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Original scientific paper

Energy and Cost Evaluation of Different HVAC Systems in an Office Building

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Abstract: Researchers state that people spend about 90 percent of their time indoors, and accordingly, the place of HVAC systems in our lives is increasing day by day. This brings about an increase in energy consumption. Considering the amount of energy consumption for developed and developing countries today, it is seen that the role of HVAC systems is quite high. Therefore, energy consumption costs and investment costs are the main factors to be considered in HVAC system selection. In this study, for a sample office building, six different HVAC systems (water-cooled and air-cooled variable flow cooling systems, air handling unit system, fan coil systems, water source and air source heat pump systems and split air conditioning system) are analyzed in terms of energy consumption, initial investment costs, operating costs and ease of operation. The advantages and disadvantages of the systems were compared with each other, and as a result of the calculations, it was seen that air-cooled systems consume an average of 33% less energy than water-cooled systems and their investment costs are 30% lower.

Keywords: HVAC systems; fan-coil; heat pump; VRV systems

1 INTRODUCTION

With the developing technology, many different mechanical installation systems can be applied to reach the desired comfort conditions in office buildings. System selection is generally made by considering criteria such as the purpose of use of the building, the climatic conditions of the region where the building is located, the new/existing building condition, mechanical system limitations (material strength classes, device capacities, etc.), architectural structure, operating cost, initial investment cost. However, many different parameters affect the system selection and one of these parameters is the floor height. The researchers experimentally compared the fan-coil system with the underfloor cooling system in terms of thermal comfort at different floor heights. In these experiments, it was seen that the fan-coil system in low ceiling rooms and the floor cooling system in high ceiling rooms are more advantageous [1]. One of the important issues in system selection is the energy source used. The effect of the energy source used on the costs has also been investigated in the literature. Christodoulides et al., in their study, compared the costs of an air source heat pump and a ground source heat pump based on a typical building in Cyprus. It has been seen that the amortization period of the ground source heat pump is twenty years advantageous compared to the air source system [2]. Other important factors in system selection are energy savings and efficiency. Li et al. has discussed the energy savings and economic efficiency of fan-coil and floor cooling systems according to Chinese climates by performing exergy analysis. It has been determined that the underfloor cooling system is approximately 30% more efficient in terms of exergy than the fan-coil system [3]. When the cooling energy performance of the water-cooled VRF system and the AHU system in a commercial building are compared, it has been observed that the VRF system provides 15% energy savings per year in cooling compared to the AHU system [4]. Another important point to be considered in the system to be selected is to save energy in annual electricity consumption. Researchers experimentally and numerically compared the air handling unit system, fan-coil units and heat recovery systems in an office building according to their electricity consumption amounts. As a result, it has been seen that the air handling unit system and the system with fan-coil units provide energy savings between 1.15% and 12.96% [5]. The climatic conditions of the region where the system will operate affect the energy saving and operating performance of the system. In this context, when VRF and VAV systems are compared in terms of energy saving potential according to the climatic conditions of the USA, it is seen that the VRF system is more advantageous than the VAV system in most of the climates in the USA [6]. In another case study conducted in China, they compared VRF and VAV systems, to operate in office buildings in China, in terms of energy performance and found that the VRF system was more efficient [7]. In another study, energy analysis was performed for VRF, VAV and fan-coil systems under cooling conditions. As a result, it has been seen that the VRF system is the most efficient system among the systems compared in terms of energy consumption [8].

One of the factors affecting efficiency in system selection is preferring individual systems instead of compact and complex systems and providing floor-based solutions. When the VRF system is examined centrally and individually for the same office building, it is seen that the individual system provides energy savings compared to the central system [9]. Luo et al. conducted a study on the energy consumption of houses in Beijing. As a result, it has been seen that decentralized systems cause less energy consumption than centralized systems [10]. One of the important factors affecting the efficiency is the use of natural energy resources in the system. The energy obtained from air, water and soil increases efficiency in the long run when used as a source by the system. When the VRF system and the ground source heat pump are compared in terms of energy efficiency, it is seen that the ground source heat pump is 9.4-24.1% more efficient than the VRF system [11]. It should also be taken into account that the soil will remain at a constant temperature in the long term if soil is used as an external source in system selection. Amir et al. compared air source heat pump and ground source heat pump in terms of thermal performance. In this study, in which a house in Canada was examined, they found that the ground source heat pump showed a more stable performance due to the constant temperature of the soil and, accordingly, it was more efficient than the air source heat pump [12].

