

Article

An Integrated HBIM Simulation Approach for Energy Retrofit of Historical Buildings Implemented in a Case Study of a Medieval Fortress in Italy

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Abstract: The Italian building stock consists of buildings mainly constructed until the mid-20th century using pre-industrial construction techniques. These buildings require energy refurbishment that takes into account the preservation of their architectural heritage. In this view, this work studies an innovative integrated modelling and simulation framework consisting of the implementation of Historical Building Information Modeling (HBIM) for the energy retrofit of historical buildings with renewable geothermal HVAC system. To this aim, the field case study is part of a medieval complex in Central Italy (Perugia), as representative ancient rural offshore architecture in the European countryside. The system involves of a ground source heat pump, a water tank for thermal-energy storage connected to a low-temperature radiant system, and an air-handling unit. The building heating energy performance, typically influenced by thermal inertia in historical buildings, when coupled to the novel HVAC system, is comparatively assessed against a traditional scenario implementing a natural-gas boiler, and made inter-operative within the HBIM ad hoc platform. Results show that the innovative renewable energy system provides relevant benefits while preserving minor visual and architectural impact within the historical complex, and also in terms of both energy saving, CO₂ emissions offset, and operation costs compared to the traditional existing system. The integrated HBIM approach may effectively drive the path toward regeneration and re-functioning of heritage in Europe.

Keywords: historical building; building energy efficiency; energy retrofit; geothermal system; Historical Building Information Modelling; dynamic simulation; renewable energy; cultural heritage; GEOFIT Horizon 2020 project

1. Introduction

Nowadays, sustainable energy and cost efficiency solutions are widely accomplished in new constructions. On the contrary, in the case of historical building retrofit, deep multidisciplinary interaction is required for the preservation of cultural heritage value. This value usually represents a relevant constraint to face during the whole construction path. Accordingly, tailored low-impact solutions, typically to be tailored with the case-specific boundary conditions, must be

developed. Moreover, the tools for the analysis of historical buildings should ease the required comprehensive approach.

In this view, the GEOFIT project [1], acronym of “Deployment of novel geothermal systems, technologies and tools for energy efficient building retrofitting”, is an integrated industry-driven (Innovation Action) project funded by the Horizon 2020 programme of the European Union that aims at developing and deploying cost-effective enhanced geothermal systems primarily for the energy retrofit of buildings [2]. These technologies and construction processes will be validated in five case study demonstration sites in four countries featuring different climatic conditions, soil types, and building typologies, including an historical building in Italy, dealt with in this study. In this case study, the feasibility of implementing a ground source heat pump (GSHP) system in historical buildings is evaluated [3]. Historical buildings, indeed, represent almost one third of the construction panorama in most of European countries [4,5] including buildings located both in historical city centers and rural in the agricultural fields. Therefore, given the massive contribution of such buildings on the overall final energy need and greenhouse gases (GHGs) emissions imputable to the construction sector, such category cannot be neglected when designing energy efficiency retrofit actions. However, a deep multidisciplinary interaction is required in this field, by paying attention to the implementation of low visual impact solutions [6].

Recently, the use of GSHP systems have been spread for both domestic and industrial building applications worldwide. However, the existing literature lacks studies about the actual implementation of these systems for retrofitting historical buildings, due to the above mentioned preservation-related limits and installation requirements [7]. For instance, Emmi et al. [8] showed the sole potential primary energy savings associated to the use of GSHP in museum buildings in two Italian cities through dynamic simulation. Carnieletto et al. [9] developed a database to correlate building typologies and climatic conditions with energy demand, for different types of residential buildings, with the aim to provide indications for the proper design of ground source heat pumps. Moreover, the few existing studies on real applications focus on their implementation in dense urban environments [10,11]. Another example of real application is described in Moretti et al. [12], who investigated the potential of GHP systems in existing commercial buildings by a pilot system in Central Italy, yet with no historical valence. The system features a geothermal heat pump with an innovative layout: a heat-storage water tank, buried just below ground level, which allowed a significant reduction of the geothermal unit size, hence requiring fewer and/or shorter boreholes (up to 75%) [13]. Finally, in the GEO4CIVHIC project [14,15] GSHP systems are studied for applications in existing and historical buildings with the main focus to deploy shallow geothermal systems for heating and cooling.

Another relevant aspect related to the analysis of historical buildings retrofit is the increasing need of integrated building design. In this view, Building Information Modeling (BIM) allows the virtual construction of the whole building, using virtual elements equivalent to the real ones. These elements are not only three-dimensional geometries, but they embody their own physical and technical characteristics and are able to interact to each other. Therefore, this recently developed design process allows the reduction of fragmentation during building design [16]. Moreover, BIM is characterized by high interoperability, i.e., the possibility to exchange model data with several software packages, including dynamic simulation engines [17]. Taking advantage from this capability, Patiño-Cambeiro et al. [18] developed a multidisciplinary approach for the energy performance evaluation of educational buildings. Najjar et al. [19], instead, used building information modeling to perform a parametric analysis aimed at designing the building performance parameters based on climate conditions towards energy efficiency. Focusing on system performance assessment, Torregrosa-Jaime et al. [20] coupled BIM and dynamic simulation to study an aerothermal heat pump system for residential buildings, finding up to more than 30% heating demand saving compared to a conventional HVAC system.

Although the BIM methodology was born as a tool for new buildings, with a high degree of standardization, HBIM, i.e. Historical BIM, is catching on in the field of historical buildings retrofit

thanks to its multidisciplinary and integrated approach [21]. In fact, it consists of the application of the principles of BIM to historical buildings renovation and retrofit [22]. Historical buildings, indeed, present some critical issues, e.g., the absence of detailed documentation on the project or the presence of multiple layers over the years. In this view, HBIM methodology allows to integrate, in a single three-dimensional model, building technical, design, and historical data, namely information about the degradation, the historical phases, and the performed interventions. On the one hand, many existing recent studies involve the use of the HBIM methodology to study the degradation and conservation of the cultural heritage [23–25], including integration with photogrammetry [26] and Geographic Information System (GIS) [27]. On the other hand, studies focus on the introduction into the BIM methodology of recurring elements and families typical of historical buildings [28,29]. With the aim to develop a tool to collect heritage information from interdisciplinary stakeholders, Palomar et al. [30] designed an online work platform that connects the intrinsic HBIM database with heritage documentary databases, which could be further improved in terms of modelling historic structures. Bolognesi et al. [31] analyzed different workflows to create a mathematical model for reproducing the geometry of a real historical vault, which can be parameterized in a BIM environment, as one of the main relevant elements characterizing historical buildings. Accordingly, Gigliarelli et al. [32] stressed the need of further standardization and interoperability between software in the HBIM workflow to provide solutions for the built heritage conservation.

In this panorama, this study, developed within the context of the H2020 GEOFIT project, has a twofold purpose. Firstly, an HBIM platform is proposed to design and model the historical case study building providing a comprehensive tool for the analysis of historical building. The approach, indeed, takes into account both historical priorities and retrofit actions for the building. In this view, different building elements, typical of historical buildings, are created from scratch in the model. Therefore, the models of such historical building elements are available to bridge this gap of BIM modelling for historical buildings. Secondly, in this context of analysis, the performance and the feasibility of innovative GSHP systems, integrating a water-to-water heat pump with ground heat exchangers, are preliminarily assessed when installed as energy retrofit strategy in the Italian historical building case study of the project. According to the goals of the GEOFIT project, novel horizontal slinky type ground source heat exchangers (GHEXs) coupled with an adsorption heat pump will be implemented in the Italian pilot. They will be placed lying flat in loops in a trench, then backfilled with in-situ sediment or with primarily sandy sediment. The loops will be overlapping at half of the loop diameter. These innovative heat exchangers allow geothermal systems to be implemented when drilling is too operatively difficult or expensive. However, in this preliminary study, the performance of a standard ground source heat pump system with vertical U-tube GHEXs, as a low temperature heat source, is analyzed. Therefore, the outcomes of this study are used to evaluate the theoretical feasibility of replacing a gas boiler with a geothermal heat pump, rather than the expected performance of the real pilot system. The real geothermal system will be specifically assessed following its comprehensive design and implementation in future studies.

