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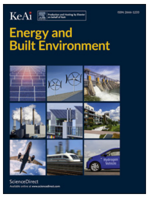

# Potential of GSHP coupled with PV systems for retrofitting urban areas in different European climates based on archetypes definition

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ABSTRACT

According to the recent policies regarding energy use in buildings and the need of retrofit strategies, the aim of this work is to support policies concerning the installation of ground source heat exchangers in urban and historical areas, raising the awareness on the potential energy saving achievable with optimal sizing and limited impact on the urban environment. Archetypes have been developed distinguishing among existing and historic buildings, focusing on single-family terrace houses, which are the typical residential buildings in European historic centres.

A methodology for the optimal sizing of ground source heat pumps, eventually considering dual-source system or air system has been developed combining simulations of a photovoltaic system to estimate the self-sufficiency and the 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. Penalty temperature was acceptable despite unbalanced energy demands. With proper inclination, photovoltaic systems could provide up to 40% of self-sufficiency share also in northern climates. An energy - economic analysis was carried out obtaining a variety of cases representing a general overview of the European building stock and the potential benefits achievable in terms of renewable energy share, energy savings and economic investments needed to be extended to simulations at urban scale.

## 1. Introduction

Geothermal energy is a very promising solution, and the European Commission is interested to increase the application of this technology in urban areas where several barriers are present. With this purpose the Horizon2020 European Project GEO4CIVHIC (Most Easy, Efficient and Low-Cost Geothermal Systems for Retrofitting Civil and Historical Buildings) [1] aims to accelerate the deployment of shallow geothermal systems for heating and cooling in retrofitting existing and historic buildings located in urban city centres, 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), investigated by an international expert group of companies and research centres.

The funding of the project, as well as most of the activities carried out at European level in the last years, belongs to the strategies developed after the Energy Performance of Building Directive (EPBD) and its recast versions [2–4], focusing on the importance of retrofitting buildings to reduce their energy consumption considering that buildings represent 40% of the final energy consumption in Europe and among them, 70% are residential buildings.

However, the definition of strategies at urban level needs the development of building archetypes to widen the perspective of the single building scale [5]. In this way, it is possible to deal with a proper representation of the most common typology of buildings for modelling purpose. This approach is important to better define the potential obstacles in the application of a specific technology or management strategy.

Archetypes are generally defined as theoretical buildings obtained by statistical analysis of building characteristics grouped based on similarities [5]. Building archetypes can be also defined as models that allow the application of simulation tools to evaluate the energy demand of a wide building stock [6]. Even though the application of archetype-based modelling requires some simplifications, literature shows that it allows the development of innovative strategies and technologies to increase the energy efficiency with acceptable results both at single building and

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**NOMENCLATURE**

| | |
|---|---|
| *A* | Area [m$^2$] |
| *AB* | Apartment block |
| *AWHP* | Air to water heat pump |
| *DDC* | Cooling degree days |
| *DDH* | Heating degree days |
| *EPW* | Energy Plus Weather file |
| *GHE* | Ground heat exchanger |
| *GSHP* | Ground source heat pump |
| *HVAC* | Heating ventilation and air conditioning |
| *L* | Required probe length to supply energy need [m] |
| *MFH* | Multi-family house |
| *PEF* | Primary energy factor |
| *PV* | Photovoltaic |
| *Q* | Energy need [kWh] |
| *SC* | Self-consumption [-] |
| *SFH* | Single-family house |
| *S/V* | Surface to volume ratio [-] |
| *SS* | Self-sufficiency [-] |
| *TH* | Terraced House |
| *U* | U-value [W/(m$^2$ K)] |
| *V* | Volume [m$^3$] |
| *Greek symbols* | |
| $\lambda$ | Thermal conductivity [W/(m K)] |
| *Subscripts* | |
| *c* | Cooling |
| *h* | Heating |
| max | maximum |

at urban scale [7–10]. Therefore, the potential reduction in energy consumption can be compared with other parameters for economic management.

The definition of reference buildings is important to know the most diffuse construction typologies, in order to get information on the possible solutions that can be proposed and combined with GSHP. Cheap-GSHPs [11] has been considered for the climatic data classification and for the types of buildings examined and presented in Section 2. The buildings present in Cheap-GSHPs are representative of European buildings, but different models have to be considered when dealing with urban dense areas or with historical urban agglomerations.

Since archetypes have been chosen to be representative of the European building stock, in the GEO4CIVHIC project the first step consisted in checking existing literature on the building sector looking at the average consumptions of buildings. 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 [12]. Hence there is a big potential in Europe, estimated in 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 the urban situation, respecting 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 retrofit of the envelope and of the system will reduce the energy need, thus the probes' length and the space needed. The application of GSHP to historic buildings has been investigated by Emmi et al.[13], 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. [14] 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., which provided space cooling and space heating to a residential building with a GHSP that was able to assists also a solar field in the production of domestic hot water [15].

Although several papers worked on the efficient integration of GSHP as generation system 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. However, upon reviewing the available information concerning archetypes already developed for the European context, such as advanced and detailed databases like TABULA and EPISCOPE [16], information concerning hourly information on energy demand, peak loads, and data to simulate the potential integration with renewable energy sources were missing. Therefore, the main aim of the project is to use the results from the simulations to create a complete database for thermal and electrical profiles that can be used to describe an integrated methodology to size the borehole field and investigate the efficiency of the photovoltaic system defining two indicators: the self-sufficiency and the self-consumption of the users. The innovative dataset collected is 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 needs urgent support towards energy use reduction. The new idea of having integrated results concerning both envelope and plant refurbishment provides a new perspective of urban modelling, including the possibility of sharing both thermal and electric energy through the development of energy communities.

## 2. Methodology

### 2.1. Climatic conditions

In order to be representative of the main European climatic conditions, a preliminary analysis has been carried out considering the weather of the three locations (Athens, Strasbourg and Helsinki) used in the standard EN 14825 [17] for evaluating the heat pumps efficiency values based on standardised profiles of energy. In order to check if these locations are representative of European climatic conditions the weather files EPW of these locations have been used to calculate the heating (DDH) and cooling (DDC) degree days according to [18], leading to the following values:

- Athens as representative of the warm climate, DDH = 995 and DDC = 1046;
- Strasbourg for a mild climate, DDH = 2746 and DDC = 115;
- Helsinki as a cold climate, DDH = 4597 and DDC = 23.

A comparison between these values and the whole European EPW weather files has been conducted by grouping the locations according to the Köppen-Geiger scale and Degree Days (DD) [19]:

- warm climates (BWh, BSk, Csa): DDH = 0 - 2000 and DDC = 500 - 1100;
- mild cold climates (Csb, Cfa, Cfb and Cfc): DDH = 1150 - 5900 and DDC = 0 - 600;
- cold climates (Dfb and Dfc): DDH = 2900 - 7000 and DDC = 0 - 250

As can be seen, the three locations may represent average conditions for the three types of climates and hence have been fixed for the following analyses.

### 2.2. Archetype definition

The main characteristics of the analysis focused on the climatic zone, period of construction, and building typology to divide the building stock into different categories. More parameters were needed to calculate the reference building energy profiles, such as geometry, envelope, heating and cooling systems, end-use. Once this information was collected, the definition of the archetypes was based on the most frequent type of construction, defining the geometric characteristics as an average between all the buildings associated with that category. Comparable results were possible because the considered areas have been decided based on the same boundary conditions, even if they could vary depending on the country.

Therefore, the second step of the research has been to look at the archetypes representative of a consolidated urban context in different locations and representative of a specific time span. For this purpose, two sets of databases have been used as prevalent for the state of art of European buildings in urban environment: one form a COST action and the other related to a couple of jointed European projects. The first project is the COST action TU0901 “Integrating and Harmonizing Sound Insulation Aspects in Sustainable Urban Housing Constructions”, in which around 90 experts from 29 European countries were involved with the scope of establishing a common framework in building acoustics throughout Europe. A reference database was defined to analyse the European housing stock regarding sound insulation, different types of sound transmission and the proportion of occupants which may experience sound transmission, collecting the most common type of housing and construction methods of each country. Using a combination of Eurostat statistics on housing conditions (2012) [20] and information gathered during the project, the proportion of population which inhabit detached housing, attached (row/terraced, semi-detached) housing or apartment (flatted) housing was described. For these building types, information on building techniques were also collected, including both acoustics and thermal properties.

The results of this project have been collected in e-books and divided into two sections [21]. The first one proposes a harmonization of the descriptors for airborne and impact sound insulation between dwellings and for airborne sound insulation of facades as well as to prepare a European classification scheme with a number of quality classes. The harmonization of such descriptors and performance levels of sound insulation classes is important to make progress and would be well received by the building industry, governments and research sectors. The second one covers the key aspects of building acoustic construction for dwellings found in 31 European countries. This collection is not an exhaustive review of each country, but it does provide specific details and characteristics of sound insulation performance. In addition, various data are also presented including construction details, historical trends, building regulations and guidelines found in the analysed countries.

