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Comparative Economic and Experimental Assessment of Air Source Heat Pump and Gas-fired boiler: A Case Study from Turkey

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Abstract: Since sustainability has become a major concern in the construction industry, making economically efficient investment decisions in energy conservation are needed to minimize energy consumption for space heating and cooling. Although Air-Source Heat Pump (ASHP) systems are used to meet buildings' heating and cooling demands worldwide, high initial setup costs limit the widespread use of these systems. This paper presents comparative assessment of ASHP system versus conventional gas-fired boiler system for a real commercial building with a floor area of 2500 m^2 in Istanbul, Turkey. The key performance variable, Coefficient of Performance (COP), of the ASHP system was experimentally evaluated. The experimental results revealed that the system's COP ranged from 3.22 to 4.32, while the outside temperature ranged from 4.8 to 18.6 °C and the supply water temperature ranged from 32.2 to 36.2 °C. Moreover, the economic analysis results showed that despite the high initial cost, ASHP systems are cost competitive against gas-fired boiler in Turkey. ASHP system could reduce the present value of total Life-Cycle Cost (LCC) by up to 26.4% (47,865 USD) compared to the conventional gas-fired boiler system because it can dramatically reduce the energy consumption per year

Keywords: heat pump; radiant heating; life cycle cost; construction management; project management

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1. Introduction

Researchers have focused on the use of renewable energy sources such as geothermal energy and solar energy due to the depletion of fossil fuel resources, pollution, and the resulting environmental problems. The consumption of energy by buildings is one of the leading causes of global environmental problems and the energy crisis [1]. A significant portion of the total global energy consumption is attributable to the heating and cooling of living spaces to ensure that daily activities can be carried out in comfortable conditions. In Europe, 40% of primary energy consumption is used to meet the energy needs of buildings, whereas, in Turkey, the proportion is 50% [2]. Utilizing a heat pump system for heating is both economically beneficial and crucial for protecting natural resources and the environment. Heat pumps offer a significant energy gain while significantly lowering energy costs when compared to conventional heating systems. In industrial applications, heat pumps that use natural sources such as air, soil, and water are widely used [3]. The cost of electricity used to power heat pump systems is the most significant expense. Electricity supplied to heat pump systems should be charged at a lower rate, and low-interest loan offers would be a significant benefit to the widespread use of heat pump systems. In order to address its environmental impact, it is necessary to consider whether the heat pump system will obtain its electrical energy from a thermal power plant or a renewable source [4].

Numerous studies on the COP of ASHP have been conducted [5–8] and some of them are discussed here. Zhang et al. [5] reviewed advances in ASHP systems used in cold climates, categorizing advanced systems as single-stage, two-stage, and multi-stage compression systems, with each focusing on both heating properties and performance. Ramaraj et al. [6] studied performance analysis of liquid flooded compression with regeneration for cold climate heat pumps. Chesser et al. [7] investigated the effectiveness of ASHPs in a field experiment of heavily retrofitted Irish homes. All trial homes qualify as producing renewable heat, although their performance varies from that of the manufacturer's laboratory tests. ASHPs with ratings of 8.5 kW (11.2 kW) underperformed the manufacturer's COP values by an average of (24%) at outdoor temperatures of 7 °C and (11%) at outdoor temperatures of 2 °C. In addition, they tested statistical and machine learning approaches, such as a random forest (RF) model, to predict COPs and assess the difference between the manufacturer's laboratory COPs and the trial findings. Yang et al. examined the performance of the ASHP FOR hot water supply temperatures of 40 °C, 45 °C, 50 °C, and 55 °C. The annual seasonal performance factor for heating systems rises by 16.7%, 19.1%, and 15.4% in London, Aughton, and Aberdeen, respectively, when the set hot-water-supply temperature is decreased from 55 °C to 40 °C. Their results indicate that low-temperature heating reduces the power usage of such heating systems significantly [8].

In terms of thermal comfort, numerous researchers [9,10] have argued that radiant heating systems are more comfortable due to the indirect heat transfer caused by a lower temperature difference. Similarly, Imanari et al. [9] concluded, based on numerical simulations and experiments, that the radiant ceiling panel system creates a more thermally comfortable environment. Al-Othmani et al. [10] reported that radiant heating systems interact directly with building occupants, achieving the desired thermal comfort in less time than convective heating systems. Lin et al. [11] and Sun et al. [12], on the other hand, argued that a fast-acting convective heating system is more comfortable than other types of radiant heating systems. However, there are still some arguments against this theory, and additional research is underway to confirm this assertion [13].

Martinopoulos et al. [14] presumed the heat pump-based air conditioning system was the best overall system among the researched areas and argued that it could be integrated with renewable energy systems. In the study, the heating systems commonly used in residential buildings were evaluated for their efficiency, life cycle, and cost of equipment, and a sensitivity analysis was performed for four climate regions in Greece that used a three-story, multi-family apartment as a case study. According to the findings, geography has a vital impact, since in the metropolitan cities, natural gas is the most cost-effective option, followed by heat pumps and pellet systems. Condensing natural gas boilers are the most economical and environmentally friendly solutions for buildings in densely populated urban environments, where the use of biomass is prohibited due to the large amount of storage space required. This is the reason for their rapid adoption in cities where it is available. Existence of the distribution infrastructure imposes limitations on natural gas usage. In regions lacking a natural gas grid, diesel oil systems are still commonly employed despite the greater cost of fuel. For rural regions with a continental climate, a pellet boiler is preferable over an oil boiler. A heat pump is the ideal technology for districts, which lie in the south and have moderate winters.

Some numerical and experimental analyses have been conducted on radiant heating and cooling systems [15–17]. However, there are still aspects of the system's design that must be improved in order to enhance thermal comfort and energy efficiency. In addition, low-enthalpy heat pump hybrid radiant wall and underfloor heating/cooling systems require comprehensive analyses, such as LCC and Life Cycle Assessment (LCA) analyses in economic and environmental terms, respectively. Despite the fact that their COP values are unrelated to the cost-effectiveness of heat pumps and geothermal energy, the use of these energy sources is likely more efficient due to their COP values [18]. The detailed computational fluid dynamics simulation model of offices with radiant ceiling panels for heating and cooling was examined by Joe et al. [19]. The model was developed using real case studies and verified using 1-year observations.

Hwang and Jeong [20] aimed to develop a proper working strategy for a radiant floor heating system that also utilizes a separate ASHP attached with convective air heating and provides energy savings and thermal comfort in residential settings. In their study, the heating capacity of radiant underfloor heating was calculated per 1 °C change in floor temperature to process heating loads with radiant underfloor heating and air source heating systems, and the remaining heating load was handled by the heating capacity of a convective air heating heat pump. It was reported that the addition of a heat pump system reduced energy consumption by 59.2% compared to radiant floor heating alone. The optimal floor temperature for preventing localized discomfort on the soles is approximately 22–23 °C, therefore, an energy savings of 31.5–37.6% could be confirmed when compared to radiant floor heating alone.