2. Methods

To evaluate the achievable energy performance improvement associated to the implementation of a geothermal system, building dynamic energy simulation was carried out.

Firstly, the architectural model of the case study building was developed via HBIM, to have an integrated building model. Therefore, it was imported in the dynamic simulation platform, where the HVAC system was further modelled. The data exchange between the BIM and the dynamic simulation software was provided via gbXML schema version 6.0.1 [33] import capability. This interoperability allows saving the time needed to redraw the building geometry.

The dynamic simulation model was validated, to allow a reliable comparison of the performance of the innovative HVAC system with the existing one. Firstly, the building envelope performance was

validated based on the thermal zone air temperature. Secondly, the whole building-system model was validated based on the heating gas consumption for the entire building.

Finally, the model was simulated when implementing the existing gas boiler or the geothermal system, with a water-to-water heat pump and ground heat exchangers, as HVAC system. Results were compared in terms of energy consumption, cost analysis, and CO₂ emissions.

2.1. Case Study

The case study building represents an ex stable building built in the second half of the XIX century (Figure 1). It is part of the medieval complex of Sant'Apollinare fortress in Perugia, Italy Figure 1c. The building was recently refurbished through seismic and energy renovations. It was converted to an office building and it currently hosts the offices of a university research center dedicated to energy and sustainable development.

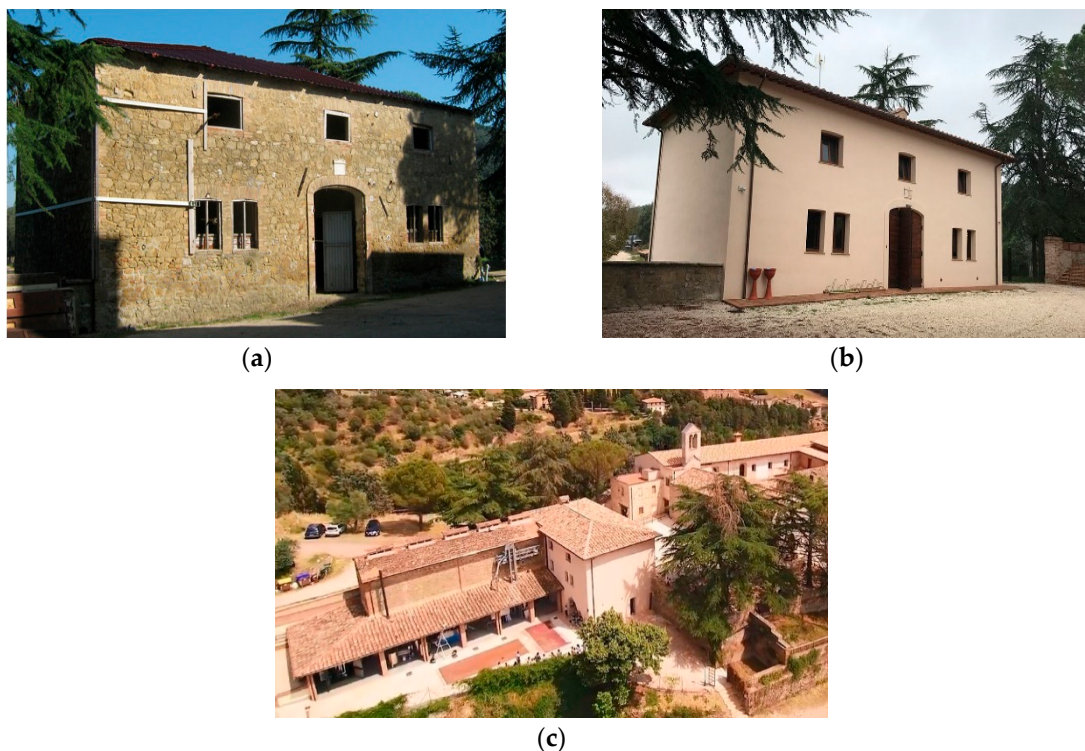


Figure 1. View of the case study building: (a) before the refurbishment; (b) after the refurbishment; (c) within the complex of Sant'Apollinare fortress.

The building consists of three floors: two above ground and a basement, for a total usable area equal to about 240 m² and a heated volume of about 700 m³. The basement is used as a laboratory, while the upper floors are intended for offices.

The structure is composed of the original external bearing walls, completely preserved, which are made of a mix of local stone and bricks. During the retrofit, windows were improved with low-emissivity glass. Moreover, external coating insulation using local recycled cork panels (0.1 m) was added to improve building envelope thermal performance, in addition to the good thermal inertia of the existing massive masonry. However, cork panels were not glued to the historical masonry, to preserve the historical aspect of the building and respect the principle of reversibility, according to which the retrofit intervention must be removed without damaging the original envelope preserved [34]. Finally, the original wooden structure of the roof was retrofitted and partially renovated before re-installation in situ.

The building retrofit procedure was also recently awarded with the Gold Certification by GBC Historic Building™ (HB) protocol [35] as very first case in the world. This environmental certification allowed monitoring the impacts of the whole refurbishment and construction process, in terms of both sustainability of the construction process and preservation of the cultural value of the artefact during the restoration process [36]. The GBC HB protocol, indeed, addresses the issue of the enhancement of the energy efficiency and cultural value of the building heritage. The combination of these two aspects drives the choice of passive and active retrofit solutions to be implemented in the building.

2.2. HBIM Model

The architectural model of the case study building was developed in the BIM design authoring platform Revit (Autodesk) [37]. The HBIM model was developed to faithfully reproduce every historical component of the building, as depicted in Figure 2. Therefore, several building elements that are generally recurrent in historical buildings were created in Revit to model the case study building, since they are currently not implemented in Revit library. Ad hoc families were modelled starting from the existing templates, when possible, to bridge this gap. As further detailed in Appendix A for allowing readers' replicability of the proposed framework, the models for the following components were developed:

- column;
- pavilion roof;
- roof clay bent tiles and tiles, that a modeled as a linear family to be arranged in lines on the roof;
- barrel vault;
- ancient wooden door;
- wooden frame with beams and joists for roof and floor.

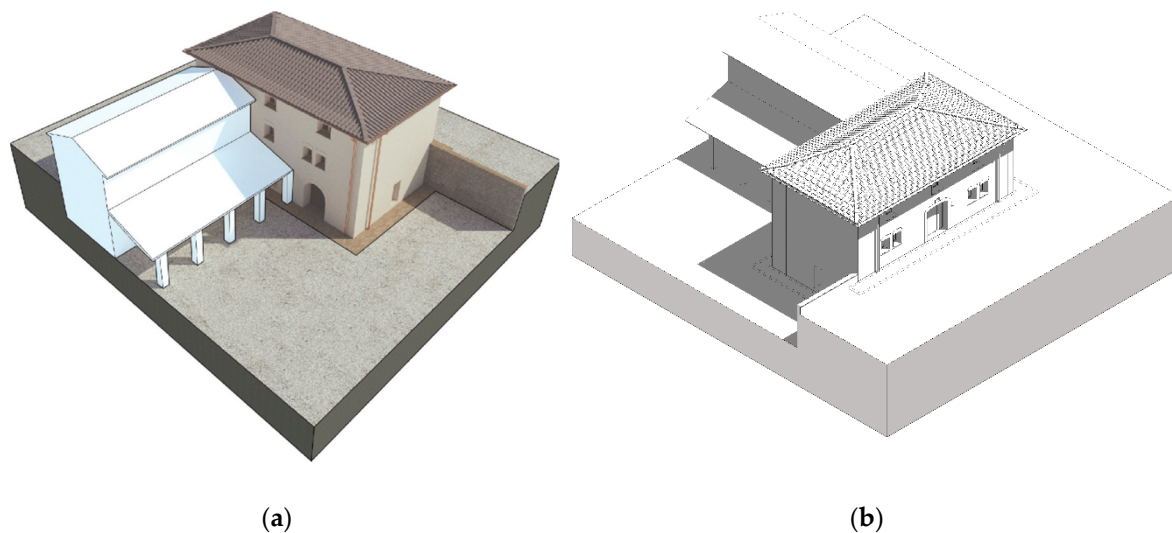


Figure 2. Historical Building Information Modeling (HBIM): (a) back rendered view; (b) front 3D view.

