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Comparison of Short and Long-Term Energy Performance and Decarbonization Potentials between Cogeneration and GSHP Systems under MARKAL Scenarios

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Abstract: In response to the call for global carbon peaking and neutrality, this study mainly focuses on the comparison of energy-related carbon emissions and the performance of two promising heating, ventilation, and air-conditioning technologies (a ground source heat pump (GSHP) and cogeneration systems) over both short (2021–2030) and long (2031–2050) periods, considering the UK decarbonization plans. The simulation model of the building with the GSHP system is validated by the actual building heating energy data in 2020 and 2021, with yearly deviations of only 0.4–0.5%. The results show that the cogeneration system performed better than the GSHP system in a scenario when there was no electricity decarbonization plan in the future. However, under all of the MARKet ALlocation (MARKAL) scenarios, the GSHP system performed much better than the cogeneration system in terms of carbon reduction in both periods, which can achieve 47.8–84.4% and maximum 97.5% carbon emission savings in short and long-term periods, respectively, compared with the cogeneration system. Due to the truth that electricity decarbonization plans will be optimized and executed in the future, the GSHP system is more promising and recommended compared with cogeneration system in both short- and long-term periods in terms of only decarbonization potentials (e.g., reducing carbon emission and achieving carbon-related environmental protection).

Keywords: cogeneration system; ground source heat pump; MARKAL model; electricity decarbonization plans; CO_2 emission reduction; carbon neutrality

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1. Introduction

Due to the global energy crisis and carbon-caused global warming, carbon peaking and neutrality targets have attracted significant attention globally [1]. Many countries have set goals and deadlines for their carbon peak and neutrality according to their national conditions. China has set the targets of 2030 and 2060 for achieving carbon emission peaking and neutrality, respectively [2], while the European Union has set a target of 2050 for achieving carbon neutrality [3]. European Union also proposed three goals for reacting to the global energy shortage and carbon-related environmental deterioration in 2014, which were reducing carbon emissions by 40% and increasing the renewable energy share and energy efficiency by 27% by 2030, compared with the levels in 1990 [4]. In addition, the UK government is also trying to achieve a total carbon emissions reduction of more than 80% by 2050 [5]. Thus, energy conservation has become a matter of global consensus and an urgent and paramount issue.

The building sector is responsible for 35–40% of the annual global energy consumption [6], exceeding that of the transportation and industrial sectors and ranking first in global energy consumption among all sectors [7,8]. In addition, buildings are also significant carbon emitters whose embodied and operational carbon emissions account for

30–40% of global carbon emission annually [9]. According to the International Energy Agency (IEA)'s Efficient World Strategy Report, the building sector could achieve around 40% and 45% energy and carbon savings, respectively, by 2040 (compared with the figures for 2013) by utilizing the currently available energy measures [10]. Thus, improving the building sector's energy efficiency and carbon performance plays a predominate role in handling the global energy crisis and carbon-related environmental deterioration.

The heating, ventilation and air-conditioning (HVAC) system is responsible for more than 40% of a building's total energy use [11,12], and thus there is no doubt that system optimization or an alternative, high-efficiency HVAC system can lead to energy conservation in building sector [13]. Many researchers have studied the system optimization of HVAC units, which includes air-conditioning equipment optimization [14], fault diagnosis [15], system operation optimization [13], etc. In addition, an alternative, high-efficiency HVAC system is also attractive to researchers, and would include heat pump systems driven by different sources (e.g., air sources [16], water sources [17], ground sources [18] and dual sources [19]), a cogeneration system [20], an adsorption chiller [21], an absorption chiller [22], evaporative cooling units [23] etc.

Ground source heat pump (GSHP) and cogeneration systems are widely studied and used in many research and actual projects, and they have the potential to improve energy efficiency greatly and to achieve energy cost savings. For instance, Wang et al. [24] proposed an innovative HAVC system combining an air-and-ground-source heat pump and thermal energy storage and optimized its performance. The results show that, compared with a typical GSHP system, the proposed system can improve the COP and decrease the system's operating cost and carbon emission by 58% and 7.1%, respectively. Hosseinnia and Sorin [25] proposed a two-stage optimization approach for a solar-assisted GSHP system and analyzed the technological feasibility and economic payback. In addition, Skordoulias et al. [26] proposed combining the medium-scale power to hydrogen system and the cogeneration system and analyzed the system performance according to its technical feasibility and economic indicators. Wang et al. [27] proposed a novel cogeneration system by adopting a waste heat recovery system via heat pumps and investigated its heat–power decoupling performance and energy-saving potentials.

Apart from the above-mentioned research, there is still much research related to GSHP and cogeneration systems, and the majority of it is focused on technical feasibility, energy savings and economic analyses. Although some studies also mentioned carbon emission-related analyses or results, they all focused on short-term carbon emission reduction rather than on comprehensive and long-term carbon emission analysis. Seldom does research focus on the long-term carbon emission performance of a GSHP system. In a rare example, Subramanyam et al. [28] compared and assessed some energy efficiency improvement options in terms of their energy-saving potentials and carbon emission, and considered both their short-term and long-term performance in terms of energy use, carbon emission and abatement costs.

To achieve the global targets of carbon peaking and neutrality, energy-related carbon emission and performance should be given more attention in both the short term and the long term. Thus, this study focuses on comparing both the short-term and long-term energy-related carbon emissions and decarbonization potentials of different HVAC systems considering the UK electricity decarbonization plans (MARKAL model) and takes two recognized and widely used energy-saving and environmental protection technologies (namely the GSHP and cogeneration systems) as subjects for comparison. The rest of this study is structured as follows. Section 2 shows the methodology used in this study, which includes a description of the building studied, the simulation tool, usage and assumptions and a description of the UK MARKAL scenario, while Section 3 presents the technical systems, including the distribution system and the GSHP and cogeneration systems. In addition, the simulation results and discussions are shown in Section 4, while Section 5 contains the conclusion as well as future research recommendations.

2. Materials and Methods

2.1. Structure of the Simulation Study

The structure of this study is shown in Figure 1. Firstly, the building's physical dimensions are obtained through a drawing-and-ruler based estimation method, which will be described in detail in Section 2.2, and are used in Google SketchUp to build a physical model of the building. Then, the established building model is imported into the TRNSYS 17 simulation software, and different building components and inputs (e.g., weather data, parameters of the building materials and construction, technical systems, occupant schedules and assumptions) are determined and linked in the TRNSYS model. When the simulation results are obtained, they are validated using the actual operating data from the university's facility management (FM) department, and, finally, the validated simulation results are post-processed and analyzed to compare both the short-term and long-term performances of the combined heat and power (CHP) and GSHP systems in terms of their energy performances and environmental impacts (e.g., decarbonization potentials).

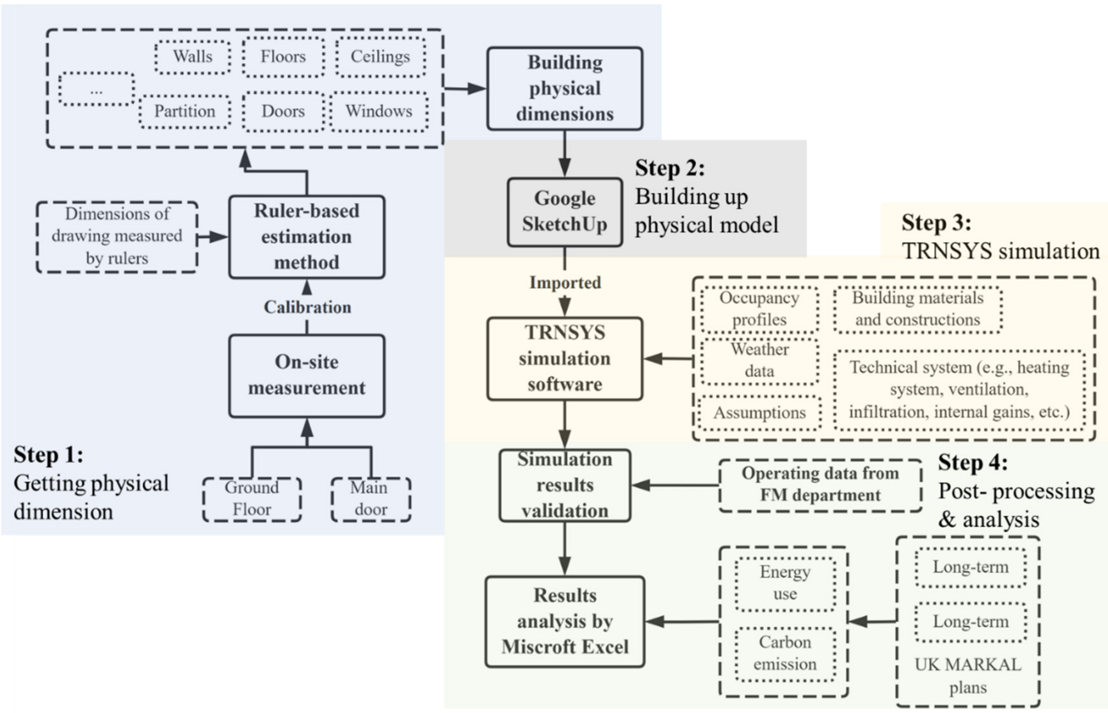

Figure 1. Structure of this study.