The second project, that collects existing building types across 21 European countries, is the well-known EU project TABULA (Typology Approach for Building Stock Energy Assessment) joined with the project EPISCOPE [16, 22], which aimed to improve the effectiveness of the energy refurbishment processes in the European housing sector. The joint projects developed guidelines for the creation of a European database of reference buildings and the definition of benchmarks of energy performance assessment, before and after building refurbishment or renovation process, that involve not only the envelope or internal spaces but also different HVAC systems. The TABULA-EPISCOPE project is based on different national criteria according to local use and condition both for the building characteristics and weather conditions. In particular, buildings envelope is classified as a function of the age class, i.e. the year of construction.

Merging the methodologies and data deriving from the two above mentioned projects, a specific geometry of the archetypes was defined in order to consider the retrofit of buildings (both partial and deep retrofit) in the urban environment. Since the aim of the GEO4CIVHIC project is to promote the installation and application of GSHPs in buildings to be retrofitted, mainly in the historical city centres, different types of buildings have been considered according to their age, components, materials, as well as the possible replacement or adaptation of HVAC systems.

The development of representative archetypes is widely used in the modelling of the building stock for economic, energy, environmental and social evaluations [23–26]. Through the typing, simplification and generalization of complex cases it is possible to achieve a balance that allows comparisons among the possible choices. However, simplification implies several approximations that must be correctly assessed on the basis of the context and purpose of the analysis [27].

From the architectural and town-planning point of view, it is necessary to carry out a preliminary specific analysis to define optimized archetypes for the energy assessment and building services integration models. In fact, a classification based only on the age of the buildings may not be sufficiently accurate in producing homogeneous groupings, especially in the historical or central areas of European cities, where uncertainties in the modelling process can be relevant [27, 28]. Historical, cultural, social and economic reasons have led to different models of urban development and a mixed approach between deterministic and probabilistic aspects in the definition of building archetypes is often necessary [29–33]. The same concept of "historical centre" has often entered into crisis after the extensive building reconstructions that took place after the Second World War [34]. On the other hand, the economic and social evolution in the urban environment through the last decades offers new perspectives for development and planning [35].

Historic urban neighbourhoods are characterised through their compact settlement structure, a broad variety of different uses with high built up densities and heterogenic ownership and user structures. This results into relatively high complexity of urban planning and building typologies, with dense structures of settlements, small footprints of land and an average uniform height of buildings. They also incorporate a comparably low amount of embodied energy, as existing buildings are constantly reused and adapted over decades, with only sporadic new construction activity. Embodied energy is the sum of energy that is incorporated in (building) material regarding its whole life cycle, including extraction of raw material, processing and manufacturing, transportation, assembly as well as disposal [36]. Hence, use of construction materials is mostly limited to refurbishments and modernisations (“Sino-German Urbanisation Partnership”).

Among the differences we may find in buildings, a quite common subdivision is between historic and non-historic buildings, although there is no unique definition on this issue. The standard EN 16883 [37] underlines the difference between a historic building and building protected by cultural heritage, considering that an historic building does not necessarily have to be designated as cultural heritage, but it is a specific form of objects, as defined in EN 15898 [38]. Therefore, a building with more than 70 years life is usually considered as attributable to cultural heritage even though it is not particularly or significantly important from the historical, architectural or artistic point of view. This practice is particularly important to understand the management strategy of the central areas of many European cities where the urban and building characteristics can be currently considered consolidated also with regard to the reconstruction and expansion interventions carried out starting from the first post-war reconstruction phase and, in many cases, until the 60s.

To consider how building typologies and building materials have been declined locally in Europe since post-war reconstruction, this study will refer to two categories of buildings belonging to central areas of European cities:

- *Historic buildings*, built until the 1950s;
- *Existing buildings*, built between the late 1950s and 1990.

Historic buildings’ category includes all those buildings which are characteristic of a specific type of construction, integrated into the urban fabric, which have not suffered damages due to the Second World War, and which have not undergone substantial transformations, adjustments or only partial retrofits. Existing buildings group regards the ones which are neither historical nor buildings of heritage significance, built after 1950s-1960s or rather planned and built in the urban development after the first post-war reconstruction.

Buildings which were built up later than 1990 have not been considered since the main target of the GEO4CIVHIC project is the installation

**Table 1**
Architectural characteristics of the archetypes

| Building Type | Sub-Type | Shape (S/V) per unit | Construction technique (by prevalent building element type) |
|---|---|---|---|
| SFH | Single or detached | Large | Load bearing composite structure (A) |
| TH | Single/coupled or attached (row) | Medium | Load bearing composite structure (A) & framed elements (B) |
| MFH<br>AB | Multi-unit | Small | Framed elements (B) and continuous structures (C) |

(A) Block work and clay-based walls (including stone/bricks/masonry)
(B) Bearing frame + curtain walls (concrete/steel/wood)
(C) Continuous/monolithic structures (load bearing walls in reinforced concrete/CLT)

of ground heat exchangers in difficult and confined urban setting such as historical city centres; therefore, it is unlikely the presence of such recent buildings or retrofit actions. Moreover, data available for typical buildings of the ‘90s are already present in the previous project Cheap-GSHPs [11].

Another consideration underlying this distinction is that, in the considered urban context, buildings typically have a rather long average time between two maintenance operations. In many European countries, the needs related to energy consumption and hydrogeological factors make massive maintenance work necessary on the existing building stock. The reasons for these interventions are many: the age of the building heritage and the obsolescence of its components (e.g.: 55% of homes in Italy insist on buildings over 40 years old, a share that rises to 70% in medium-sized cities and to 76% in metropolitan cities [39]; on the whole, the median of the ages of houses built after 1962 is 29.5 years [40]); the adjustment to European regulations in some sectors (electrical, heating systems, etc.); the short life cycle of HVAC systems if compared with the entire building life; national or local incentive policies. The combination of these aspects justifies from an economic point of view the inclusion of integrated PV and GSPH systems in this particular urban context.

### 2.3. Geometry of the archetypes

Once defined the general rules for the archetypes of the European building stock in an urban context, a subdivision based on four parameters has been set (Table 1):

- Typological scheme;
- Construction subtype;
- Form factor;
- Typology of prevailing building elements.

Isolated single-family houses (SFH), possibly combined in two independent units, typically have a large surface to volume ratio (S/V), as a consequence of the reduced overall height. The prevailing construction techniques are composite load-bearing structures (load-bearing or confined masonry, made with blocks of brick or calcium-silicate, where the building acts as a whole with walls, columns, roofs and slabs tied together to support each other). In this case the roof often represents the main heat loss [16, 21].

The terrace houses (TH), in their different sub-types, are characterised by the sharing of at least one internal separation surface between heated rooms; they have a reduced surface to volume ratio and prevalent heat loss through the vertical elements of the envelope. In addition to the building elements previously presented, the most typical of this group are those typical of the framed structures [21].

The block buildings, tower and in-line building typologies (MFH/AB), are characterised by a high number of housing units: they present the prevalence of thermal losses through the façade elements, since the roof surface is in proportion less relevant than that of the remaining parts of the envelope. These buildings may be built up with continuous prefabricated building elements or with frame structures (“TU0901 E-Books — Cost Action TU0901”).

From the analysis of the typical representative urban environment, it emerges that the main representative types of edifices are linear buildings. These can be divided into two main archetypes:

- Terrace House (TH): independent land-to-sky building with one or two floors, built as part of a continuous row of similar houses joined together by their side walls.
- Apartment Blocks (AB): a large building that is divided into apartments.

Even if four different building typologies are present in the Tabula web tool (apartment block, single family house, multi-family house and terraced house), Single Family houses and Multi- Family houses have been excluded from the present work since, as already explained, the main area of interest is the urban centre of cities with medium-high population density and with a consolidated presence of aggregate housing complexes, where usually these typologies of buildings are not or seldom present. Fig. 1 represents the typical configuration considered for the project.

The criteria applied in the typological analysis concern buildings suitable for the application of retrofitting techniques and capable of integrating PV and GSHP applications, also considering economic aspects related to the long-term management and maintenance of the buildings.

The TH and AB together constitute the most relevant group among the different types of dwelling in Europe. In 2018, 46.0% of people in the EU-27 lived in “flats” (housing units in non-individual building typology), close to one fifth (18.6 %) in semi-detached houses and over one third (34.7 %) in detached houses [41].

Moreover, TH and AB are among the most common types in Europe for social housing buildings [42]. In this sector, substantial investments are expected in the coming years for energy efficiency, in order reduce the energy use and eventually to integrate renewable energy sources. The most innovative initiatives in this area use, for instance, standardization of renovation techniques and increase scale to speed up and reduce costs linked with the refurbishment process [43].

In order to obtain a generalized profile based on the building typology, each building must have standard shape and orientation. The apartment block has been defined as a sum of single housing units with common stairwells. According to statistical data coming from TABULA and COST TU0901 database, a 5-floor building has been selected to be considered as reference building for the apartment block solution.

