GSHP, the heating and cooling terminal units are changed either with fan coils (3a) or radiant system (3b) and the insulation of the building is improved.

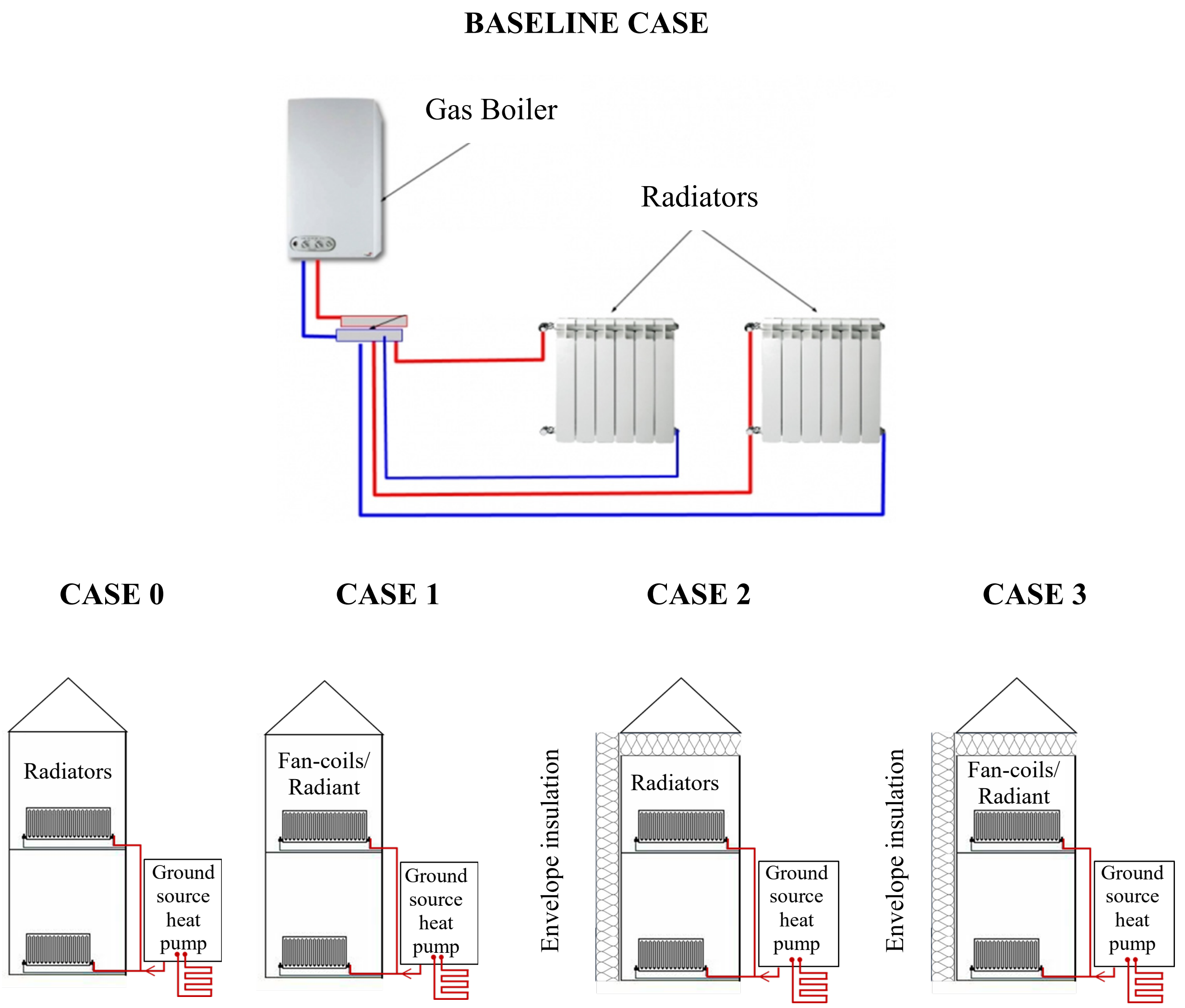

Figure 2-1. Simplified scheme of the retrofit strategies applied

2.2. Sizing of the ground source heat exchangers

The total borehole length required to supply space heating and cooling and the extension of the borehole field of double U-tube ground heat exchangers has been estimated using the ASHRAE method (ASHRAE, 2011). The inputs required are the seasonal thermal energy demand and the peak load for space heating and cooling. Results can be compared to previous projects such as Cheap GSHPs and with the WebTool as TABULA[7].

To consider the interference of adjacent boreholes in the calculation of the total required borehole length, the ASHRAE method has been applied twice in a row, applying the tool developed by Capozza et al. (Capozza and Zarrella, 2015). In the first calculation, the required bore lengths for heating (Lh) and cooling (Lc) are calculated. Once calculated the ideal overall depth based on the line source model, the highest value between Lc and Lh is divided by the GHEs depth, which are considered of equal length. The spacing between the borehole heat exchangers has been set to 7m to limit thermal interference, according to the site characteristics (Lee and Park, 2021). With the second iteration, Lh and Lc are evaluated more accurately considering the penalty temperature (t_p).

The optimal sizing of the borehole length for the installation depends on the energy demand of the building; in cooling dominated conditions, for example, it is frequently the summer season that imposes the most critical condition for the sizing of the system. The reduction of transmission losses obtained insulating the building envelope can increase the time constant of the building, which can be beneficial for the cooling demand in cooling-dominant locations.

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[7] Available at: https://webtool.building-typology.eu

Typical values of COP and EER considering the heat pump connected to different heating and cooling terminal units (radiators, fan-coils, radiant floor) are presented in Table 2-1 referring to three climatic conditions representative of a warm (Athens), mild (Strasbourg) and cold (Helsinki) location. These values were determined referring to the datasheets of real heat pumps, choosing the seasonal values of COP and EER according to design criteria of the system. Based on the local temperatures, it can be seen that the colder the climate, the lower the COP and the higher the EER.

Table 2-1. Design and seasonal values of the heat pump connected to the different heating and cooling systems

			ATHENS		**STRASBOURG**		**HELSINKI**	
		Inlet/Outlet Temperature [°C]	**Design COP/EER**	**Seasonal COP/EER**	**Design COP/EER**	**Seasonal COP/EER**	**Design COP/EER**	**Seasonal COP/EER**
Heating	**Radiator**	75 - 65	2.4	2.5	2. 4	2.5	2.4	2.5
	Fan-coil	45 - 40	3.6	4.1	3	3.3	2.7	3
	Radiant	35 - 30	4.8	5.3	3.8	4.3	3.4	3.8
Cooling	**Fan-coil/ Radiant**	7 - 12	4	4.4	5	5.5	5.9	6.5

Three values of thermal conductivity and volume thermal capacity are specified in Table 2-2 as reference values for the most common types of ground. These thermal properties values were selected according to the main results presented by several research projects focused on determining the ground thermal properties for shallow ground sourrce heat pump applications, collecting data on unconsolidated deposits, sedimentary, metamorphic and igneous rocks (Galgaro and Dalla Santa, 2021). In the application presented in this the following chapters, only the heat exchange conduction component between probe and ground is considered. The convection contribution due to groundwater flow, which could increase the underground equivalent thermal conductivity and thus reduce the overall length required for ground exchangers, is here neglected for the sake of simplicity.

Table 2-2. Thermal properties of the three considered types of ground

Thermal conductivity [W/(m K)]	1.5	2.2	3.0
Specific volume thermal capacity [MJ/(m^3 K)]	2.0	2.5	2.6

The installation of GSHP systems in urban areas is usually complicated mainly due to the limited area available which usually corresponds to small internal courtyards or gardens.