In this study, six different mechanical installation systems (Air cooled variable flow cooling systems, Water cooled variable flow cooling systems, Air handling unit system-AHU, Fan coil systems, Air source heat pump systems, Water source heat pump systems) were applied on a model office building. The advantages and disadvantages of the systems against each other, initial investment costs, operating costs, ease of operation and amortization periods are compared, and it is examined which system is the most efficient. For the sample office building, system modeling was done with the Carrier Hap® program and heating/cooling loads were calculated. Devices were selected using the results obtained. According to the devices selected for each system, operating and initial investment costs were calculated and the systems were analyzed using the data obtained.

2 MATERIALS AND METHODS

2.1 Building and System Description

The model office building discussed in this study consists of a basement, ground floor, first floor and attic. It has a total area of 3250 m^2, of which the basement floor is 850 m^2, the ground floor is 850 m^2, the first floor is 800 m^2 and the attic is 750 m^2. Fig. 1 shows the section view of the model office building.

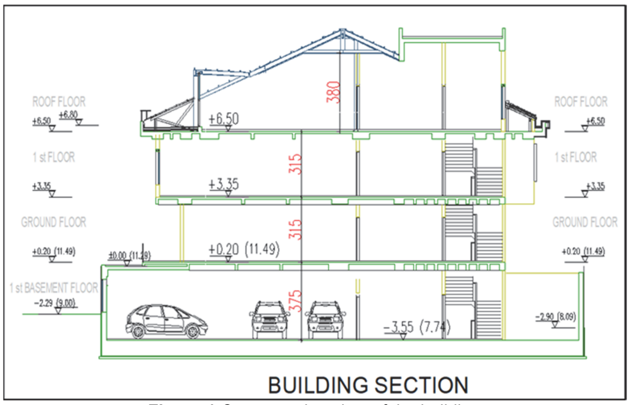

Figure 1 Cross-section view of the building

There are technical offices and a car park in the basement, and office units on the ground floor and the first floor and the attic. Floor heights; 3.75 m in the basement, 3.15 m in the ground and first floors, and 3.45 m in the attic floor. The section view of the model office building is shown in Fig. 2.

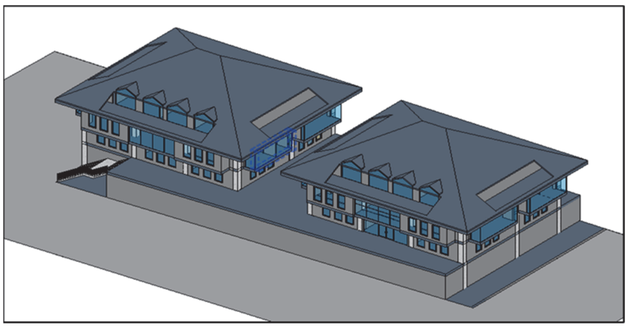

Figure 2 Plan of the building

Heating system, air conditioning system and ventilation system were designed for the model office building. In addition to these, a clean water installation has been designed only in water-cooled systems. The building is located in Istanbul. The calculation and design of the air conditioning and ventilation system has been made in accordance with DIN, BS, ASHRAE, SMACNA standards. Heating and cooling have been made in all parts of the building except for the parking lot and mechanical areas. Alternative systems calculated for the model office building are as follows: Air-cooled Variable Flow Cooling System, Water-cooled Variable Flow Cooling System, Air Handling Unit System, Four-pipe Fan-Coil System, Air-source Heat Pump System (Four-pipes Fan-coil), Water-source Heat Pump System (Four-pipes Fan-Coil).

2.2 System Design Conditions

The building is at 41.0° latitude, –28.8° longitude coordinates and is 11 m above sea level. The outdoor design conditions taken into account in the calculations are given in Tab. 1 [13].