2.3. Building Thermal-Energy Model

Numerical analysis was performed within EnergyPlus v8.9 [38] simulation environment with DesignBuilder graphical Interface [39]. The building thermal-energy model was derived directly from the related HBIM model made in Revit, while the HVAC system was modelled directly in DesignBuilder. To facilitate the compatibility with the dynamic simulation software, the architectural model was simplified in Revit before export, as shown in Figure 3a. The final geometry of the building thermal-energy model after importing the gbXML file into DesignBuilder is depicted in Figure 3b.

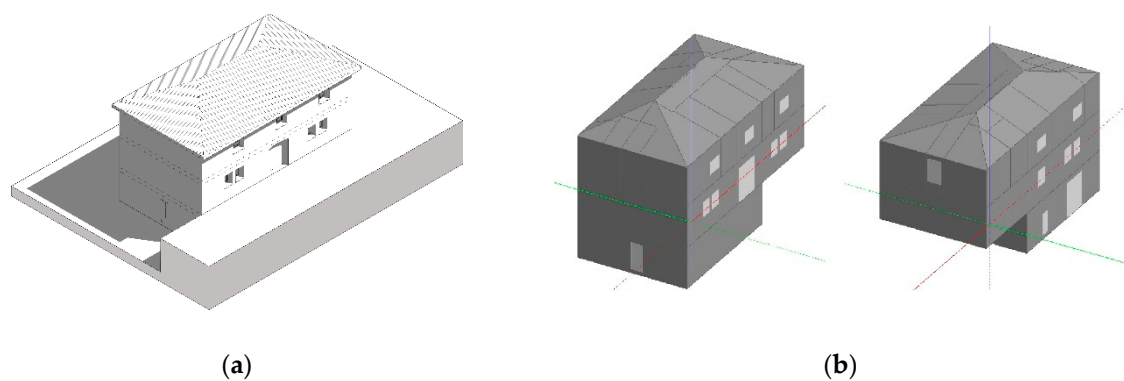


Figure 3. Building model: (a) simplified Revit model to be imported in DesignBuilder; (b) simulation model, front and back view.

The building model was divided into 17 thermal zones, according to the intended use. Three of them are free running, namely the technical room lodging the heating and the domestic hot water systems (basement), the technical room for the electrical and automation system (basement), and the stairwell. The basement is in direct contact with the ground on the front side.

As for the envelope materials, transparent surfaces were modelled in terms of thickness, transmittance, g-factor, and reflectance to solar radiation, emissivity, thermal conductivity, and visible transmittance (Table 1). Windows, which were replaced during the energy retrofit, consist of low-emissivity double pane glass with Argon in the cavity (4 mm - 15 mm - 4 mm), characterized by U-value equal to 1.317 W/m² K. Moreover, the characteristics of the main opaque envelope components are summarized in Table 2.

Table 1. Thermo-physical properties of transparent materials.

Material	Thickness (m)	Solar Transmittance (-)	Front Solar Reflectance (-)	Back Solar Reflectance (-)	Front Thermal Emissivity (-)	Back Thermal Emissivity (-)	Conductivity (W/m K)
External glass	0.006	0.600	0.170	0.220	0.840	0.100	0.900
Internal glass	0.006	0.775	0.071	0.071	0.840	0.840	0.900

Table 2. Thermo-physical characteristics of the main opaque envelope components.

Envelope Component	Layers	Thickness (m)	Thermal Transmittance (W/m ² K)
External wall	<i>outdoor</i>		
	Weber cote action coating	0.006	
	Cork panel	0.100	
	Weber lime plaster	0.013	0.36
	Stone masonry	0.390 *	
	Webertherm insulating panel	0.030	
Wall against the ground	<i>indoor</i>		
	<i>outdoor</i>		
	Lime mortar	0.010	
	Stone masonry	0.740	
	Lime mortar	0.013	0.70
	Cork panel	0.040	
	Webertherm insulating panel	0.030	
	<i>indoor</i>		

Table 2. Cont.

Envelope Component	Layers	Thickness (m)	Thermal Transmittance (W/m ² K)
Ground floor	<i>outdoor</i>		
	Concrete slab	0.100	
	Underfloor air cavity	0.450	
	Reinforced concrete	0.050	
	LEKA screed	0.120	
	Lime mortar	0.300	
	Concrete slab	0.050	
	Insulation radiant floor	0.040	
	MR18 metal screed	0.060	
	Ceramic floor tiles	0.014	
Sloped roof	<i>indoor</i>		
	<i>outdoor</i>		
	Roof clay tiles	0.030	
	OSB board	0.012	
	Wood fiber insulation	0.140	
	Clay tiles	0.040	
	Wood beams	0.120	
	<i>indoor</i>		

* The stone masonry layer thickness varies for the different building walls. This is the most common value.

The schedules of occupancy and internal heat gains associated to electrical and lighting equipment, as well as HVAC system operation, were inputted according to the real typical use of the building considering office as main intended use. These schedules follow a typical profile of an office building with peak load by the end of the morning and during mid-afternoon. The building is occupied only on working weekdays and the occupancy schedule is shown in Figure 4. For occupancy density, a value of 0.025 people/m² was set, which means one person every 40 m². This value represents the maximum possible occupation of the building. For office equipment, the following values were considered:

- power density equal to 2 W/m², representing the maximum achievable value;
- emitted radiant fraction equal to 0.10;
- schedule based on the occupancy schedule.

Air infiltration was set equal to 0.3 ac/h, according to the ASHRAE method [40]. Finally, heating system set-point temperature was set equal to 20 °C in each thermal zone, according to indoor thermal comfort standards [41] and building simulation analysis practice [42], except for the unheated zones.

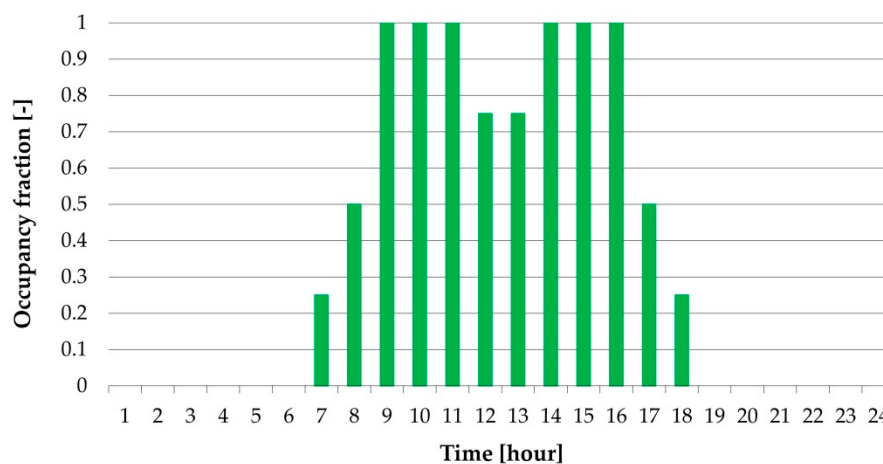


Figure 4. Occupancy presence schedule on working weekdays (where occupancy fraction is the fraction of the maximum possible occupancy density).

