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Dynamic modelling of geothermal heat pump system coupled with positive-energy building

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ABSTRACT

During the last decades, several studies have shown that heat pumps are a promising solution to reach the European Union targets on climate change mitigation, since they satisfy the energy needs for heating, cooling and hot water production employing a single device and using a significant share of renewable energy. However, the full exploitation of the energy-saving potential of heat pumps is a difficult task for designers to achieve, as several factors, such as the variability of outdoor climatic conditions, the control logic of the system and the system configuration, influence the energy performance. High Coefficient of Performance (COP) and low environmental impact make Ground Source Heat Pump (GSHP) systems one of the most suitable technologies for the heating and cooling services, to promote the decarbonization of the building sector, especially in urban areas. The objective of this study is to assess a range of strategies for heat pump systems to achieve optimal performance that can be fully utilized.

To do this, the authors analyse the performance of a 'positive' office building, located in Swansea University Bay, which is already featured with renewable energy technologies for electricity and heat generation: an integrated photovoltaic roof to generate electricity and a wall-photovoltaic thermal system. The current configuration ('baseline scenario') of the building-plant system was modelled in TRNSYS 17 environment and the influence of different parameters on the energy performances was studied. To complement the already high use of renewables the authors propose an alternative scenario for the Active Office Building integrating the use of geothermal heat pumps with the existing systems. By comparing the two scenarios on an energy and environmental point of view, it was possible to assess an 11% decrease in primary energy consumption, leading to a corresponding 11% reduction in greenhouse gas (GHG) emissions.

1. Introduction

Heat pumps are a suitable solution for the replacement of boilers in new and retrofitted buildings and can contribute at achieving the targets reported by the mentioned European Directives, since aero-thermal, geothermal and hydrothermal sources have been recognized as renewable energy sources, with the Directive 2009/28/EC [1]. According to the European Heat Pump Association [2], EHPA, the European heat pump market in 2019 contributed to 40.6 Mt of CO_2 emission savings; 159 TWh renewable energy and 514 GW storage capacity. Air-source heat pumps have been used for many years for both space heating and cooling; however, their efficiency is affected by the variation of the outside air temperature. In contrast, geothermal heat pumps overcome the problem of resource variations, as ground temperatures remain constant throughout the year. Depending on the soil type and moisture conditions, the soil (and groundwater) temperatures undergo little if any seasonal variation below about 10 m. High Coefficient of Performance (COP), low energy consumption and environmentally friendly performance make Ground Source Heat Pump (GSHP) systems one of the most suitable renewable energy technologies today for heating and cooling residential and public buildings.

The energy performance of an electric heat pump system in heating mode is determined by the Coefficient of Performance (COP) which is defined as the ratio of the thermal energy supplied to the environment we want to heat up and the electricity supplied at the input (i.e. the compressor and the auxiliary electrical power). In cooling mode, the performance of the system is evaluated through the Energy Efficiency Ratio (EER); its formulation is like the COP, with the only difference

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being the EER, referring to the cooling cycles, focuses on the heat removed from the cold spring. A detailed method to evaluate the heat pump system used in a positive building is the dynamic simulation which can consider the dynamic variation of all the variables that influence the behavior of the system, such as the building load, the source temperature of the heat pump, etc.

In literature, several approaches are available for the simulation of a heat pump. Selecting suitable software and a simulation model depend on the type of system and the level of details to be simulated. For example, software like TRNSYS [3], Polysun [4], IDA ICE [5], Carnot/Matlab [6] are suitable to study the influence on the performance from system design, but on the other hand, they have the disadvantage that the construction of the system through software such as TRNSYS, Modelica [7] and Carnot can take a very long time for design and research, however, they remain the most flexible tools for design and research.

Most of the articles in the literature preferred the use of TRNSYS for modelling the building system not only with conventional plants, like air–to–water heat pump [8] but especially for smart buildings with solar plants installation like PVTs or CSPs systems. Usually, these works deal with feasibility analysis of retrofit actions, different configurations of plants to maximize the consumption of RES or the evaluation of the operating parameters that influence the system's performances.

In [9], Rashad et al. analyse the energy demand of a detached single-family building. Different parameters were changed in 7 scenarios to analyse the variations in heating and cooling demand: the differences in total annual energy demand that occur between the different scenarios confirm how important it is to accurately determine the building's construction and occupancy, since in can vary up till 70.16%.

Behzadi et al. [10] model a smart building system integrated with PVT panels to supply the electricity demand and domestic hot water need. The proposed system employs a heat storage tank to make a smart interaction between the building and district heating and electricity networks to decrease the cost of the system compared to other similar solutions using batteries. Additionally, comprehensive energy and exergy assessment are performed using TRNSYS software. The proposed smart building system is optimized using the TRNOPT tool of TRNSYS to minimize the yearly total product cost and maximize the annual 2nd law efficiency.

In [11] the authors present the model description and validation of an electrical and thermal PVT collector model and its implementation in TRNSYS. The authors observed that in case of high thermal capacities the thermal results show a more inaccurate fit of the dynamic behaviour. This emphasizes the importance of an accurate determination of the thermal capacity of PVT collectors. Nevertheless, the results show a very good agreement of the modelled energy production in all investigated cases. While solar systems' dynamic behavior is frequently investigated using TRNSYS, researchers are also exploring other types of renewable applications [12]. In Ref. [13], for example, the authors implement a dynamic model of an innovative layout for biomethane production from organic waste, including concentrating PVT collectors and a biomass heater, considering the dynamic heat and power demand of the digestion process and estimating biogas production as a function of the most important design and operating parameters.

Safa et al., in Ref. [14] analyse the performance of GSHP systems with horizontal coupled ground loop pipes. The system includes a horizontal ground loop heat exchanger, the GSHP, a buffer tank for thermal storage and a fan coil AHU radiant in-floor heating depending on the season. Also, Chargui et al. [15] model and simulate in TRNSYS environment a heat pump in heating mode (where the CO_2 is the refrigerant used) by using the geothermal source in southern Tunisia. For the dual-source heat pump is used Type 20. The same author in a later study [16] to simulate the combined system with a residential house and heat pump, utilized TRNSYS again. For estimating heating and cooling load for a residential house the Type 56 is employed, Type 2 is engaged to control fluid flow through the heat pump loop based on two input temperatures.

In [17], the authors also simulated a reversible water-to-water heat pump with different configurations and refrigerant fluids in TRNSYS environment to evaluate the system's overall thermal behaviour and investigate control strategies to increase energy performance. In this case, a new Type was tested for a ground-source heat pump system in a historic building under three climates and coupled to different emission systems, with an internal link to REFPROP 10.0 allows simulating the thermodynamic cycle of a heat pump based on coupled heat transfer, mass and energy equations. The main results for the case studies are related to the performances of the system and can be helpful to the user to evaluate the choice of the refrigerant and get more information about the working conditions of the analysed unit.

In [18] order to evaluate the feasibility and performance GSHP, installed in an office building, a TRNSYS model has been implemented and simulated for three cities located in cold climate zone, in China. Also in this case, ten years operation was simulated to show the stability of the performance based on the outlet/inlet temperature of buried pipes and soil temperature.