Table 1 Outdoor design conditions

Design parameters	Temperature
Outdoor temperature (winter conditions)	–3 °C
Dry-bulb temperature	33 °C
Tday-Tnight	10.5 °C
Unconditioned space temperature	30 °C
Unheated space temperature	12 °C
Ground temperature adjacent to the outer wall	3 °C

In the calculations, it is foreseen that the wet areas will not be heated to 20 °C in the winter and not cooled in the summer, while the other spaces will be heated to 20 °C in the winter and cooled to 24 °C in the summer. The internal calculation conditions of the spaces are given in Table 2 [14].

Table 2 Indoor design temperatures

Space	Temperature (Summer Conditions)	Temperature (Winter Conditions)
Lounge	24 °C	20 °C
WC	30 °C	20 °C
Hallway, entree	24 °C	20 °C
Office	24 °C	20 °C
Meeting room	24 °C	20 °C

The thermal conductivity coefficient U (W/m^{2}K) of the building materials was determined by considering the TS 825 (ICS 91.120.10) standards [13]. Calculations were made by accepting the shading coefficient of the glasses as 0.40.

2.3 Minimum Fresh Air Requirements

The number of people in the rooms and the required minimum amount of fresh air must be known for the heat gain calculations of the building. The amount of fresh air and the number of people admitted to the rooms are shown in Tab. 3.

The amount of exhausted air and hourly air exchange values from wet areas and storeroom are given in Tab. 4.

Table 3 Fresh air requirements and occupancy

Space	Minimum fresh air requirements	Number of people
Lounge	30 m^3/h per person	According to furnishing
Meeting hall	30 m^3/h per person	According to furnishing
Administration office	36 m^3/h per person	1 person in 7 m^2
Resting room	36 m^3/h per person	According to furnishing
General areas	30 m^3/h per person	1 person in 5 m^2
Office	36 m^3/h per person	1 person in 5 m^2

Table 4 Hourly air exhaust amounts

Space	Hourly air exhaust amounts	External air-source
WC	8-12	With leakage from neighboring areas
Storeroom	2-12	With leakage from neighboring areas
Kitchen hood	250-400 m^3/h person	With leakage from window

2.4 Lighting and Device Loads

One of the factors that cause heat gain is the electrical load of the lamps and devices that provide lighting in the conditioned spaces. The electrical and lighting load values that vary depending on the use of the spaces are given in Tab. 5.

Table 5 Lighting and device loads of spaces

Space	Lighting loads / W/m^2	Device loads
Office	25	250 W/person
Meeting hall	25	500-750 W
Administration office	25	1000 W
Resting room	25	250 W

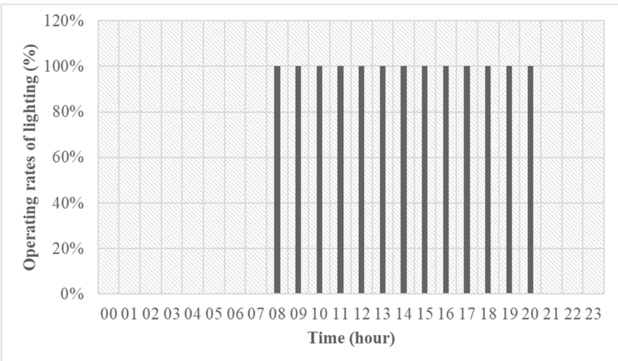

Figure 3 Operating rates of lighting according to time zones

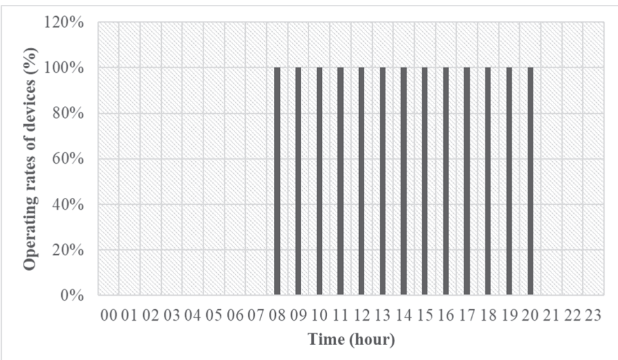

Figure 4 Operating rates of devices according to time zones

The building generally consists of offices. The amount of lighting in the offices, the working time of the devices and the time that people are in the office are shown in Figs. 3, 4 and 5, [14].