There are papers in the literature comparing the performance of heat pumps and boilers for heating from economic and environmental viewpoints. Naumann and Schropp [21] examined the environmental implications of a condensing gas boiler and ASHP. According to their findings, the consequential LCA method reduces the environmental effect of heat pumps by an average of 46% compared to the attributional method, and the carbon intensity of ASHPs is 70% less than that of condensing gas boilers. Lin et al. [22] performed an LCA comparison of a condensing gas boiler and a hybrid heating pump for a typical kind of existing UK residence. In the baseline settings, the hybrid heat pump might reduce greenhouse gas emissions by 30% compared to the condensing gas boiler. Famiglietti et al. [23] examined the environmental characteristics of a condensing boiler and a gas-driven absorption heat pump as competing technologies to offer space heating and domestic hot water in pre-1980-built buildings that were not renovated. According to their findings, the gas-powered absorption heat pump had a smaller environmental impact than the condensing boiler, primarily because it used less natural gas throughout the usage phase. Particularly, an average reduction of 27% was discovered for CO_2 equivalent, 25% for use of fossil resources, and 22% for weighing results. Luo et al. [24] studied the thermo-economic performance of replacing a coal-fired boiler with a Groundwater Heat Pump system for a greenhouse, where the GWHP system was built to cut emissions and also offer cooling. Despite the fact that the boiler has lower capital costs and operating costs, the analysis of Average Energy Price (AEP) indicates that the GWHP system has a higher economic performance since it has a lower AEP of 0.040 USD/kWh in heating and 0.023 USD/kWh in cooling over an expected lifetime of 20 years, compared to the boiler at 0.052 USD/kWh over a lifetime of 10 years. In the current research, a radiant heating system is used in conjunction with a heat pump to improve the heat pump's performance of the system, although heating systems were not examined in the previous investigations. In addition, this research was performed in a commercial facility of real size and under realistic working conditions.

Hin and Zmeureanu [25] performed life cycle exergy (LCX) and LCC analyses to optimize a solar energy system with four different optimal configurations based on the objective function used. When compared to the base system, optimizations reduced 19% of the system's lifecycle cost, 34% of lifecycle energy use, and 33% of lifecycle exergy. All configurations were reported to be inefficient and economically unviable due to the high cost of solar equipment relative to Quebec's low electricity prices, which prevented them from generating an acceptable financial return. In the calculation, a service life of forty years was used. Transient simulation yields results such as HVAC system performance, COP, heat energy, heat flux, and temperature over a one-year period [26]. In the LCC analysis, scrap costs [27], fossil fuel consumption, and harmful emission values [28] should be included. The LCC is the total cost of owning, operating, maintaining, and (eventually) disposing of the building structure during a given operating period (usually related to the life of the project [28]). Lee [29] included the installation cost at the construction stage, maintenance cost at the maintenance stage, and energy consumption during the operation stage in their life cycle energy and cost analysis. Na et al. [30] used a computer simulation to determine the initial cost of each alternative, such as the construction cost of the air conditioning system, and calculated the energy cost as the operating cost based on the energy consumption of each system.

The use of renewable energy sources has not yet proliferated due to relatively high initial investment costs, and it is necessary to reduce the initial investment costs and/or increase their efficiency (e.g., reducing operating costs), thereby reducing the payback time and making the system economically viable. From a holistic point of view, it is necessary to select heating systems (heat dissipator) that are compatible with energy conversion systems (heat pumps, solar, biogas, or biomass systems, etc.) that use renewable energy sources and to increase their efficiencies. Within the context of this paper, an ASHP system capable of low-temperature heating was paired with a radiant heating system.

Throughout history, various resources have been used to meet the demand load of a growing population [31]. This demand, coupled with ever-increasing constraints, has led to the synergistic combination of diverse sources [32]. For example, a hybrid hydronic radiant heating system designed to achieve significant energy efficiency through synergy was intended to be used in buildings. This system consists of two components: a radiant system and an ASHP. The hybrid system was eventually applied to an office building in order to create synergy. The aim of the paper was to determine whether the ASHP integrated radiant panel wall and ceiling heating system will provide performance at a lower cost in the long run despite its higher initial cost. Although LCC is not considered when designing or selecting HVAC systems and calculations are based on the initial investment cost, it should be considered when assessing the energy–economic performance of renewable energy systems. A realistic LCC analysis could reveal the cost-effectiveness of renewable energy systems over time. In this study, a radiant heating system and an ASHP were implemented in a 2500 m^2 office building. Experimentally, the ASHPs operating costs (electricity consumption) and COP were determined.

Utilizing measurement data, LCC analyses for the proposed system and the alternative gas-fired boiler system were performed. The evaluation results from both systems were compared. It is anticipated that the findings of this study will support the dissemination of the proposed system and inform the decision-making processes. The present study differs from previous studies in the literature in several significant ways. Compared to smaller-scale or lab-based studies, the experiments in this study were conducted in a real-size building and during actual working conditions. Another feature of the radiant system is that it addresses both wall and ceiling surfaces. During the literature review, no studies on commercial or office buildings were found, and there are only a few studies on a small or laboratory scale.

2. Experimental Approach

In this study, experimental measurements were made on an ASHP integrated radiant heating system to evaluate the system performance. Besides similar heating loads (similar outdoor air temperatures and the same building) energy consumption of the gas-fired boiler-driven radiant heating system was also examined to conduct an LCC analysis of both systems. The LCC analysis was carried out, not only based on purchasing and installation costs, but also considering the long-term experimental measurements of thermal and economic parameters during operation. The measurements were taken weekdays between 8:00 and 18:00. Each portion of the structure equipped with a thermostat that allows the occupants to regulate and adjust the temperature. Moreover, the occupations of sections may vary during the day and from day to day, which has an immediate impact on energy usage.

2.1. Building

The building was built as 3 floors on an area of approximately 2500 m^2. There are 3 fabrication areas on the first floor, laboratories, and seminar halls on the second floor, whereas on the third floor there are 4 officer rooms, an open office, an archive, a warehouse, a dining hall, and a fabrication shop. Mechanical equipment, including the ASHP and other devices and immovable ventilation equipment, is located in the equipment room in the attic. The exterior and interior view of the building is given in Figure 1 and the floor plan of the building is given in Figure 2.

Figure 1. Exterior and interior views of the building.

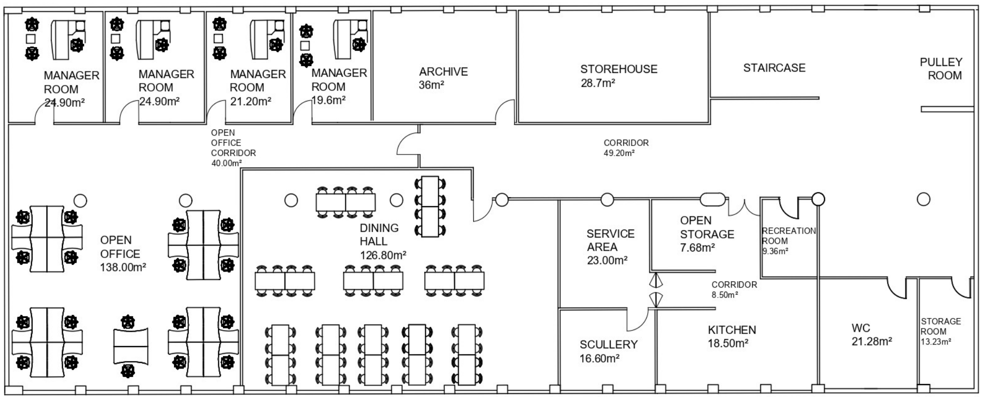

Figure 2. Floor plan.