2.2. Building Description

The building studied is a commercial building on a university campus in Reading, UK, serving as general university offices and meeting rooms for the most part. Reading is very close to London, UK, and they share similar weather conditions. Figure 2 shows the actual building studied, with five floors altogether (four upper floors and a basement). Only the ground, first and second floors are used for personnel activities, and they have a total floor area of 2224 m^2.

Figure 2. The building studied.

2.2.1. Building Size Acquisition Method

The building is an irregularly shaped building with rough length and width of 40 and 14.5 m, respectively. Drawings of the building were obtained from the university's technical manual department, but no specific dimensions were found. Due to the irregular shape of the building, many dimensions (e.g., window size on the first and second floors) cannot be directly measured out of concern for the safety for the surveyors. Thus, a special method is used to obtain the building's exact dimensions. Here, the drawings are printed out at an appropriate scale for all five floors, and the building dimensions (e.g., floor, doors and windows) are measured using measuring equipment (e.g., a ruler and tape measure). Then, estimated building dimensions are obtained by multiplying the ruler-based ones by the scale. Furthermore, the available on-site measurement data (e.g., the length and width of the ground floor of the building, the dimensions of windows and doors) are used to validate the estimated building dimensions. Finally, relatively accurate building dimensions (e.g., of floors, windows, doors) are obtained.

The heights of different parts of the building vary, as is shown in Table 1, while the widths of its windows and doors, obtained by the measuring method mentioned above, are not uniform. In addition, the surface parameters for the three floors studied are shown in Table 2.

Table 1. Height parameters of different parts.

Part	Height (m)	Description
Floor-to-floor	4.0 (Above floor)	Floor height
	2.5 (Basement)	
Floor-to-ceiling	3.0	Room height
Doors	2.0	
Windows	3.8	Ultra
	1.0	Big
	0.25	Small

Table 2. Surface areas of each floor (e.g., floors, walls, ceilings, windows).

Floor (m^2)	Floor	Ceiling	Exterior Wall	External Roof	Windows
Basement	15.6	15.6	29.4	0	0
Ground	633.0	633.0	456.2	0	187
First	723.5	714.2	509.6	9.3	160
Second	714.2	10.8	503.2	703.4	126
Third (Roughly)	4.0	4.0	15.0	20.0	0

2.2.2. Establishing the Physical Model

When the validated dimensions (e.g., of floors, ceilings, roofs, walls, openings) are obtained, Google SketchUp software is used to establish the physical model of the building. It is a 3D drawing program [29] created by Google to facilitate building designs for the 3D city display on Google satellite maps [30]. To simplify the model, each floor is reduced to an entire zone without any complex partitioning. Figure 3 shows the physical model of the building produced by Google SketchUp, and the yellow, navy-blue and red colors represent the exterior walls, windows/doors and roofs, respectively.

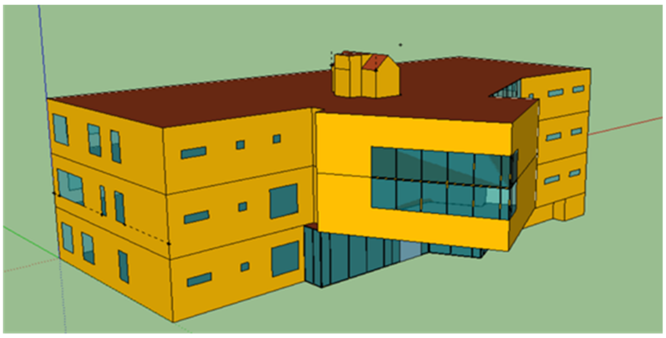

Figure 3. The model of the studied building in Google SketchUp.

2.3. TRNSYS Simulation Tool

Many simulation packages (e.g., TRNSYS [31], EnergyPlus [32], Polysun [33]) can be used for the simulation of the buildings, systems (e.g., heating, cooling and electricity) and both [34]. Transient system simulation (TRNSYS) is frequently used to simulate buildings with GSHP and CHP systems [35]. For example, Liu et al. [36] applied TRNSYS to study the feasibility and energy performance of a GSHP system in Chinese cold-climate cities, and Zhou et al. [37] used TRNSYS to build up a GSHP system for domestic hot water (DHW) and studied the feasibility via operation and performance analysis. For CHP system studies, Jung et al. [38] applied TRNSYS to establish a medium-size residential building adopting a micro-CHP system, and proposed multiple criteria for evaluating its performance. Similarly, Martinez et al. [39] used TRNSYS to build up a solar integrated micro-CHP system and to study its system operation and energy performances. In addition, there is much more research on TRNSYS-based simulation for GSHP and CHP systems [40–42], which proves the feasibility and applicability of TRNSYS for the simulation of buildings and energy systems.

According to the TRNSYS TESS library [43], "TRNSYS is a TRANsient systems simulation program, displayed as a modular structure, and identifies a system description language that users use to specify the components that make up the system and their connection methods". TRNSYS can also be connected to other software (e.g., Ansys, Excel, EES and other kinds of data pre-processing and post-processing software) [44]. Compared with other simulation software (e.g., EnergyPlus, IDA ICE), TRNSYS has built-in components/modules, which makes it easier to use. Thus, after a literature review and package comparisons, the TRNSYS package is adopted in this study for the simulation study of a building with CHP and GSHP systems.

2.4. Usage and Assumptions

The usage profiles of the building studied are followed by the schedules between 8 a.m. and 18 p.m. on workdays for the occupants, the lighting system and the equipment. The internal gains (e.g., personnel, equipment and artificial gains) are listed in Table 3 and are assumed based on the Chartered Institution of Building Services Engineering (CIBSE) energy benchmark technical memorandum (TM46): 2008 [45]. Eighty-six persons are assumed to work on the studied floors, and their personnel activity levels belong to 'standing, working lightly or slowly'. In addition, there are 12 personal computers with a 140 W power load each, and altogether 1680 W for each floor. Then, the artificial lighting is set as 10 w/m^2 for all three floors. The other assumptions are shown in Table 4.

Table 3. Assumed internal gains for each floor studied.

Floor	Persons (P)	Human Body Heat Rejection (W/Person)		Computers (W)	Artificial Lighting (w/m^2)
		Sensible	Latent		
Ground	32	75	55	1680	10.0
First	30			1680	10.0
Second	24			1680	10.0

Table 4. Other assumptions applied in the TRNSYS model [46,47].

Type	Parameter	Values	Notes
Infiltration	Air change of Infiltration	0.3 air change per hour	
Ventilation	Air change rate	10 (L/s person)	
Room temperature control	Set temperature for heating	22 °C	
Comfort	Clothing factor	1 clothes	Air velocity < 0.15 m/s
	Metabolic rate	1.2 met	
	External work	0 met	
	Relative air velocity	0.1 m/s	

In addition, the material properties of the building parts (e.g., floors, roofs and externals walls) are assumed and determined from the embedded TESS libraries in the TRNBUILD of TRNSYS and are followed by the CIBSE 2015 [48] and the Energy Savings Trust. Table 5 shows the building material properties, which meet the UK building regulation before 2007, because the building was constructed and completed in 2007. Thus, UK building regulation 2000 [49] is adopted as the guidance, and the building U-values should follow its requirement, as shown in Table 6.

Table 5. Building material properties selected from the TRNBUILD [49].

Layer/Units		λ	c	P	Exterior Wall	Ceiling	Exterior Floor	Internal Floor	Roof
		(W/m K)	(kJ/kg K)	(kg/m^3)	(m)	(m)	(m)	(m)	(m)
PB		0.11	0.84	95250	0.013	0.013	–	–	0.02
Insulation materials	PS	0.13	1.25	40	–	0.1	–	–	0.03
	PU20	0.07	2.09	600	0.05	–	0.12	0.04	–
	LC	0.34	1.1	2400	–	–	–	0.06	–
Concrete	RC	2.3	1.0	1400	–	–	–	–	0.36
	CB	1.32	1.0	1400	0.12	–	0.05	0.15	0.1
	CS	1.32	1.0	1400	–	0.15	0.15	0.15	–
	Screed	3.13	1.0	1800	–	0.05	–	–	–
WB		0.79	1.0	500	0.105	–	–	–	–
Total thickness		–	–	–	0.288	0.313	0.32	0.4	0.51
U-value (W/m^2 K)		–	–	–	0.35	0.226	0.231	0.237	0.181

Notations: PB=Plasterboard; PS = Polystyrene; PU20 = Poly-urethan-20; LC = lightweight concrete; RC = Reinforced concrete; CB = Concrete-block; CS = Concrete-slab; WB = Wallboard.

Table 6. U-value standards following UK building regulation 2000 [49].