Other works, could also provide a validation of the model, like for example, in Ref. [19], the authors investigate the operating characteristics of a GSHP system by analyzing the running data of the system in two years, finding that the system performance in the second year results inferior to that in the first year, which, mainly due to the increase of the ground temperature. To do that, the authors implement a TRNSYS model of the GSHP system and validate it by the comparison between the simulated and measured water and ground temperatures. The simulation showed that the ground temperature would rise by 10.5 °C and the performance value would decrease by 12.82% after 20-years running. As a remedy, DHW system was supposed to be operated in the following years, allowing to obtain lower ground temperature and higher performances.

In response to the fact that most existing residential buildings have been designed far away to be effectively efficient, and also to the fact that a significant amount of the energy produced by industrialized countries is consumed by buildings for space heating and cooling, this research study seeks to develop standards that can be used on residential buildings in the future from an energy perspective, with further suggestions for other optimization measures can be used in such buildings to increase overall efficiency: Cost-effective and sustainable new construction.

This is done by modelling and simulating a building equipped to be a 'positive building' as it is and analyzing different scenarios for its operation and considering the use of a further renewable energy available on site: geothermal energy.

As in the works previously mentioned, the present one uses a dynamic simulation model to evaluate the energy and environmental performances of an existing building. However, unlike the works mentioned, the case study is represented by the case study 'Active Office', the first positive office in the UK, equipped with an innovative heating and electricity supply system, consisting mainly in a PVT system and an air-to air heat pump for which a validation with measured data, related both to the plant and envelope of the building, is provided, together with the implementation of an optimized plant configuration scenario, in which another available on-site RES is exploited.

2. Materials and methods

The work is implemented through the following methodological steps: i. energy model implementation in TRNSYS17 environment; ii. validation with the measured data; iii. implementation of an alternative scenario; iv. technoeconomic assessment for each scenario; v. comparison of the results and a sensitivity analysis. The object of this study is represented by the UK's first Positive-Energy Office, designed to generate more energy than it uses in the year's cycle. The methodology outline is described in the following Fig. 1.

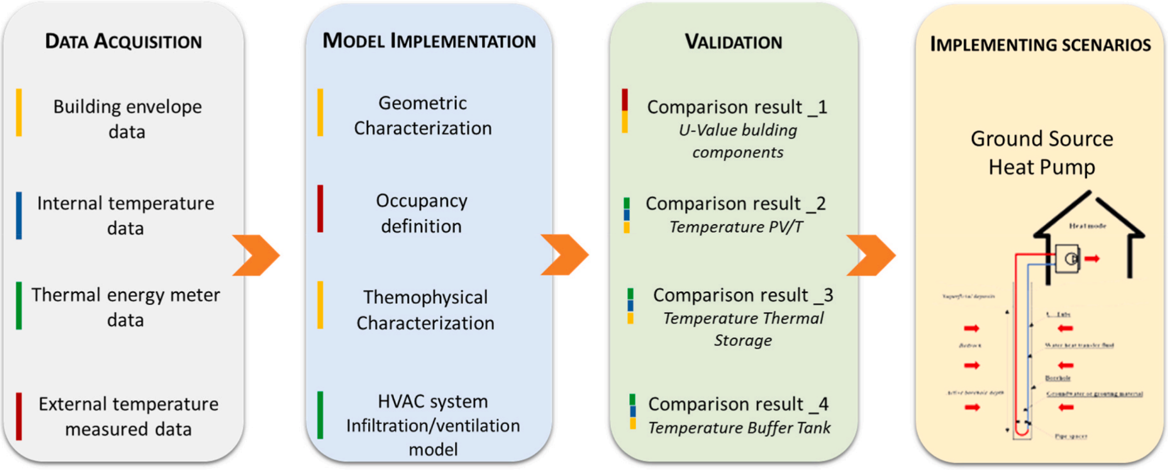


Fig. 1. Methodology outline.

2.1. *Positive-Energy Office*

SPECIFIC is a national Innovation and Knowledge Centre (IKC) [20], led by Swansea University, established in 2011 to investigate the concept of turning buildings into power stations using solar energy to functionalise building envelopes. To aid this investigation, they have constructed several demonstrator buildings using a mix of pre-commercial and commercially available technologies, to achieve the energy positive philosophy. These are known as 'Active Buildings'. The case study analysed is represented by the so-called Active Office and it was designed and built using pre-assembled modules (Wermick's Rapidplan system) which were then clad with pre-finished Colorcoat Prisma® steel. It is the latest demonstrator led by SPECIFIC's Active Building demonstrators' program and it is equipped with innovative technologies to generate, store and release solar energy. It is equipped with an integrated photovoltaic roof to generate electricity and a wall-mounted photovoltaic thermal (PVT) system for electricity and heat generation. It is composed of two floors with a curved roof and sits on concrete pad foundations. The building consists of two floors and each room has different use, as it is possible to notice in the following Figs. 2 and 3.

2.1.1. *The building envelope*

The external walls of the building are boxed in with composite panels approximately 1.2 m wide and insulated with a solid EHD polystyrene sheet, while the internal part is made of plasterboard with a painted finish. Inner partitions are composed of 12.5 mm plasterboards on 72 metal studs and an insulation core.

Fig. 2. Picture of the active office.

The ground and first floors are formed using 38 mm chipboard on a frame of galvanised steel beams and cross joints, with a combination of Stylite Plustherm EPS and Rockwool insulation between the structural elements.

Finally, the curved roof consists of an insulated warm deck flat roof, consisting of Kingspan KS1000DR composite sheets, as part of the modules, with timber trusses above to form the curved profile. The curved trusses are covered in Tata Colorcoat Urban® plank sheeting with integrated PV bonded to each 'plank'. Besides, a living wall was installed on the east elevation of the building to provide an element of biodiversity and for use as an engagement tool. On the South elevation, a PVT system is also implemented. This system consists of a series of evacuated tubes, with individual PV cells within, the size of which determines the tube diameter. The thermophysical properties of the envelope of the building necessary for the energy model were based on the technical drawings provided by the research group that developed the project and listed in the following Table 1.