Standard height for the ceiling in existing buildings has been set equal to 2.5 m, while in historical buildings an average height of about 3.15 m has been considered (25% higher than the height of existing buildings). The glazed/net floor surface ratio ($A_{glazed}/A_{floor}$) has been found to be typically in the range 12-24%, hence 19% as average value has been considered in existing buildings. In historical buildings an increased glazed surface has been considered according to the corresponding ceiling height, i.e. 22% as ratio between the glazed area and the net floor area.

Existing and historical single-family buildings have been considered as linear terraced houses. According to statistical data coming from TABULA database, a 3-floor building has been considered. The standard

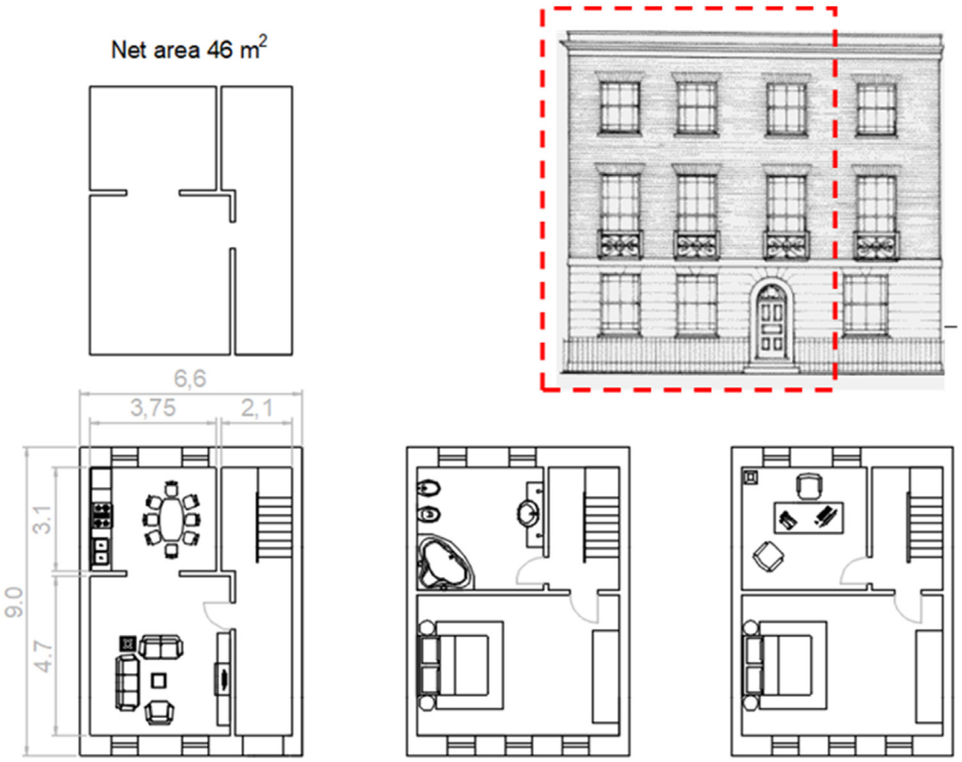


**Fig. 1.** Example of terraced house representing a single user (3 storeys)

height for ceiling and the glazed/net floor surface ratio has been considered the same as the apartment blocks. In this case the building has been considered only residential.

Although both TH and AB archetypes have been taken into account in GEO4CIVHIC project, in this paper the results of the simulations will be presented limited to the TH, both historical and existing, under different types of renovations. Proportionally, a TH has more available space for the installation of GSHP compared to an AB, allowing more interesting results in terms of renewable energy share. Moreover, the main reasons of this methodologic choice are related to the need to deepen the application of energy efficiency techniques based on the combination of PV and GSHP on types of building so far considered unattractive in the context of private economic initiative, but potentially relevant in the context of urban redevelopment initiatives and public or participatory projects [44, 45]. Although private initiatives could be more demanding in terms of investment costs, it could be easier with TH because a single owner may decide in an autonomous way, hence leading to an easier choice by the owner.

### 2.4. Building structure and thermal properties

Dynamic simulations have been carried out to calculate the energy demand of the buildings with the software TRNSYS [46]. The first assumption needed is the definition of the thermal zones, according to the criteria that the higher the number of the thermal zones, the more accurate are the simulations due to the higher level of input data that can be used. This is valid for relatively small archetypes, such as terrace houses or single-family houses that can be simulated considering each room as a single thermal zone, grouped into sleeping and living zones.

Historic buildings (i.e. built before 1950) have been modelled considering external walls with solid bricks (50 cm) eventually separated by an air gap of 5 cm according to the reference transmittance for each climate. Typical roofs of historic buildings have wooden trussed roof that supports a wooden layer with the tiles. The attic below is divided from the rooms through a non-walkable attic formed by another wooden layer supported by joist. Considering the structural function of the roof slopes, especially in cold climates, the step between the beams that hold up the wood decreases with increasing latitude. The structure of the internal slabs, which do not influence heat losses but mainly the thermal inertia of the building, has been defined as wooden beams covered with a wooden plank, a concrete screed and finishing tiles.

The external walls of existing buildings were defined as 25 cm perforated blocks or cellular blocks in bricks, eventually separated by an air gap of 5 cm. The typical stratigraphy of the internal slabs is made of a brick-concrete slab with concrete screed and tile, while ground floors were considered made of pebbles and sand, with a concrete casting, screed and finishing tiles. Roofs in Strasbourg and Helsinki were considered with a structure similar to the internal floors, while in Athens horizontal roofs have concrete beams and brick hollow flat blocks.

Table 2 summarizes the archetypes' characteristics regarding both the structure and the envelope, defining areas, volumes, and thermal properties of opaque structures and windows. These data have been considered according to the climate and similarity of building techniques, verifying that the colder the climate the lower should be the transmittance to decrease the energy needed for space heating, according to TABULA database for each climate.

### 2.5. Scheduling of internal loads and set-point temperatures

As for the internal loads, schedules of sensible and latent heat sources mainly due to people, lighting, and equipment have been set following ISO 13790 [47]. According to the type of building, the standard defines the sensible load fraction due to the presence of people that corresponds to 70 W/person with an average occupancy of 60 $m^2$/person.

The sensible load related to equipment has been calculated from the standard ISO 13790 that suggests reference values for sensible load related (Table 3) both to equipment and people for residential use. Values are slightly higher for the night zone during the weekend, considering the higher presence of people.

Sensible loads related to people have been implemented sharing the contribution as 60% radiative and 40% convective, while equipment has been equally spread as 50 %. A family of four people has been considered

**Table 2**
Characteristics of the archetypes for thermal modelling

| Building Type | Gross Volume [$m^3$] | $A_{glazed}/A_{floor}$ [-] | Net Floor Area per user [$m^2$] | Climate | $U_{roof}$ [$W/(m^2 K)$] | $U_{wall}$ [$W/(m^2 K)$] | $U_{Floor}$ [$W/(m^2 K)$] | $U_{Windows}$ [$W/(m^2 K)$] |
|---|---|---|---|---|---|---|---|---|
| Existing | 500 | 0.17 | 138 | Athens | 1.65 | 0.89 | 1.36 | 3.55 |
| | | | | Strasbourg | 0.70 | 1.05 | 1.01 | 2.85 |
| | | | | Helsinki | 0.29 | 0.35 | 0.41 | 2.35 |
| Historical | 610 | 0.21 | 138 | Athens | 2.30 | 1.75 | 1.29 | 4.97 |
| | | | | Strasbourg | 1.19 | 1.75 | 1.38 | 3.69 |
| | | | | Helsinki | 0.54 | 1.11 | 0.79 | 2.72 |

**Table 3**
Sensible load related to people and equipment for residential buildings - UNI EN 13790

| Days | Hours | Living room plus kitchen [$W/m^2$] | Other conditioned areas (e.g. bedrooms) [$W/m^2$] |
|---|---|---|---|
| Monday to Friday | 7 am – 5 pm | 8 | 1 |
| | 5 pm – 11 pm | 20 | 1 |
| | 11 pm – 7 am | 2 | 6 |
| | Average | 9 | 2.7 |
| Saturday and Sunday | 7 am – 5 pm | 8 | 2 |
| | 5 pm – 11 pm | 20 | 4 |
| | 11 pm – 7 am | 2 | 6 |
| | Average | 9 | 3.8 |
| Average | | 9 | 3 |

**Table 4**
Schedule example for latent loads based on the building typology

| Time | | Activity kg/h | People kg/(h px) | Other kg/h |
|---|---|---|---|---|
| From | To | | | |
| 7 am | 9 am | 1 | 0.05 | 0.1 |
| 9 am | 5 pm | 0.3 | 0.09 | 0.1 |
| 5 pm | 7 pm | 0.3 | 0.09 | 0.1 |
| 7 pm | 9 pm | 0.65 | 0.09 | 0.1 |
| 9 pm | 11 pm | 0.31 | 0.09 | 0.1 |
| 11 pm | 7 am | 1.5 | 0.05 | 0.1 |

present in the unit, according to the occupancy fraction defined by EN 16798 [48].