As shown in Figure 3, the experimental schematic consists of a new experimental radiant heating system, an ASHP, an accumulation tank, collectors, pumps, valves, temperature and pressure sensors, and an expansion tank as well as the piping system. In the system, ASHP was used as the heat source and a radiant system as the heat dissipater. The water heated in the ASHP is sent to the accumulation tank where it is then transferred to the radiant system by the pumps; as for the return line, the water circulating in the radiant system first arrives in the accumulation tank (where the temperature is stabilized) and then being sent to the heat source.

The design heating load (heat demand) of the building has been calculated as around 98 kW according to the design temperature (minimum temperature) of −3 °C. However, the thermal capacity of the mechanical systems (ASHP and condensing boiler) was chosen slightly lower since the minimum temperatures are seen at nights when there are no occupants and devices are non-operational.

2.2. Mechanical Subsystems

The mechanical system is installed in the equipment room built in the attic to protect all the devices and equipment in it against humidity, extreme cold, and extreme heat. A close-up view of the equipment located in the room can be seen in Figure 4.

In closed heating circuits, an expansion tank is employed as a piece of safety equipment to prevent the fluid that expands due to high temperature from damaging the system elements due to high steam pressure by eliminating the pressure increases in the system and thus preventing fluid leakage. The piping was fixed being covered with insulation material to prevent heat loss/gain. The piping also featured gauges to monitor the water pressure, at the inlet and outlet of each of the two pumps, and two at the expansion tank. The accumulation tank, which is ideal for high water temperatures, is used to store the water to be transferred to the radiant heating system and heat the water when needed, i.e., when the water coming from the ASHP is not hot enough, by means of a heat exchanger contained within. The accumulation tank also contributes to extra savings by increasing the efficiency of the ASHP in the system.

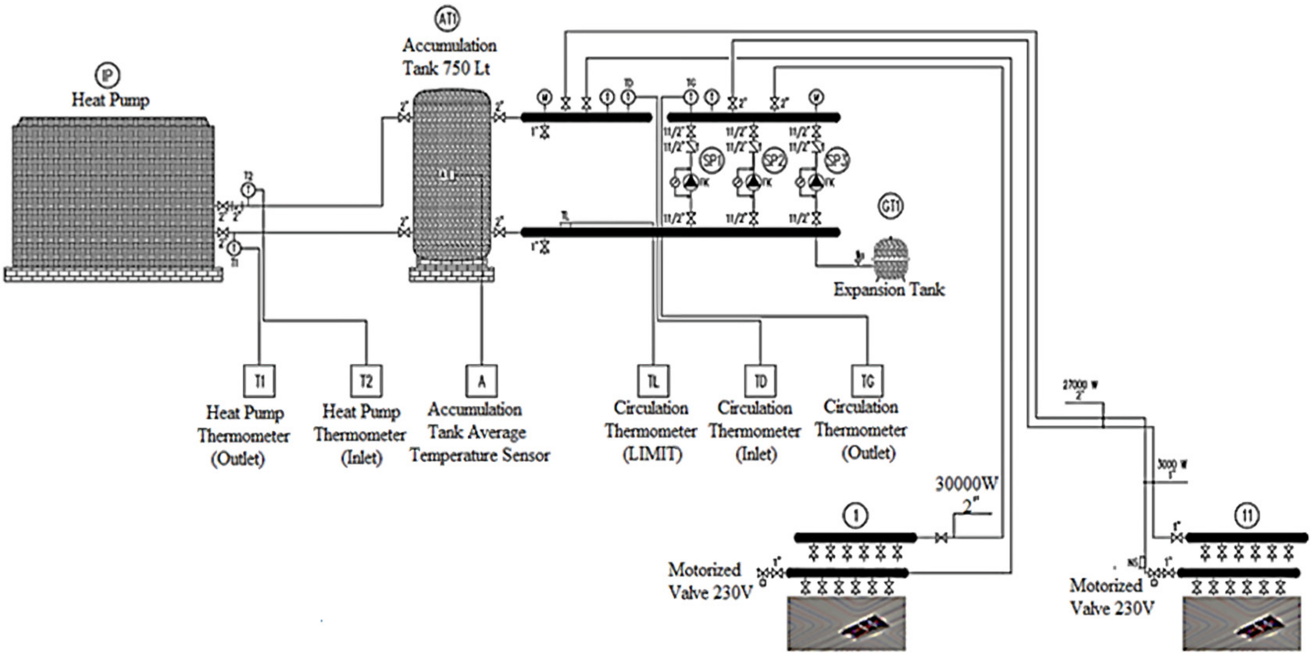

Figure 3. Schematic view of the experimental system.

Figure 4. Mechanical subsystems.

2.3. The Heat Pump

Heat pumps are high-efficiency appliances that meet the demand for heating or cooling even at low temperatures. It also provides hot water while performing the heating or cooling. Heat pumps can be air, ground, or water-source and are capable of efficiently transferring energy from the environment they are fed at cost of low electrical energy consumption. The capacities and power values of the ASHP may vary according to the heating and cooling conditions. In the system, an E75 type air-to-water heat pump, seen in Figure 5, operating at 50 Hz, 400 V, and 30.5 A between −5 °C and 35 °C temperature range was used. The dimensions of this ASHP are 1610 × 1792.5 × 1970 mm and its weight is 905 kg. The ASHP used the R-410A fluid as the refrigerant. The water flow was 13.76 m^3/h, and the connection diameter was 3 inches. There were 2 compressors and 4 fans in the interior installation. In heating mode, the capacity was 80 kW, and the power consumption was 20.5 kW whereas in cooling mode the capacity was 68.8 kW, and the power consumption was 21.2 kW (from the technical specification of the product).