Element	Area-Weighted Average U-Value (W/m^2·K)	Limiting U-Values (W/m^2·K)
Roof	0.25	0.35
Floor	0.25	0.7
Wall	0.35	0.7
Windows	2.2	3.3

2.5. UK MARKAL Scenarios

This study adopts the MARKet ALlocation (MARKAL) model to analyze the energy-related carbon emissions for the GHSP and CHP systems in the building studied. MARKAL is an electricity decarbonization plan proposed by the UK government [50], and its model is to achieve dynamic energy optimization for simultaneous energy system total cost and carbon emissions mitigation by 80% by 2050 compared with the levels in 1990 [51]. The MARKAL model is particularly suitable for long-term energy systems, though both short-term and long-term carbon emissions will be analyzed by the MARKAL model in this study. There are altogether eight types of electricity decarbonization plans in the MARKAL model, which are illustrated in Figure 4 [50] and Table 7 [52].

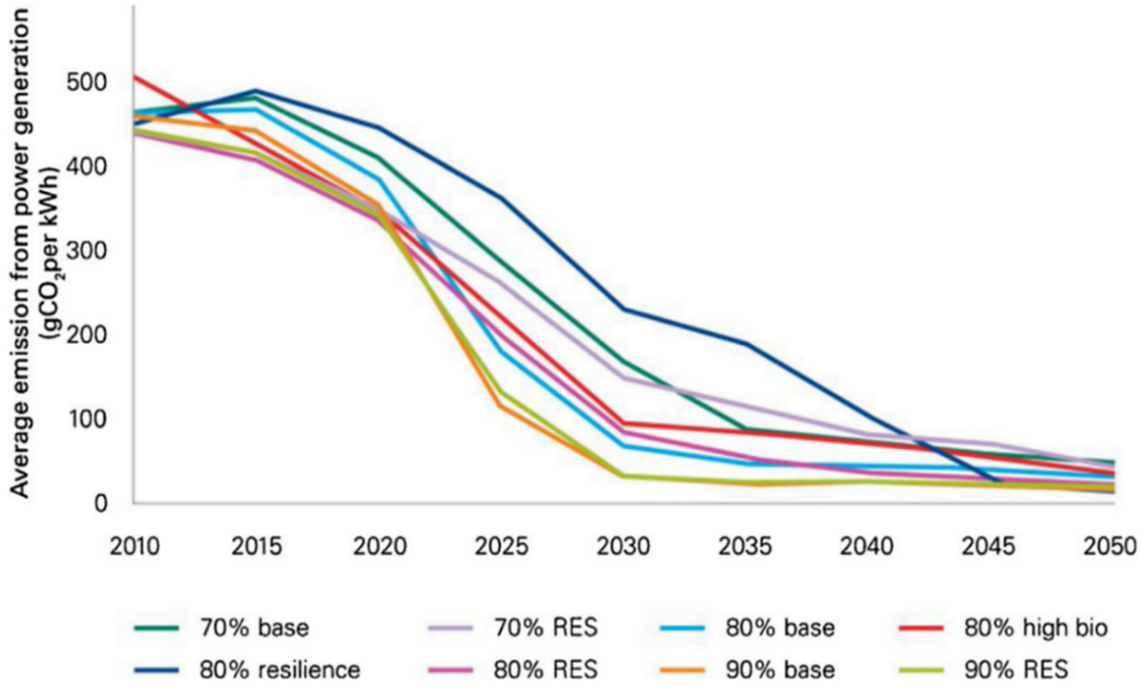

Figure 4. Rate of electricity decarbonization under different UK MARKAL plans [50].

Table 7. Description of the UK MARKAL plans [52].

Scenario Name	Compared to Levels in 1990, Carbon Emission Decline (%)		Assumptions	Commission
	In 2020	In 2050		
70% base	28	70	Max nuclear and Carbon Capture and Storage (CCS) build rate –3 GW p.a. in the 2020s –5 GW p.a. thereafter	CCC
70% RES	29	70	–Models are constrained to provide enough renewable energy generation in 2020 to meet renewable energy targets	DECC
80% ‘resilience’ (Low electricity)	26	80	–Decrease the energy demand by minimum 1.2% per year –Limit the proportion of single energy below 40% in primary energy mix –Constrain the expected unserved energy level –Supplement power sector models to better explain intermittency	UKERC
80% RES	29	80	–Models are constrained to provide enough renewable energy generation in 2020 to meet renewable energy targets	DECC
80% high bioenergy	31	80	To fulfill the renewable energy target: –Domestic and imported biomass high availability –High biomass liquids capacity	Defra

Table 7. *Cont.*

Scenario Name	Compared to Levels in 1990, Carbon Emission Decline (%)		Assumptions	Commission
	In 2020	In 2050		
80% base	33	80	Max nuclear and Carbon Capture and Storage (CCS) build rate –3 GW p.a. in the 2020s –5 GW p.a. thereafter	CCC
90% RES	29	90	–Models are constrained to provide enough renewable energy generation in 2020 to meet renewable energy targets	DECC
90% base	38	90	Max nuclear and Carbon Capture and Storage (CCS) build rate –3 GW p.a. in the 2020s –5 GW p.a. thereafter	CCC

Notations: UKERC = UK Energy Research Centre; DECC = Department of Energy and Climate Change; Defra = Department for Environment, Food and Rural Affairs; CCC = Committee on Climate Change.

3. Technical Systems (Energy Generation and Distribution Systems)

The technical systems in this study include the energy generation systems (GSHP unit and CHP system) and the space heating distribution system. The selected components are from the built-in component library and are selected for the TRNSYS model. Table 8 lists the components used in the TRNSYS simulation in this study, whose selection criteria are based on open references (e.g., publications, governmental documents and legislation).

Table 8. Components used in TRNSYS simulation in this study.

Component	Type	Component	Type
Heating coil	Type 753e	Tank	Type 531- No Plug in
Fan coil	Type 600	Heat pump	Type 927
AD valve	Type 646	Pump	Type 114
FD valve	Type 647	CHP system	Type 907
FM valve	Type 649	Weekly profile	Type 516
Controller	Type 1502	Weather data	Type 15-6
Heat exchanger/source	Type 557a	Displayer	Type 65c-7

Notations: AD = Air diversion; FD = Fluid diversion; FM = Fluid mixing; CHP: Combined heat and power.

3.1. Space Heating Distribution System

The building heating profiles are obtained from the university's facility management (FM) department and are based on 24/8 h operation every day from 1 October to 30 April every year, and the heating setpoint is 22 °C. Figure 5 shows the schematic of the space heating distribution system applied in this study. To simplify, each floor is only equipped with one fan coil, for a total of three fan coils. Both the heating and the coil fan coils are linked to the building, pump and control units. The control units are used to determine the on-off of the heating and fan coils and pump. Table 9 shows the parameter settings of the fan and heating coils and the pump in the model. The maximum mass flow rate is the same as the rated air flow rate of 15,428 kJ/h, which can balance the mismatch between the annual total energy supplied from the GSHP/CHP system and the building's annual heating demand. If the annual provided energy were to drop below the annual building heating demand, the mass flow rate would also decrease.

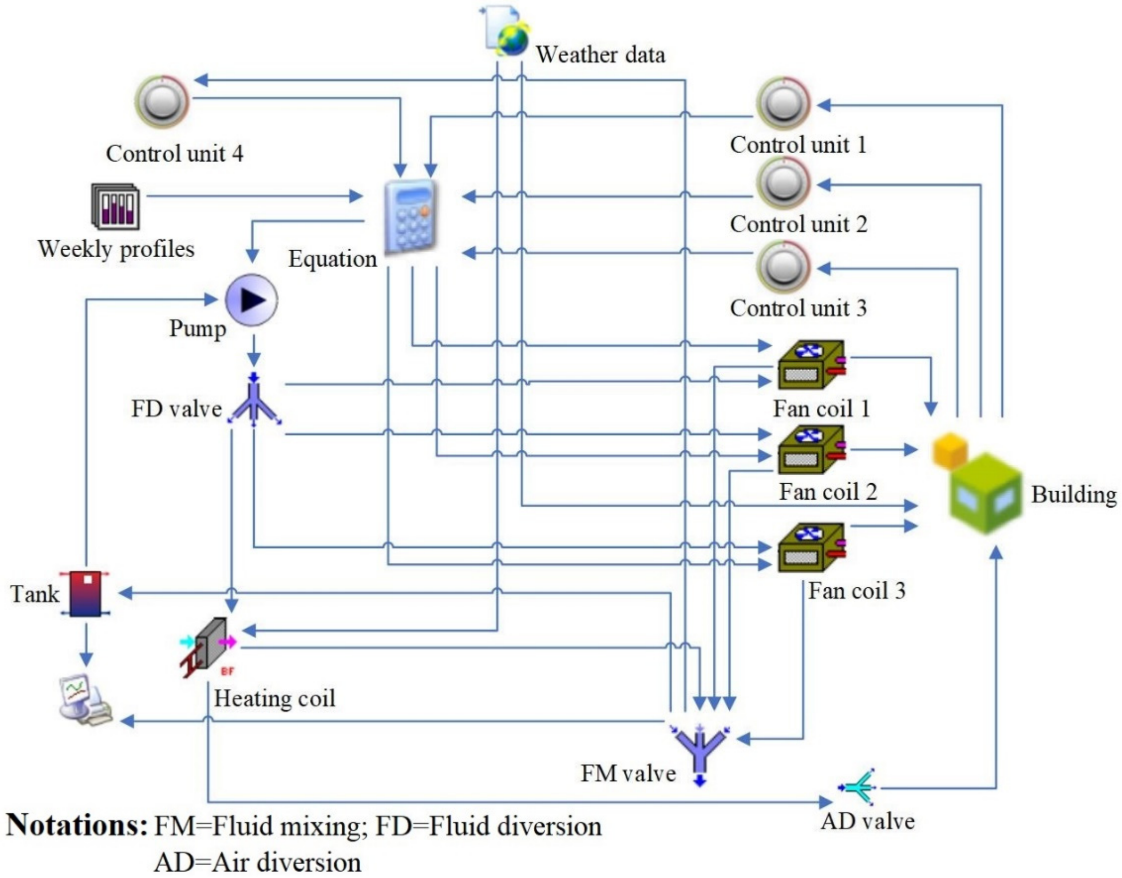

Figure 5. Components and links of space heating distribution system in TRNSYS.