2.3. Optimal probes' length

Summing up the results presented in the last paragraph, Figure 2-2 and Table 2-3 show the possible scenarios, comparing the maximum length available (L_{max}) with the probes' length needed to satisfy the building energy demand for cooling (L_c) and heating (L_h). There are three options:

- A: Enough available space for the probes to satisfy the energy required
- B: Only heating or cooling energy demand can be satisfied compared to the available space ($L_{max}<L_h$ or $L_{max}<L_c$)
- C: There is not enough space for satisfying neither the heating demand nor the cooling demand of the building ($L_h>L_{max}$ and $L_c>L_{max}$).

When the length of the probes is not sufficient to supply the energy demand of the building, the combination with an air to water heat pump (AWHP) has been investigated to enable the combined system to supply the required thermal demand.

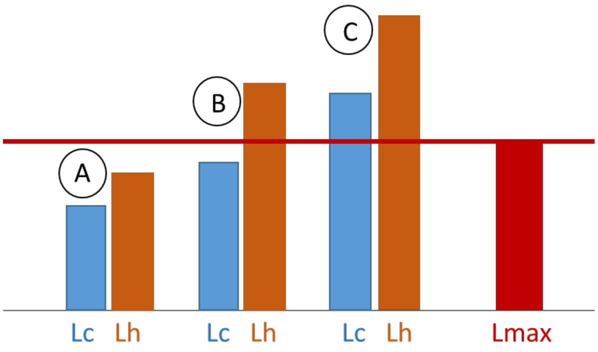


Figure 2-2. Possible scenarios of the case studies

A) LH, LC < Lmax	
1 - Lh ≈ Lc (15% deviation accepted)	L = max (Lh, Lc)
2– Lh > Lc	2a) L = Lh 2b) L = Lc + AWHP
3– Lc > Lh	3a) L = Lc 3b) L = Lh + AWHP
1 LH or LC > Lmax	
1– Lh > Lmax	L = Lc + AWHP
2– Lc > Lmax	L = Lh + AWHP
2 LH, LC > Lmax	
L = Lmax + AWHP	

Table 2-3. Optimal length of the probes

Considering the combination of possible scenarios, different cases can be studied to decide the optimal probe length, in particular:

- Case A1: the length of the probes is almost the same for heating and cooling, the maximum of the two can be chosen (full demand of the building with a water-to-water reversible heat pump). A deviation of about 15% has been adopted.
- Cases A2 and A3: if the difference between Lh and Lc is larger than 15%, the choice can be done considering either the longest length of the probes (sub-cases 2a and 3a with full GSHP) or the shortest length of the probes (sub-cases 2b and 3b) with a hybrid system that uses two sources, water and air (GSHP+AWHP); in this case a suitable machine implementing two sources at the same time is feasible to adopt/consider (Zarrella and Zecchin, 2019).
- Cases B1 and B2: if one of the borehole lengths is shorter than the maximum available length and the other one is longer, a hybrid system is the unique solution, letting the GSHP cope with the balanced part of the base-load and the AWHP take the rest of the loads – i.e. the optimal total length of the boreholes is the shortest one, and the energy which is not supplied by GSHP is supplied by the air source (GSHP+AWHP). In this way the utilization factor of the GSHP is maximized.
- Case C: if both lengths are greater than the maximum available length, the optimal length of the probe to be installed is the maximum allowed, integrating the surplus energy in a hybrid solution (GSHP+AWHP). In this way, similiarly to Case B1 and B2, the utilization factor of GSHP is maximized balancing the base-load and the remaining load is supplied by AWHP.

3. CASE STUDIES

The following paragraphs will present the results obtained from three case studies developed for the GEO4CIVHIC project. Table 3-1 shows the energy demand both for residential existing and historical buildings, for Athens, Strasbourg, and Helsinki as baseline for the sizing of GHE. Energy reduction is significant when looking at retrofitted buildings both for existing and historical cases, due to the lower transmission losses through the envelope. Comparing the results obtained for the baseline cases (i.e., existing and historical buildings without retrofit), in mild and cold climates the heating energy demand in buildings is dominant, whereas warm climates present a dominant cooling energy demand. In contrast, the energy demands for heating and cooling are similar for retrofitted buildings in Strasbourg, which is an important result for the sizing of ground heat exchangers.

Table 3-1. Energy loads for heating and cooling in the three locations [kWh/(m^2 y)]

Energy demand [kWh/(m^2 y)]		Existing		Historic	
		Baseline	Retrofit	Baseline	Retrofit
Athens	**Heating**	13.1	0.4	32.6	1.1
	Cooling	69.5	44.1	78.7	48.8
Strasbourg	**Heating**	72.6	21.5	104.2	26.4
	Cooling	30.2	27.3	35.6	31.2
Helsinki	**Heating**	122.3	41.9	158.4	50.5
	Cooling	19.1	18.5	23.3	25.4

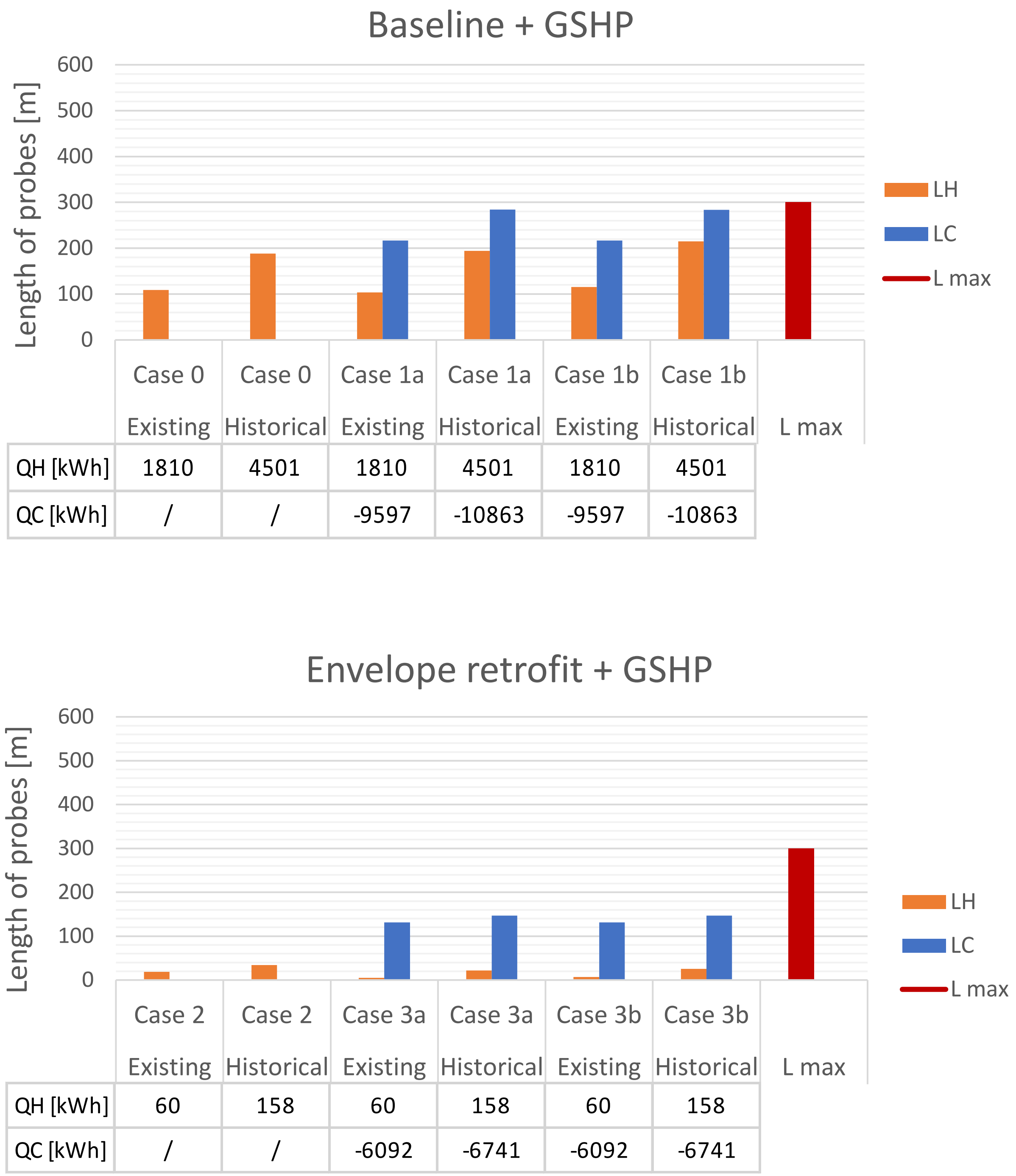
As already know, the GSHP performance is influenced by the thermal conductivity of the ground. The average thermal conductivity of 2.2 W/(m K) and specific volume thermal capacity of 2.5 MJ/(m^3 K) were chosen for the detailed analysis of the results shown in this section.