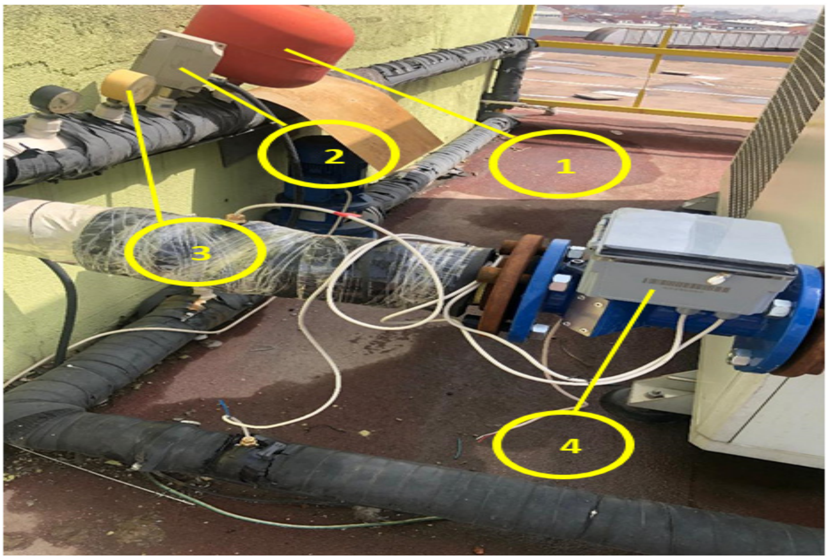

Figure 5. ASHP employed in the system. (1) ASHP expansion tank. (2) Thermocouple and locking system. (3) Analog pressure gauges. (4) UKM-50 ultrasonic flowmeter and calorimeter.

2.4. Measuring Devices

The system employed the ATLAS UKM-50 ultrasonic calorimeter (manufactured by ATLAS SAYAC AS, an R&D and manufacturing business based in Kayseri, Turkey in 2021, which has far greater precision than mechanical meters). The system employed the ATLAS UKM-50 ultrasonic calorimeter (manufactured by ATLAS SAYAC AS, an R&D and manufacturing business based in Kayseri, Turkey in 2021, which has far greater precision than mechanical meters). The UKM-50 can measure at flow rates as low as 0.15 m^3/h and starts metering at a minimum temperature difference of 0.1°C with the help of a pair of heat sensors capable of linear measurement. The Atlas UKM-50 comes with 2 pcs PT100 temperature sensors, which are among the most preferred circuit elements, which enables the flow meter to read the temperature of the fluid and adjust itself accordingly. The specifications of the pumps used in the system are DIN-50, minimum measurement accuracy is 0.1 °C, temperature measurement range is 5–90 °C, maximum applicable pressure (MAP) 16 bar (PN16), and nominal flow 15 m^3/h, minimum flow is 0.15 m^3/h, maximum flow is 30 m^3/h. The accuracy of temperature sensors was Class B (0.15 °C). The precision of the heat meters was Class 3, whereas the accuracy of the electricity meters was Class A, in accordance with the worldwide measuring instruments directive. Class A meters have a maximum allowable error of 3.5% for the operating circumstances observed during the field experiment, whereas Class 3 meters have a maximum permissible error of 5%.

2.5. Control Panel and Data Acquisition Device

The control panel of the system, which shows an energy analyzer, is a monitoring device that enables the continuous monitoring of electrical energy and recording of measurement data, capable of transmitting the records to remote devices through a software and connection interface when necessary. The energy analyzer can also be used to prevent inefficient use of electrical energy that may be encountered as erroneous billing or fines in the future, by monitoring the electrical energy delivered to the end-user. Another reason to use an energy analyzer is that it may be used to measure and record instant rises (swell) and drops that may occur in the electric grid that cause electric devices and electronic cards in all equipment to fail. The data can be transferred to another computer in various formats.

2.6. Gas-Fired Boiler

In order to conduct a comparative study between the ASHP and gas-fired boiler, two wall-hung condensing boilers were attached to the system. The nominal thermal power of each boiler is 48 kW and they are working with 97.5% efficiency for the supply and return temperatures of 50–30 °C (Figure 6). The natural gas consumption of the boiler was measured by the gas flow meter.

Figure 6. Gas-fired boiler.

2.7. The Radiant Heating System

Thermal comfort, the optimum climatic conditions required by human physiology, was aimed to be provided by a heating/cooling system that makes use of radiative heat transfer, which is the most important feature, by which the system provides homogeneous heat distribution. This system, which does not operate in a high-temperature range, as do the conventional heating systems, does not create a hot–cold situation on the surfaces, as the temperature differences are not very high. While the heat transfer in conventional systems is mostly by convection, in a radiant system heat is transferred by radiation. The operating temperature of the system varies between 16–35 °C. The operating temperature of the system is also low since values close to human body temperature are taken as a basis when heating or cooling. This feature, which also extends the life of the device, paved the way for sustainability. Considering that heating is performed by considering the radiative effect, thermal comfort can be achieved even at 2–3°C temperature differences and the heat loss/gain of the building is reduced by up to 15% [15].

The wall and ceiling panels manufactured within the scope of this study consist of three components: plasterboard, serpentine pipes, and insulation material [33]. The components/layers of the radiant panel system and piping are shown in Figure 7.

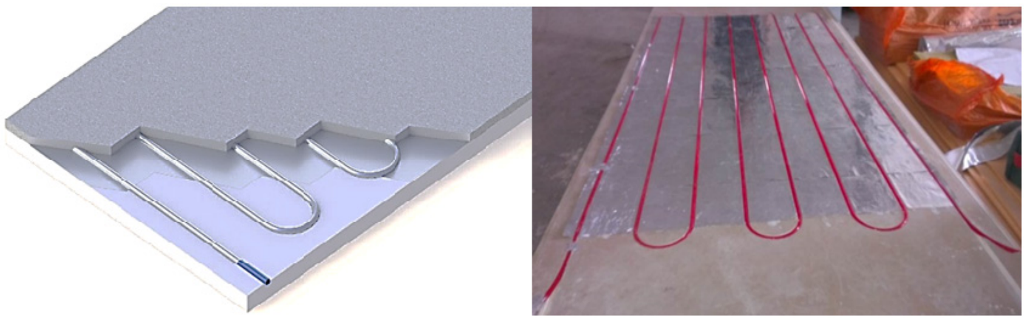

Figure 7. The radiant heating panel [33–35].

Cross-linked 10.1 mm × 1.1 mm × 8 mm inner diameter polyethylene pipes were used in the panels (PEX-a) as embedded in the 15 mm thick plasterboards insulated with 3 cm polystyrene as seen in Figure 7 [34,35]. The distance between the radiant heating pipes is 5 cm and the total length of pipes (including ceiling and walls) is 13.365 m.

Radiant panels were mounted on ceilings and side walls. The number of panels, the location they are installed, and the collectors are given in Table 1, and the overall heating surface area and the total piping length are given in Table 2.

Table 1. The number of panels of the radiant system in the zones.

	Location Conditioned	Number of Panels Fed		
		Wall	Ceiling	Total
1st Collector	Large Office Wall+Ceiling	17	33	50
2nd Collector	Large Office+Executive Office 1, Wall+Ceiling	27	22	49
3rd Collector	Executive Office 2 Wall+Ceiling	5	15	20
4th Collector	Large Office Ceiling+Wall, Dining Hall Ceiling	0	37	37
5th Collector	Large Office Ceiling, Dining Hall Ceiling,	5	44	49
6th Collector	Dining Hall+Executive Office 4 Wall+Ceiling	13	36	49
7th Collector	Executive Office 5 Wall+Ceiling, Warehouse Ceiling	9	39	48
8th Collector	Executive Office 4 Ceiling, Hallway Ceiling,	9	51	60
9th Collector	Hallway Ceiling+Warehouse Ceiling	0	55	55
10th Collector	Kitchen+Dishwasher+Tea House Ceiling	0	47	47
11th Collector	Fabrication Shop Wall+Ceiling	114	313	427

Table 2. Total heating surface area and piping length of the radiant system.