2.4. HVAC System Model

Firstly, the HVAC system was modeled in order to best represent the actual system installed in the case study building. The heating load of the building is satisfied by a gas boiler connected to radiant floor in all rooms, except for service rooms where wall radiators are installed. The water distribution to the various terminal units is carried out thanks to a small water storage tank. The tank is maintained at the required set-point temperature by means of a plate heat exchanger between the gas boiler and the tank itself. Moreover, a 2000 L thermally insulated water tank is installed for domestic hot water. However, since this study focuses on the analysis of the sole space heating need, it was not accounted for in this study.

Furthermore, an air-handling unit (AHU) is used to supply fresh air to any zones. The system allows to partially recirculate air with inlets in office rooms, in the first and second floor, and outlet in the service rooms. To this aim, the AHU includes a cross-flow heat exchanger for the exhaust air and a water heating coil, connected to the gas boiler, that conditions the mixed air.

Therefore, the space heating system was modelled via an air loop and three water loops. For the proper modelling, each system was divided into two complementary parts: one for the supply side and the other for the demand side [43]. The three water loops are depicted in Figure 5 and organized as follows:

- Hot Water Loop 1: the loop on the heat generation side of the system with the gas boiler on the supply side and the plate heat exchanger on the demand side.
- Hot Water Loop 2: the intermediate loop between the generation side and the distribution side, where the plate heat exchanger provides the necessary heat to the water storage tank.
- Hot Water Loop 3: the final side of the system between the tank and the distribution to the various terminal units (radiant floors, wall radiators, and AHU heating coil).

The set-point temperature of the heat transfer fluid in the system is set to 68 °C, which is the temperature required by the wall radiators and the AHU heating coil. The set-point temperature required by the radiant floor is considerably lower, i.e., 38 °C. The daily operation profile of the HVAC system is defined based on occupancy schedules and metabolic activity.

The air loop is similar to the hydraulic loops, as shown in Figure 6. The air terminal units, namely diffusers, are set up on the demand side and connected to the thermal zones. On the other hand, the supply side is composed by a half loop, with elements in series representing the technological equipment of the AHU. Moreover, as previously mentioned, the economizer on the exhaust path of outdoor air mixer allows free-cooling, especially during the intermediate seasons, when indoor and outdoor air temperature and relative humidity look suitable for contributing to the thermal load reduction.

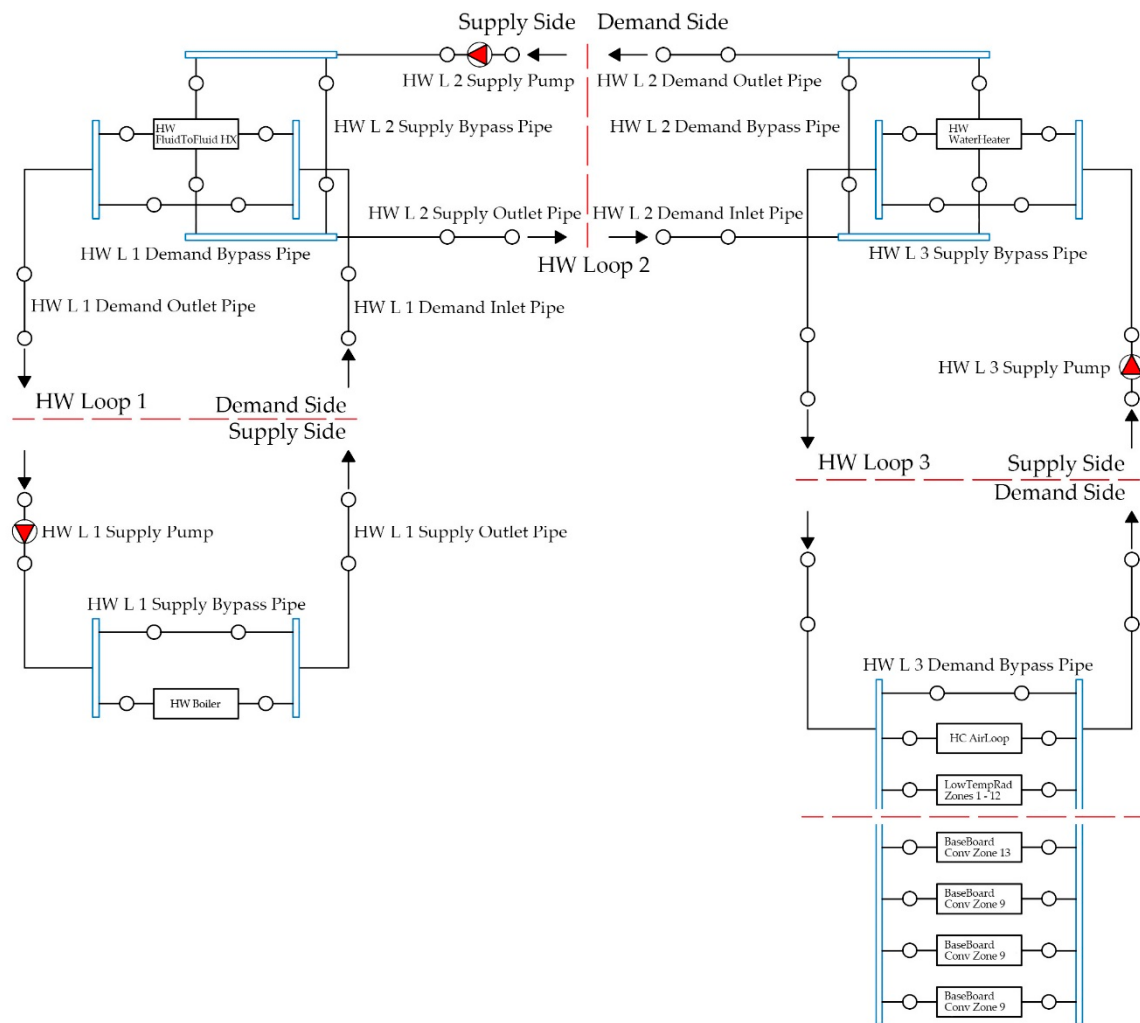


Figure 5. Hot Water Loops 1, 2, 3 and connections.

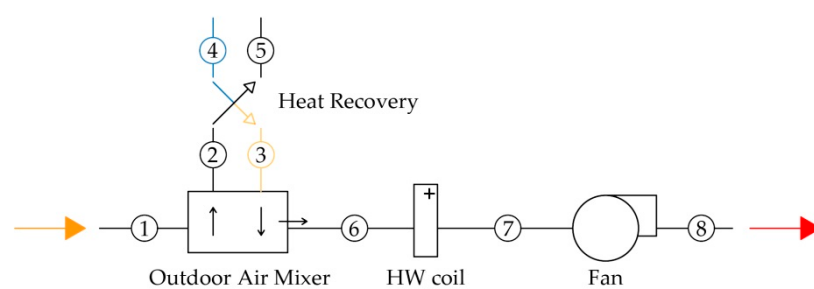


Figure 6. Air loop on supply side.

The management of thermal load in the zones where both the radiant floor and AHU units are installed, is arranged by assigning the priority to the radiant system. Typically, almost all the heating load is satisfied by the radiant floor, leaving to the AHU its main function of fresh air supply.

The main components of the HVAC model [44] are detailed as follows:

1. Hot Water Boiler: the gas boiler, which can be characterized in terms of efficiency curves and type of fuel used, e.g., natural gas in this case.

2. Fluid-to-Fluid Heat Exchanger: type of heat exchanger that models a general heat exchange from fluid to fluid, whose heat transfer rate and efficiency are described in Equations (1) and (2), respectively:

$$\dot{Q} = \varepsilon (\dot{m}c_p)_{\min} (T_{\text{SupLoop,in}} - T_{\text{DmdLoop,in}}) \quad (1)$$

$$\varepsilon = \frac{1 - e^{-NTU(1-R_c)}}{(1 - R_c) \times e^{-NTU(1-R_c)}} \quad (2)$$

where $\dot{m}$ is the mass flow rate, c_p is the specific heat capacity, $T_{\text{SupLoop,in}}$ and $T_{\text{DmdLoop,in}}$ are the fluid temperatures entering the heat exchanger on the supply side and on the demand side of the loop, respectively, NTU is the Number of Transfer Units [44], and R_c is the flow thermal capacity ratio [44].