The final results of the ASHRAE method that will be presented for each case study correspond to the required borehole lengths for heating (Lh) and cooling (Lc), which are compared to the maximum possible length. The archetype refers to a typical terrace house that can host the GHEs arranged linearly in the courtyard at about 3.3 m from the neighborhood and of 7 m between them to avoid thermal interference. These assumptions lead to a maximum of 3 BHEs for the installation, thus the length limitation for LH and LC is 300 m. The analysis has been carried out assuming that the necessary soil investigation and permits have already been required and obtained by the responsible local authority as required by the convention for protecting the World Cultural and Natural Heritage (UNESCO, 1972).

3.1. Athens

In Athens, considering the installation of GSHP without any insulation of the building's envelope (Figure 3-1a) and with envelope retrofit (Figure 3-1b), the thermal load required by the building is unbalanced. The energy exchanged with the ground in summer, thus the required borehole length for cooling (Lc), is much greater than the energy required for heating (Lh). Lc has been defined because originally no cooling system was supposed to be present, while Lh decreased to 6% and 13% for existing and historic buildings respectively comparing the baseline condition with the Case 3-1b (envelope retrofit combined with distribution and generation systems' replacement). Despite the unbalanced thermal load, the GSHP can be used to avoid problems concerning the ground thermal drift, because the penalty temperature, calculated with the ASHRAE method, is lower than 1 °C in all cases. As shown in the diagrams, if the retrofit of the envelope is performed the required borehole length for heating is greatly reduced because of the lower energy demand required by the building due to the reduction of transmission losses. In this case, the cooling length of the probe is slightly decreased, indicating an increase of the unbalance between heating and cooling thermal load.

Considering the average performing characteristics of the ground, the required borehole lengths are shorter than the case with thermal conductivity of 1.5 W/(m K) (see Appendix), therefore Lh and Lc are shorter than the maximum length allowed (Lmax). The opposite effect is even more evident for λ=3 W/(m K).



a)

	Case 0 Existing	Case 0 Historical	Case 1a Existing	Case 1a Historical	Case 1b Existing	Case 1b Historical
QH [kWh]	1810	4501	1810	4501	1810	4501
QC [kWh]	/	/	-9597	-10863	-9597	-10863

b)

	Case 2 Existing	Case 2 Historical	Case 3a Existing	Case 3a Historical	Case 3b Existing	Case 3b Historical
QH [kWh]	60	158	60	158	60	158
QC [kWh]	/	/	-6092	-6741	-6092	-6741

Figure 3-1. Comparison between the maximum length available and the required borehole length to satisfy the energy demand for the three building typologies for Athens without (a) and with (b) envelope insulation

3.2. Strasbourg

The cases with a retrofitted envelope (Figure 3-2b) shows balanced heating and cooling energy demand thanks to a reduction of the thermal load during the heating season, while the case without insulation (Figure 3-2a) has unbalanced thermal load with higher energy demand in heating mode. Therefore, the application of deep retrofit allows an optimized sizing of the probe, assuming an installation depth that can hypothetically supply almost the complete energy demand for heating and cooling. The length of the probes to supply space heating is reduced by 50% and 55% for existing and historic buildings respectively, while a design length of the probes has been provided for space cooling.

	Case 0 Existing	Case 0 Historical	Case 1a Existing	Case 1a Historical	Case 1b Existing	Case 1b Historical
QH [kWh]	10018	14376	10018	14376	10018	14376
QC [kWh]	/	/	-4167	-4908	-4167	-4908

	Case 2 Existing	Case 2 Historical	Case 3a Existing	Case 3a Historical	Case 3b Existing	Case 3b Historical
QH [kWh]	2972	3638	2972	3638	2972	3638
QC [kWh]	/	/	-3761	-4311	-3761	-4311

Figure 3-2. Comparison between the maximum length available and the required borehole length to satisfy the energy demand for the three building typologies for Strasbourg without (a) and with (b) envelope insulation

3.3. Helsinki

Considering the cases located in Helsinki, the unbalanced thermal load of the non-retrofitted envelope (Figure 3-3a), is slightly more pronounced than Strasbourg. Although the application of deep retrofit requires a smaller heating length, which is reduced by 45% to 61% for existing and historic buildings comparing the baseline case with case 3-3b, the heating load is still dominant, complicating the sizing of the probes to supply efficiently the energy demand of the building.

Figure 3-3. Comparison between the maximum length available and the required borehole length to satisfy the energy demand typologies for Helsinki without (a) and with (b) envelope insulation

3.4. Optimal probes' length

The methodology explained in Section 2.2.1 and reported in Table 2-3 has been used to correctly define the optimal length of the probe that should be installed to avoid issues such as thermal drift due to the extremely unbalanced thermal load of the buildings (see Table 3-2 for the final reference cases).

When the heat exchanged in the ground is almost balanced between the heating period (heat extracted from the ground) and the cooling period (heat released into the ground), the optimal choice is to fix the same length in heating and cooling to avoid ground temperature drifting. Working with the air source when the ground source is not sufficient allows the optimization of the energy sources available, increasing the efficiency of the system since AWHP is more efficient during the middle seasons, in particular when the air temperature is higher than the ground temperature (Zarrella and Zecchin, 2018).

Among the different cases, when deep retrofit is carried out, probes' length is significantly reduced in winter (L_h), whereas the length necessary for cooling (L_c) remains almost constant. For this reason, case B is more frequent when considering warm climates, since heating energy demand can be neglected but the cooling energy demand is significantly high.