Table 9. Parameter setting of fan and heating coils and the pump in the model.

Parameters	Liquid Specific Heat (kJ/(kg·K)	Humidity Mode	Rated Air Flow Rate (kJ/)	Rated Power (kJ/h)
Pump	4.19	–	15,428	2648
Heating coil		2	–	–
Fan coil		2	21,600	617

3.2. GSHP System

Figure 6 shows the components and links of the whole established system with the GSHP system in TRNSYS, while the whole system is divided into three parts, which are the building, the GSHP system and the space heating distribution system. The GSHP system is an existing system in the building studied that is composed of a heat source (a vertical U-tube ground heat exchanger), a water-to-water heat pump, circulation pumps, a thermal storage tank and controllers, while weekly profiles should be provided in TRNSYS for the GHSP system. The GSHP consumes the most electricity in the building studied, and thus its selection is the key to balancing the energy efficiency and the thermal load requirement met by the nominal capacity. Table 10 shows the parameters of the vertical U-tube ground heat exchanger. The rated heating power and capacity for the water-to-water heat pump system are 129,000 and 649,000 kJ/h, respectively, and its rated source and rated load flow share the same rate of 4.3 L/s.

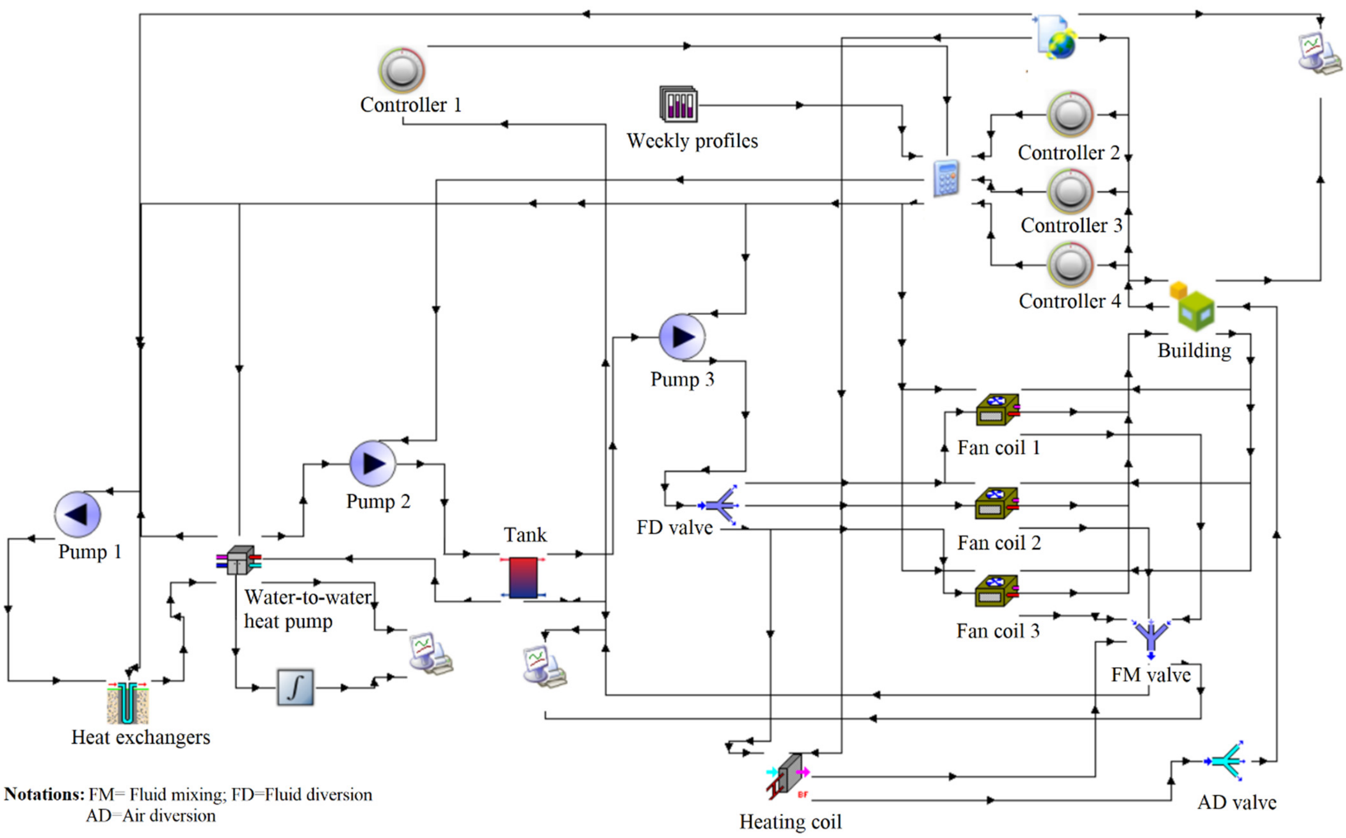

Figure 6. Components and links of GSHP system in TRNSYS.

Table 10. The parameters of the vertical U-tube ground heat exchanger.

Parameter	Value	Parameter	Value
Storage volume (m^3)	13,000	U-tube pipe outer radius (m)	0.01664
Depth of boreholes (m)	100	U-tube pipe inner radius (m)	0.01372
Number of boreholes	6	Center-to-center half distance (m)	0.0254
Radius of boreholes (m)	0.102	Fill thermal conductivity (kJ/(h·m·K))	4.68
Number of boreholes in series	3	Pipe thermal conductivity (kJ/(h·m·K))	1.5122
Storage thermal conductivity (kJ/(h·m·K))	4.68	Gap thermal conductivity (kJ/(h·m·K))	5.04
Storage heat capacity (kJ/(m^3·K))	2016	Fluid specific heat (kJ/(kg·K))	4.19

3.3. CHP System

Figure 7 shows the components and links of the whole established system with the CHP system in TRNSYS, while the whole system is divided into three parts, which are the building, the CHP system and the space heating distribution system. The CHP system is only a theoretical assumption in this study, and it is composed of a CHP unit, controllers, a circulation pump, a thermal storage tank and fluid mixing/diversion valves, while weekly profiles should be provided in TRNSYS for the CHP system. Table 11 shows the selected parameters for the CHP system.