Since no specific European standard was available for the precise definition of latent loads, the hourly vapour production is expressed as a function of people occupancy and type of activity according to the standard ASHRAE 160 [49]. For example, in the morning 220g/h per person were defined for the shower, 200 g/h per family is the hypothetical latent load corresponding to and the breakfast time and an average value of 0.1 kg/h was included for other general activities, obtaining the results presented in Table 4 and leading to overall 27 kg of vapour per day.

The heating season has been considered from October to April. According to thermal comfort parameters, air node set point temperature for heating was set at 20°C without controls for the humidity, while in the cooling season temperature was set at 26°C, with a maximum relative humidity of 50%. The scheduling starts at 7 a.m. ending at 9 p.m. in the heating season and from 10 a.m. to 12 p.m. in summer for cooling, if needed.

Considering the most common types of heating and cooling systems in existing buildings, the heat generation system for the cases without retrofit is a standard non-condensing gas boiler that supplies high temperature terminal units (radiators); the cooling energy demand has been considered generally supplied both in existing and historical buildings by a standard split system air conditioner.

### 2.6. Possible retrofit actions

As already mentioned, the project GEO4CIVHIC looks at the retrofit of existing and historic buildings in urban city centres, applying GSHPs. The proposed solutions may be used for high temperature terminals as well as for mid and low temperature heating emission systems (i.e. fan-coils and radiant systems). Since many historical buildings are listed buildings where it is not possible to install insulation, the possibility to replace the gas boiler with a high temperature GSHP maintaining the radiators has been considered as well.

In case of envelope retrofit the insulation on the opaque walls and the replacement of windows have been considered. External walls have been retrofitted using 12 cm of expanded polystyrene (EPS), applied on the inner side to consider the limitations related to two main potential problems. The first one is the protection of the cultural heritage or the urban layout which may not allow to use external insulation in city centres. The second one is related to the reduction of pavement area and hence the reduction of the pedestrian zone. The thickness of the insulation layer is an average value that does not reduce excessively the inner net floor area available, thus being positively considered from the user. Internal floors have been slightly insulated even if they are usually dividing isothermal zones, in order to consider the installation of radiant systems that can be better coupled with ground source heat pumps due to the lower temperature required [50]. No limitations were set concerning the insulation thickness of the ground floor and the roof, thus achieving the minimum required local transmittance for the retrofit.

Standard gas boilers have been replaced by a more efficient GSHP, combined with the replacement of medium or low temperature emission systems (i.e. fan-coil or radiant systems) both for heating and cooling.

Hence, overall four main retrofit potential solutions have been investigated (Fig. 2):

- 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.

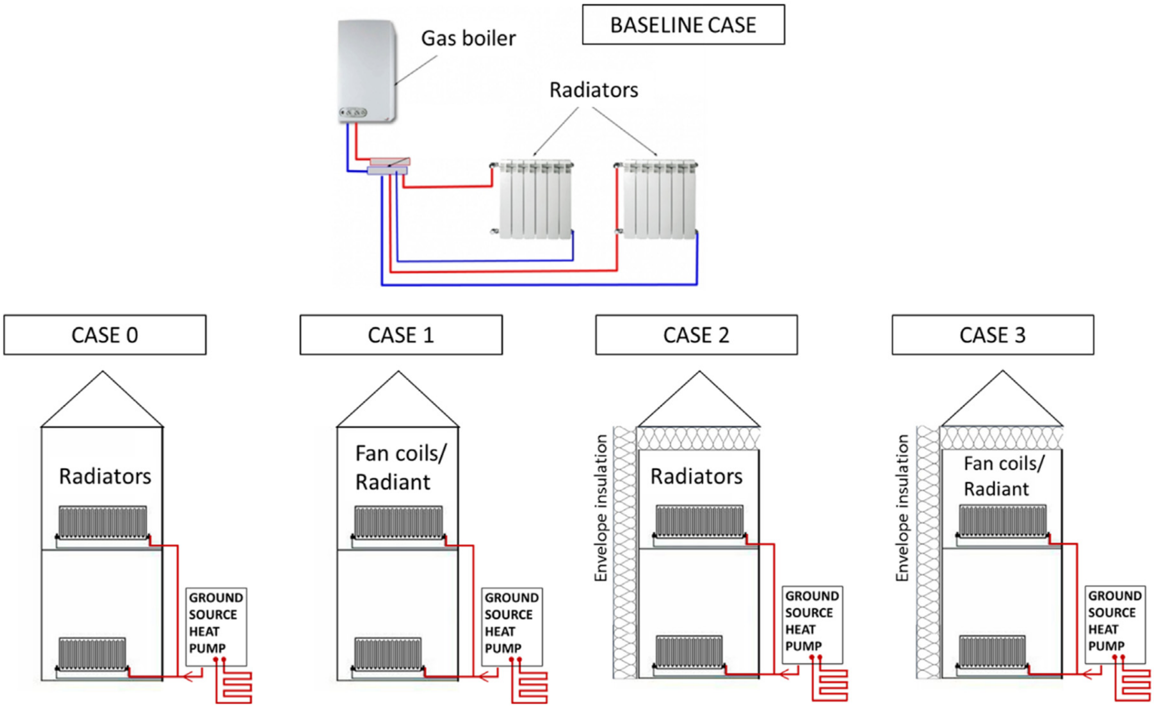


**Fig. 2.** Simplified scheme of the retrofit strategies applied

**Table 5**
Energy loads for heating and cooling in the three locations [kWh]

| Energy demand [kWh] | | Existing | | Historic | |
|---|---|---|---|---|---|
| | | Baseline | Retrofit | Baseline | Retrofit |
| Athens | Heating | 1810 | 60 | 4501 | 158 |
| | Cooling | 9597 | 6092 | 10863 | 6741 |
| Strasbourg | Heating | 10018 | 2972 | 14376 | 3638 |
| | Cooling | 4167 | 3761 | 4908 | 4311 |
| Helsinki | Heating | 16884 | 5780 | 21855 | 6964 |
| | Cooling | 2634 | 2547 | 3210 | 3500 |

- 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.

### 2.7. Energy loads for heating and cooling

Overall, 12 dynamic simulations have been carried out to determine the seasonal values of heating and cooling energy demands as well as the peak load for heating and cooling. Results have been compared to the previous project Cheap GSHPs and with the WebTool provided by the project TABULA[16], obtaining a good matching. Table 5 shows the energy demand both for existing and historical buildings, for Athens, Strasbourg, and Helsinki.

Comparing 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, while warm climates present a dominant cooling energy demand. On the contrary, 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. In fact, the most critical condition for the sizing process could be the summer season, since the energy which has to be injected into the ground has to include the energy of the compressor of the chiller, while in heating conditions the energy which has to be extracted by the ground is the difference between the energy load of the building and the energy required by the compressor.

Energy reduction is significant when looking at retrofitted buildings both for existing and historical cases, due to the lower transmission losses through the envelope. At the same time, the reduction of transmission losses increases the time constant of the building, which is also beneficial for the cooling demand in Athens.

## 3. Sizing of the geothermal probes

### 3.1. Method

The total required borehole lengths for heating and cooling and then the extension of the borehole field of double U-tube ground heat exchangers have been calculated by means of the well-known ASHRAE method [51], applying the tool developed by Capozza et al. [52]. The complete procedure has been implemented in an Excel tool whose scheme is explained in Fig. 3, where the inputs are framed in red and the outputs in green.

The ASHRAE method has been applied two times in a row to assess the total required borehole length. In the first calculation, the required bore lengths for heating (Lh) and cooling (Lc) are calculated disregarding the interference of adjacent boreholes. 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 7 m to limit thermal interference [53]. With the second iteration, Lh and Lc are evaluated more accurately considering the penalty temperature ($t_p$), following the steps as shown in Fig. 4.

### 3.2. Inputs

Table 6 presents design values of COP and EER considering the heat pump connected to different heating and cooling terminal units (radiators, fan-coils, radiant floor) and three climatic locations (Athens, Strasbourg, Helsinki). 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. As it might be seen, based

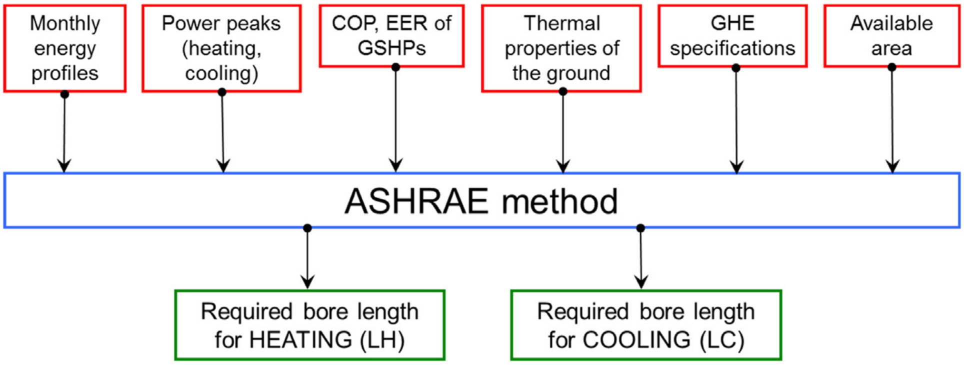


**Fig. 3.** Simplified conceptual framework of the applied procedure

**Table 6**
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 |

**Table 7**
Thermal properties of the three considered types of ground

| | | | |
|---|---|---|---|
| Thermal conductivity [W/(m K)] | 1.5 | 2.2 | 3.0 |
| Thermal capacity [MJ/(m$^3$ K)] | 2.0 | 2.5 | 2.6 |

**Table 8**
Specifications of the considered double U heat exchanger

| | | |
|---|---|---|
| Pipe | Internal diameter [mm] | 26 |
| | External diameter [mm] | 32 |
| | Thermal conductivity [W/(m K)] | 0.35 |
| Grouting material | Borehole diameter [mm] | 120 |
| | Thermal conductivity [W/(m K)] | 1.5 |

on the local temperatures the colder the climate the lower the COP and the higher the EER.