3. Mixed Water Thermal Tank: water heater with only water storage function and, therefore, without auxiliary heater capacity. Due to the small volume, it is not affected by stratification phenomena and simulates a well-mixed water tank. The storage energy balance equation is as follows (Equation (3)):

$$\rho V c_p \frac{dT}{dt} = q_{\text{net}} \quad (3)$$

where ρ and c_p are water density and specific heat, respectively, V is the tank volume, T is the temperature of the water tank, and q_{net} is the net heat transfer rate to the tank water.

4. Low Temperature Radiant Variable Flow: represents the radiant floor when integrated as a tailored type of internal source within floor construction layers to calculate the relative conduction transfer function (CTF).
5. Water Convective Baseboard: radiators installed in service rooms, which split the thermal power emitted into radiant and convective.
6. Water Heating Coil: downstream heating coil in the AHU, equipped with a water controller to vary the flow of hot water depending on the thermal load.
7. Air-to-Air Sensible Heat Exchanger: sensible heat recovery for ventilation system, characterized by an efficiency equal to 0.8 in design conditions.

In order to check the correct sizing of the HVAC system, the building was simulated during the month of February. Figure 7 shows the trend of indoor air temperature, mean radiant temperature, and operative temperature with respect to outdoor dry-bulb temperature for a representative thermal zone with hourly time step. The proximity among operative temperature, mean radiant temperature, and air temperature trends especially during the occupied hours confirms the proper operation of the heating system, also thanks to building thermal insulation and inertia. Furthermore, during occupied periods, indoor air temperature is slightly higher than mean radiant temperature, thanks to internal heat gains, while it falls below it during the free-running hours.

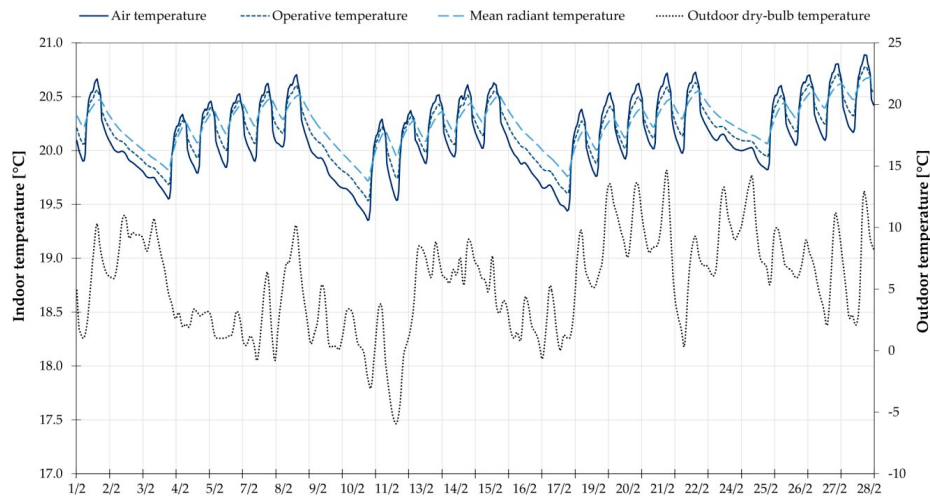


Figure 7. Simulated zone temperatures with respect to outdoor dry-bulb air temperature (February).

2.5. Geothermal System Model

To evaluate the potential benefits associated to the proposed innovative HVAC system, the gas boiler was then replaced with a ground source heat pump (GSHP). Therefore, the energy model was modified by adding a vapor compression water-to-water heat pump, with thermal power of 15 kW, and GHEXs, while maintaining the storage water tank connected to the radiant system and the air-handling unit. Accordingly, an additional water loop was added to model the two vertical U-tube GHEXs, as depicted in Figure 8. The U-tubes were characterized by a depth of 70 m and a diameter of 0.03 m.

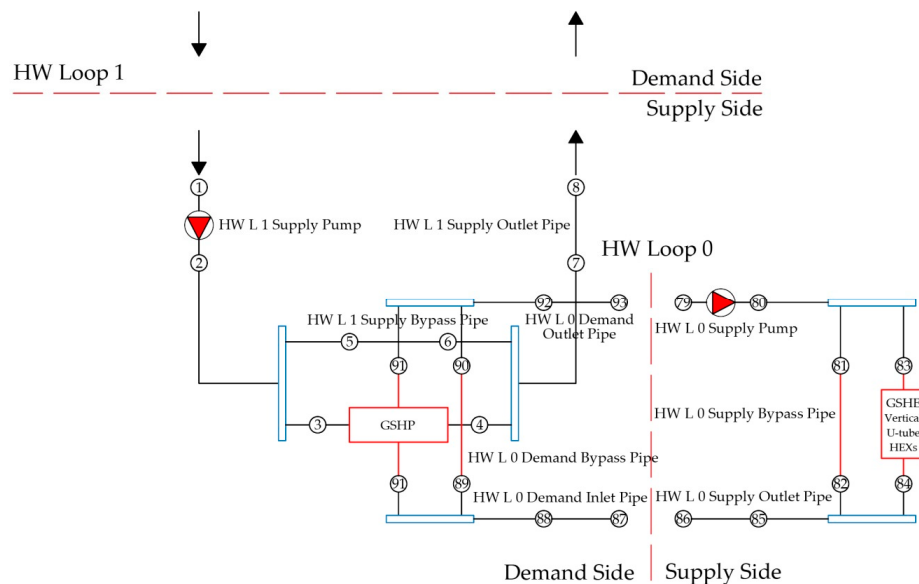


Figure 8. Ground source hot water loop.

Two types of mathematical models co-operate within EnergyPlus to simulate the operation of a GSHP: (i) the curve-fit model [45] and (ii) the parameter estimation-based model [46]. The first, classified as an equation fit component model by Hamilton and Miller [45], treats the system as black box using four dimensionless curves, which are useful to predict the heat pump performance in heating and cooling mode. In detail, the generalized least square method generates a set of coefficients, from the catalogue data used in the model, to simulate the behavior of the heat pump [47]. The second is a method between the black box and the deterministic model [46]. Specifically, a simplified model, based on

thermodynamic heat and mass balance equations [48], is applied to each internal component of the heat pump. The required parameter values are defined by means of a multi-variable optimization algorithm using manufacturers catalogue data [49]. This latter method is suitable for alternative compressor heat pumps. However, when varying the type of compressor of the heat pump, the evaluation of the parameters has a high level of uncertainty. Therefore, in this study, the mathematical model selected for the heat pump was the curve-fit model. The model uses two non-dimensional equations or curves to predict the heat pump performance in heating mode [47]. The generalized least square method was used to generate a set of performance coefficients from the heat pump catalogue data at indicated reference conditions. Thereafter, the respective coefficients and indicated reference conditions were used in the model to simulate the heat pump performance. The variables influencing the water-to-water heat pump performance are (i) entering load side water temperature, (ii) entering source side water temperature, (iii) source side water flow rate, and (iv) load side water flow rate. The governing equations for the heating mode are Equations (4) and (5):

$$\frac{Q_h}{Q_{h,ref}} = C1 + C2 \left[\frac{T_{L,in}}{T_{ref}} \right] + C3 \left[\frac{T_{S,in}}{T_{ref}} \right] + C4 \left[\frac{\dot{V}_L}{\dot{V}_{L,ref}} \right] + C5 \left[\frac{\dot{V}_S}{\dot{V}_{S,ref}} \right] \quad (4)$$

$$\frac{Power_h}{Power_{h,ref}} = D1 + D2 \left[\frac{T_{L,in}}{T_{ref}} \right] + D3 \left[\frac{T_{S,in}}{T_{ref}} \right] + D4 \left[\frac{\dot{V}_L}{\dot{V}_{L,ref}} \right] + D5 \left[\frac{\dot{V}_S}{\dot{V}_{S,ref}} \right] \quad (5)$$

where C1 and D5 are the equation fit coefficients, $T_{L,in}$ is the entering load side water temperature, $T_{S,in}$ is the entering source side water temperature, T_{ref} is the reference temperature, equal to 283.15 K (temperature unit of Kelvin is used to ensure a positive value of the ratio between the water inlet temperature and reference temperature even if the water inlet temperature drops below the freezing point), $\dot{V}_L$ is the load side water flow rate, $\dot{V}_S$ is the source side water flow rate, Q_h is the load side heat transfer rate in heating mode, $Power_h$ is the power consumption in heating mode, and $\dot{V}_{L,ref}$, $\dot{V}_{S,ref}$, $Q_{h,ref}$, and $Power_{h,ref}$ are the same conditions when the heat pump is operating at the highest heating capacity, namely the reference heating capacity (as indicated in the heat pump manufacturer's catalogue).