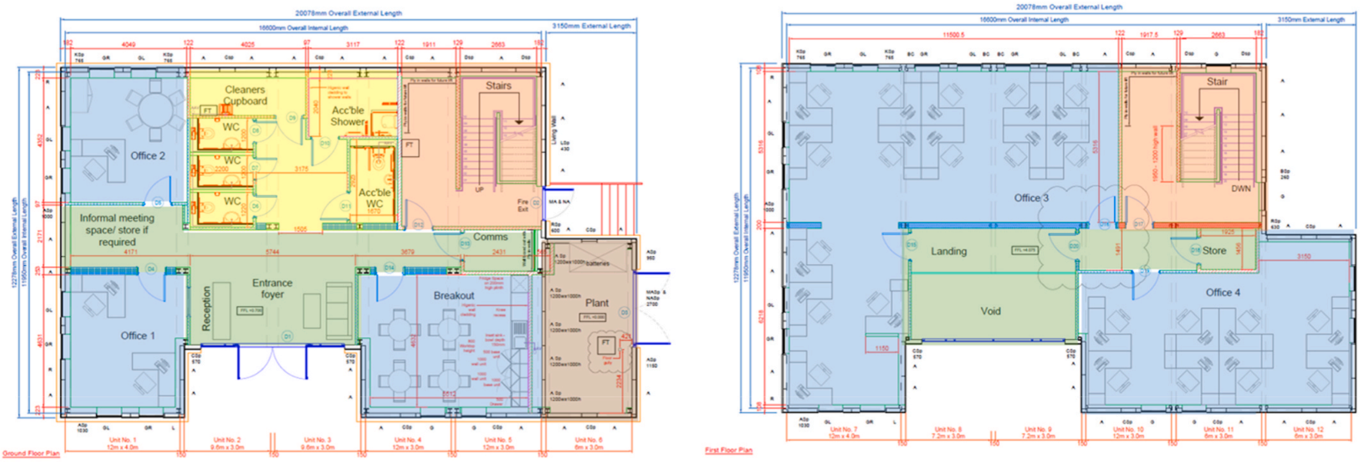
2.1.2. *Technological units*

The technological units of the building are responsible for all the electrical and thermal generation. The key components of the technological configuration are in Table 3: 1. electric energy generation on the roof, using a system; 2. a combined solar thermal and PV (PVT) system for space heating and hot water; 3. electrical and thermal energy storage to control of import and export of energy to and from the building; 4. An Air Souce Heat Pump (ASHP) with Air Handling Unit (AHU); 5. smart EV charge points, working as part of a remote virtual power plant. Moreover, the whole configuration is equipped with an extensive data monitoring system.

2.1.3. *Control strategies*

The control strategies aim to reduce the carbon impact on the grid; extend battery life and operate off-grid. The control logic developed by SPECIFIC allows the individual technology components to work together to optimize the operation of the building. The SPECIFIC team has implemented a platform (Fig. 5) for monitoring performance parameters to keep track of and be able to optimize the operation of the building.

The primary source for space heating and hot water production is a sensible thermal storage tank containing 2000 L of water which can increase its temperature by (in order of preference operational



DESTINATION OF USE	VOLUME [m³]	INCIDENCE PERCENTAGE
OFFICE	1358	68,50%
CONNECTIONS	180,12	9,10%
STAIRS	215	10,85%
WC	164	8,30%
PLANT	64,4	3,25%
TOTAL	1981,52	100%

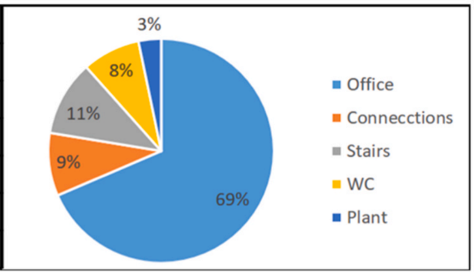


Fig. 3. Synoptic map with identification of destinations of use.

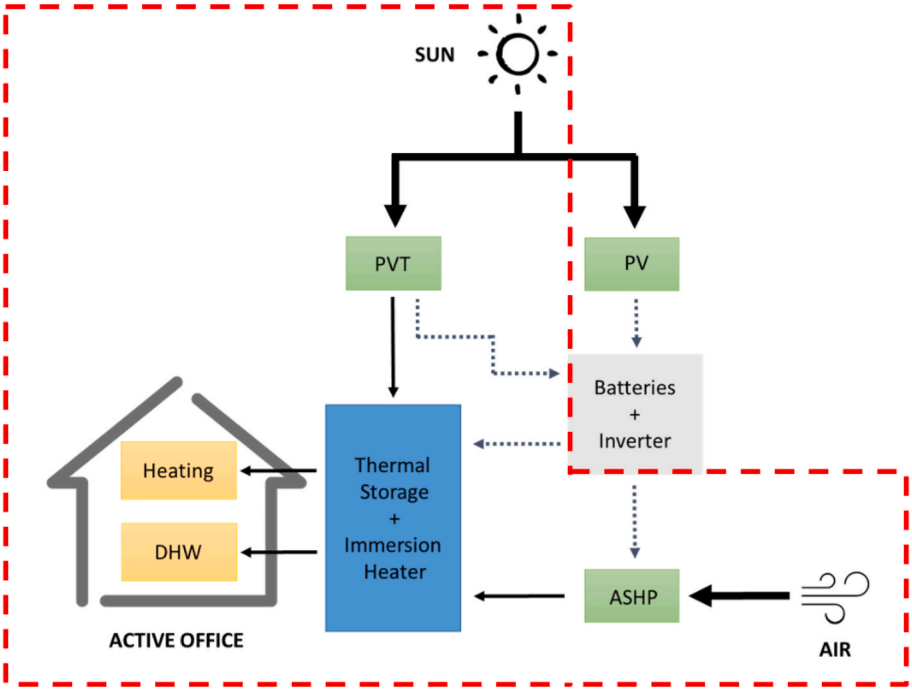


Fig. 4. Energy Strategy Scheme of Generation, Storage and Employment of Energy for the Active Office Building (in red strategies for heating production).

preference): 1. PVT Tubes - solar thermal (and electrical) generation; 2. Hitachi Air Source Heat Pump (ASHP); 3. 6 kWp electric immersion heater.

In heating mode, the only heat source for the AHUs comes from thermal storage through LTHW pipework, which provides the same temperature water to both units. Remotely controlled three-way valves control the volume of water passing through the heat exchanger in each AHU, enabling independent flow temperatures to be set for the ground floor and the second floor. The air supplying all areas on each floor level is at the same temperature.

The heating system was designed to meet the 10 kWp heating load of the building, at a supply temperature of 45 °C, to minimize the electrical

Table 1
Layer structure of the opaque components.

Constructive component	Layer structure		Thickness [m]	Thermal Conductivity		Specific Heat capacity [kJ/kgK]	Density [kg/m^3]
				[W/mK]	[kJ/hmK]		
External Walls	Tata Colorcoat composite panels	Seam steel	0.025	50.2	180.72	0.49	7.982
		Vapour control layer	0.0006	0.17	0.612	0.840	615
		Plywood/OSB3	0.018	0.13	0.468	2.5	460
		Foam insulation [polyurethane]	0.12	0.025	0.09	1.5	30
	CELOTEX insulation		0.075	0.023	0.0828	1.453	36
	Air cavity		0.025	0.024	0.0864	1.0	1.225
	Gypsum wallboard		0.0125	0.19	0.684	1.09	664
Inner Partitions 'Type B47/30F R'	Single layer of plasterboard		0.0125	0.19	0.684	1.09	664
	ISOVER insulation layer		0.072	0.035	0.126	1.03	18
	Single layer of plasterboard		0.0125	0.19	0.684	1.09	664
First Floor	Decking in chipboard		0.038	0.15	0.54	2.1	140
	Rockwool		0.03	0.039	0.14	1.030	28
	Stylite Plustherm sheet insulation [Expanded Polystyrene – EPS]		0.150	0.030	0.108	1.350	20
Ground Floor	Decking in chipboard		0.038	0.15	0.54	2.1	140
	Rockwool		0.17	0.039	0.14	1.030	28
	Stylite Plustherm sheet insulation [Expanded Polystyrene – EPS]		0.1	0.030	0.108	1.350	20
Curved Roof	Tata Urban Cladding system	Seam steel	0.025	50.2	180.72	0.49	7.982
		Vapour control layer	0.0006	0.17	0.612	0.840	615
		Plywood/OSB3	0.018	0.13	0.468	2.5	460
		Foam insulation [polyurethane]	0.105	0.025	0.09	1.5	30

The glazed components (windows and curtain walling), these are composed of an aluminium frame with low-e-glass characterized by U-value = 1.6 W/m^2K and g-value = 0.47. To summarize, the project highlights are listed below Table 2:.