Table 3-2. Final length selected for the probes

			Lh	**Lc**	**Case***	**L installed (a)**	**L installed (b)**
			[m]	[m]		[m]	[m]
Case 0 radiators	Athens	Existing	85	-	2a	85	-
		Historic	150	-	2a	150	-
	Strasbourg	Existing	190	-	2a	190	-
		Historic	280	-	2a	280	-
	Helsinki	Existing	265	-	2a	265	-
		Historic	375	-	4	-	300
Case 1 fan-coils	Athens	Existing	75	200	3a/3b	200	75
		Historic	140	250	3a/3b	250	140
	Strasbourg	Existing	180	140	2a/2b	180	140
		Historic	265	170	2a/2b	265	170
	Helsinki	Existing	250	100	2a/2b	250	100
		Historic	355	135	2a/2b	300	135
Case 1 radiant system	Athens	Existing	80	200	3a/3b	200	80
		Historic	150	250	3a/3b	250	150
	Strasbourg	Existing	200	140	2a/2b	200	140
		Historic	295	170	2a/2b	295	170
	Helsinki	Existing	275	100	2a/2b	275	100
		Historic	400	130	4	300	130
Case 2 radiators	Athens	Existing	15	-	2a	15**	-
		Historic	25	-	2a	25**	-
	Strasbourg	Existing	85	-	2a	85	-
		Historic	105	-	2a	105	-
	Helsinki	Existing	115	-	2a	115	-
		Historic	155	-	2a	155	-
Case 3 fan-coils	Athens	Existing	5	115	3a	115	-
		Historic	15	135	3a	135	-
	Strasbourg	Existing	75	105	3a/3b	105	75
		Historic	95	120	3a/3b	120	95
	Helsinki	Existing	105	80	2a/2b	105	80
		Historic	140	110	2a/2b	140	110
Case 3 radiant system	Athens	Existing	5	115	3a	115	-
		Historic	15	135	3a	135	-
	Strasbourg	Existing	80	105	1	105	-
		Historic	105	125	3a/3b	125	-
	Helsinki	Existing	120	80	2a/2b	120	80
		Historic	155	110	2a/2b	110	155

**** Ref. Table 2-3***
***** When max (Lh, Lc) << L probe, GSHP is not needed***

4. INTEGRATION OF GROUND SOURCE HEAT PUMPS WITH OTHER RES

In a nZEB, energy use targets can be achieved and energy economics can be improved by integrating GSHPs with renewable electricity and/or with other renewable thermal energy supplying systems. These systems are termed as Hybrid GSHPs (HGSHP). They can also lead to balanced annual heating and cooling building loads, which is necessary to avoid degradation of the ground temperature. The availability of onsite renewable electricity by PV panels or micro wind turbines can effectively minimize CO_2 emissions resulting from electricity use at the heat pump compressor, the water circulating pumps of the hydronic system and the fans of the indoor terminal units. Integration with energy storage components, either thermal (e.g. tanks filled with phase change materials, PCM) or electrical (e.g. batteries) can further improve the economics and overall energy efficiency.

To ensure smooth system operation and improved energy usage, advanced control algorithms need to be adopted. Integration with other renewable energy sources complicates matters enforcing the introduction of optimized control strategies. Traditional rule-based control strategies are simple, easy to implement and transfer between similar systems. Their drawbacks are the limited parameters considered, lack of flexibility, and conservative tendency on the comfort side. Mathematical optimization techniques (either model-based, data-driven, or model-free), for their part, exhibit better performance, although they are also more complex to implement, requiring physical models or data-sets. Among them, AI algorithms enable learning of optimal operation considering a vast number of parameters for non-linear problems, which makes them suitable for handling the complexity of GSHP system, especially when combined with other RES, and for implementing autonomous and adaptable intelligent controls. However, they need large data sets for their development. The choice of the approach, in each case, will be a trade-off between system performance and complexity of implementation.

4.1. Renewable electricity assisted ground source heat pumps

Coupling of wind turbines or photovoltaic (PV) panels with GSHP is performed in terms of electricity supply to the GSHP when renewable electricity is available. The GSHP uses the renewable electricity for domestic hot water (DHW) production, heating or cooling of the building, as well as for storing thermal energy in water and PCM for later use to cover building peak heating or cooling loads. When no GSHP load is needed, renewable energy is stored in the batteries for later use, or supplied to the power grid.

The basic configuration of a wind or PV coupled GSHP system is shown in Figure 4-1. The wind turbine or the PV panels generate renewable electricity that is stored in priority to the batteries, while excess electricity is diverted to the power grid. The GSHP provides heat either to the DHW tank, or to the buffer tank at different temperature levels, with priority given to the DHW. The buffer tank is connected to the HOT or COLD PCM tank depending on heating or cooling mode respectively. In times of wind/PV electricity availability (generated or stored in the batteries) the GSHP charges the PCM tank by matching the buffer tank setting point to the PCM level. When no renewable electricity is available (generated or stored in the batteries) the GSHP covers the basic load of the building and the PCM the peak loads.

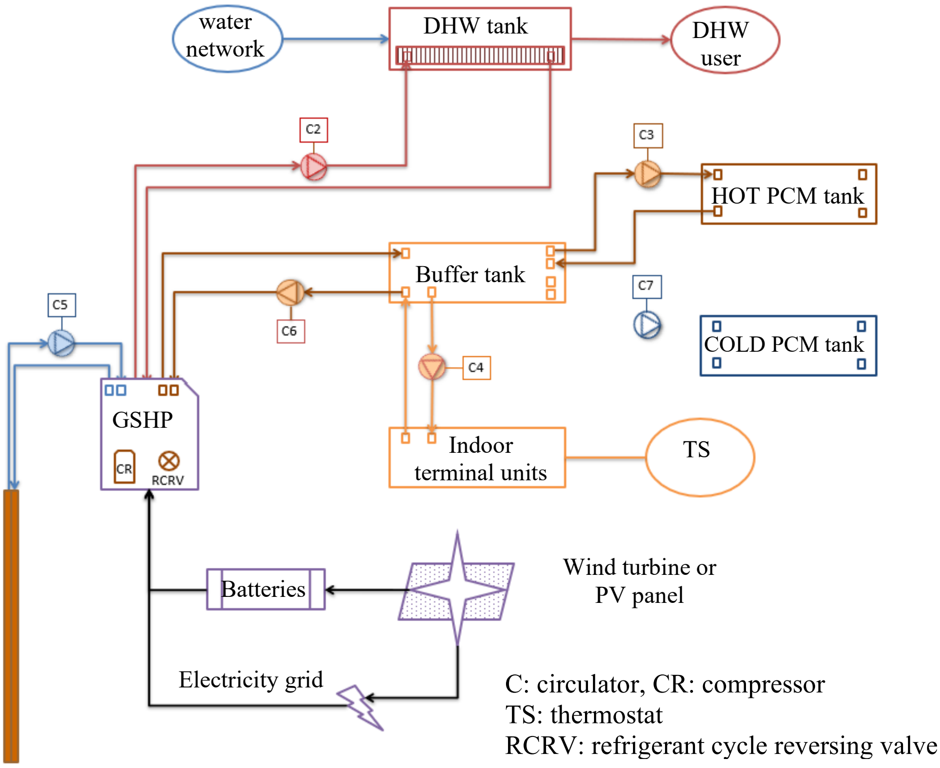


Figure 4-1. Wind/PV assisted ground source heat pump system layout

The main principles of the control strategy are:

- Refrigerant cycle reversing valve is in the HEAT or COOL position depending on operation mode, except when domestic hot water circulator is ON, when it is always automatically switched in HEAT position
- Heat pump charges the DHW tank in priority
- Heat is exchanged between buffer tank and PCM according to user loads
- GSHP charges the PCM when wind electricity is available, so that its temperature is maintained at desired level plus/minus half temperature bandwidth
- GSHP and PCM charge the buffer tank, so that a) its water temperature is maintained at desired level plus/minus half temperature bandwidth and b) the GSHP covers base load and PCM peak load
- Indoor system uses hot/cold water from the buffer tank according to indoor temperature, so that indoor air temperature is maintained at desired level plus/minus half temperature bandwidth

4.2. Solar thermal assisted ground source heat pumps

The basic configuration of coupling solar thermal collectors with a GSHP is presented in Figure 4-2. In this configuration, the GSHP provides thermal energy into a buffer tank, which is hydraulically connected to a PCM tank and the building heating/cooling system, and thermally connected to the domestic hot water tank via a heat exchanger. The solar thermal collectors provide thermal energy to the domestic hot water tank. The configuration philosophy is that thermal energy is continually exchanged between the buffer tank, the GSHP, the PCM, the DHW and building according to solar energy availability, electricity tariffs and user needs in terms of heat/cold and hot water.