The inlet variables are divided by the reference conditions to allow the coefficients falling into a smaller range of values. Moreover, the value of the coefficient indirectly represents the sensitivity of the output to the specific inlet variable. The reference conditions used in the model must be the same as the reference conditions used to generate the performance coefficients. Assuming no losses, the source side heat transfer rate in heating mode ($Q_{source,h}$) can be calculated through Equation (6):

$$Q_{source,h} = Q_h - Power_h \quad (6)$$

The heat pump modeled in this study has a reference COP equal to 5 and the equation fit coefficients used in the model are listed in Table 3.

The model used to represent ground thermal behavior was developed Kusuda and Achenebach [50] as a function of time and depth. Therefore, it is correlated to the average annual soil surface temperature, the amplitude of the soil temperature variation along the year or the day with minimum surface temperature, and to ground thermal diffusivity. For the ground temperature, the deep monthly temperature available at the case study location (according to the weather file from the EnergyPlus database [51]) was considered. It is equal to 14 °C in every month. Accordingly, the ground temperature variation is null in this case.

Table 3. Heat pump equation fit model coefficients.

Coefficient	Value (-)
Heating Capacity Coefficient 1 (C1)	−3.33491153
Heating Capacity Coefficient 2 (C2)	−0.51451946
Heating Capacity Coefficient 3 (C3)	4.51592706
Heating Capacity Coefficient 4 (C4)	0.01797107
Heating Capacity Coefficient 5 (C5)	0.15579766
Heating Compressor Power Coefficient 1 (D1)	−8.93121751
Heating Compressor Power Coefficient 2 (D2)	8.57035762
Heating Compressor Power Coefficient 3 (D3)	1.29660976
Heating Compressor Power Coefficient 4 (D4)	−0.21629222
Heating Compressor Power Coefficient 5 (D5)	0.03386238

The vertical U-Tube heat exchangers model is based on the work of Eskilson [52]. The problem of heat transmission for boreholes is solved by means of a mixed numerical and analytical method that determines the response factors under constant initial and boundary conditions over a long time period. Yavutzurk and Splitter [53] provided the integration of this model for a short time step by considering also the thermal capacity of ground and grout, the thermal resistance of the pipe, and the fluid flow. In this work, the thermal response of the vertical U-tube GHEs was determined as a predefined dataset of response factors, based on the above-mentioned properties and the boreholes field configuration. The configuration of the boreholes field has a significant influence on the response factors, which must be evaluated before every simulation [54].

2.6. Model Validation

The building thermal-energy model was validated by verifying the reliability of both the sole building envelope modelling and the whole building-system model. For the envelope performance validation, a specific weather file was developed by considering in-field monitored data in the month of August 2018. In fact, it was the only period in free-running conditions and without building occupancy. The climatic data for the construction of the weather file were collected thanks to a dedicated on-site weather station, which allows measuring outdoor dry-bulb air temperature and relative humidity, used to develop the weather file, and additional parameters. On the other hand, for the annual building-system model validation, a specific weather file was developed by considering in-field monitored data by the same weather station during the whole year 2018. Therefore, the annual dynamic simulations for the assessment of building thermal-energy performance were carried out when using the typical meteorological year (TMY) weather file from the EnergyPlus database [51].

For the envelope performance validation, the measured indoor air temperature was compared with the simulated one for selected thermal zones with available monitored data. In fact, the building is equipped with an integrated monitoring system able to measure air temperature (°C), relative humidity (%), and velocity (m/s) in different office rooms within the building. The indoor monitoring setup is based on a XWeb Monitoring system that allows collecting the mentioned parameters with a frequency up to 10 min. The model accuracy was evaluated by means of the NMBE (Normalized Mean Bias Error) and CV(RMSE) (Variation of the Root Mean Square Error) indices, shown in Equations (7) and (8), respectively. Their analytical expression is represented as follows:

$$NMBE = \frac{\sum (V_{\text{measured}} - V_{\text{simulated}})}{(N - 1) \times \text{mean}(V_{\text{measured}})} \quad (7)$$

$$CV(RMSE) = \frac{\sqrt{\frac{\sum (V_{\text{measured}} - V_{\text{simulated}})^2}{(N - 1)}}}{\text{mean}(V_{\text{measured}})} \quad (8)$$

where V states for value. These statistical indicators quantify the discrepancy between the simulated output data and the measured data [40]. According to the indications of the ASHRAE Guideline 14, a model can be considered calibrated when $CV(RMSE) < 30\%$ and $NMBE < 10\%$ [55], when sub-hourly values are considered.

The annual building-system model validation was carried out through direct comparison with the data of gas consumption for heating available for the case study building, which cover one year following the commissioning of the system and the occupation of the building after the retrofit. For the purpose of this additional validation, the same indices were calculated when comparing the actual energy performance with the simulated one.

3. Results and Discussion

3.1. Building Envelope Performance Validation and Modelling

The building integrated modelling and multidimensional BIM integration represents the key general outcome of the paper, which procedure may be replicated for guiding and inspiring energy efficient, sustainable, and comfortable retrofits of historic buildings. Therefore, the whole modelling effort and replicable reported procedure included in the previous section represents itself a “lesson learnt” result of the research.

As regards the building envelope performance validation, the comparison between the simulated indoor air temperature and the values measured by the monitoring system shows an excellent accuracy of the model in the evaluated month, with $NMBE$ equal to 2% and $CV(RMSE)$ equal to 5%. The results of the validation for the monitored thermal zone mostly exposed to weather conditions in summer, i.e., an office room in the second floor above ground, are depicted in Figure 9 for the whole month of August 2018.

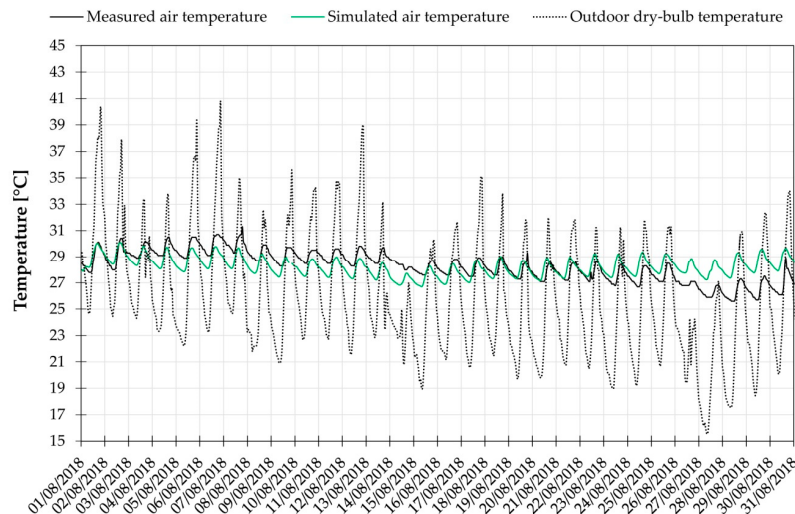


Figure 9. Building envelope performance validation based on measured air temperature in the selected office room during the month of August.