	1st Floor	2nd Floor	3rd Floor
Total heating surface area, m^2	199	692	891
Total Piping, m	2.985	10.380	13.365

Arrangement of the ceiling heating system, piping system, and connection details on the 3rd floor are given in Figure 8.

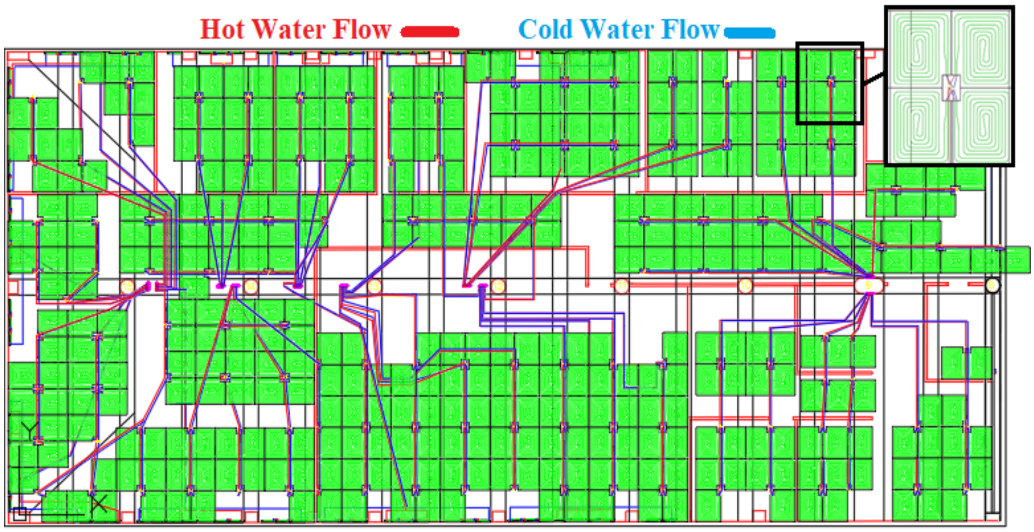

Figure 8. Technical drawing for ceiling panels used in the radiant system (3rd floor).

3. Experimental Data Reduction

The most important characteristic of a heat pump is its COP. The majority of heat pumps operate on the vapor compression cycle principle. The main elements of an ordinary heat pump are the compressor, expansion valve, evaporator, and condenser.

The actual COP is calculated as the ratio of total heat passing from the condenser to the water to the work (energy) input to the system.

$$COP = \frac{Q_{out}}{W_{in}} = \frac{Q_{useful}}{P_{system}} \quad (1)$$

$$Q_{useful} = \dot{m}cp(T_{out} - T_{in}) \quad (2)$$

$$COP = \frac{\dot{m}cp(T_{out} - T_{in})}{P_{system}} \quad (3)$$

where the Q_{useful} was calculated by means of experimental measurements of supply (T_{in}) and return (T_{out}) temperatures and the mass flow rate ($\dot{m}$) via Equation (2). P_{system} was directly measured by the Energy analyzer and (cp) specific heat at constant pressure; it is equal to the change in enthalpy per unit temperature and (W_{in}) is the amount of work given to the system.

4. Results and Discussion

4.1. Thermal Performance of the ASHP System Integrated with a Radiant System

Low-temperature radiant wall/ceiling heating systems pair well with heat pump systems. The huge heat exchange area permits low supply water temperatures, whilst the high thermal capacity permits the reduction of thermal power peaks. Both have a favorable effect on the heat pump's COP. Comparing the performance of a modulating air-to-water heat pump coupled to a radiant wall/ceiling heating system and a gas-fired boiler system in a commercial building is the purpose of the current research. To undertake LCC analysis, the energy consumptions of both systems were experimentally measured.

Experiments were carried out on the ASHP unit integrated with a radiant system in Istanbul from September to April during the heating period in 2020–2021. However, the measurement values between 18 March and 21 April were used to calculate COPs. As there were no employees in the building over the weekend, the system utilized minimal energy and was occasionally turned off. Therefore, weekend measurements were disregarded.

During the experiments, the ambient temperature varied between 8 and 18.6 °C. The COP values of the ASHP and the overall system are important for evaluating efficiency. The typical measurement data (Outdoor Air Temperature, HP Feed Water Temperature, HP Return Water Temperature, Accumulation Tank Water Temperature, Feed Water Mass Flow Rate, Energy Consumption of the Building, Energy Consumption of the HP compressor and auxiliary equipment, Daily average COP of ASHP unit), temperature change and energy consumption for the ASHP system used in the study are given in Table 3 and respective Figures (Figures 9–12) for the weekdays between 18 March and April 21.

The variation in energy consumption of the building and the ASHP in the period between 18 March and 21 April is shown in Figures 9 and 10. The peaks in the energy consumption are seen to occur on weekdays, and relatively lower values were observed on the weekends (data were not included in the chart for weekends). According to the field measurement, the demanded thermal energy value reaches 680 kWh, the corresponding el. energy consumption reaches 199 kWh.

Figures 11 and 12 are the average air temperatures and supply water temperatures for the weekdays between 18 March and April 21. The temperature of the water in the storage tank varies between 32 °C and 36 °C on different days. So, the temperature of the supply water changes according to the flow rates of circulation pumps and the heating demands of the zones. As can be seen from the figures, the main parameter for the supply water temperature is the outside temperature. However, as mentioned in Figure 2, there are several sections in the conditioned area, and each section has a thermostat which enables to the end users to on–off control and alter the temperature settings. Moreover, the occupations of subsection may change during the day and day-by-day, which directly affects the heating demand. For this reason, cumulative effects of the above-mentioned parameters effect the supply water temperature as well as the supply water mass flow rates.

Figure 13 shows the COP of the ASHP during the examined heating period seasons. In order to retain the conditioned area at the same temperature, we must use more electricity, hence the amount of electricity used by ASHP rises as the outside temperature drops. As can be seen in Figure 13, the COP values somewhat fluctuated during the experimentation period, but not that obviously. Although COP values were measured hourly, daily averaged values were used. According to the results, the COP of the ASHP system ranged between 3.22 to 4.32, while the outdoor temperature varied from 4.8 to 18.6 °C.

Table 3. Operating data and COP of the system on weekdays in March and April 2021.