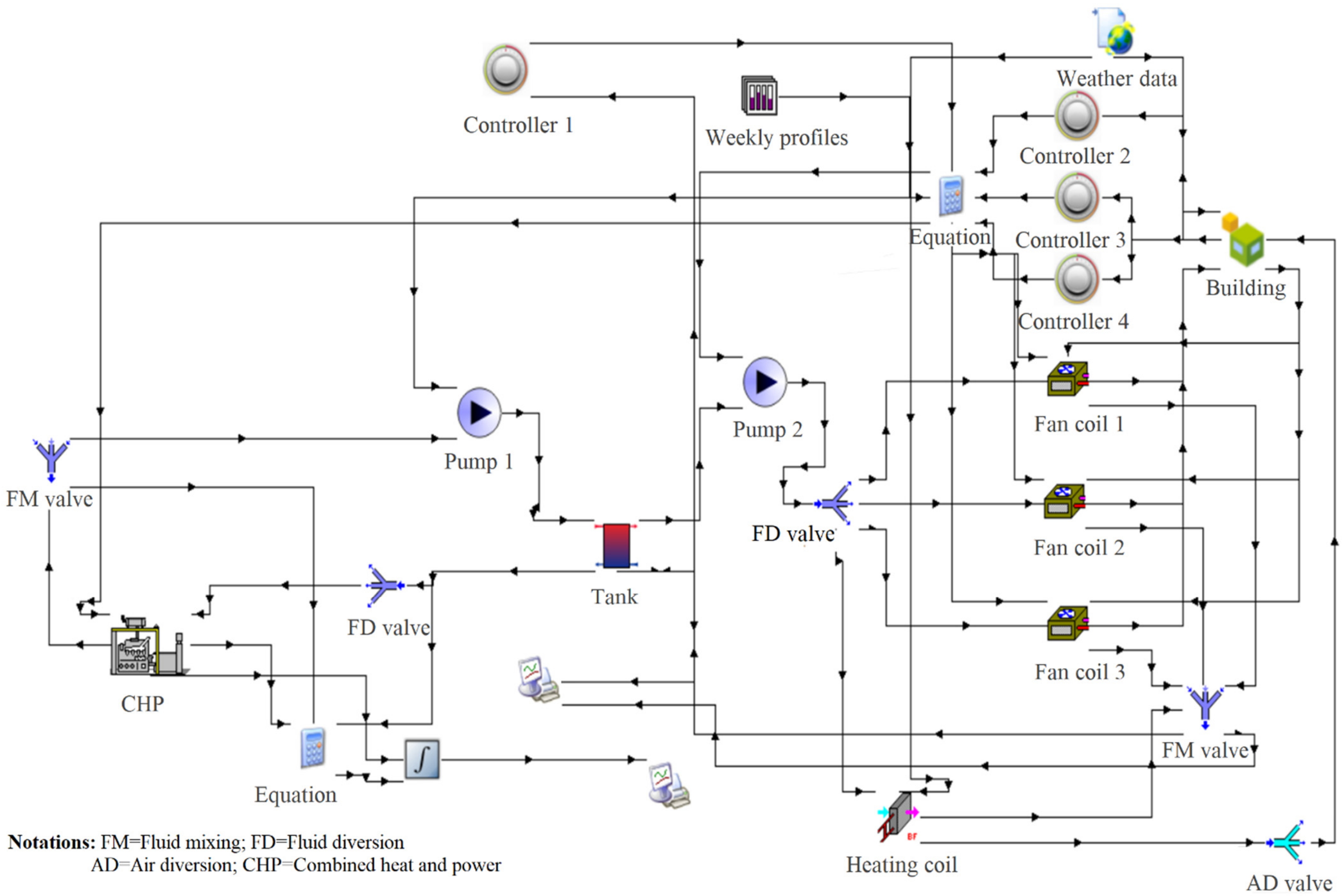

Figure 7. Components and links of CHP system in TRNSYS.

Table 11. The selected parameters for the CHP system.

Parameter	Value
CHP capacity (kW)	111.11
Maximum power output (kJ/h)	400,000
Jacket water fluid specific heat (kJ/(kg·K))	4.19
Oil cooler fluid specific heat (kJ/(kg·K))	4.19
Exhaust air specific heat (kJ/(kg·K))	1.007
After-cooler fluid specific heat (kJ/(kg·K))	1.007
Rated exhaust air flow rate (kg/h)	700

4. Results and Discussions

4.1. Simulation Results

Figure 8 shows the hourly ambient temperatures in the area where the building studied is located for a period of one year. The ambient temperatures are below 16 °C for the majority of the time from October to December and January to April in the simulated year, and these periods can be considered as the heating seasons, while there is no day with an ambient temperature over 30 °C. Thus, heating is required and should be supplied in the building studied during the whole heating season, but a cooling supply is not needed in the building studied.

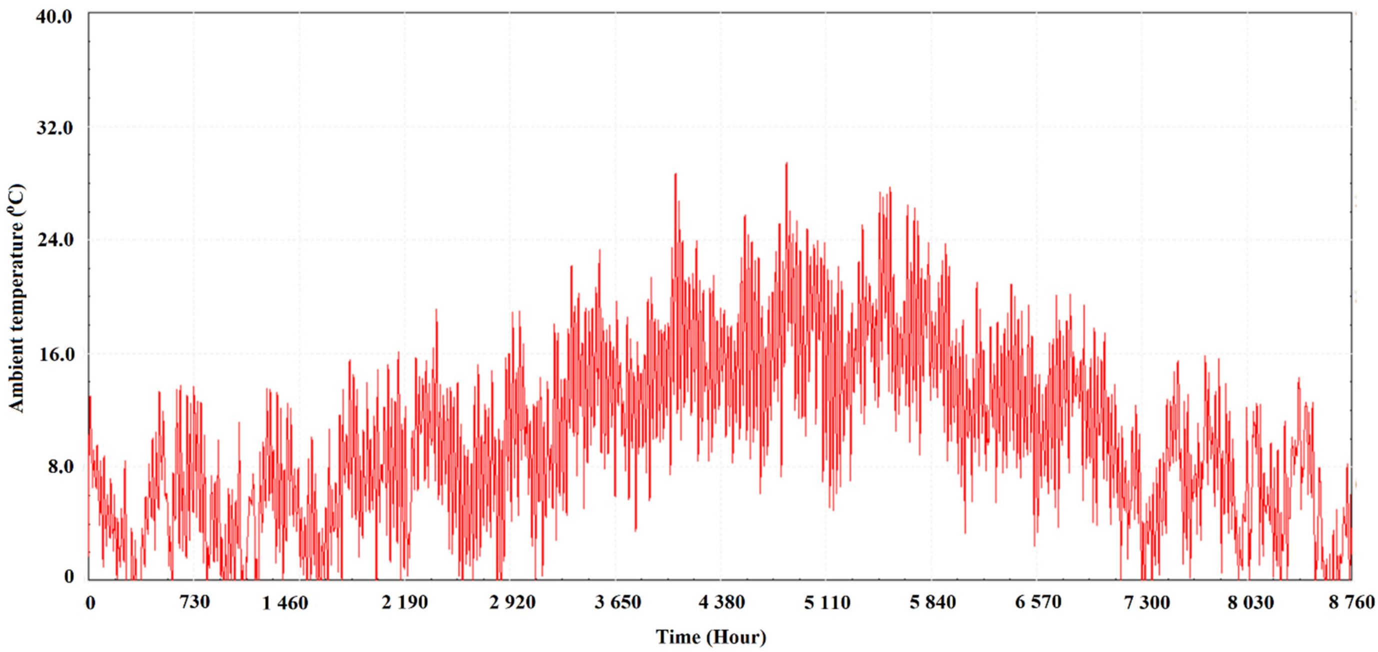

Figure 8. The whole-year ambient temperature profile of the area where the building studied is located.

Figure 9 shows the indoor air temperature profiles for each floor in the building studied for the whole year. The indoor air setpoint temperature is 22 °C. During the heating season, heating supply units are switched on in the building studied when the indoor air temperatures are below the set temperature (22 °C). The overall indoor temperature trend remains consistent on each floor. In addition, according to the simulation results, the maximum heating load is about 785,000 kJ/h in the building studied, which is used for the capacity calculation for both the GSHP and CHP systems.

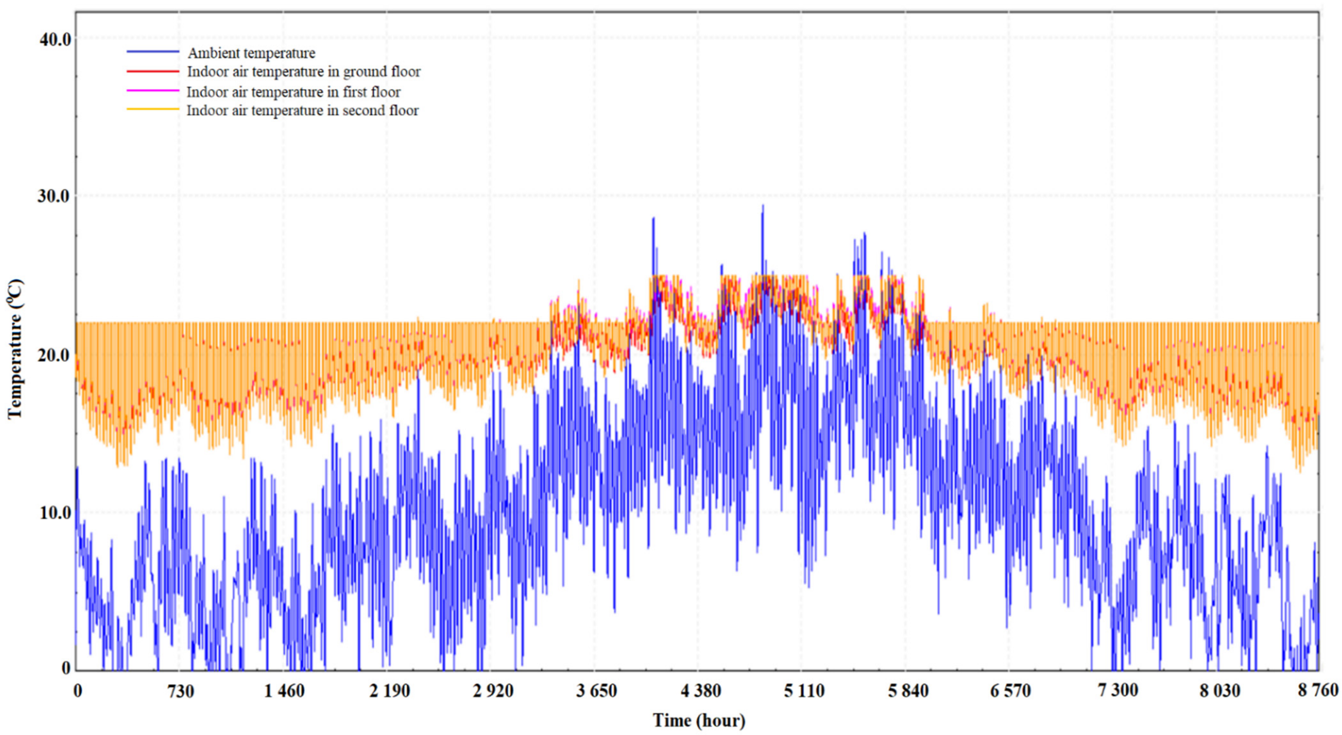

Figure 9. Indoor air temperature profiles of each floor for the whole year.