Table 2
Highlights of active office building.

Construction	Modular construction on concrete pad foundations
Building envelope	Thermally efficiency - Floor → U-value = 0.13 [W/m^2K] - Walls → U-value = 0.15 [W/m^2K] - Roof → U-value = 0.12 [W/m^2K]
Heating system description	Solar thermal and ASHP supplying a thermal store, dissipated through AHUs
Hot water generation description	Solar thermal, ASHP and immersion heater
Main Ventilation Type	Natural, supplemented with night-time purge ventilation
Other information	No cooling system Smart EV charge points Electric heating system (no gas connection)

Table 3
Data of components of heating system.

Component	Reference
ASHP	Hitachi RAS-4WHVNPE (External), RWH-4.0VNFE (internal)
Solar thermal Pumping station	PAW solar pumping station with Wilo Stratos PARA 30/1–12 T2 pump (0–10V)
Ahu's	Systemair Topvex FC02 HWL-R
Pumps	Grundfos UPS2 15–50/60 (HWS), UPS2 25–80 (LTHW)
DHW tank	Gledhill PLUIN090
Inverter models	Victron Quattro 48V | 15000VA | 200Amp (Inverter), MPPT 250 | 100 - Tr
PV Roof	BIPVCo metektron CIGS panels, 22kWp in total
PVT Tubes	Naked Energy Virtu combined PVT system (Evacuated tubes with Si PV cells inside) 2.4kWp PV and 9.6kWpth (40 tubes in total in a single loop)
Batteries	8 x 13.8 kWh BYD LiFePO4 batteries 48V system total 110 kWh using Victron charge controllers

power required by the ASHP to maintain the thermal storage tank set-point during periods when there was insufficient solar thermal generation. The heat pump can only be controlled by setting the set point of the heat storage tank. While the AHUs control the supply air temperature by varying the water flow rate through the heat exchanger and monitoring the supply air temperature. Ideally, the 6 kWp electric immersion heater would only be used in exceptional circumstances, such as equipment failure or extremely low winter temperatures.

The control strategy for the domestic hot water system was to provide pre-heating from the thermal storage tank, refilled by a 3 kWp immersion heater, to have a safe operating temperature and to ensure periodic disinfection cycles with a temperature of 60 °C.

SPECIFIC's designers chose to keep the heating on all the time and use a setback temperature at nights and weekends of only 2 °C lower than the daytime set point: the goal is to keep the building at a comfortable temperature between 08:00 and 18:00, Monday through Friday. Currently, the building is controlled with a set point of 19 °C during the day and a return temperature of 17 °C.

There is no cooling capacity: if some rooms need heating and others need cooling - then heating has priority.

The heating loads are differentiated in a low-temperature hot water (LTHW) circuit, which provides space heating on the ground and first floors, and the domestic hot water circuit (DHW), which supplies the heat exchanger in a 90-L tank for showers and washbasins in the toilets. The thermal storage unit feeds two identical AHUs with heat recovery located on the ground and second floor, it is refilled by the PVT, the ASHP and the electric immersion heater. The technological components considered in this work are those related to the heating system, for the sake of clearness a qualitative scheme of the energy flows and the boundary of the system modelled are represented in Fig. 4.

For the integrated modelling of the building, Sketchup and TRNSYS 17 are the software employed. The use of the first one allowed the geometrical modelling of the building, while the second one allowed to set the thermophysical parameters of the envelope and the plant components to define the scenarios.

2.2. *Energy model: TRNSYS simulation components*

The space heating and hot water system are dynamically designed and simulated using TRNSYS software. The Simulation tool calculates

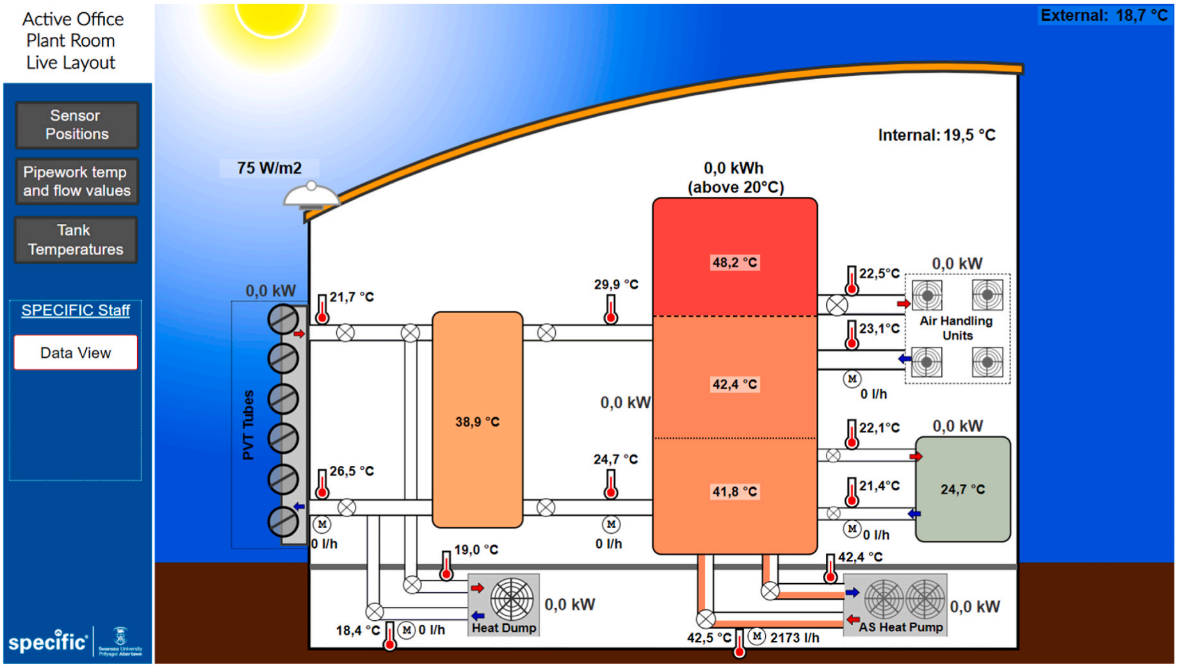


Fig. 5. Active office – plant room – live layout.

energy and mass flows and temperature profiles for the system components for any time interval. In addition, the software includes an extensive library of embedded components developed from experimentally validated data. The operating strategy of the system is stated as follows: Type 56 (building) is the central component of the TRNSYS global model, which receives the external weather conditions as input, determines the thermal balance, and delivers the internal conditions to the thermostat. Consequently, the thermostat controls the distribution components to maintain the desired indoor temperature and humidity previously set in the schedules.