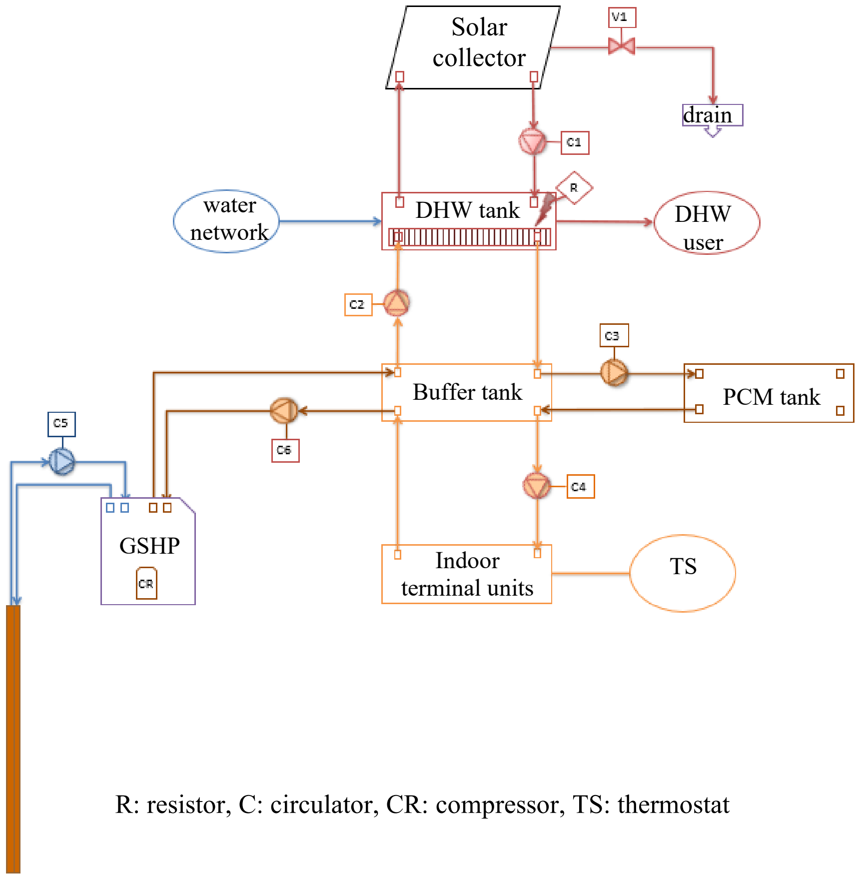


Figure 4-2. Solar thermal assisted ground source heat pump system layout

The coupling between the GSHP and the solar thermal collectors is done during winter in heating mode only through the heat transfer between the main buffer tank and the domestic hot water tank. During summer, no coupling between the two systems is foreseen, as the solar thermal collectors are expected to be able to cover all DHW needs of the user.

The main principles of the control strategy are:

- Solar collectors charge DHW tank in hours of high solar radiation; during winter time, electrical resistor at the DHW tank is turned on a few minutes per week according to local legionella protection regulations (time programming)
- In heating mode, heat is exchanged between DHW tank, buffer tank and PCM according to user loads
- In heating mode, GSHP charges the PCM in low electricity tariff hours, so that its temperature is maintained at desired set point plus/minus half temperature bandwidth
- In cooling mode, the solar thermal collectors and the GSHP are decoupled, so that the domestic hot water is provided only by solar thermal energy, which is expected to be able to cover 100% of the DHW needs
- In both modes GSHP charges the buffer tank, so that its temperature is maintained at desired water set point plus/minus half temperature bandwidth
- Indoor system uses thermal energy from the buffer tank according to indoor air temperature, so that indoor temperature is maintained at desired room set point plus/minus half temperature bandwidth

The installation of the GEO4CIVHIC GSHP coupled to solar thermal system results in considerable primary energy savings depending on building type and climatic conditions. Annual economic savings are also important, with investment payback times depending on building type, envelope insulation and the climate.

4.3. Air source assisted ground source heat pumps

There are two main options for incorporating air as a supplementary energy source, depending on whether air is used as one of the possible main energy sources (air-to-water heat pump) or whether it supports geothermal energy as a sink or source (cooling tower/dry cooler). In the first case, the system integrates both an air-to-water heat pump (ASHP) and a ground-to-water heat pump (GSHP). The system can provide heating or cooling with ASHP or GSHP regardless of whether the air source is used for heating or cooling. This approach of HGSHP is to include air as a supplementary source for heat injection or extraction and only use the ground heat exchanger (GHE) to inject or extract part of the thermal energy demands of the building. There are different possibilities to include air as a supplementary source, one of them is the addition of cooling towers (for cooling only) or dry coolers (Figure 4-3) as a new element independent of the GHE with different configurations depending on the HVAC system needs and optimisation. Another possibility is a dual source heat pump (DSHP) (Figure 4-4) designed with all elements inside the same HP, the fans and heat exchangers for the air source and the heat exchanger for the ground source in the same body of the HP.

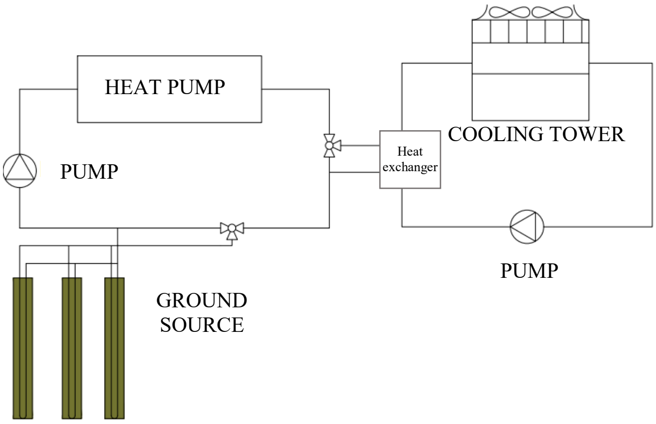


Figure 4-3. Connection diagram of cooling tower or dry cooler with a Ground Source heat pump

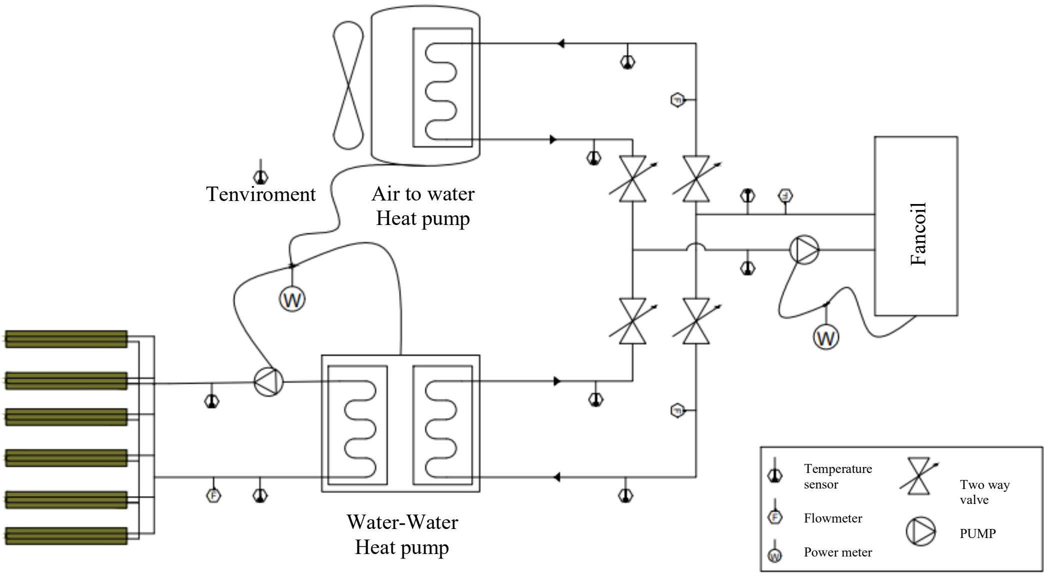


Figure 4-4. Connection scheme Air Source Heat pump (Air-Water HP) coupled to GSHP

Combining both air source and ground source slightly increases the energy performance and therefore results in economic savings. However, the great economic advantage of this option lies in the fact that by using air as the source, the installation of the borehole field can be reduced by up to 40%, drastically reducing drilling costs and therefore the investment of the installation. Further advanced control strategies need to be explored to support this scenario.