Figure 10 shows the power consumed and heat generated in the GSHP system. The GSHP system annually consumes around 289,000,000 kJ/h (equal to 80,277 kWh), and annually generates approximately 886,000,000 kJ/h (equal to 246,111 kWh) heat at the same time. Thus, the Coefficient of Performance (COP) of the GSHP system is around 3.1.

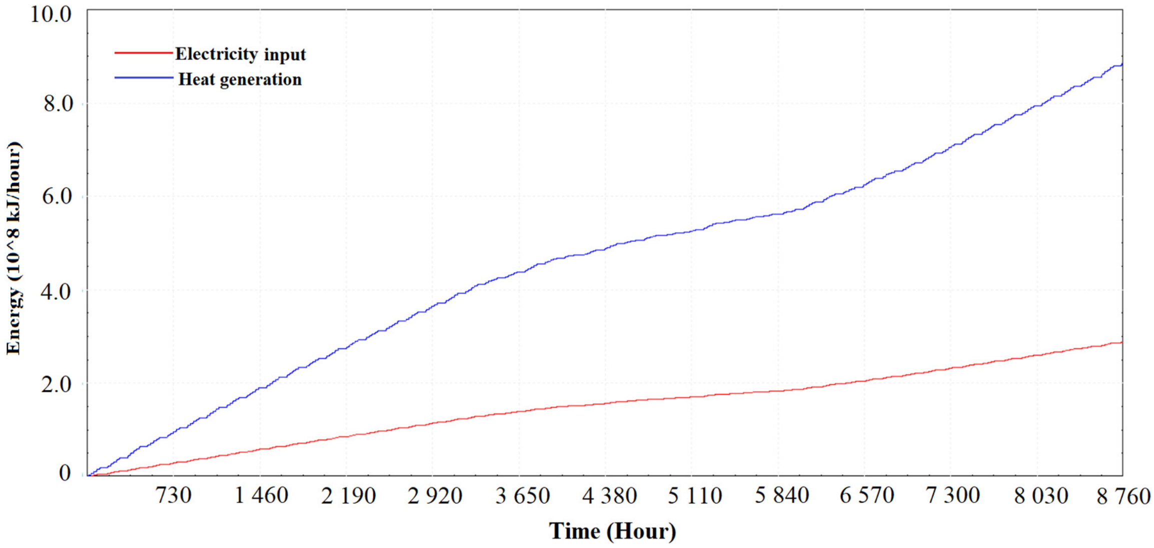

Figure 10. The power input and heat generation in the GSHP system.

4.2. Energy Performance

4.2.1. Compliance with Regulations

Office buildings are divided into four types based on Energy Consumption Guide 19 (ECG 19) [53], and the building studied belongs to Office Type 3: Air-conditioned standard office. According to the ECG 19 [53], there are two patterns of annual delivered energy use, which are the 'Typical' and 'Good practice' energy consumption patterns. The annual heating energy uses for 'Typical' and 'Good practice' patterns are 178 and 97 kWh/m^2, respectively, including space heating and domestic hot water.

However, the ideal heating energy consumption excludes domestic hot water. Thus, the actual heating energy consumption regulations in the 'Typical' and 'Good practice' patterns are 158 and 85 kWh/m^2, respectively, excluding the heating demand for hot water of 20 and 12 kWh/m^2, respectively. The ideal heating demand (110 kWh/m^2) is lower than the 'Typical' pattern value (158 kWh/m^2), but beyond the 'Good practice' pattern value (85 kWh/m^2). In general, the ideal heating demand follows the regulations of ECG 19 [53].

In addition, the building studied meets the requirement of the general office category of energy benchmarks CIBSE TM46 because it is composed of general offices and meeting spaces with an operational schedule on workdays, and is equipped with lighting, heating and employee appliances. The energy benchmarks stipulates that the electricity and fossil-thermal demands for the general offices are 95 and 120 kWh/m^2, respectively. Table 12. shows the ideal building heating demand and building heating demand standards based on the regulations (ECG 19 and CIBSE TM46).

Table 12. The ideal building heating demand and building heating demand standards based on ECG 19, CIBSE TM46 [45,53].

Items		Heating Demand (kWh/m^2)
Building (ideal heating demand)		110
ECG 19	Typical (with hot water)	178
	Typical (without hot water)	158
	Good practice (with hot water)	97
	Good practice (without hot water)	85
CIBSE TM46		120

4.2.2. Model Validation

Table 13 compares the monthly and annual electricity consumptions of the GSHP system based on the simulation results and data from 2020 and 2021 from university's FM department. As mentioned above, the heating seasons are from January to April and from October to December. It can be found that, regardless of whether one looks at 2020 or 2021, the simulated monthly GSHP energy consumptions have acceptable deviations from the actual energy consumptions (maximum deviation of 16.8%). In addition, the deviations between the simulated annual GSHP power use and the annual data from FM department in 2020 or 2021 are tiny, which are 0.4 and 0.5%. Thus, the simulation building with the GSHP system is validated.

Table 13. Comparison of GSHP power consumptions between simulation results and data from FM department.

Month	Simulation Results (kWh)	Data in 2020 from FM Department (kWh)	Data in 2021 from FM Department (kWh)	Deviation (2020)	Deviation (2021)
Jan.	2806	3112	3117	10.9%	11.1%
Feb.	2463	2653	2878	7.7%	16.8%
Mar.	2657	2559	2479	−3.7%	−6.7%
Apr.	2630	2610	2451	−0.8%	−6.8%
Oct.	2685	2394	2333	−10.8%	−13.1%
Nov.	2593	2588	2461	−0.2%	−5.1%
Dec.	2593	2444	2608	−5.7%	−0.6%
Total	18,427	18,360	18,327	−0.4%	−0.5%

4.2.3. Energy Costs

According to the simulation results, the GSHP system annually consumes about 18,427 kWh energy, and its energy input is electricity. In addition, the CHP system annually consumes about 84,259 kWh energy, and its energy input is gas, but it also produces about 28,796 kWh electricity. Based on Energy Consumption Guide 19, the average total cost of electricity is 4 p/kWh, while that of gas is 1.4 p/kWh. The Climate Change Levy is included in these two costs and is a tax applied to energy use in the commerce, agriculture, industry and public sectors. Thus, the annual power costs for GSHP and CHP are 737 and 1180 pounds, respectively. However, in addition to the heating supply, the CHP system also generates considerable electricity, which can be used for other electrical consumers in the building. Although the GSHP system is superior to the CHP system in terms of the heating energy costs, the latter generates considerable electricity that can be used for the building's electrical energy supply, so it is difficult to simply compare the advantages and disadvantages of the two systems in terms of energy performance. Thus, their energy-related carbon emissions should be compared.

4.3. Decarbonization Potentials

In this study, the annual energy usages of the GSHP and CHP systems are assumed to be consistent until 2050 and are 18,427 and 84,259 kWh, respectively, while the GSHP and CHP systems use electricity and gas, respectively, as input. The energy-related CO_2 emissions of the GSHP and CHP systems will be compared in both the short and long terms over two periods, Period 1: 2021–2030, and Period 2: 2031–2050. The carbon intensity of gas is consistent at 0.19 $kgCO_2/kWh$, while that of the fuel for electricity generation will keep decreasing in the future. In this study, we determine the carbon intensity of electricity based on the decarbonization rate of electricity under the UK MARKAL scenarios [47]. Appendix A lists the annual energy consumptions and carbon intensities of fuels for the GSHP and CHP systems from 2021 to 2050, while Appendices B and C list the CO_2 emissions of the GSHP and CHP systems from 2021 to 2050 under the circumstances of the UK decarbonization plans and no plan. Here, the calculation of the carbon emissions of the GHSP and CHP systems is as follows:

$$ACE_{GSHP} = AEU_{GSHP} \times CI_{electricity} \quad (1)$$

$$ACE_{CHP} = AGU_{CHP} \times CI_{Gas} - \left[EG_{CHP} \times \left(CI_{electricity} - CI_{Gas}\right)\right] \quad (2)$$

where *ACE* = Annual carbon emission, *AEU* = Annual electricity use, *CI* = Carbon intensity, *AGU* = Annual gas use, and *EG* = Electricity generation.