Simulations were performed considering three values of thermal conductivity and volume thermal capacity specified in Table 7 which correspond to the most common types of ground. These thermal properties values were selected according to the main results obtained in several research projects focused on determining the ground thermal properties for shallow geothermal properties applications, collecting data on unconsolidated deposits, sedimentary, metamorphic and igneous rocks [54–56]. In this work only the heat exchange conduction component between probe and ground is considered, while the convection contribution due to groundwater flow, able to increase the underground equivalent thermal conductivity and thus to reduce the overall length required for ground exchangers, is here neglected for the sake of simplicity.

The considered borehole heat exchanger is a typical double U-tube, characterised by the specifications listed in Table 8. The two U-loops are coupled in parallel, like all the borehole heat exchangers, which are supposed to be hydraulically balanced.

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.

The terraced house will host the GHEs arranged linearly in the courtyard at a distance of 3.3 m from the neighbourhoods and of 7 m between them. With the assumptions previously defined, a maximum of 3 BHEs can be installed, thus the length limitation for Lh and Lc is 300 m.

## 4. Results and discussion

### 4.1. Results of GSHP application

As well known the GSHP performance is influenced by the thermal conductivity of the ground. The aim of this work is to check the potentialities of the GSHP coupled with PVs, hence the average thermal conductivity of 2.2 W/(m K) and thermal capacity of 2.5 MJ/(m3 K) have been chosen for the detailed analysis of the results shown in this section, while all results for the other types of ground are presented in the Annex.

The final results of the ASHRAE method, implemented in the Excel tool presented in the previous paragraph, correspond to the required borehole lengths for heating (Lh) and cooling (Lc), which are compared to the maximum possible length (300 m). In the following diagrams, the comparison between the results is performed considering the different heating systems in existing and historical buildings. Then the diagrams of current and post-retrofit envelopes have been placed side by side to cross-check the results. The analysis has been carried out supposing that the necessary soil investigation and permits have been already required and obtained by the responsible local authority as required by the convention for the protection of the World Cultural and Natural Heritage [57].

### 4.2. Athens

In Athens, considering the installation of GSHP without any insulation of the building's envelope (Fig. 5a) and with envelope retrofit (Fig. 5b), 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 3b (envelope retrofit combined with distribution and generation systems' replacement). Despite the unbalanced thermal load,

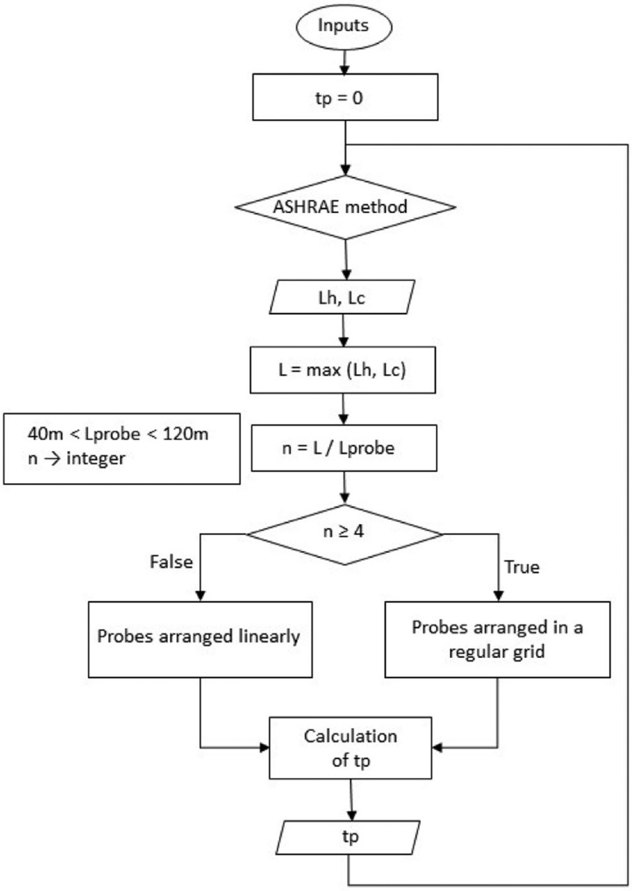


**Fig. 4.** Flowchart of the ASHARE method as implemented in the tool

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, whereas 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 $\lambda$=3 W/(m K).

**Table 9**
Optimal length of the probes

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

### 4.2.1. Strasbourg

The cases with a retrofitted envelope (Fig. 6b) shows balanced heating and cooling energy demand thanks to a reduction of the thermal load during the heating season, while the case without insulation (Fig. 6a) 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

### 4.2.2. Helsinki

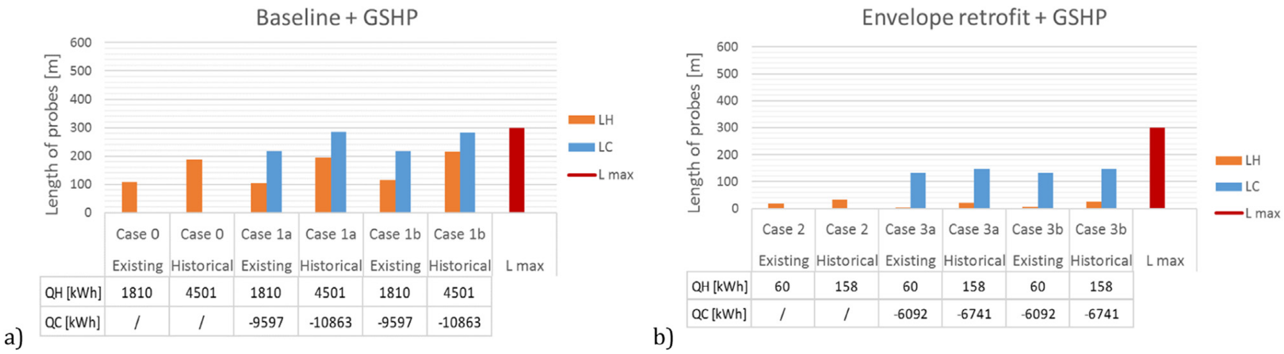
Considering the cases located in Helsinki, the unbalanced thermal load of the non-retrofitted envelope (Fig. 7a), is slightly more pronounced than Strasbourg. Although the application of deep retrofit requires a smaller heating length, which is reduced by 45% to 61% for existing and historic buildings comparing the baseline case with case 3b, the heating load is still dominant, complicating the sizing of the probes to supply efficiently the energy demand of the building.

## 4.3. Optimal probes' length

Summing up the results presented in the last paragraph, Fig. 8 and Table 9 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 $L_c>L_{max}$).

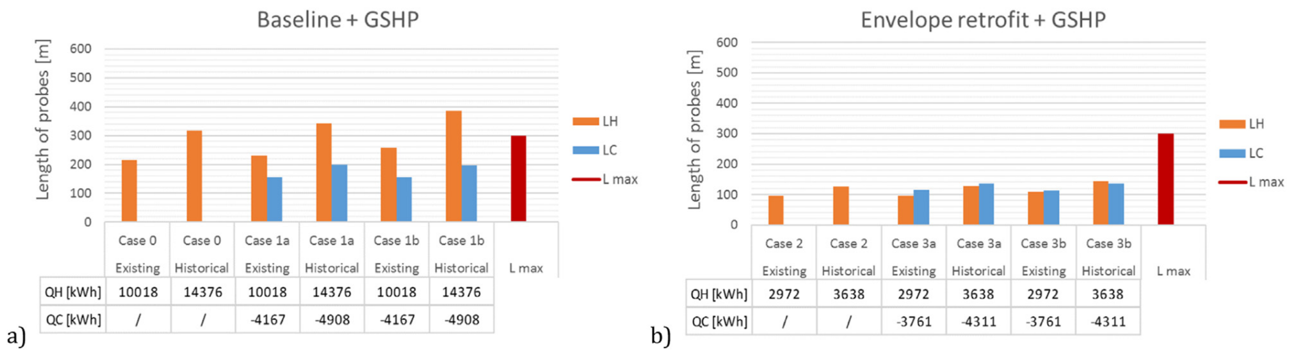
When the length of the probes is not sufficient to supply the energy demand of the building, the combination with an air to water heat pump