The distribution system is composed of two air handling units (AHU), which work exchanging heat between the air inside the building and the water circuit. The air source heat pump (HP) heats the water of the distribution system and thus supplies energy to the AHUs and the Domestic Hot Water (DHW) systems. The core of the heating system is the stratified vertical cylinder to ensure the correct operation of the HP, reducing the frequency and increasing the length of its operating cycles. This is a hybrid system in which the heat pump is assisted by a PV/T system located on the south elevation of the building. A Simplified heating and DHW system layout is presented in the following Fig. 6.

The reference building was modelled as multi-zone element: two main zones representing the ground floor and first floor which were then divided into 4 adjacent sub-zones. All these zones have the same characteristics in terms of Building Structure, Windows type, Infiltration and

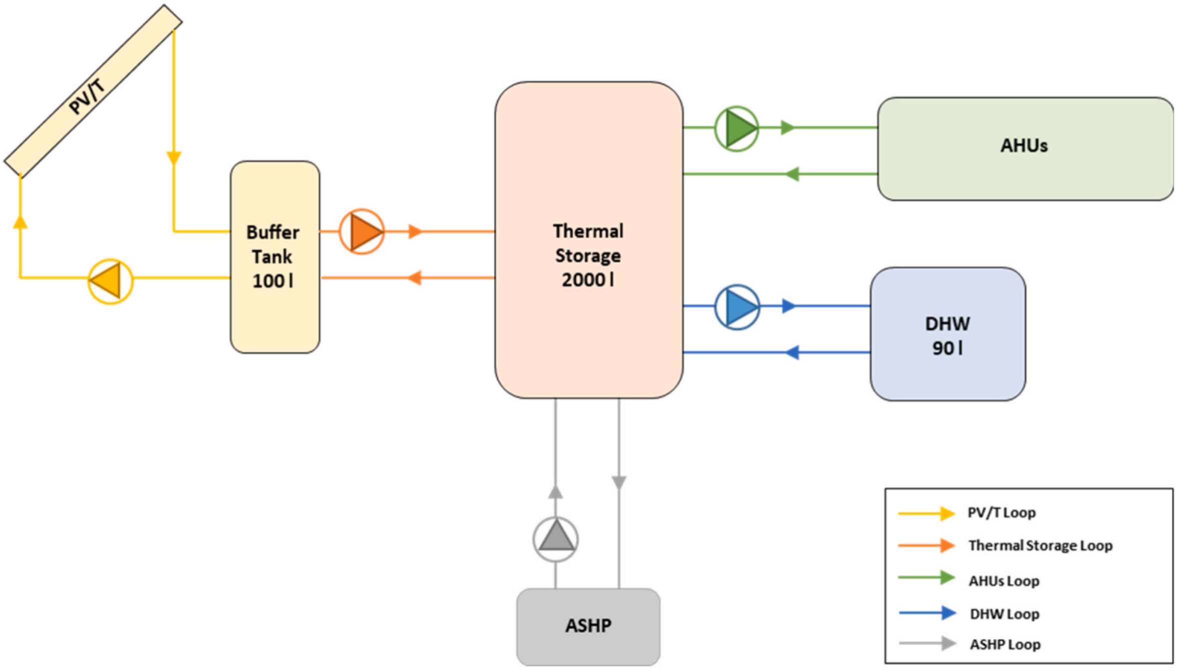


Fig. 6. Simplified heating and DHW system layout. (AHU, Air Handling Unit; DHW, Domestic Hot Water; ASHP, Air Source Heat Pump).

Radiation Mode, but different internal gains, roof zones are excluded. The following Fig. 7 represents the Google SketchUp™ model.

A mixed-mode ventilation strategy was adopted for the building, combining natural ventilation through opening windows with mechanical ventilation through the air handling unit system. The latter was designed to provide the required ventilation in office spaces, of 10 L/s. Although in some mixed-mode ventilation systems, natural ventilation is managed through the automatic opening and closing of windows, in the Active Office, the windows are manually controlled, allowing building occupants to choose when to open or close them depending on the desired comfort level.

The simulation model is created uses the Type list in Table 4.

For the sake of brevity, the description of the components used to perform the simulation is restricted to the core centre of the plant configuration. However, for detailed information on the component models adopted, the software reference TRNSYS can be found in Ref. [6].

2.2.1. Multizone building - type 56

Type 56 models the thermal behaviour of a building divided into different thermal zones. To use this type, a separate pre-processing program must first be executed: a dynamic 3D-building simulation will carry out by TRNSYS using the 3D drawing capabilities of Trnsys3d for Google Sketch-up, then importing the geometrical information into the Type 56 (Multi-zone building model).

For the reference building, the geometric and construction data of the building in Table 1 were used. As for meteorological data, these were imported using the Metereonorm 7.3 software, according to the weather conditions in Swansea (heating season middle of October to the end of March). The personal occupancy density was set to 0.1 people/m^2, fresh air per person equal to 30 m^3/h, the lighting power density assumed equal to 9 W/m^2, whereas the equipment power density is 13 W/m^2, from 9:00 a.m. to 5:00 p.m. except weekends and holidays.

2.2.2. Combined PV/T solar collector - type 563

This component is intended to model a solar collector which has the dual purpose of creating power from embedded photovoltaic (PV) cells and providing heat to a fluid stream passing through tubes bonded to an absorber plate located beneath the PV cells. This model relies on linear factors relating the efficiency of the PV cells to the cell temperature and the incident solar radiation. The cells are assumed to be operating at their maximum power point condition. The thermal model of this collector relies on algorithms presented in “Solar Engineering of Thermal Processes” [21].

2.2.3. Storage tank (thermal storage) - type 534

The tank model is divided into isothermal temperature nodes (to model stratification) with the possibility to set the number of “nodes”. Each constant-volume node interacts thermally with the nodes above and below through several mechanisms: fluid conduction between nodes, and through fluid movement. The model also considers temperature-dependent fluid properties.

Table 4
TRNSYS types used in the proposed system model.

Components	Type
Weather data reader	15–6
Building	56
Controllers	2b, 1502
Scheduler	14e
PVT Tubes	563
AHUs	760, 753e, 112a, 641
Buffer tank	4c
Thermal Storage	534
DHW tank	4c
Air –to Water Heat Pump	941
Water–to–water heat pump	927
Borehole	557a
Flows pumps	3
Diverter, mixers	11, 646
Outputs	65c, 65d

2.2.4. Air-to-water heat pump - type 941

This component models a single-stage air source heat pump that has a liquid stream on the load side. This model is based on user-supplied data files containing catalog data for the capacity and power. As a function of entering water temperature to the heat pump, the entering water flow rate and the air flow rate.

2.2.5. Normalized water-to-water heat pump - type 927

This model is a performance map meaning that its results are based on information contained in a user-supplied data files containing catalog data for the capacity and power draw as a function of entering load and source temperatures.