Date	Average Temperature, °C				Feed Water Mass Flow Rate m^3/h	Energy Consumption kWh		Daily Average COP of HP
	Outdoor Air	Feed Water	Return Water	Accumulation Tank		Building	HP	
18 March 2021	8.0	33.1	31.8	34.8	44.90	393.8	107	3.68
19 March 2021	9.4	34.3	31.7	35.0	19.54	345.9	92	3.76
22 March 2021	10.5	34.8	30.9	33.6	19.88	505.7	130	3.89
23 March 2021	6.2	32.3	30.2	33.4	47.85	652.4	188	3.47
24 March 2021	4.8	32.6	29.7	32.4	30.94	602.1	187	3.22
25 March 2021	5.9	33.7	30.7	33.0	33.65	680.6	199	3.42
26 March 2021	7.5	33.6	30.6	32.4	30.30	609.8	173	3.53
29 March 2021	11.5	35.1	31.6	34.3	21.30	491.7	122	4.03
30 March 2021	7.9	34.4	31.1	34.3	16.94	373.9	103	3.63
31 March 2021	9.8	34.2	31.0	34.3	18.77	394.3	106	3.72
1 April 2021	10.1	34.7	31.6	34.4	19.87	415.5	108	3.85
2 April 2021	10.6	33.3	31.2	34.4	28.97	393.1	100	3.93
3 April 2021	8.1	34.3	31.1	35.0	18.67	399.9	107	3.74
6 April 2021	16.3	34.1	30.7	34.5	11.34	257.7	61	4.23
7 April 2021	9.3	34.0	31.2	34.8	18.24	338.0	87	3.89
9 April 2021	14.8	36.2	31.0	35.3	14.36	487.3	118	4.13
10 April 2021	16.9	32.2	30.0	33.7	27.09	388.1	92	4.22
11 April 2021	14.3	34.6	31.0	35.8	15.02	359.1	90	3.99
14 April 2021	14.9	35.4	30.8	32.2	11.34	345.7	83	4.17
18 April 2021	14.6	34.4	31.3	34.3	23.45	484.9	118	4.11
21 April 2021	18.6	36.1	31.0	34.0	13.07	436.4	101	4.32

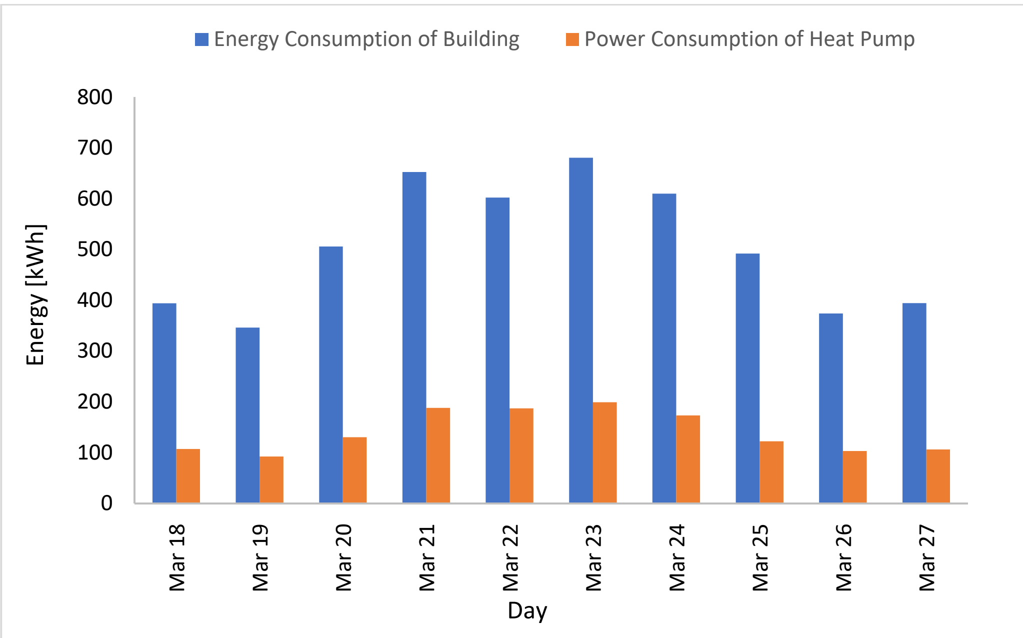

Figure 9. Energy consumption of the building and ASHP between 18 March and 31 March (2021).

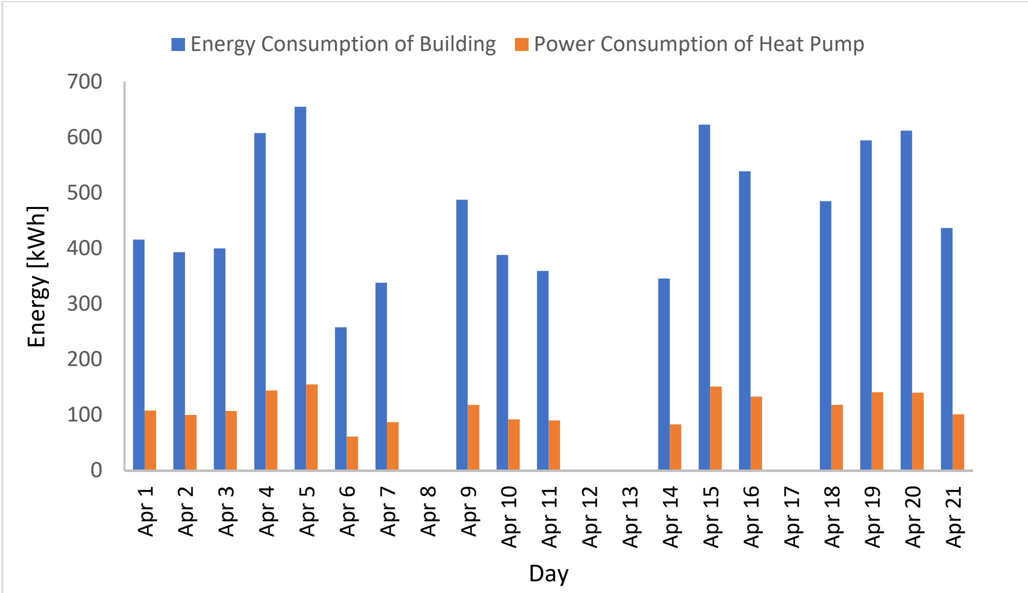

Figure 10. Energy consumption of the building and ASHP between 1 April and 21 April (2021).