The summary of the CO_2 emissions and the carbon emission performances for both the GSHP and CHP systems in different periods are shown in Figure 11 and Table 14, respectively. The carbon emission performance of the GSHP system is much better than that of the CHP system both in the short-term and long-term periods considering the UK decarbonization plans, which means that the GSHP system has better decarbonization potentials than the CHP system in the next 30 years. However, if there is no decarbonization plan for electricity production, the CHP system performs better than the GSHP system in terms of CO_2 emission reduction. In the short term, compared with the CHP system, the GSHP system can reduce the CO_2 emission by 48% to 84.4% based on different decarbonization plans, while, in all of the scenarios except for scenario 5, the GSHP system can achieve at least a 63.3% reduction of CO_2 emission compared with the CHP system. In long term, the GSHP system can reduce CO_2 emission up to a 97.5% maximum compared with the CHP system, while, for all of the scenarios except for scenario 5, the GSHP system can achieve at least 91.1% reduction of CO_2 emission compared with the CHP system. From another perspective, the carbon emissions of the CHP system are 1.9–6.6 times those of the GSHP system in short term, while they are 9.4–39.3 times those of the GSHP system in the long term under the UK decarbonization plans. Thus, in the context of global carbon peaking and carbon neutrality, the GSHP system is superior to the CHP system in both the short and long term, considering the decarbonization potentials under the UK decarbonization plans. In other words, given the circumstances of the electricity decarbonization plans, GSHP is more promising than CHP systems for the period from 2021 to 2050, considering the global decarbonization background.

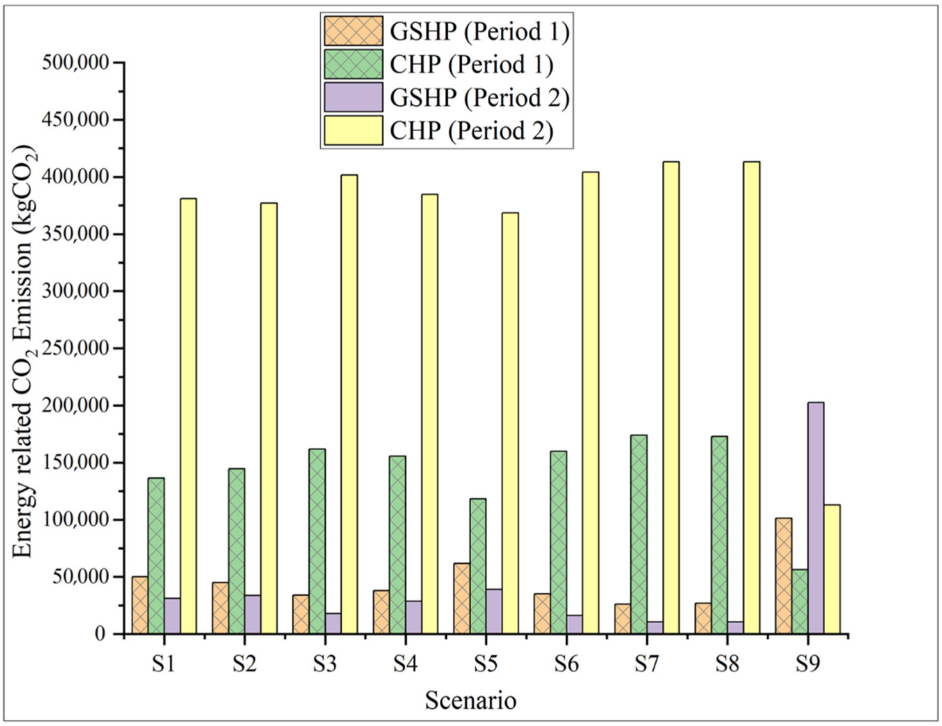

Figure 11. Comparison of CO_2 emissions for both GSHP and CHP systems in different periods.

Table 14. Summary of carbon emission performances of GSHP and CHP systems in both short- and long-term periods.

Scenario	Scenario Description	Short-Term (2021–2030)		CO_2 Emissions Reduction of GSHP System Compared to CHP System (%)	Long-Term (2031–2050)		CO_2 Emissions Reduction of GSHP System Compared to CHP System (%)
		GSHP	CHP		GSHP	CHP	
S1	70% base	☆		−63.3%	☆		−91.8%
S2	70% RES	☆		−68.9%	☆		−91.1%
S3	80% base	☆		−79.0%	☆		−95.6%
S4	80% high bio	☆		−75.6%	☆		−92.5%
S5	80% resilience	☆		−47.8%	☆		−89.4%
S6	80% RES	☆		−78.0%	☆		−96.0%
S7	90% base	☆		−85.0%	☆		−97.5%
S8	90% RES	☆		−84.4%	☆		−97.5%
S9	No electricity decarbonization plan		☆	79.6%		☆	79.6%

Notations: The '☆' represents better choice.

5. Conclusions

This study mainly focuses on the energy-related carbon emission performance and reduction potentials of different energy-saving, environmentally friendly and economical HVAC systems in both the short term (2021–2030) and the long term (2031–2050) under the circumstances of the UK MARKAL scenarios, and it selected GSHP and combined heat and power systems used in a university office building in the UK as subjects for comparison. The simulation results are validated by the actual operation results. The energy performance and carbon emission analysis and comparison results of the two systems are as follows.

The simulation model of the building with the GSHP system is validated by the actual building energy consumption data in 2020 and 2021, with a monthly maximum deviation of 16.8% and yearly deviation of only 0.4–0.5%.

Whether in the short or long term, the cogeneration system performed better than the GSHP system in terms of its decarbonization potentials in the scenario where the carbon intensity of electricity is maintained at its current level in the future.

Under all of the MARKAL scenarios, however, compared with the cogeneration system, the GSHP system can save 47.8–84.4% carbon emission in the short-term period, while the GSHP system can achieve a maximum of a 97.5% reduction of carbon emissions in the long-term period.

Considering the fact that electricity decarbonization plans really exist now, and will in the future, the GSHP system is more promising and is recommended in comparison with the cogeneration system in both short and long term when only the decarbonization potentials are considered.

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Conflicts of Interest: The authors declare no conflict of interest.

Appendix A

Table A1. Annual energy consumptions and carbon intensity of fuels for GSHP and CHP systems from 2021 to 2050.

Year	Energy Use (kWh)		Electricity Generation by CHP (kWh)	Carbon Intensity of Electricity ($kgCO_2$/kWh)									
					GSHP (Electricity)								
	CHP	GSHP		CHP (Gas)	70% Base	70% RES	80% Base	80% High-Bio	80% Re-silience	80% RES	90% Base	90% RES	No. Plan
2021	84,259	18,427	28,796	0.19	0.38	0.38	0.32	0.31	0.42	0.29	0.29	0.29	0.55
2022	84,259	18,427	28,796	0.19	0.35	0.30	0.29	0.29	0.40	0.27	0.25	0.25	0.55
2023	84,259	18,427	28,796	0.19	0.33	0.28	0.25	0.25	0.39	0.25	0.21	0.21	0.55
2024	84,259	18,427	28,796	0.19	0.30	0.27	0.22	0.24	0.38	0.22	0.17	0.17	0.55
2025	84,259	18,427	28,796	0.19	0.28	0.25	0.18	0.22	0.36	0.2	0.12	0.14	0.55
2026	84,259	18,427	28,796	0.19	0.25	0.23	0.16	0.20	0.32	0.18	0.11	0.12	0.55
2027	84,259	18,427	28,796	0.19	0.24	0.21	0.13	0.17	0.31	0.15	0.09	0.10	0.55
2028	84,259	18,427	28,796	0.19	0.22	0.20	0.12	0.15	0.28	0.14	0.08	0.08	0.55