2.2.6. Vertical ground heat exchanger - type 557a

The heat exchangers of the GSHP system are designed to fulfil the heating load requirement. Type 557a was chosen to model its behaviour in TRNSYS; this component, described as the vertical U-tube, is compiled using a Duct Ground Heat Storage (DST) calculation model developed by Hellstrom [22], which is capable of exchanging heat with a heat transfer medium within the ground and giving a very accurate analysis calculation.

2.3. Validation of the Building-HVAC integrated model on TRNSYS studio

The experimental data collected from the monitoring of real data acquired for the year 2019 were used to validate the heating system model. The calibration of the model was performed using the Buffer Tank and Thermal Storage temperatures.

Thus, as mentioned above, the comparative analysis for the validation of the model created in TRNSYS was carried out over one year of operation. For the parameters analysed above, the average value for both the monitored data (2019) and the calculated ones (TRNSYS) was calculated on a one-year scale. For the sake of clarity, the diagrams are plotted weekly.

The comparison of the temperatures of the Thermal Storage is

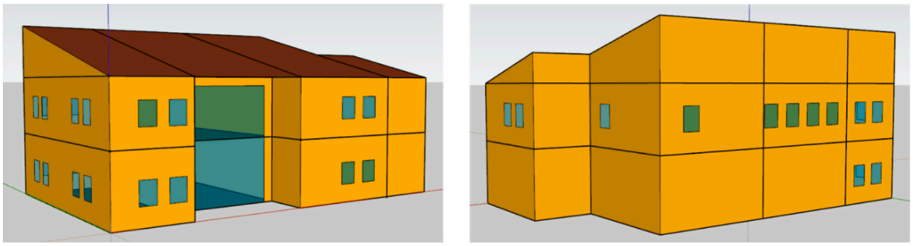


Fig. 7. Multi-zone building trnsys 3D model.

illustrated in Fig. 8. The analysis performed on a weekly scale displays an almost same trend, except for a deviation of about 4 °C in the time considered in this plot.

The PVT flow temperature was also observed for comparison between the reference building and the model simulated in TRNSYS. The deviations between the monitored data (2019) and those calculated using the model simulated in TRNSYS are listed in Table 5.

3. Alternative scenario

An alternative scenario for the Active Office Building based on the use of geothermal heat pumps was considered. Based on Swansea’s meteorological data and the building envelope thermal characteristics, the building model previously created was coupled with a GSHP for supplying heating and DHW demand for the building in TRNSYS, in which the HP exchanges heat with the ground through the BHEs according to the schematic of the GSHP system’s design shown in Fig. 9.

The heat pump is selected based on the value of the maximum calculated heating demand. The main parameters of the heat pump are listed in Table 6 and the component Type 927 represents the water-to-water heat pump in the TRNSYS simulation model.

The case study is located in the town of Swansea in Wales. Since the peak heat output is less than 20 kW, a reference was made to the information in the literature and specifically produced by the British Geological Survey application for the soil characteristics.

An approximation has been made regarding the soil thermal property data for the heat exchanger design of this model. The assumption is reliable due to the impossibility of finding experimental data for the reference city. Therefore, reference was made to the town of Penmaen, which is geographically the closest (distance Swansea - Penmaen approx. 22.5 km) and more importantly has the same soil texture. The data of the thermal properties of the soil can are listed in Table 7.

Table 5
Deviations measured by the comparison between the experimental data collected and the model outputs.

Measurements	Reference building (°C)	TRNSYS Model (°C)	Deviation (%)
$T_{top\_buffer\_tank}$	36.78	33.01	10
$T_{average\_buffer\_tank}$	32.56	31.85	2
$T_{top\_thermal\_storage}$	52.13	51.87	0
$T_{bottom\_thermal\_storage}$	32.05	30.52	5
T_{S3_PVT}	19.57	17.62	10
T_{S1_PVT}	20.02	15.96	20

The values, calculated as annual averages, showed that the TRNSYS model is quite reliable as deviations of less than 5% were recorded for the top temperature of the thermal storage and the average temperature of the buffer tank and just 5% for the bottom temperature of the thermal storage. On the other hand, as regards the top temperature of the buffer tank and the flow temperature (S3) of the PVT, the result of these investigated parameters reported a deviation of 10%. Therefore, although a percentage deviation of 10% or less was recorded for most of the parameters taken as a reference, a deviation of 20% was recorded for the return temperature (S1).

The unit linear meter heat exchanger capacity for the reference texture soil is assumed to be 45 W/m, while the in-ground heat exchange, Q’ (kW), (data provided by the GSI manufacturer), the borehole length is calculated using the following equation:

$$L_{borehole} = \frac{Q'}{unit\ linear\ meter\ heat\ exchange\ capacity}$$

The storage volume is calculated according to the following equation [6]:

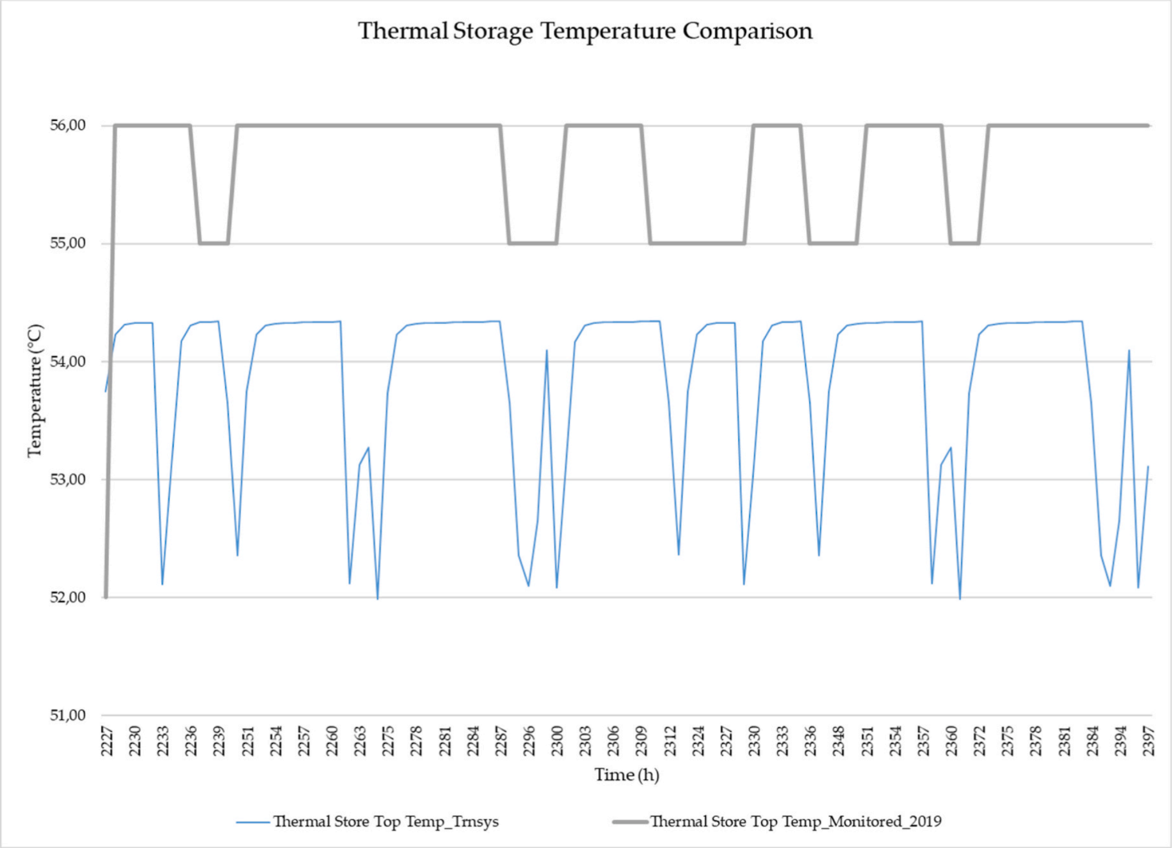


Fig. 8. Weekly dynamic analysis of thermal storage top temperatures: comparison between monitored and data calculated (TRNSYS).