3.2. Building-System Model Validation

As for the building-system model validation, the gas consumption data recorded in the first year of operation, shown in Figure 10, include the periods of commissioning and initial start-up of the HVAC system during December 2017 and the further commissioning during February–March 2018, when the outputs of the simulation model deviate significantly from the real data.

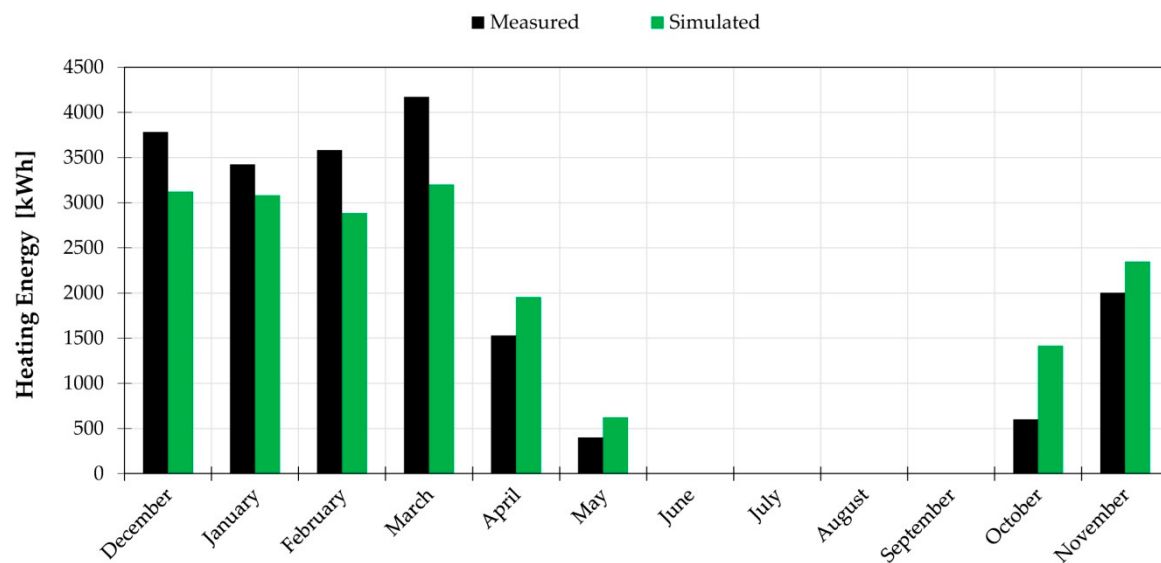


Figure 10. Building-system model annual validation based on data of gas consumption for heating.

Nevertheless, the building-system model behaves acceptably with a CV(RMSE) equal to 5% over a monthly period (with hourly time step simulations). Moreover, the NBME is equal to 4.4% and rather within the limits. Since at least three consecutive years of monitored consumption data are not yet available, it is not possible at this stage to definite this as an accurate validation. However, this annual validation allows verifying the consistency of the model with the same order of magnitude of the real building heating consumption.

3.3. Building Energy Performance

The dynamic thermal-energy simulation shows that the predicted annual electricity demand for heating the case study building with the novel GSHP system is equal to 2920 kWh. The monthly demand distribution is reported in the Figure 11. Therefore, the building energy performance with the water-to-water heat pump and ground heat exchangers as heating system is compared with the actual scenario (gas boiler) in terms of source energy demand. Results, depicted in Figure 12, show an achievable energy saving for space heating up to more than 70% with the novel GSHP system, thanks to the exploitation of renewable ground thermal potential and the higher efficiency of this system. This finding stresses the relevant energy efficiency potential of the proposed innovative system, with total annual energy saving equal to about 12,121 kWh.

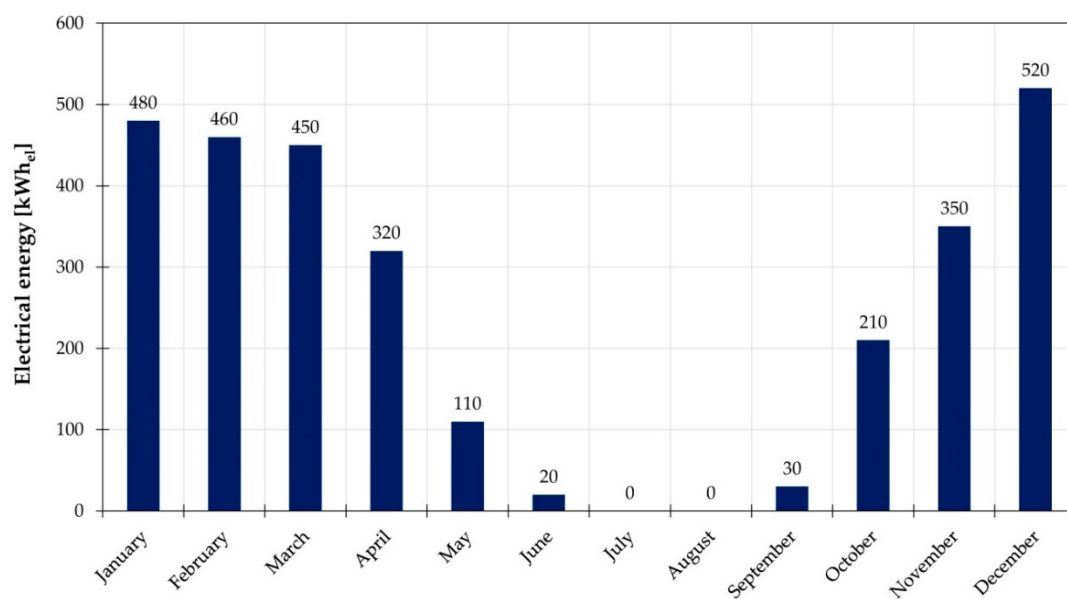


Figure 11. Monthly building electricity energy demand for heating with the ground source heat pump (GSHP) system.

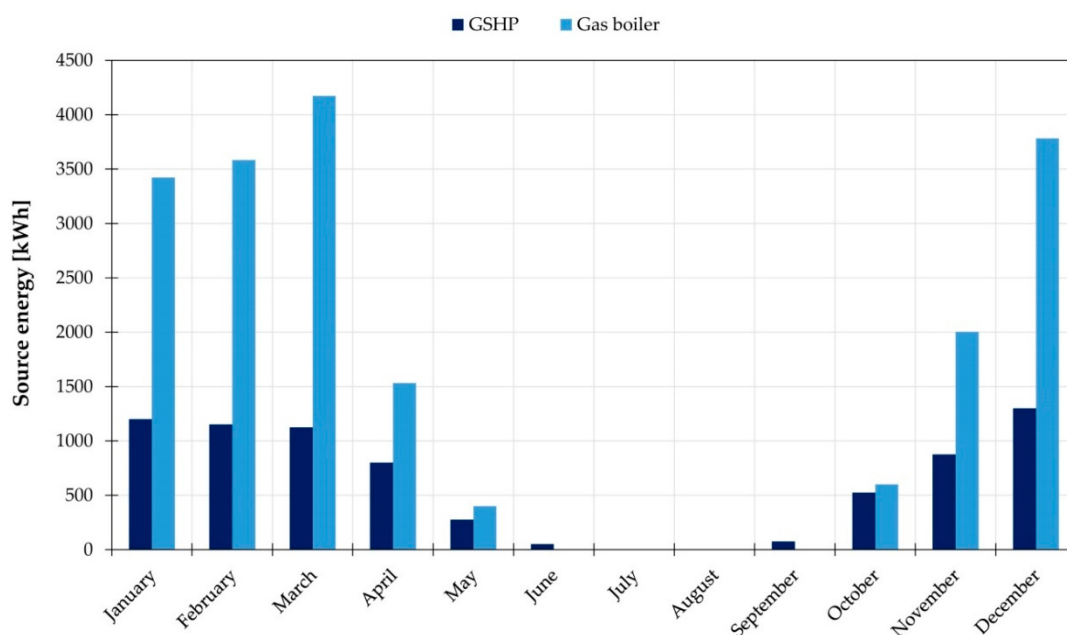


Figure 12. Building heating energy saving in terms of monthly source energy demand with the ground source heat pump system compared to the gas boiler.