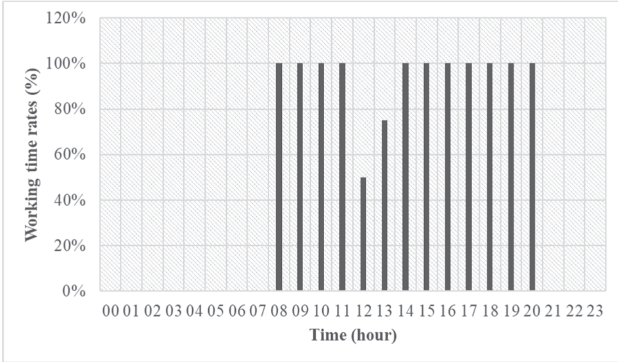

Figure 5 Working time rates according to time zones

3 RESULTS AND DISCUSSION
3.1 Air-Cooled Variable Flow Cooling System

In this system, the boiler meets the need for heating the domestic water, while the heating and cooling processes of the spaces are provided by the Air-cooled variable flow (VRV) unit, and the ventilation need is provided by the Heat Recovery (HRV) system. The heating and cooling loads needed by the spaces were calculated in the Carrier Hap 4.50 program and device selections were made. The initial investment cost for the air sourced VRV system was calculated by designing in line with the results obtained. Energy analysis was made using the system data created in the program. As a result of the energy analysis, the operating cost was calculated, and system graphics were created on an annual and monthly basis. In the VRV system, there is no annual natural gas fuel consumption since the heating and cooling processes of the spaces are done with VRV devices.

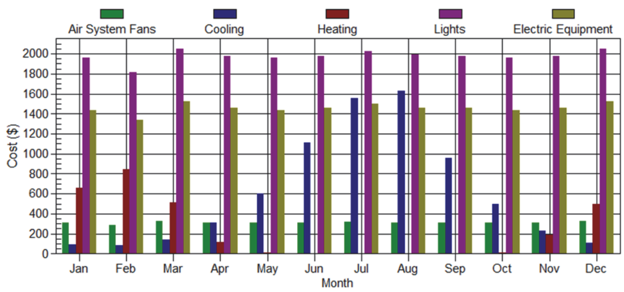

Figure 6 Monthly cost graph of system components

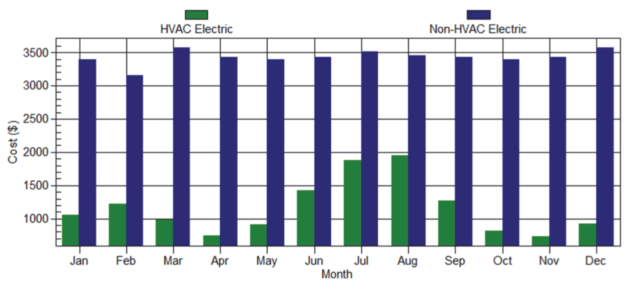

Figure 7 Monthly energy cost graph

For the air-cooled VRV system, monthly cost graphs and monthly energy cost graphs of system components are shown in Figs. 6 and 7, respectively. While the HVAC system equipment constitutes 25.2% of the annual electricity consumption of the building, the remaining

74.8% is due to lighting, electrical devices, and similar equipment. While the need for hot water constitutes 81% of the annual natural gas consumption of the building, 19% is due to the need for the kitchen (cooking).

3.2 Water-cooled variable flow cooling system

The only difference of this system from the first alternative system is that the VRV outdoor unit, which provides the heating and cooling needs of the spaces, uses water instead of air as an external source. Compared to the air-cooled system, additional devices such as the cooling tower and the pump feeding the cooling tower, the hydrophore, increase the operating and investment costs for this system.