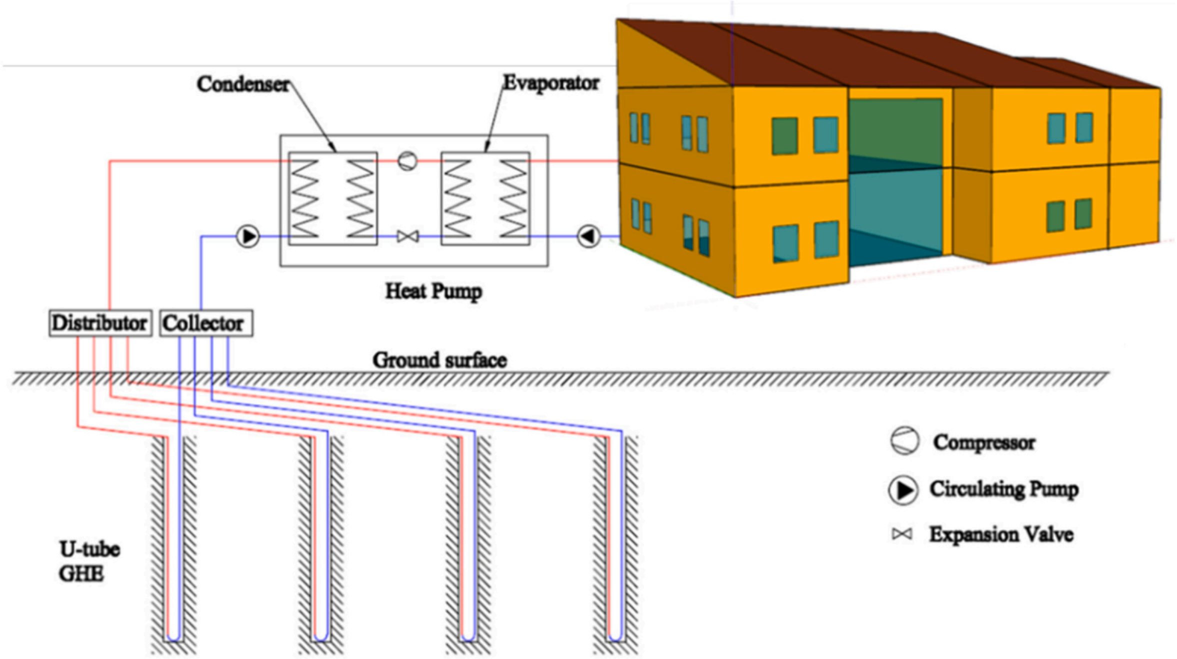


Fig. 9. Schematic layout of the Ground Source Heat Pump (GSHP) system.

Table 6
GSHP data.

Heating Capacity (kW)	Geothermal Power (kW)	COP
13.2	9.8	3.44

$$Storage\ volume = \pi * numbers_{boreholes} * depth_{borehole} * (0.525 * Spacing_{borehole})^2$$

The main exchanger design parameters are listed in Table 8.

4. Results and discussion

A one-year simulation is conducted to analyse the system's performance over its first year of operations. The average COP of the GSHP simulated in TRNSYS was compared with the COP performance of the baseline scenario that reproduces the current plant layout, equipped with an ASHP.

Fig. 10 represents the typical trend of the average daily COP, in the cold time of the year, for both the air source heat pump and the geothermal pump. In the first case (ASHP), since the outside air temperature fluctuates considerably during the year, these variations have a significant effect on the heating capacity of the heat pump and consequently on the COP, which is between 2.60 and 3.50. In the second case (GSHP), the COP is practically constant at around 4.30.

During the summer season (Fig. 11) the COP of the ASHP heat pump increases due to the milder external air temperatures, while the COP of the GSHP heat pump has a constant trend, showing a slight decrease compared to the values recorded for the winter season. The comparative analysis in terms of COP of the two systems was extended over one year of operation and the deviation was estimated. The result of the simulation reveals that the adoption of a geothermal system generates a higher COP compared to that using an air source heat pump equal to 20% for one year of operation.

Both systems were also compared in terms of energy savings and environmental impact. The primary energy demand of the existing reference system (ASHP) and the proposed system (GSHP) was calculated by analysing and comparing the power consumption of both the air source heat pump system and the geothermal one and taking $\eta_{EL} = 0.40$ as the reference value for the national electricity efficiency for the UK territory. Denoting F_{EE} as the GHG emission factor for EE, in kg CO_2 equivalent per kWh (in the UK, approximately 0.45 kg/kWh), GHG emissions were then estimated for both the reference system (ASHP) and the proposed system (GSHP), shown in Fig. 12.

The energy analysis carried out showed an energy saving in terms of primary energy and a reduction in greenhouse gas emissions into the

Table 7
Parameters and descriptions of the soil textures used for the model [7].

Station name	Thermal diffusivity (x 10^{-6} $m^2\ s^{-1}$)	Soil texture	Bulk density (gcm^{-3})	Particle density (gcm^{-3})	Porosity	Specific heat ($Jkg^{-1}K^{-1}$)	Thermal conductivity ($Wm^{-1}K^{-1}$)
PENMAEN	2.4691	S_NL*	1.52	2.62	0.42	1014	3.81

Note * S_NL = SAND TO SANDY, CLAYEY AND SILTY LOAMS.

Table 8
Main heat exchanger design parameters.

Borehole Depth (m)	Borehole Number	Pipe Diameter (mm)	Distance between Boreholes (m)	Unit Linear Meter Heat Exchanger (W/m)	Q' (kW)	Storage Volume (m^3)
110	2	32	6	45	9.8	6855

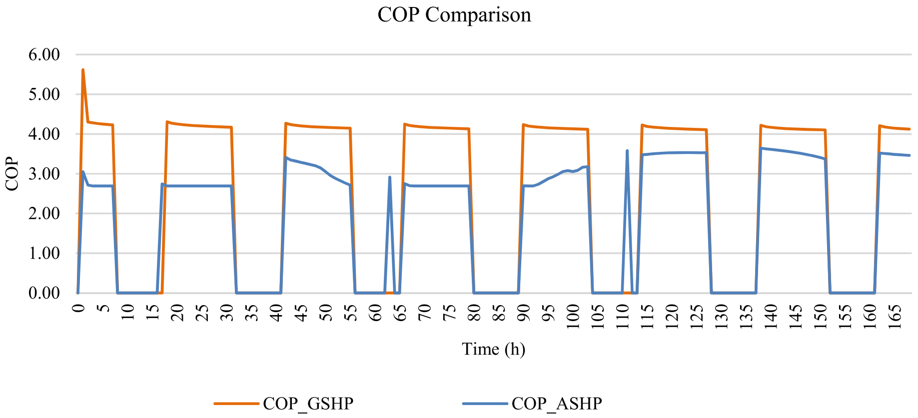


Fig. 10. COP Analysis for one week of operation in winter: Comparison between baseline scenario (ASHP system) alternative scenario (GSHP).