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

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

**Fig. 5.** 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



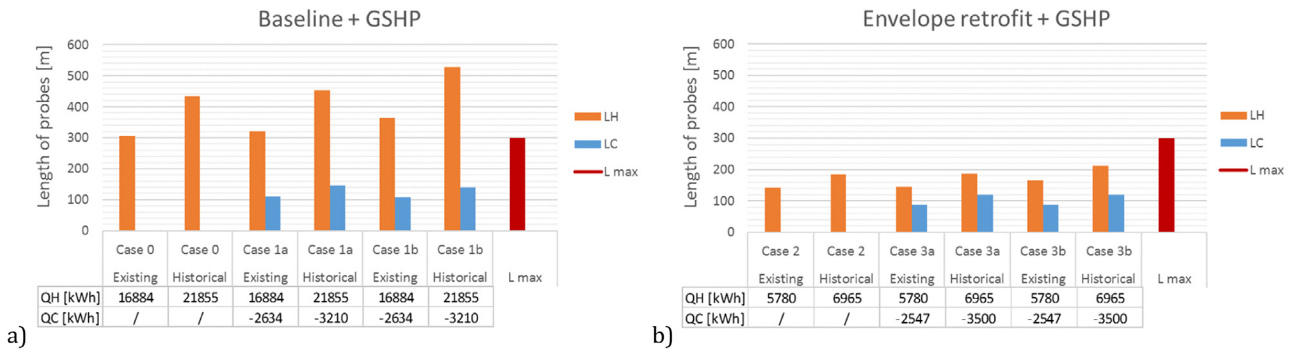
a)

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

b)

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

**Fig. 6.** 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)



a)

| | Case 0 Existing | Case 0 Historical | Case 1a Existing | Case 1a Historical | Case 1b Existing | Case 1b Historical | L max |
|---|---|---|---|---|---|---|---|
| QH [kWh] | 16884 | 21855 | 16884 | 21855 | 16884 | 21855 | |
| QC [kWh] | / | / | -2634 | -3210 | -2634 | -3210 | |

b)

| | Case 2 Existing | Case 2 Historical | Case 3a Existing | Case 3a Historical | Case 3b Existing | Case 3b Historical | L max |
|---|---|---|---|---|---|---|---|
| QH [kWh] | 5780 | 6965 | 5780 | 6965 | 5780 | 6965 | |
| QC [kWh] | / | / | -2547 | -3500 | -2547 | -3500 | |

**Fig. 7.** 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

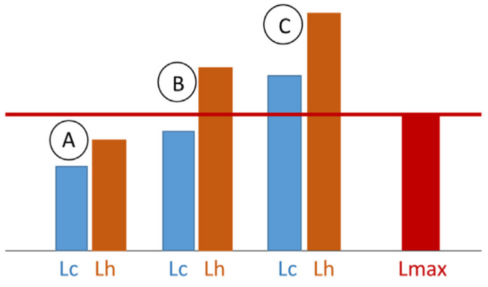


**Fig. 8.** Possible scenarios of the case studies

(AWHP) has been investigated to improve the energy efficiency of the whole system.

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.
- Case A2 and A3: if one of the two borehole lengths is greater 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 which 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 [14].
- Case 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, and the optimal total length of the boreholes is the shortest one. The energy which is not supplied by the heat extracted o released in the ground is supplied by the air source (GSHP+AWHP)
- 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).

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 [14, 58, 59].

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.

The methodology reported in Table 9 has been later used to correctly calculate the final and primary energy for the different possible solutions (see Table 10 for the final reference cases).

### 4.4. Analysis of the photovoltaic production

In order 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 as well, leading to a comprehensive analysis coupling envelope refurbishment, GSHP and PV production. As a matter of fact, there are many advantages related to the use of PV systems, considering that solar energy is clean

**Table 10**
Final length selected for the probes

| | | | Lh [m] | Lc [m] | Case* | L installed (a) [m] | L installed (b) [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-colis** | 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 11
** When max (Lh, Lc) << L probe, GSHP is not needed

**Table 11**
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 |

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 has to 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 [60] and spread on an hourly base according to a profile suggested by [61].

Table 11 shows the average hourly consumption of the electrical appliances and lighting by season and day of the week.

**Table 12**
Daily electric cooker use [Wh]

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

The electric cooker is commonly used three times per day, as explained in Table 12, varying the intensity depending on the time and the day of the week.

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

**Table 13**
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 |

**Table 14**
Annual energy produced by the photovoltaic system

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

**Table 15**
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 |

electric load profile of a residential user (Tables 11 and 12), the total electric energy required by the housing units are shown in Table 13 for each climate and type of building.

The total electric profile of the building was compared on an hourly base to the energy produced by the photovoltaic system, evaluating two indicators [62]: the self-sufficiency (SS) and the self-consumption (SC), each of them depending in the self-used energy Equation (1), that is the difference between the energy consumed and the energy supplied from the grid.

$$Self\ Used\ Energy = Energy\ Consumed - Energy\ supplied\ from\ the\ grid\ [kWh] \tag{1}$$

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.

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

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.

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

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 14 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.

The roof area and the sizing parameters (Table 15) 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.

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. On the contrary, 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 analysed for 5 different orientations of the panels, therefore a total of 180 cases have been simulated for existing and historic buildings.

Table 16 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 present 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.

Similarly, Table 17 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.

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, or to maximizing self-consumed energy, 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.

**Table 16**
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 | | | | |
| | | 0° | 45° | 90° | 180° | 270° | 0° | 45° | 90° | 180° | 270° |
| **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 3Radiant** | **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% |

**Table 17**
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 | | | | |
| | | 0° | 45° | 90° | 180° | 270° | 0° | 45° | 90° | 180° | 270° |
| **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% |

### 4.5. *Cost analysis*

Archetype buildings are useful to estimate the energy need of national and international building stocks and the potential energy saving achievable applying retrofit actions. However, the retrofit interventions are strictly related to the investment costs affordable by the user, thus a cost analysis is needed to complete the dataset information.

The costs have been estimated through a market analysis given by the partners involved in the project, considering the characteristics of the cases presented in Section 2.6, in particular:

- Case 0: replacement of the gas boiler with GSHP
- Case 1a: replacement of the gas boiler with GSHP and installation of fan coils instead of high temperature radiators, reducing the supply temperature
- Case 1b: replacement of the gas boiler with GSHP and installation of radiant systems instead of high temperature radiators, further reducing the supply temperature compared to 1a
- Case 2: envelope insulation and replacement of the gas boiler with GSHP
- Case 3a: envelope insulation, replacement of the gas boiler with GSHP and installation of fan coils instead of radiators
- Case 3b: envelope insulation, replacement of the gas boiler with GSHP and installation of radiant systems instead of radiators.

**Table 18**
Primary energy conversion factors

| | Gas | Electricity |
|---|---|---|
| Athens (Diesel) | 1.15 | 2.18 |
| Strasbourg | 1.1 | 2.83 |
| Helsinki | 1.1 | 2.02 |

Primary energy use has been calculated considering all energy needs; the impact of the retrofit actions does not only deal with the final and primary energy savings but also the investnment costs. The primary energy conversion factors used in this work are reported in Table 18 and they have been provided by Eurostat [63] for electricity, while for gas and diesel the Buildings Performance Institute Europe (BPIE) [64].