Table A1. *Cont.*

Year	Energy Use (kWh)		Electricity Generation by CHP (kWh)	Carbon Intensity of Electricity ($kgCO_2/kWh$)										
					GSHP (Electricity)									
	CHP	GSHP		CHP (Gas)	70% Base	70% RES	80% Base	80% High-Bio	80% Re-silience	80% RES	90% Base	90% RES	No. Plan
2029	84,259	18,427	28,796	0.19	0.20	0.17	0.10	0.13	0.25	0.12	0.06	0.06	0.55
2030	84,259	18,427	28,796	0.19	0.17	0.15	0.07	0.10	0.24	0.09	0.04	0.04	0.55
2031	84,259	18,427	28,796	0.19	0.15	0.14	0.06	0.10	0.23	0.08	0.04	0.04	0.55
2032	84,259	18,427	28,796	0.19	0.14	0.14	0.06	0.10	0.22	0.08	0.04	0.04	0.55
2033	84,259	18,427	28,796	0.19	0.13	0.13	0.06	0.10	0.21	0.08	0.04	0.04	0.55
2034	84,259	18,427	28,796	0.19	0.11	0.12	0.06	0.10	0.20	0.08	0.04	0.04	0.55
2035	84,259	18,427	28,796	0.19	0.09	0.11	0.06	0.09	0.19	0.06	0.03	0.03	0.55
2036	84,259	18,427	28,796	0.19	0.09	0.10	0.05	0.09	0.17	0.06	0.03	0.03	0.55
2037	84,259	18,427	28,796	0.19	0.09	0.10	0.05	0.09	0.15	0.05	0.03	0.03	0.55
2038	84,259	18,427	28,796	0.19	0.09	0.09	0.05	0.09	0.14	0.05	0.03	0.03	0.55
2039	84,259	18,427	28,796	0.19	0.09	0.09	0.05	0.09	0.12	0.05	0.03	0.03	0.55
2040	84,259	18,427	28,796	0.19	0.08	0.09	0.05	0.08	0.10	0.04	0.03	0.03	0.55
2041	84,259	18,427	28,796	0.19	0.08	0.09	0.05	0.08	0.09	0.04	0.03	0.03	0.55
2042	84,259	18,427	28,796	0.19	0.08	0.08	0.05	0.08	0.07	0.03	0.03	0.03	0.55
2043	84,259	18,427	28,796	0.19	0.08	0.08	0.05	0.08	0.05	0.03	0.03	0.03	0.55
2044	84,259	18,427	28,796	0.19	0.07	0.08	0.05	0.07	0.04	0.03	0.02	0.02	0.55
2045	84,259	18,427	28,796	0.19	0.06	0.07	0.04	0.06	0.03	0.02	0.02	0.02	0.55
2046	84,259	18,427	28,796	0.19	0.06	0.07	0.04	0.06	0.03	0.02	0.02	0.02	0.55
2047	84,259	18,427	28,796	0.19	0.05	0.07	0.04	0.05	0.02	0.02	0.02	0.02	0.55
2048	84,259	18,427	28,796	0.19	0.05	0.06	0.04	0.05	0.02	0.02	0.02	0.02	0.55
2049	84,259	18,427	28,796	0.19	0.05	0.06	0.03	0.05	0.02	0.02	0.02	0.02	0.55
2050	84,259	18,427	28,796	0.19	0.05	0.06	0.03	0.05	0.02	0.02	0.02	0.02	0.55

Appendix B

Table A2. Energy-related CO_2 emission of the GSHP system from 2021 to 2050 with UK decarbonization plans and no plan.

Year	CO_2 Emissions ($kgCO_2$)								
	GSHP (Electricity)								
	70% Base	70% RES	80% Base	80% High-Bio	80% Resilience	80% RES	90% Base	90% RES	No. Plan
2021	7002	7002	5896	5712	7739	5344	5344	5344	10,134
2022	6449	5528	5344	5344	7370	4975	4607	4607	10,134
2023	6081	5159	4607	4607	7186	4607	3869	3869	10,134
2024	5528	4975	4054	4422	7002	4054	3132	3132	10,134
2025	5159	4607	3317	4054	6633	3685	2211	2580	10,134
2026	4607	4238	2948	3685	5896	3317	2027	2211	10,134
2027	4422	3869	2395	3132	5712	2764	1658	1843	10,134

Table A2. *Cont.*

Year	CO_2 Emissions ($kgCO_2$)								
	GSHP (Electricity)								
	70% Base	70% RES	80% Base	80% High-Bio	80% Resilience	80% RES	90% Base	90% RES	No. Plan
2028	4054	3685	2211	2764	5159	2580	1474	1474	10,134
2029	3685	3132	1843	2395	4607	2211	1106	1106	10,134
2030	3132	2764	1290	1843	4422	1658	737	737	10,134
Short-term sum up	50,119	44,959	33,905	37,958	61,726	35,195	26,165	26,903	101,340
2031	2764	2580	1106	1843	4238	1474	737	737	10,134
2032	2580	2580	1106	1843	4054	1474	737	737	10,134
2033	2395	2395	1106	1843	3869	1474	737	737	10,134
2034	2027	2211	1106	1843	3685	1474	737	737	10,134
2035	1658	2027	1106	1658	3501	1106	553	553	10,134
2036	1658	1843	921	1658	3132	1106	553	553	10,134
2037	1658	1843	921	1658	2764	921	553	553	10,134
2038	1658	1658	921	1658	2580	921	553	553	10,134
2039	1658	1658	921	1658	2211	921	553	553	10,134
2040	1474	1658	921	1474	1843	737	553	553	10,134
2041	1474	1658	921	1474	1658	737	553	553	10,134
2042	1474	1474	921	1474	1290	553	553	553	10,134
2043	1474	1474	921	1474	921	553	553	553	10,134
2044	1290	1474	921	1290	737	553	369	369	10,134
2045	1106	1290	737	1106	553	369	369	369	10,134
2046	1106	1290	737	1106	553	369	369	369	10,134
2047	921	1290	737	921	369	369	369	369	10,134
2048	921	1106	737	921	369	369	369	369	10,134
2049	921	1106	553	921	369	369	369	369	10,134
2050	921	1106	553	921	369	369	369	369	10,134
Long-term sum up	31,138	33,721	17,873	28,744	39,065	16,218	10,508	10,508	202,680

Appendix C

Table A3. Emission of CHP system from 2021 to 2050 with UK decarbonization plans and no plan.

Year	CO_2 Emissions ($kgCO_2$)								
	CHP (Gas)								
	70% Base	70% RES	80% Base	80% High-Bio	80% Resilience	80% RES	90% Base	90% RES	No. Plan
2021	10,538	10,538	12,266	12,554	9386	13,130	13,130	13,130	5643
2022	11,402	12,842	13,130	13,130	9962	13,706	14,281	14,281	5643
2023	11,978	13,418	14,281	14,281	10,250	14,281	15,433	15,433	5643
2024	12,842	13,706	15,145	14,569	10,538	15,145	16,585	16,585	5643
2025	13,418	14,281	16,297	15,145	11,114	15,721	18,025	17,449	5643
2026	14,281	14,857	16,873	15,721	12,266	16,297	18,313	18,025	5643
2027	14,569	15,433	17,737	16,585	12,554	17,161	18,889	18,601	5643

Table A3. *Cont.*

Year	CO_2 Emissions ($kgCO_2$)								
	CHP (Gas)								
	70% Base	70% RES	80% Base	80% High-Bio	80% Resilience	80% RES	90% Base	90% RES	No. Plan
2028	15,145	15,721	18,025	17,161	13,418	17,449	19,177	19,177	5643
2029	15,721	16,585	18,601	17,737	14,281	18,025	19,753	19,753	5643
2030	16,585	17,161	19,465	18,601	14,569	18,889	20,329	20,329	5643
Sum up	136,479	144,542	161,820	155,484	118,338	159,804	173,915	172,763	56,430
2031	17,161	17,449	19,753	18,601	14,857	19,177	20,329	20,329	5643
2032	17,449	17,449	19,753	18,601	15,145	19,177	20,329	20,329	5643
2033	17,737	17,737	19,753	18,601	15,433	19,177	20,329	20329	5643
2034	18,313	18,025	19,753	18,601	15,721	19,177	20,329	20329	5643
2035	18,889	18,313	19,753	18,889	16,009	19,753	20,617	20,617	5643
2036	18,889	18,601	20,041	18,889	16,585	19,753	20,617	20,617	5643
2037	18,889	18,601	20,041	18,889	17,161	20,041	20,617	20,617	5643
2038	18,889	18,889	20,041	18,889	17,449	20,041	20,617	20,617	5643
2039	18,889	18,889	20,041	18,889	18,025	20,041	20,617	20,617	5643
2040	19,177	18,889	20,041	19,177	18,601	20,329	20,617	20,617	5643
2041	19,177	18,889	20,041	19,177	18,889	20,329	20,617	20,617	5643
2042	19,177	19,177	20,041	19,177	19,465	20,617	20,617	20,617	5643
2043	19,177	19,177	20,041	19,177	20,041	20,617	20,617	20,617	5643
2044	19,465	19,177	20,041	19,465	20,329	20,617	20,905	20,905	5643
2045	19,753	19,465	20,329	19,753	20,617	20,905	20,905	20,905	5643
2046	19,753	19,465	20,329	19,753	20,617	20,905	20,905	20,905	5643
2047	20,041	19,465	20,329	20,041	20,905	20,905	20,905	20,905	5643
2048	20,041	19,753	20,329	20,041	20,905	20,905	20,905	20,905	5643
2049	20,041	19,753	20,617	20,041	20,905	20,905	20,905	20,905	5643
2050	20,041	19,753	20,617	20,041	20,905	20,905	20,905	20,905	5643
Sum up	380,948	376,916	401,684	384,692	368,564	404,276	413,204	413,204	112,860

Notations: $ACE_{CHP} = AGU_{CHP} \times CI_{Gas} - \left[EG_{CHP} \times \left(CI_{electricity} - CI_{Gas}\right)\right]$, where ACE = Annual carbon emission, CI = Carbon intensity, AGU = Annual gas use, EG = Electricity generation.

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