Moreover, the two systems were compared in terms of economic and environmental benefits to provide a comprehensive operational assessment of the GSHP system. Specific whole economic assessment will be carried out once the technology is fully available into the market at the end of the project. Nevertheless, current operating-phase results confirm the significantly improved performance also in terms of costs and CO₂ emissions savings. For the cost analysis, an average global cost equal to 0.22 €/kWh for electricity and an average global cost equal to 0.8 €/m³ for natural gas were considered according to the energy market prices. Moreover, considering the current national energy mix, the consumption of electricity from the grid involves 0.44 kg/kWh of CO₂ emissions, while the combustion of 1 m³ of natural gas is responsible for 1.89 kg of CO₂ emissions. The achievable economic and CO₂ savings associated to the implementation of the GSHP system are depicted in Figure 13. In the

case study context, the replacement of a gas boiler with a GSHP system allows annual CO₂ savings associated to the need of space heating equal to 3032 kg CO₂. Additionally, annual cost savings for heating are up to the 69%, corresponding to 1336 €/year.

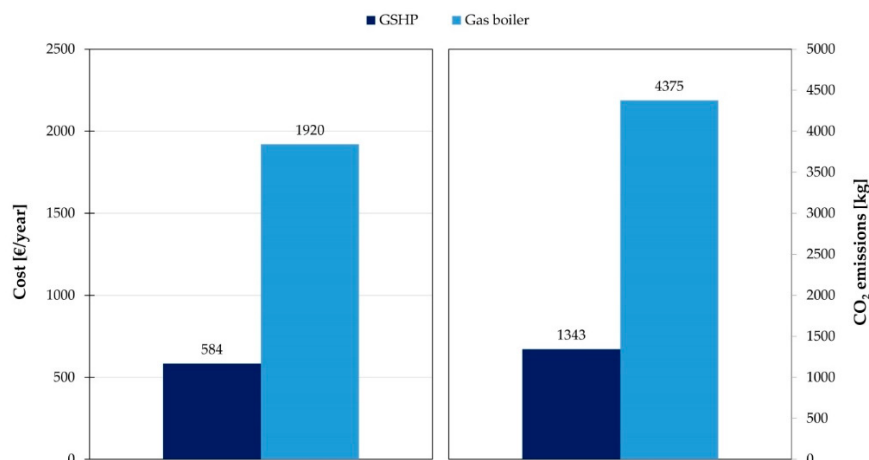


Figure 13. Building annual savings for space heating operation costs and CO₂ emission with the ground source heat pump system compared to the gas boiler.

4. Conclusions and Future Developments

Given the need to develop effective and low-impact solutions for retrofitting historical buildings, this work aimed at investigating a new holistic modelling and simulation framework working as a support tool for design and implementation of energy retrofits in historical buildings. An innovative geothermal HVAC technology and novel procedures of analysis specifically tailored for historical buildings were indeed integrated within a tailored HBIM approach. Therefore, the energy, environmental, and economic performance of a GSHP system was assessed as potentially ready for implementation in historical building retrofit, as heating system. This system was developed within the context of the ongoing H2020 GEOFIT project.

Building energy dynamic simulation was carried out to compare building performance with the ground source heat pump system with respect to the existing gas boiler. Results show considerable benefits associated to the implementation of the innovative system in terms of source energy savings (up to 73% heating energy need reduction), while maintaining the same operation and comfort conditions for the occupants. Furthermore, CO₂ emissions savings reach about 69% of the total and operating costs are significantly cut accordingly. Therefore, the benefits achievable through the implementation of the proposed geothermal system in historical buildings are both energetic, economic, and environmental, thanks to the exploitation of renewable heat from the ground without compromising the architectural heritage of the complex.

A new HBIM platform is proposed to model the case study historical building. This modelling approach aims at considering historical building priorities together with energy/structural retrofit actions. The same level of careful detail is therefore reached through the proposed inter-operative modelling, design, and implementation. The proposed methodology demonstrated its effectiveness and will be implemented into the GEOFIT project with the purpose to act as demonstrator for historical building retrofits and foster similar interventions in Europe and outside EU. In fact, it combines indoor wellbeing, environmental sustainability, architectural preservation but also energy efficiency, building functionality, structural safety, and reliability, in order to preserve cultural heritage through an holistic approach. It indeed allows to take advantage of the same cultural heritage peculiarities for the development of new technologies with low architectural and environmental impact, such as the proposed geothermal and storage systems. This model will be further developed during the project thanks to the integration within a GEOBIM platform, i.e., an integrated environment where

architectural and technical information are integrated with geographical information covering also the geothermal conditions of the building site. Additionally, economic assessments will be also carried out, once the technology implementation is finalized, in order to further integrate a whole evaluation protocol into the proposed platform, including maintenance and economic aspects, representing future developments of the work.

Another future development consists of the effective implementation of the real ground source heat pump system, involving horizontal slinky type GHEs, in the case study historical building and the experimental assessment of the pilot performance.

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Appendix A

There are building elements recurrent in the majority of historical buildings and at the moment there is a lack of families in the Revit library [37] or downloadable from the web modeling them. This underlines that the software for BIM modeling are currently mainly used for modeling new buildings with a high degree of standardization. Therefore, in this study ad hoc families were created in Revit, starting from the templates provided by the program database, to represent these common components of historical buildings.

The first element is the column, which is modeled starting from the “Metric Column” template. The pedestal of the column is modeled using the command “Extrusion”, while for the column itself the command “Revolution” is used. The top and bottom of both column and pedestal are constrained at a proper reference plane. The distances between the reference planes are then parameterized. Once the family is loaded into a project and placed with the command “Place Component” at the specific level, the height of the pillar is fixed with the command “Attach top/base”.

The roof modeling is divided into two phases: the model of the slab and that one of the tiles. First, the stratigraphy of the roof is created from the “System family: base roof”. Thereafter, the roof pitches are defined with the commands “Perimeter roof” and “Modify secondary elements”. Roof clay bent tiles and tiles require the use of multiple families, nested together. Uppermost, four profile families are created with the template “Metric Profile”. Then, the obtained profiles (two for the bent tile and two for the tile) are imported in two new families, starting from “Metric Generic Model” family template. Starting from two profiles, the “Solid Sweep Blend” command is used to achieve a single tile. The family containing the single tile is then loaded within a new family created from the “Metric generic model line based” template. Therefore, an array of tiles is created, and the number of tiles is parameterized in function of the length of the array itself. Finally, the grid for the positioning of the linear families is created through the family “Curtain Wall”. The two linear families are then placed with the command “Place Component”.

The barrel vault family is created starting from the template “Generic model line based”. An empty volume is created with the command “Void-Extrusion”. When the barrel vault family is positioned, this void cuts the host element. In order to create a family that can be used in multiple projects,

the dimensions of the vault are parameterized. The extrusion representing the intrados of bricks of the vault is created using the same procedure. In the “Parameters and Categories of Families”, the option “Cut with Voids when Loaded” is selected. Therefore, the barrel vault is placed with the command “Place Component” at the proper level.

The ancient wooden door is created through a slightly different procedure, namely using a “Local Model”. The appropriate voids and solids are created with the command “Creates”.

Finally, the wooden frame does not require the creation of ad hoc families. Firstly, the “Wood” family located in Revit “Italy” library inside the “Structural Frame” folder and the “Wood” subfolder is loaded. From this family, three types of needed beams are created. The “Ceiling Plants” views are fundamental for the correct positioning of the beams. Thereafter, in the “Structure” tab, the “Beam System” command is selected, and the lower surface of the floor is set as the reference plane. At this point, the outline of the area is drawn with the command “Outline” and the direction of the beams is specified with the command “Beam Direction”.

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