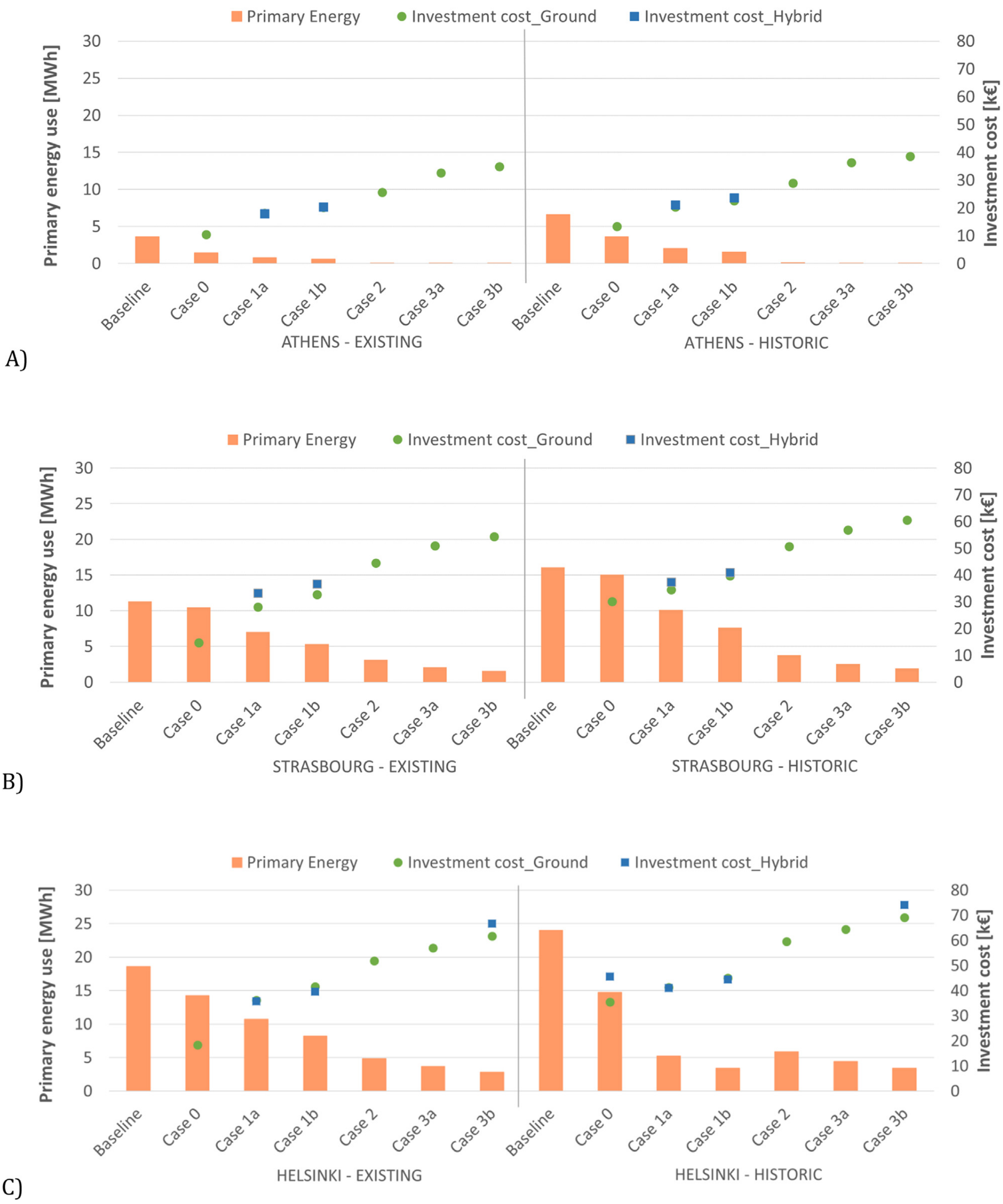


**Fig. 9.** Primary energy use and investment cost of the different cases for A) Athens, B) Strasbourg and C) Helsinki

Investment costs are generally the lowest ones in Athens compared to other climates, mostly due to the lower energy demand. Both for historic and existing buildings in warm climates, in fact, the envelope refurbishment combined to the boiler replacement can lead to a negligible primary energy use (Fig. 9A, Case 2 compared to Case 1) with an investment cost around 40% higher compared to the simple replacement of the gas boiler. In this case, the cost increased by 60% of the hybrid solution balances the drilling costs for the GSHP, therefore the investment for hybrid or ground source heat pumps is similar.

In mild climates as Strasbourg, the reduced space heating energy demand due to the installation of envelope insulation eliminates the potential need of a hybrid source, because the length of the probes needed to fully supply both heating and cooling is similar, avoiding plants oversizing and related thermal drift (Fig. 9B).

On the contrary the hybrid source could be more suitable solution in Helsinki, where non insulated buildings require bigger probes' length than the maximum available (Fig. 9C - Case 0, Case 1a, Case 1b). This solution could be interesting also in Case 3b that estimates a cooling length significantly greater than the heating length and investing 8% more in favour of a hybrid source could help reducing the ground thermal drift and increasing the efficiency of the system.

In general, the graphs show that higher investment costs correspond to significantly lower primary energy use compared to the baseline cases. According to the economic availability of the interested user, several strategies can be chosen, obtaining different primary energy savings according to the solution and leading to lower operation costs related to the use of energy vectors.

## 5. Conclusion and further applications

The work done within the GEO4CIVHIC project aims at showing the potential of energy reduction of the European building stock in urban areas due to the retrofit by means of shallow geothermal systems. For this purpose, it is necessary to define archetypes which may represent the most frequent cases inside urban areas. These archetypes have been examined in terms of geometry, thermal properties of the envelope, end use, type of HVAC installed. 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 methodology used to define the archetypes has been shown, identifying a single-user building, named terrace house, which has been considered only for residential end use.

A further subdivision has been made considering the construction period, defining as "historic" buildings built before 1960 and "existing" buildings built after 1960. For these two types of buildings both current and post-retrofit envelopes have been considered.

Twelve dynamic simulations were carried out to determine the heating and cooling energy demand later used to size geothermal 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.

In particular:

- A methodology has been defined for the calculation of 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 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 projections for energy communities.
- The cost analysis shows that increasing the number of retrofit strategies applied, thus the investment costs, could significantly reduce the primary energy use leading to a reduction of the energy costs through the operation time of the plant. 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 literature, the extensive use of archetype buildings applied to urban modelling allows more extensive applications of energy modelling by reducing the simulation time due to the complexity of the data mining, thus leading to a wider usability by experts without loosing the quality of the results. Therefore, a new methodology to build a complete and integrated database at European scale is a new perspective for designers and policy makers, supporting higher renewable energy share with the installation of ground source heat exchangers and photovoltaic panels.
- The dataset collected provides a new tool for urban planners and policy makers to analyse wide stock of buildings and plants, including their refurbishment, thus 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.

## Declaration of competing interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

## CRediT authorship contribution statement

**Laura Carnieletto:** Conceptualization, Software, Investigation, Formal analysis, Writing – original draft, Writing – review & editing. **Antonino Di Bella:** Investigation, Writing – original draft, Writing – review & editing. **Davide Quaggiotto:** Investigation, Software, Formal analysis. **Giuseppe Emmi:** Investigation, Formal analysis, Writing – review & editing. **Adriana Bernardi:** Funding acquisition, Project administration. **Michele De Carli:** Supervision, Writing – review & editing, Funding acquisition.

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## Appendix

### *A1. Ground thermal conductivity 1.5 W/(m K)*

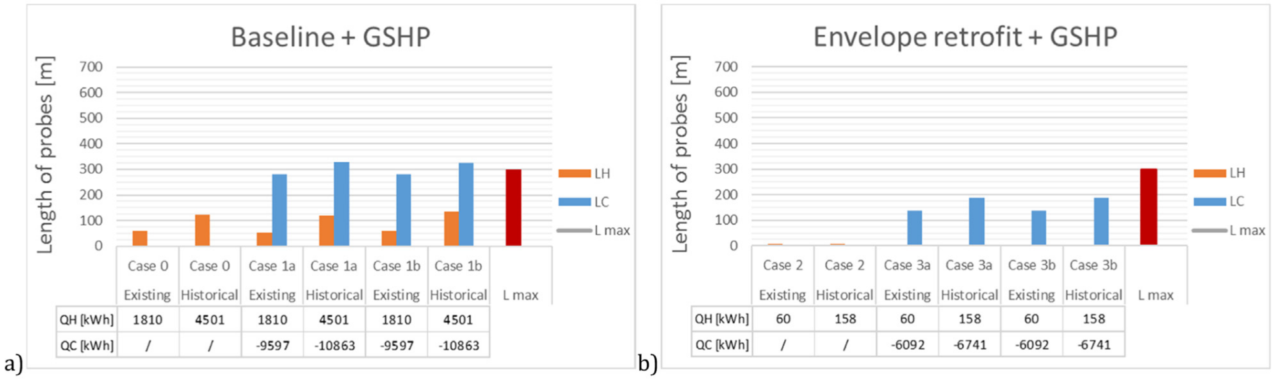
The first value of ground thermal conductivity which has been considered is the lowest, equal to 1.5 W/(m K). Fig. 10 Comparison between the maximum length available and the required borehole length to satisfy the energy demand both in the baseline and deep retrofit conditions for Helsinki.

### *A2. Ground thermal conductivity 3 W/(m K)*

Fig. 11 shows the comparison between the maximum length available and the required borehole length to satisfy the energy demand for the three building typologies both in the baseline and deep retrofit conditions in case of ground thermal conductivity equal to 3 W/(m K).