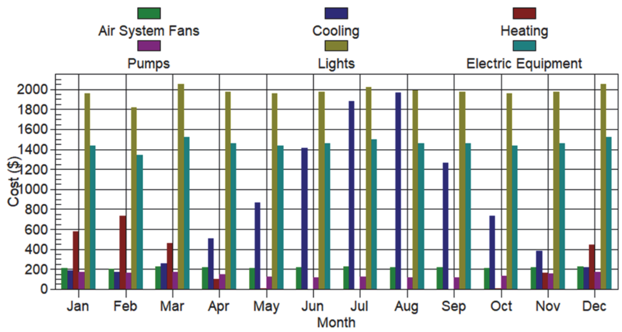

Figure 8 Monthly cost graph of system components

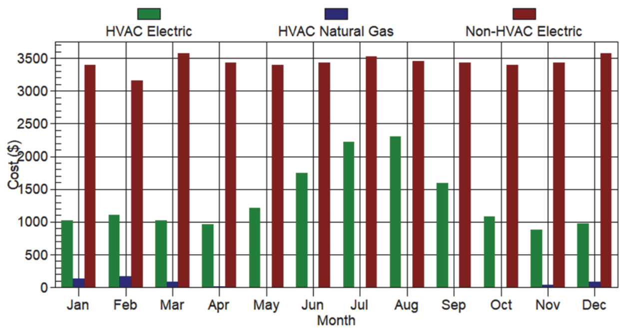

Figure 9 Monthly energy cost graph

In the VRV system, there is no annual natural gas fuel consumption since the heating and cooling processes of the spaces are done with VRV devices. For the water-cooled VRV system, monthly cost graphs and monthly energy cost graphs of system components are shown in Figs. 8 and 9, respectively. While HVAC system equipment constitutes 28.8% of the annual electricity consumption of the building, the remaining 71.2% is due to lighting, electrical devices and similar equipment. While 92% of the annual natural gas consumption of the building is due to the need for hot water and water-cooled VRV, 8% is due to the need for the kitchen (cooking).

3.3 Air Handling Unit System

In this system, the boiler meets the domestic water heating requirement and the heating load required for the air handling unit heater coil, while the heating, cooling and ventilation needs of the spaces are provided by the air handling unit.

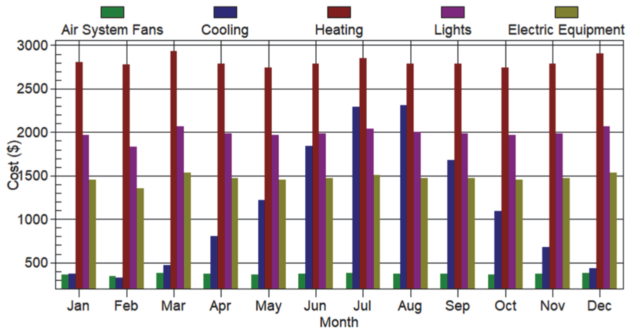

Figure 10 Monthly cost graph of system components

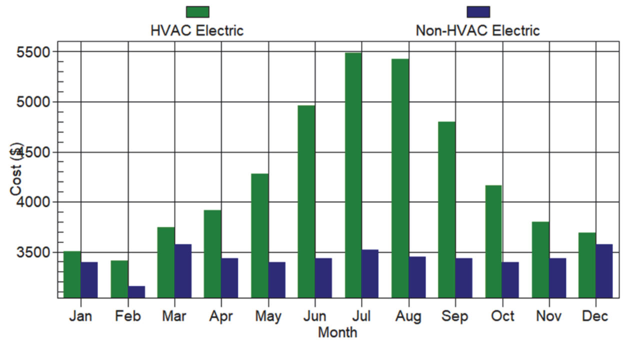

Figure 11 Monthly energy cost graph

For the air handling unit system, monthly cost graphs and monthly energy cost graphs of system components are shown in Figs. 10 and 11, respectively. While 55.4% of the annual electricity consumption of the building consists of HVAC system equipment, the remaining 44.6% is due to lighting, electrical devices and similar equipment. While 93% of the annual natural gas consumption of the building is due to the need for hot water and the air handling unit coil, 7% is due to the need for the kitchen (cooking).

3.4 Four-Pipe Fan-Coil System

In this system, the heating and cooling needs of the spaces are provided by four-pipe fan coil units. While the fan coil heating need is met by the boiler, the cooling need is met by the chiller. In the four-pipe fan coil system, the cooling and heating needs of the office units are met at the same time. While heating is done in one of the office units, cooling can be done in another unit at the same time. In this system, four pipes feed the fan coil indoor units, namely the heating flow and return, and the cooling flow and return pipes.