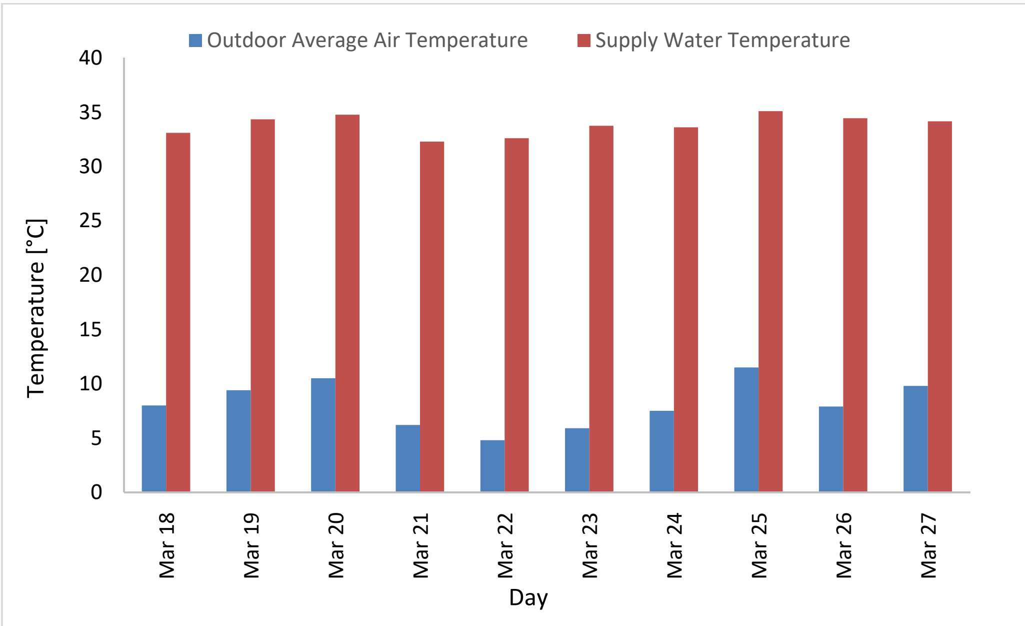

Figure 11. Average outdoor air temperature and HP supply water temperature between 18 March and 31 March (2021).

There is a strong correlation between outside air temperature and COP, which means that changes in the source temperature (in this example, outside air temperature) were a major contributor to the observed fluctuation. The empirical relation between the average outdoor air temperature ($T_{o,ave}$) and the COP value are provided below.

$$COP = 0.0722 \times (T_{o,ave}) + 3.0618 \quad (4)$$

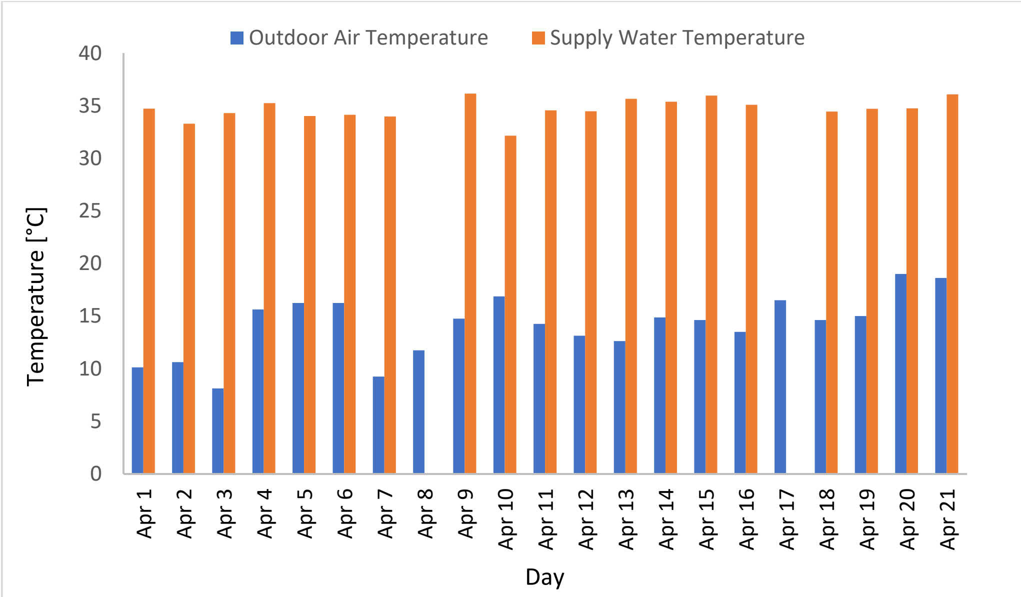

Figure 12. Average outdoor air temperature and HP supply water temperature between 1 April and 21 April (2021).

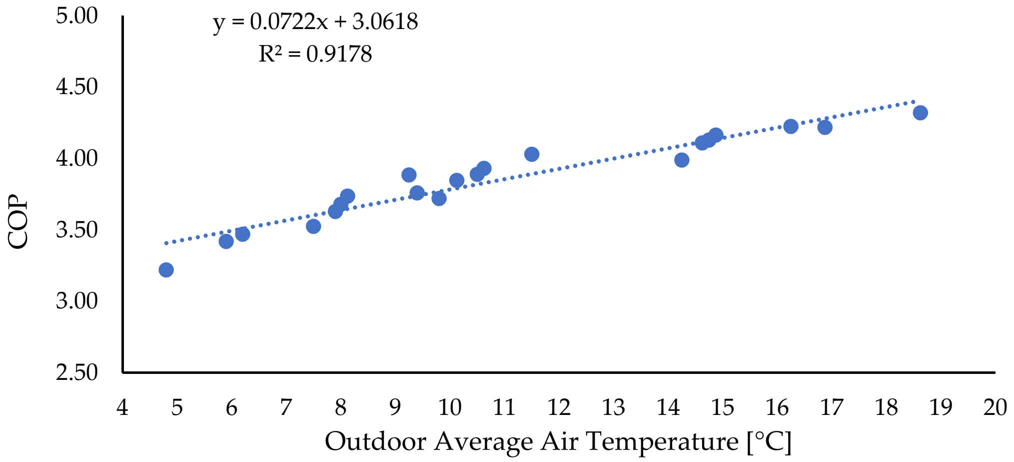

Figure 13. Variations of COP of the ASHP with outdoor air temperature.

4.2. Life Cycle Cost Analysis (LCC)

Energy or fuel usage records from previous operations may give trustworthy and precise estimations. As a result, when the ASHP was not utilized, prior year (2019–2020) statistics were used for the boiler's fuel usage. The ASHP measurement of the heating season in 2020–2021 figures were utilized for the power consumption of the ASHP. The data were acquired through measurement devices set up in the office building and were then used in the LCC analysis, the details of which are presented below. The comparison of an ASHP to a gas-fired boiler necessitates the use of the life-cycle cost analysis to evaluate energy conservation. The life-cycle cost analysis was selected to treat this problem because the technique is suitable for assessing the impact of the heating system alternatives on energy cost.

The primary factor affecting the energy consumption and boiler-ASHP consumption of a building in 2020 and 2021 is the outside air temperature during both study periods. In this study, the performance of the ASHP and the gas-fired boiler systems was analyzed from September through April using numerical analysis; thus, only the heating energy demand for this period was considered. Considering the entire heating season (September to April), the average outside air temperature for both systems in 2020 and 2021 is approximately 11.8 °C and 11.1 °C, respectively. Although there is a small difference between the two distinct periods, the outcomes were not varied significantly. In LCC analysis of ASHP and boiler, examinations were carried out in the heating season (September–April), while for COP examinations of ASHP, only March–April data were utilized. During the periods analyzed, the overall energy consumption of the ASHP and of the condensing boilers are given in Table 4. The electricity consumption of the ASHP was measured by an energy analyzer, whereas a gas meter was used for the natural gas consumption of the boiler.