## Athens

### Terraced house



a)

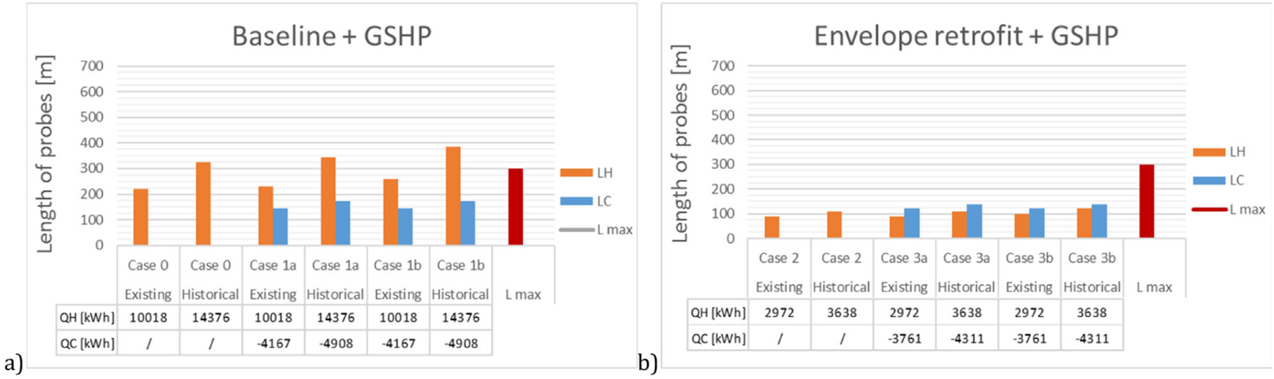
| | Case 0 Existing | Case 0 Historical | Case 1a Existing | Case 1a Historical | Case 1b Existing | Case 1b Historical | L max |
|---|---|---|---|---|---|---|---|
| QH [kWh] | 1810 | 4501 | 1810 | 4501 | 1810 | 4501 | |
| QC [kWh] | / | / | -9597 | -10863 | -9597 | -10863 | |

b)

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

## Strasbourg

### Terraced house



a)

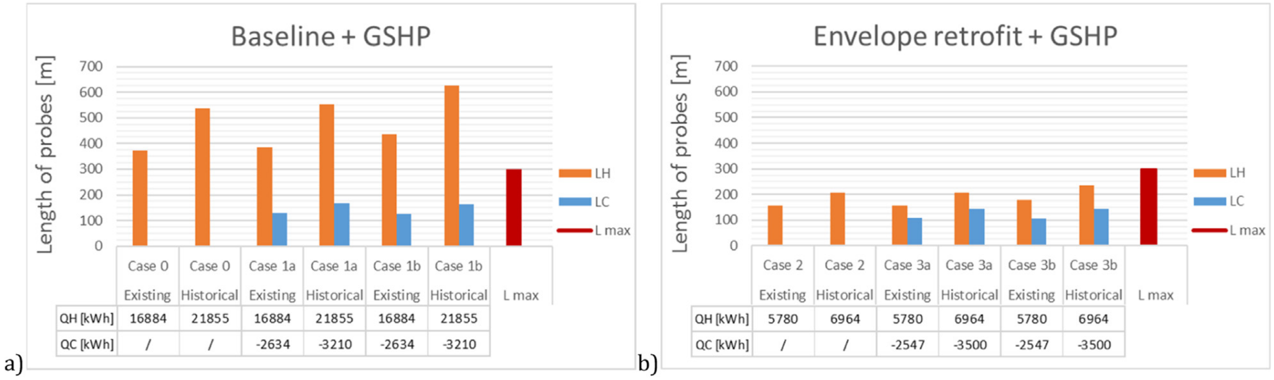
| | Case 0 Existing | Case 0 Historical | Case 1a Existing | Case 1a Historical | Case 1b Existing | Case 1b Historical | L max |
|---|---|---|---|---|---|---|---|
| QH [kWh] | 10018 | 14376 | 10018 | 14376 | 10018 | 14376 | |
| QC [kWh] | / | / | -4167 | -4908 | -4167 | -4908 | |

b)

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

## Helsinki

### Terraced house



a)

| | Case 0 Existing | Case 0 Historical | Case 1a Existing | Case 1a Historical | Case 1b Existing | Case 1b Historical | L max |
|---|---|---|---|---|---|---|---|
| QH [kWh] | 16884 | 21855 | 16884 | 21855 | 16884 | 21855 | |
| QC [kWh] | / | / | -2634 | -3210 | -2634 | -3210 | |

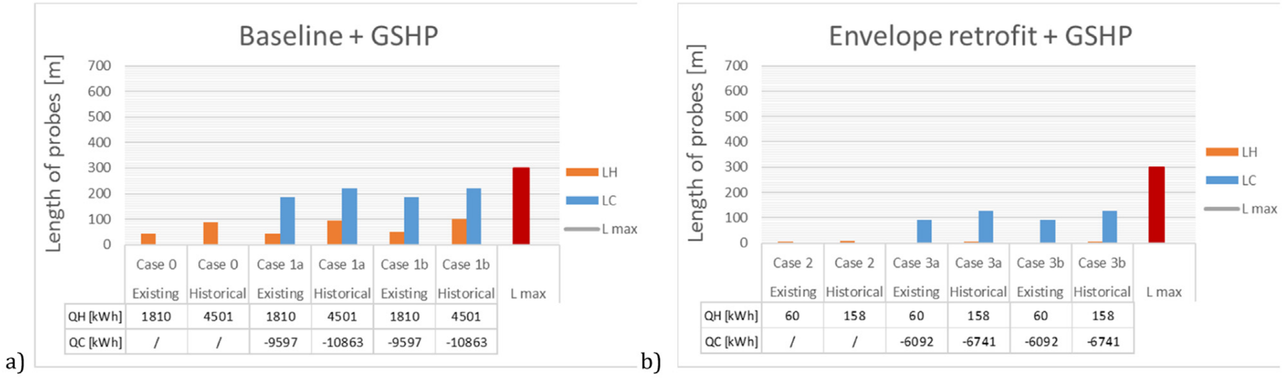
b)

| | Case 2 Existing | Case 2 Historical | Case 3a Existing | Case 3a Historical | Case 3b Existing | Case 3b Historical | L max |
|---|---|---|---|---|---|---|---|
| QH [kWh] | 5780 | 6964 | 5780 | 6964 | 5780 | 6964 | |
| QC [kWh] | / | / | -2547 | -3500 | -2547 | -3500 | |

**Fig. 10.** Comparison between the maximum length available and the required borehole length to satisfy the energy demand typologies for Athens, Strasbourg, Helsinki without (a) and with (b) envelope insulation

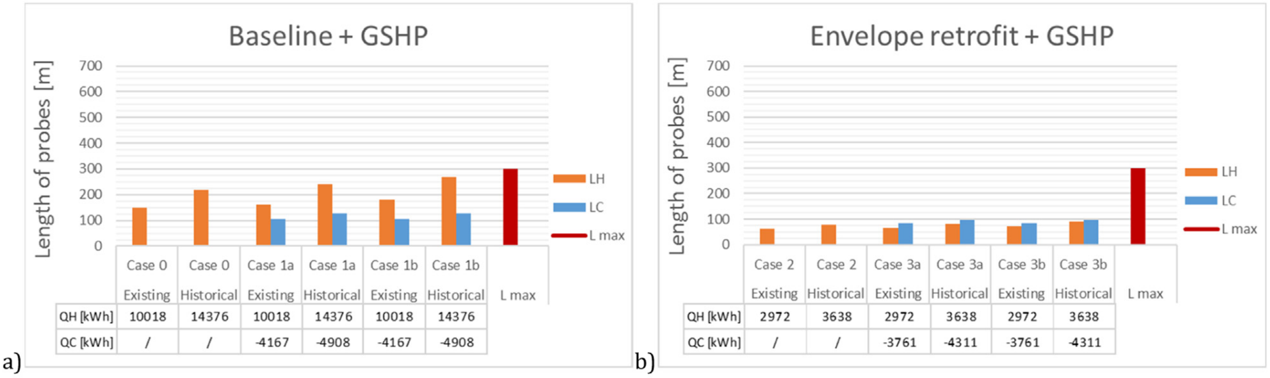
## Athens

### Terraced house



## Strasbourg

### Terraced house



## Helsinki

### Terraced house

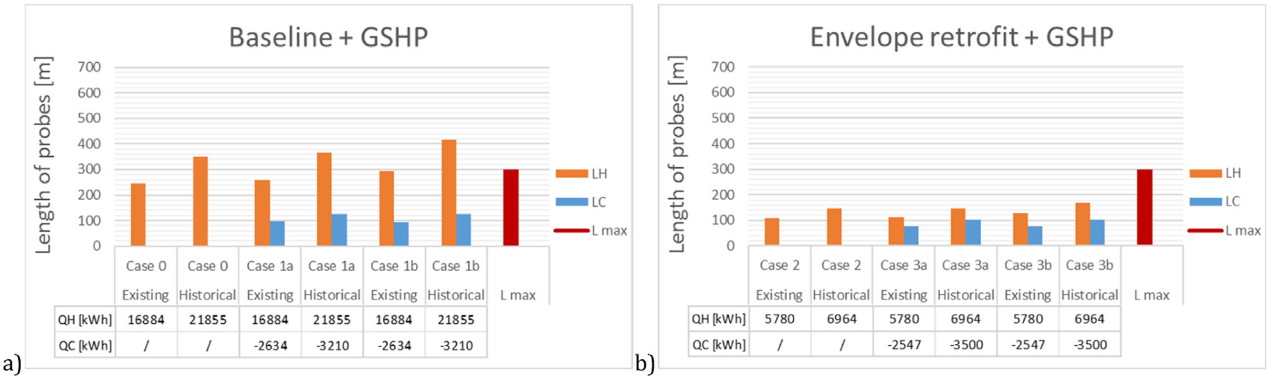


**Fig. 11.** Comparison between the maximum length available and the required borehole length to satisfy the energy demand typologies for Athens, Strasbourg, Helsinki without (a) and with (b) envelope insulation

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