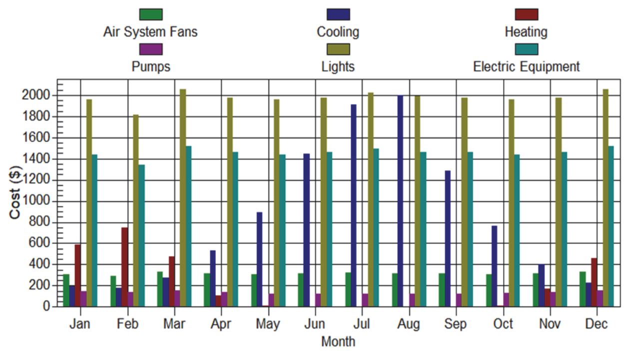

Figure 12 Monthly cost graph of system components

For a four-pipe fan coil system, monthly cost graphs of system components and monthly energy cost graphs are shown in Figs. 12 and 13, respectively. While 30.4% of the annual electricity consumption of the building consists of HVAC system equipment, the remaining 69.6% is due to lighting, electrical devices and similar equipment. While 92% of the annual natural gas consumption of the building is due to the need for hot water and fan coil heating, 7% is due to the need of the kitchen (cooking).

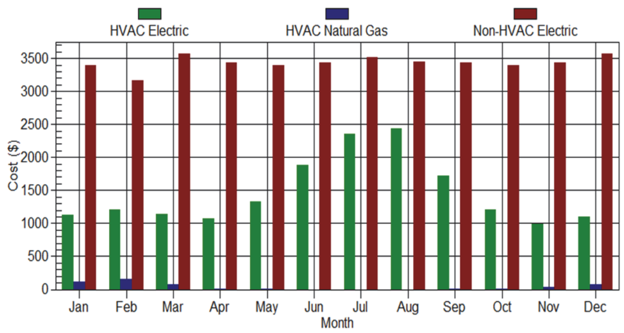

Figure 13 Monthly energy cost graph

3.5 Air-Source Heat Pump System

In the air source heat pump system, the heating and cooling of the spaces are provided by four-pipe fan coil indoor units, while the alternative of meeting the heating and cooling load with an air source heat pump has been considered. In this alternative system, the heat pump does the work of the boiler that meets the heating needs and the chiller devices that meet the cooling needs in the four-pipe fan coil system. In the air source four-pipe heat pump system, heating and cooling can be done simultaneously due to the four-pipe fan coil infrastructure. In the four-pipe heat pump system, in addition to the heating and cooling needs of the fancoil indoor units, the heating need of the domestic hot water tank is also provided by the heat pump.

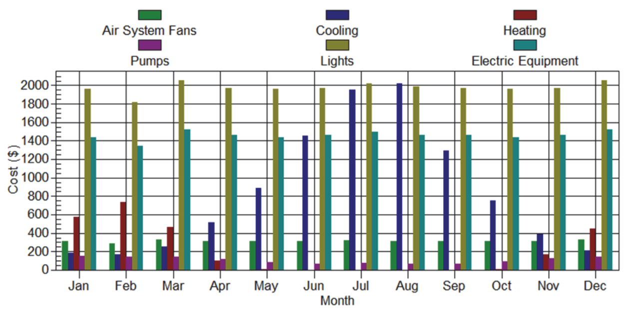

Figure 14 Monthly cost graph of system components

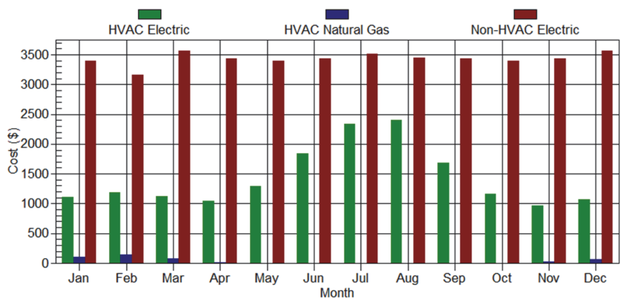

Figure 15 Monthly energy cost graph

For the air source heat pump system, monthly cost graphs and monthly energy cost graphs of system components are shown in Figs. 14 and 15, respectively. While 30% of the annual electricity consumption of the building consists of HVAC system equipment, the remaining 70% is due to lighting, electrical devices and similar equipment. All of the annual natural gas consumption of the building is due to the need of the kitchen.