4.4. PV-Thermal assisted gorund source heat pumps

The use of photovoltaic thermal panels (PVT) allows saving roof space, compared to the solution of separate solar thermal collectors and photovoltaic panels, as well as improving overall solar conversion efficiency as PVT collectors are more efficient for both thermal energy and electricity supply than the two conventional systems together. With this technology the solar field contributes a higher temperature thermal source, while at the same time it also covers the electrical needs of the heat pump.

When coupling the ground and the PVT fields as the thermal sources for the heat pump, giving the priority to the domestic hot water production during both heating and cooling seasons, the direct thermal contribution from the solar installations is, as expected, higher for the localities with greater values of incident solar radiation. In detail, this share increases from 27% for the case study of Helsinki, to 34% in Strasbourg and Bilbao, and to 64% in Athens.

4.5. Case studies application: self-sufficiency and self-consumption indexes for GEO4CIVHIC archetypes

To show the potential of renewable energy sources' integration in the retrofit of existing buildings in city centres, the photovoltaic systems (PV) integration on the roof has been investigated within the GEO4CIVHIC project, leading to a comprehensive analysis coupling envelope refurbishment, GSHP and PV production. As a matter of fact, many advantages are related to the use of PV systems, considering that solar energy is clean and free, the installation phase is not complicated, and it can be designed according to the needs of the user. The main disadvantage is the intermittent operation, which can be partially solved with a storage system, if possible, increasing on the other hand the installation cost. For a complete analysis, the energy performance of the PV system must be evaluated properly, considering many factors such as location, inclination, orientation and the presence of shading elements; for this reason, the simulations have been carried out using the dynamic tool TRNSYS.

The electric load of the building has been calculated according to the energy values provided by Eurostat (Eurostat) and spread on an hourly base according to a profile suggested by Wilson and Engebrecht (2014).

Table 4-1 shows the average hourly consumption of the electrical appliances and lighting by season and day of the week.

Table 4-1. Average hourly electric energy used [Wh]

	Summer		Winter		Spring /Autumn	
[Wh]	**Mon-Fri**	**Sat-Sun**	**Mon-Fri**	**Sat-Sun**	**Mon-Fri**	**Sat-Sun**
Washing machine	28	30	28	30	28	30
Fridge + Freezer	130	130	130	130	130	130
PC	14	14	14	14	14	14
TV	14	14	14	14	14	14
Video	8	8	8	8	8	8
Lighting	40	40	53	53	51	51

The electric cooker is commonly used three times per day, as explained in Table 4-2, varying the intensity depending on the time and the day of the week.

Table 4-2. Daily electric cooker used [Wh]

		Weekday [Wh]	**Weekend** [Wh]
Breakfast	7:00h	100	200
Lunch	12:00h	300	600
Dinner	19:00h	1000	1500

Starting from the energy demand calculated in Section 2.7, considering the corresponding COP and EER for each case, the electric profiles related to the heat pump generation has been calculated. Adding the resulting hourly electric energy need of the heat pump to the common electric load profile of a residential user (Table 4-1 and Table 4-2), the total electric energy required by the housing units are shown in Table 4-3 for each climate and type of building.

Table 4-3. Total electric consumption including heat pump, lighting and appliances [kWh]

Existing	**Case 0**	**Case 1 - Fan Coil**	**Case 1 - Radiant**	**Case 2**	**Case 3 - Fan Coil**	**Case 3 - Radiant**
Athens	7305	7022	6923	5809	5799	5796
Strasbourg	9206	8224	7511	6266	5975	5764
Helsinki	12920	12210	11017	8866	8475	8064
Historic	**Case 0**	**Case 1 - Fan Coil**	**Case 1 - Radiant**	**Case 2**	**Case 3 - Fan Coil**	**Case 3 - Radiant**
Athens	8696	7987	7736	5995	5971	5962
Strasbourg	11085	9680	8660	6647	6290	6030
Helsinki	15422	13957	12415	9481	9012	8519

The total electric profile of the building was compared on an hourly base to the energy produced by the photovoltaic system, evaluating two indicators (Luthander and Widén, 2015): the self-sufficiency (SS) and the self-consumption (SC), each of them depending in the self-used energy (1), that is the difference between the energy consumed and the energy supplied from the grid.

$$\mathit{Self\ Used\ Energy} = \mathit{Energy\ consumed} - \mathit{Energy\ supplied\ from\ the\ grid} \qquad [kWh] \qquad [1]$$

Self-sufficiency is defined by Equation (2) as the ratio between the self-used energy and the total energy consumed, thus it is the percentage of energy consumed that is produced by the PV system installed on the building.

$$SS = \frac{Self\ Used\ Energy}{Total\ Consumed}\ [\%] \qquad [2]$$

Equation (3) defines the self-consumption as the self-used energy divided by the total energy produced by the PV system, which is the percentage of solar energy produced and consumed in the building compared to the total amount of solar energy produced.

$$SC = \frac{Self\ Used\ Energy}{Total\ Produced}\ [\%] \qquad [3]$$

The evaluation of these indicators strictly depends on the hourly analysis of the load, defining the amount of energy used or supplied to the grid according to the energy produced by the system and the energy used by the user. Therefore, dynamic simulations have been implemented using the software TRNSYS to calculate the hourly energy produced by the PV panels for different orientations, in order to compare the efficiency of the system considering the multiple possible orientations of the building in an urban context. The results presented in Table 4-4 show that the highest energy is produced when oriented to the South or South-West, while the North orientation reduces it by 30 to 50% according to the location.

Table 4-4. Annual energy produced by the photovoltaic system

	Energy produced by PV system [kWh/year]				
Location	**0°**	**45°**	**90°**	**180°**	**270°**
	South	**South-West**	**West**	**North**	**East**
Athens	19533	19255	17229	12828	15563
Strasbourg	15930	15767	14250	10997	12880
Helsinki	14118	13577	11385	7292	10311

The roof area and the sizing parameters (Table 4-5) have been calculated according to the geometry of the building, considering the different inclination of the roof according to the climate and reducing it by 5% to allow a suitable space for the technical maintenance of the panels. In Athens, the roof has been considered horizontal, therefore the space available is further reduced due to the space needed to avoid the mutual shading between the panels. This is the reason for the lower installed power (6 kW) compared to the other locations (12 kW). Polycrystalline PV modules have been selected; for the modules and the inverter, reference was made to technical data sheets available on the market.