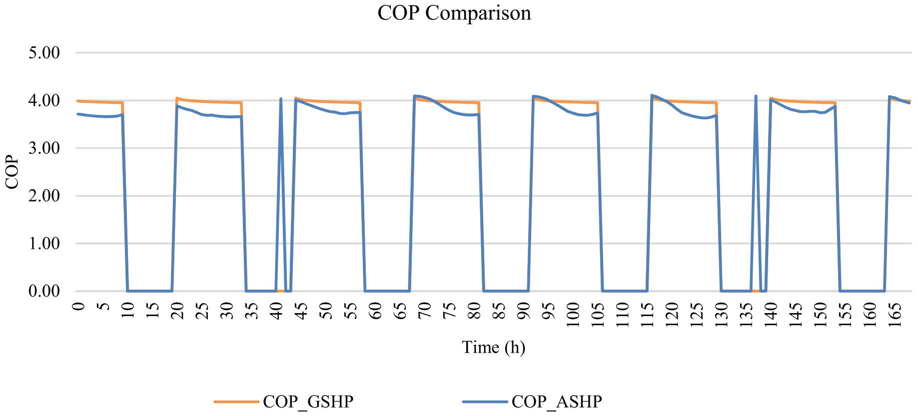


Fig. 11. COP Analysis for one week of operation in summer: Comparison between baseline scenario (ASHP system) alternative scenario (GSHP).

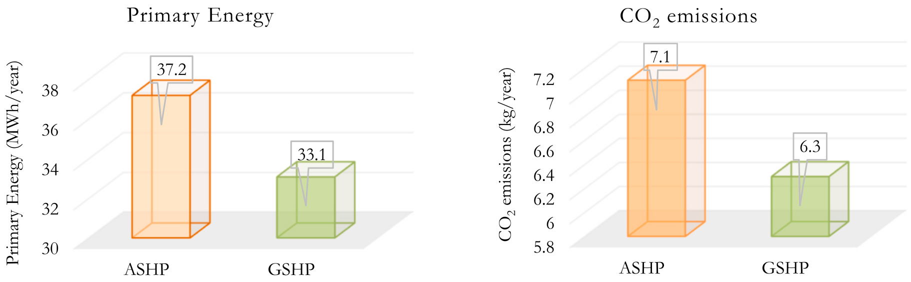


Fig. 12. Assessment of energy savings and CO_2 emissions for the two systems analysed.

atmosphere of 11%, as well as the CO_2 emission reduction.

As mentioned in the introduction, in summary, the benefits of GSHP in comparison to ASHP can be outlined as follows: (1) they have lower energy consumption during operation, (2) they eliminate the need for supplementary heating during extremely cold outdoor temperatures, (3) they require less refrigerant, (4) they typically feature a simple design and part of the plant is not exposed to the environment, resulting in reduced maintenance. The aforementioned characteristics of GSHP make them particularly intriguing in challenging climates, as well as in urbanized areas, like the city of Swansea.

However, they do have the initial disadvantage of a higher initial capital cost: a geothermal system is about 30–50% more expensive than an air unit. Equivalent technical feasibility is not easy to estimate for each country, because drilling costs differ from country to country depending on the maturity of the market, the soils and geology of the subsoil, the hydrology and the competitiveness of the drilling companies. That said, according to the study published in 2018 by Muller et al. [23], the average costs of a standard geothermal plant does not depend much on materials (probe, filler), whereas the installation has a 14.2% share of the costs, the device takes the second largest part with 27.7%, while the largest cost factor is drilling with 39.3%.

Hence, rock drillability assumes significant importance when evaluating the installation of GSHPs. Furthermore, by considering the soil properties outlined in Table 7 along with the drillability charts provided in Refs. [24,25], it becomes evident that GSHP installations emerge as a favorable choice for locations like Swansea.

5. Conclusions

The present work consists of the adoption of a dynamic simulation model for the evaluation of the performance of an energy system consisting of a Positive building, located in Swansea (UK). The current actual configuration ('baseline scenario') of the building-plant system was modelled in TRNSYS environment and the influence of different parameters was studied, such as the control logic of the heat pump and the PVT and the thermal inertia of the building. A validation of the calculation was made based on the comparison between the measured data and the results of the simulation.

Finally, the adoption of a vertical ground-coupled heat pump coupled to the reference building to replace the existing air source heat pump was proposed as an alternative scenario and its performance was compared.

GSHP systems, these in the last decades have attracted great interest among heating and cooling operators and have undergone a considerable increase in the number of installations. However, this technology has not yet achieved the expected attractiveness compared to other high-efficiency solutions. This is probably due to the particular energy and economic context (e.g. temperate climate, reduced building requirements, energy taxes, installation costs, lack of specific incentives) and the application of a design methodology based on the peak-load approach.

The comparison showed an increase of 20%, in terms of the coefficient of performance (COP), with the adoption of a GSHP system. The energy analysis shows an energy saving of 11% in terms of primary energy and a reduction of GHG emissions.

The same methodological approach can be applied to other GSHP configurations, such as shallow heat exchangers and groundwater heat pump systems; as well as the study of optimal coupling strategies between GSHPs and other HVAC technologies (e.g. solar systems) and other equipment layouts.

Laura Vanoli: Writing – review & editing; Conceptualization; Funding acquisition.- Vittoria Battaglia: Writing – original draft; Formal analysis; writing (equal).- Clara Verde: Writing – original draft; Formal analysis; writing (equal).- Perumal Nithiarasu: Conceptualization; Funding acquisition.- Justin R. Searle: Conceptualization; Funding acquisition

Declaration of competing interest

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.

Data availability

The data that has been used is confidential.

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Nomenclature

AHP	Absorption Heat Pump
AHUs	Air Handling Units
ASHP	Air Source Heat Pump
BHEs	Borehole Heat Exchangers
COP	Coefficient Of Performance
EE	Energy Efficiency
EED	Energy Efficiency Directive
EER	Energy Efficiency Ratio
EGEC	European Geothermal Energy Council
EHPA	European Heat Pump Association
EPBD	Energy Performance of Buildings Directive
EU	European Union
GCHPs	Coupled Ground Heat Pumps
GHG	Greenhouse Gas emissions
GSHP	Ground Source Heat Pump
GWP	Global Warming Potential
HP	Heat Pump
HVAC	Heating, Cooling and Air Conditioning Systems
NZEB	Nearly Zero Energy Building
RES	increase the share of Renewable Energy Sources
SCOP	Seasonal Coefficient of Performance

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