Table 4. Energy consumption of both systems.

Period	Cost ($)	Energy Consumption (kWh)	Period	Cost ($)	Energy Consumption (kWh)
	Gas-Fired Boiler			ASHP	
September (2019)	550.0	2323.9	September (2020)	262.1	1242.7
October (2019)	721.9	3050.1	October (2020)	349.5	1656.9
November (2019)	888.4	3754.0	November (2020)	476.5	2259.4
December (2019)	1155.0	4880.1	December (2020)	655.2	3106.7
January (2020)	1924.9	8133.6	January (2021)	1310.5	6213.5
February (2020)	2309.9	9760.3	February (2021)	1747.3	8284.6
March (2020)	1283.3	5422.4	March (2021)	748.8	3550.6
April (2020)	1050.0	4436.5	April (2021)	476.5	2259.4

This study compares an ASHP to a gas-fired boiler producing heat for a real commercial building with a floor area of 2500 m^2 in Istanbul, Turkey. The measured energy consumptions and costs for each case are listed in Table 4.

The following equation shows an alternative LCC formulation that describes the discounting of future costs to present value and their summation into a single LCC number [36]:

$$PVLCC = IC + AEC \times UPV* + AOM \times UPV \tag{5}$$

where

PVLLC = the present value of total life-cycle cost,

IC = Initial cost (purchase and installation cost)

AEC = Annual energy cost for heating

AOM = Annual operation and maintenance cost

UPV = Uniform Present Value Factor

UPV* = Modified Uniform Present Value Factor

The UPV factor is the appropriate choice in this case because the costs are annually recurring. The discount factors provided with this study are based on real discount rates and are therefore intended for use only with economic analyses conducted in constant dollars (in which the purchasing power of the dollar is held constant). The UPV* is used to calculate the PV recurring annual amounts that change from year to year at a constant escalation rate, *e*, over *N* years, given discount rate (*d*).

$$UPV* = \left(\frac{1+e}{d-e}\right)\left[1-\left(\frac{1+e}{d-e}\right)^{N}\right] \tag{6}$$

Turkey 2021 Energy Policy Review of The International Energy Agency can be used to calculate energy price escalation rates.

Table 5 is a listing of the major costs for each alternative.

It is assumed that both alternatives will last 20 years (t), and they are both assumed to have no salvage value remaining at the end of the 20-year study period [37]. The yearly electricity cost, evaluated at the present price of electricity, is shown in Table 5.

Table 5. Costs of the considered systems.

Type of Costs	ASHP	Gas-fired Boiler
Initial Cost (Purchase and Installation)	$41,500	$35,720
Initial Annual Electricity Cost	$6026.5	$9883.4
Initial Annual Maintenance and Operation Cost	$640.25	$529.5

It is crucial to note that there is uncertainty regarding how future energy prices will develop. Sensitivity analysis can be useful for treating uncertainty. Using Equation (5), the range of PV (or net savings) that results from inserting different values for the rate of energy price escalation rates is shown below.

Example 1: The UPV* factor is based on a 10% discount rate, a 6% escalation rate for electricity, and 20 years. Furthermore, it is believed that occupants will fund the cost of the heating system by private investment rather than taking out loans or any other type of credit.

$$\text{PVLCC (ASHP)} = \$41.500 + \$640.25 \times \text{UPV (d = 10\%, 20 years)} + \$6026.5 \times \text{UPV* (e = 6\%, d = 10\%, 20 years)}$$

(The UPV* factor is derived from Energy Price Indices and Discount Factors for Life-Cycle Cost Analysis—2022: Annual Supplement to NIST Handbook 135)

$$\text{PVLCC (ASHP)} = \$41{,}500 + \$640.25 \times 8514 + \$6026.5 \times 13{,}867 = \$130{,}520.56$$

$$\text{PVLCC (Gas-fired boiler)} = \$35{,}720 + \$529.5 \times 8514 + \$9883.4 \times 13{,}867 = \$177{,}281.27$$

Example 2: 10% discount rate; 0% energy price escalation rates, and 20 years.

$$\text{PVLCC (ASHP)} = \$41{,}500 + (\$640.25 + \$6026.5) \times \text{UPV (d = 10\%, 20 years)} = \$41{,}500 + \$6666.75 \times 8514 = \$98{,}260.7095$$

$$\text{PVLCC (Gas-fired boiler)} = \$35{,}720 + (\$529.5 + \$9883.4) \times 8514 = \$124{,}375.4306 \quad (7)$$

Thus, the savings range goes from a positive $26,114. 7211 at a zero rate of % energy price escalation up to $46,760 for a 6% rate of price escalation.

5. Conclusions

Examining the utilization of renewable energy sources, especially heat pumps, can be seen to have drawn a great deal of attention for being environmentally friendly and economical. However, the use of renewable energy sources has not proliferated due to the high initial investment cost. Therefore, it is necessary to reduce the initial investment costs and/or increase their efficiency (e.g., reducing operating costs). For this purpose, from a holistic point of view, the selection of heating systems should be compatible with energy generation systems running on renewable energy sources, and their efficiencies should be improved. For these purposes, a radiant heating system integrated with an ASHP system was examined experimentally. The COP was experimentally calculated for various outdoor and supply air temperatures (source and sink temperature). Then, the LCC analysis of the ASHP system was carried out, and the results were compared with those of gas-fired boilers.

The testing was carried out in a real commercial building in Istanbul, Turkey, with a floor area of 2500 m^2. The ASHP coupled with the radiant system's main performance characteristic, COP, was experimentally examined. In order to acquire data for thermal and economic parameters, necessary equipment such as meters and thermocouple sensors were supplied and made ready for use prior. In the experimental part of the research, after selecting the proper devices to acquire measurement data for parameters of interest, such as temperature, flow rate, heat flux, and energy consumption at the inlet and/or outlet of each component, all measurement devices were connected to a data-logger, which is connected to a computer over a software interface, and experimental data were recorded. The experimental findings showed that the system's COP varied from 3.22 to 4.32, for the experimental conditions of supply water temperature ranging from 32.2 °C to 36.2 °C and the ambient temperature ranging from 4.8 °C to 18.6 °C.

This study also concludes that the ASHP system has a higher initial cost than the gas-fired boiler. However, in terms of LCC analysis, the ASHP is more effective than the gas-fired boiler.

According to the results, the annual operating cost of the gas-fired boiler is about 64% higher than the ASHP system. Considering the total cost for a 20-year period, the ASHP used in this study was found to be more advantageous than a gas-fired boiler system in terms of the economic point of view. PVLCC of the ASHP system is about $130,520 for 20 years, while this value in the gas-fired boiler system is about $177.281. When compared to a gas-fired boiler, the ASHP is expected to save a total of $46.760 over its lifespan. Further studies should focus on the performance evaluation of ASHP integrated with radiant cooling systems.

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