Table 4-5. Sizing parameters of the PV system

	Athens	Strasbourg	Helsinki
Gross roof area [m^2]	59	117	121
Roof Inclination	0°	30°	40°
Number of panels	18	35	37
Number of strings	3	9	9
Installed Peak Power [kWp]	6.0	11.9	12.3

The results obtained have been divided in dump energy and grid energy, according to the hourly self-used energy indicator (Eq. 1). When the energy generated is greater than the energy required at that timestep, it has been assumed that excess energy is supplied to the grid. In contrast, when the required energy is higher than that generated, the missing energy is purchased from the grid.

Each retrofit strategy explained in Section 3.6 has been analyzed for five different orientations of the panels, therefore a total of 180 cases have been simulated for existing and historic buildings.

Table 4-6 summarizes the results obtained for the existing terrace house for each climate, orientation, and retrofit configuration. For Athens, each orientation of the panels can supply more than 50% of the energy needed from the user, even though the energy used is only 20-30% of the total energy produced.

The self-consumption indicator is similar on average in Strasbourg, around 20-30%, but the self-sufficiency is around 40-50%, because the total radiation is lower than Athens, thus the energy produced is lower. The same results were obtained for Helsinki with lower percentages.

South, South-West and West orientation have similar results in terms of self-sufficiency, determining a great percentage of energy used compared to the energy needed. The North orientation presents significant results in terms of self-consumption, because the solar radiation is lower but the self-used energy is similar compared to other orientations, therefore the ratio corresponding to the self-consumption indicator is higher.

Table 4-6. Summary of the self-sufficiency and self-consumption results for the existing terrace house

EXISTING		Self-sufficiency (%)					Self-consumption (%)				
		Orientation of the PV					Orientation of the PV				
		0º	45º	90º	180º	270º	0º	45º	90º	180º	270º
Case 0	**Athens**	57%	59%	58%	57%	54%	21%	22%	25%	32%	26%
	Strasbourg	40%	40%	39%	37%	38%	23%	23%	25%	31%	27%
	Helsinki	26%	25%	24%	21%	23%	23%	24%	27%	38%	28%
Case 1 Fan-coil	**Athens**	58%	60%	60%	58%	55%	21%	22%	24%	32%	25%
	Strasbourg	43%	43%	42%	41%	41%	22%	23%	25%	30%	26%
	Helsinki	30%	30%	28%	25%	27%	26%	27%	30%	43%	32%
Case 1 Radiant	**Athens**	58%	60%	60%	59%	55%	21%	22%	24%	32%	25%
	Strasbourg	46%	46%	45%	44%	44%	22%	22%	24%	30%	26%
	Helsinki	32%	32%	31%	28%	29%	25%	26%	30%	42%	31%
Case 2	**Athens**	57%	59%	59%	58%	55%	17%	18%	20%	26%	21%
	Strasbourg	48%	48%	48%	47%	47%	19%	19%	21%	27%	23%
	Helsinki	36%	36%	35%	34%	34%	23%	24%	28%	41%	29%
Case 3 Fan-coil	**Athens**	57%	60%	60%	58%	55%	17%	18%	20%	26%	21%
	Strasbourg	50%	50%	50%	49%	48%	19%	19%	21%	26%	22%
	Helsinki	37%	38%	37%	35%	35%	22%	24%	29%	41%	29%
Case 3 Radiant	**Athens**	58%	60%	60%	58%	55%	17%	18%	20%	26%	21%
	Strasbourg	51%	51%	51%	50%	49%	18%	19%	20%	26%	22%
	Helsinki	39%	39%	38%	36%	37%	22%	23%	27%	40%	29%

Similarly, Table 4-7 summarizes the results obtained for the historic terrace house. Results obtained are more interesting in terms of energy use rather than self-sufficiency, due to the reduction of the energy needed from the grid by using a renewable energy source.

Table 4-7. Summary of the self-sufficiency and self-consumption results for the historic terrace house

HISTORIC		Self-sufficiency (%)					Self-consumption (%)				
		Orientation of the PV					Orientation of the PV				
		0º	45º	90º	180º	270º	0º	45º	90º	180º	270º
Case 0	Athens	54%	56%	55%	53%	52%	24%	25%	28%	36%	29%
	Strasbourg	36%	36%	35%	32%	34%	25%	25%	27%	33%	29%
	Helsinki	25%	24%	23%	21%	22%	27%	28%	31%	44%	33%
Case 1 Fan-coil	Athens	57%	59%	58%	57%	54%	23%	24%	27%	35%	28%
	Strasbourg	40%	39%	39%	36%	37%	24%	24%	26%	32%	28%
	Helsinki	27%	27%	25%	23%	24%	26%	27%	31%	44%	32%
Case 1 Radiant	Athens	58%	60%	59%	58%	55%	23%	24%	27%	35%	27%
	Strasbourg	43%	43%	42%	40%	41%	23%	23%	25%	32%	27%
	Helsinki	29%	29%	28%	26%	27%	26%	27%	30%	43%	32%
Case 2	Athens	58%	60%	60%	58%	55%	18%	19%	21%	27%	21%
	Strasbourg	47%	47%	47%	46%	46%	20%	20%	22%	28%	24%
	Helsinki	35%	35%	34%	33%	33%	24%	25%	29%	43%	30%
Case 3 Fan-coil	Athens	58%	60%	60%	58%	56%	18%	19%	21%	27%	56%
	Strasbourg	49%	49%	49%	48%	48%	19%	20%	22%	28%	23%
	Helsinki	37%	37%	36%	34%	34%	23%	25%	29%	42%	30%
Case 3 Radiant	Athens	58%	60%	60%	58%	56%	18%	19%	21%	27%	21%
	Strasbourg	50%	51%	50%	50%	49%	19%	19%	21%	27%	23%
	Helsinki	38%	39%	38%	36%	36%	23%	24%	28%	42%	30%

The use of an electric storage would increase the self-used energy, thus both the indexes calculated; however, the sizing of the battery and the definition of the operation depends on several factors. In particular, the designer has to choose whether to give priority to battery conservation, minimizing the charge-discharge cycles, to maximizing self-consumed energy or to minimizing the supply from the distribution network. Many hypotheses can be done to estimate the behaviour of the storage to extend the application of the results obtained for these archetypes at urban scale, defining also different energy use profiles by the consumers to plan and support the development of energy communities. For this purpose, further investigation will be carried out in future works.

5. CONCLUSIONS AND FURTHER APPLICATIONS

The Manual 1 of the GEO4CIVHIC project aims at showing the importance of the energy need reduction to help the coupling with renewable energy sources, thus supporting the development of zero, nearly-zero and plus energy buildings, as required by recent national and international policies. To investigate the potential of the European building stock in urban areas, archetypes have been developed in terms of geometry, thermal properties of the envelope, end use, type of HVAC installed and later used as case studies to investigate the results of the integration of renewable energy sources. The detailed characteristics have been presented in (Carnieletto, 2022). Based on the different possible strategies and options, both shallow and deep retrofit have been examined. The decrease of the energy needs refers mostly to the annual energy balance, since high insulation levels reduce heat losses and maximizes the contribution of the internal gains. On the contrary, highly insulated buildings have higher cooling energy demand, due to a decrease of the heat transfer of the envelope.

The presented document analyses the synergy of GSHP with other RES to define optimal solutions for the different building types and climates. Several applications of optimal integration between GSHPs and other renewable energy sources have been presented, although limited at a typical terrace house located in different climates.

Dynamic simulations were carried out to determine the heating and cooling energy demand later used to size ground heat exchangers considering the variety of the geological contexts by using three typical underground thermal conditions, of 1.5 W/(m K), 2.2 W/(m K) and 3 W/(m K), thus widening the application of the results obtained. The proper sizing of the systems can possibly reduce the length of heat exchanger to be installed, thus installation costs and related payback time, preventing performance degradation over time. The integration with several sources brings more complexity to the system and further need for an optimized control strategy. A methodology has been defined for calculating the optimal length of the probes according to the thermal load of the building and the space availability, avoiding the oversizing of the system and improving the energy efficiency with the integration of a double source heat pump or an air source heat pump. This solution will increase the performances in middle seasons, thus showing a cost saving to the final users. Extreme results have been obtained for warm climates, where the heating energy demand becomes negligible and free cooling systems rather than traditional cooling systems are needed even in wintertime. In this case the penalty temperature was acceptable even if the energy demand was unbalanced, thus supporting the installation of GSHP when correctly sized

The installation of GSHP coupled to solar thermal system results in significant primary energy savings depending on building type and climatic conditions. Considering the electrical energy produced by the solar field and consumed by the heat pump, the self-used ratio, is higher for non-retrofitted buildings. The lower share for retrofitted buildings is due to the lower probability to use all the energy produced within the same timestep, since the energy demand is lower due to the retrofit solutions applied. The highest values correspond to the warmer climates since it depends on the possibility to match energy demand and energy produced within the same timestep.

The installation of a photovoltaic system has been analysed, studying the influence of the orientation on the self-sufficiency and self-consumption indicators, which can give a realistic projection for energy communities. The coverage ratio is generally higher for the retrofitted buildings, compared to the non-retrofitted ones. Comparing the three climatic conditions, the coverage value obtained from the PV installation is high for warm and mild climates (Athens and Strasbourg) between 46 and 67%, while Helsinki shows a lower share due to the higher energy demand and the lower energy availability form the solar radiation. The installation of an electric storage could further reduce the primary energy use; however, some issues for the correct battery sizing must be solved to avoid battery oversizing or fast disruption of the charge performance.

As recently studied in the literature, the extensive use of archetype buildings applied to urban modeling allows more extensive applications of energy modeling by reducing the simulation time due to the complexity of data mining, thus leading to a wider usability by experts without losing the quality of the results. Thus, the results obtained can help the analysis of wide stock of buildings and plants, including their refurbishment, defining a priority list of actions towards a limitation of energy use. These information aim to influence the development of energy policies for energy communities, optimizing the share of thermal and electric energy among different users, exploiting a different contemporaneity of loads, thus enhancing the efficiency of the systems. Therefore, working toward the construction of zero, nearly zero and plus energy buildings.

As shown by the different solutions presented and investigated, many strategies can be adopted according to the climate, end use and the energy demand of the building, which is related to the construction year or to the retrofit actions applied. Even though the location significantly influences the availability of solar radiation, results show interesting impacts on the energy savings and the related energy costs, thus confirming the potential of GSHP installation in urban city centres.

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AUTHORS

1. CONSIGLIO NAZIONALE DELLE RICERCHE (CNR)

CNR – ISAC
Adriana BERNARDI
Alessandro BORTOLIN
Gianluca CADELANO

CNR – ITC
Sergio BOBBO
Laura FEDELE
Stefano ROSSI
Mauro SCATTOLINI

2. UNIVERSITA DEGLI STUDI DI PADOVA (UNIPD)

Department of Industrial Engineering
Michele DE CARLI
Angelo ZARRELLA
Giuseppe EMMI
Laura CARNIELETTO
Samantha GRACI
Davide QUAGGIOTTO

Department of Geosciences DG Unit
Antonio GALGARO
Eloisa DI SIPIO
Giorgia DALLA SANTA
Alberto CARRERA

3 UNIVERSITAT POLITECNICA DE VALENCIA (UPV)

Javier F. URCHUEGUÍA
Borja BADENES
Hossein JAVADI
Miguel Á. MATEO

4. R.E.D. SRL RESEARCH AND ENVIRONMENTAL DEVICES (RED)

Luc POCKELÉ
Giulia MEZZASALMA
Silvia CONTINI
Mattia CHINELLO
Nicola MUTINELLI

5. TERRA GEOSERV LIMITED (GEOSERV)

Riccardo PASQUALI
Aisling CUNNINGHAM

6. GALLETTI BELGIUM / HIREF (GALLETTI)

Fabio POLETTO
Andrea TARABOTTI
Enrico PACCHIN

7. FUNDACION TECNALIA RESEARCH & INNOVATION (TECNALIA)

Miguel Ángel ANTÓN
Amaia CASTELRUIZ
Sarah NOYÉ
Beatriz SÁNCHEZ
Arantza LÓPEZ

8. TERRA INFRASTRUCTURE (FORMER THYSSENKRUPP INFRASTRUCTURE)

Arno ROMANOWSKI
Franziska HELBIG

9. UNESCO REGIONAL BUREAU FOR SCIENCE AND CULTURE IN EUROPE

Jonathan BAKER
Francesca BAMPA
Matteo ROSATI
Iuliia KOZLOVA
Francesco LIPPARINI
Anh Thi Ngoc NGUYEN
Akémi LAMARCHE VADEL

10. FRIEDRICH-ALEXANDERUNIVERSITAET ERLANGEN NUERNBERG (FAU)

David BERTERMANN
Oliver SUFT
Moritz FAUDE
Johannes MULLER

11. SOCIETATEA ROMANA GEOEXCHANGE / ROMANIAN GEOEXCHANGE SOCIETY (SRG - RGS)

Robert GAVRILIUC
Doinița- Iuliana CUCUEȚEANU
Tiberiu CATALINA
Marian ALEXANDRU

12. CENTRE FOR RENEWABLE ENERGY SOURCES AND SAVING FONDATION (CRES)

Dimitrios MENDRINOS
Constantine KARYTSAS
Ioannis CHOROPANITIS
Ioannis CHALDEZOS
Spyridon KARYTSAS

13. HYDRA SRL (HYDRA)

Davide RIGHINI
Elisabetta GARDENGHI

14. UBEG DR ERICH MANDS U MARC SAUER GBR (UBEG)

Burkhard SANNER
Erich MANDS
Marc SAUER

15. GEO-GREEN SPRL (GEO-GREEN)

Jacques VERCRUYSSE

16. PIETRE EDIL SRL (PIETRE)

Elena Loredana FODOR
Leonardo ROSSI
Alexandru TĂNASE

17. SOLINTEL M&P SL (SOLINTEL)

Dery TORRES
Hugo GRASSET
Miguel Angel GOMEZ

18. DIN L-ART HELWA (DLH)

Luciano MULE'STAGNO
Daniel MICALLEF
Ingrid GALEA
Davide POLETTO
Daniele SFERRA
Manuel SCARPA

19. SCUOLA UNIVERSITARIA PROFESSIONALE DELLA SVIZZERA ITALIANA (SUPSI)

Marco BELLIARDI
Linda SOMA
Sebastian PERA
Rodolfo PEREGO

PARTNERS

INSTITUTE OF ATMOSPHERIC SCIENCES AND CLIMATE
NATIONAL RESEARCH COUNCIL (CNR – ISAC)
www.isac.cnr.it

INSTITUTE OF CONSTRUCTION
TECHNOLOGIES NATIONAL
RESEARCH COUNCIL (CNR-ITC)
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www.cres.gr

HYDRA SRL
(HYDRA)
www.hydrahammer.it

UBEG DR ERICH MANDS
U MARC SAUER
GBR (UBEG)
www.ubeg.de

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PROFESSIONALE
DELLA SVIZZERA ITALIANA
(SUPSI)
www.supsi.ch

PIETRE EDIL SRL
(PIETRE EDIL)
www.pietre-edil.ro

SOLINTEL M&P SL
(SOLINTEL)
www.solintel.eu

DIN L-ART HELWA (DLH)
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www.geo4civhic.eu