3.6 Water-Source Heat Pump System

In the water source heat pump system, the heating and cooling of the spaces are provided by four-pipe fan coil indoor units, while the alternative of meeting the heating and cooling load with a water source heat pump has been considered. The difference from the air source heat pump is that the heat pump uses water instead of air as an external source. In this alternative system, the heat pump does the work of the boiler, which meets the heating needs and the chiller devices that meet the cooling needs in the four-pipe fan coil system. According to the air-cooled heat pump system, additional devices such as the cooling tower, the pump feeding the cooling tower, and the hydrophore make a difference in the cost of this system.

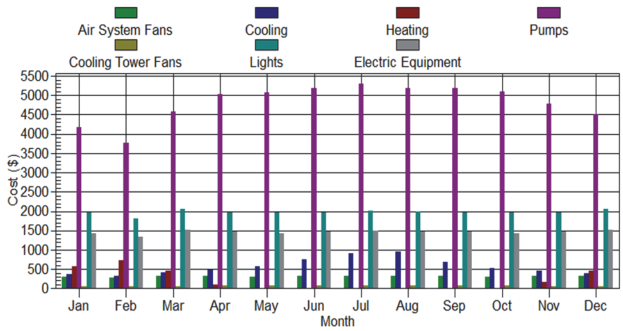

Figure 16 Monthly cost graph of system components

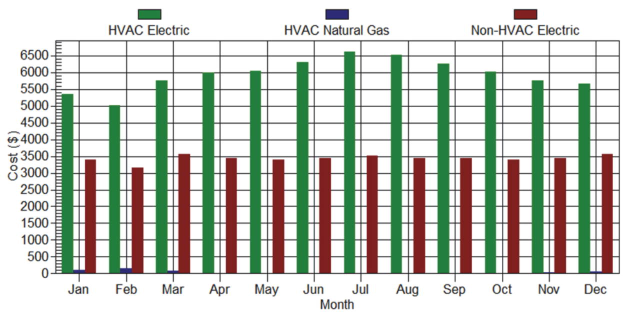

Figure 17 Monthly energy cost graph

For the water source heat pump system, monthly cost graphs and monthly energy cost graphs of system components are shown in Figs. 16 and 17, respectively. While HVAC system equipment constitutes 63.5% of the annual electricity consumption of the building, the remaining 36.5% is due to lighting, electrical devices and similar equipment. While 78% of the building's annual natural gas consumption is due to hot water needs, 22% is due to the need of kitchen (cooking).

Energy analysis was performed for each system and then the annual total energy cost value, annual fuel consumption values and annual fuel cost data per unit area were obtained. These data for each system are shown in Tab. 6.

In these installations where different components are used for each system, a quantity study was made to calculate investment costs. In the study, armatures, valves, pipes, devices, ducts used for installations, in brief, all parts used in the project are counted separately, and pricing was made for these parts. As a consequence of the pricing study, the systems' investment costs data are shown in Tab. 7.

Table 6 Annual energy analysis of alternative systems

System	Fuel cost per unit area / \$/m²	Total energy cost / \$	Electricity consumption / kWh	Natural gas consumption / m³
Air-cooled variable flow cooling system	31.438	55 101	500 919	0
Water-cooled variable flow cooling system	32.992	57 826	521 069	1 847
Air handling unit system	52.694	92 826	839 605	0
Four-pipe fan-coil system	33.778	59 203	533 952	1704
Air-source heat pump system	33.579	58 853	531 324	1517
Water-source heat pump system	64.431	112 928	1 022 722	1558

Table 7 Investment cost of alternative systems

System	Cost of material / \$	Workmanship / \$	Total cost / \$
Air-cooled variable flow cooling system	133 253	15 137	148 390
Water-cooled variable flow cooling system	216 679	17244	233 923
Air handling unit system	93 918	29917	123 835
Four-pipe fan-coil system	197 259	20 899	218 158
Air-source heat pump system	182 546	21 015	203 561
Water-source heat pump system	244 793	23 150	267 973

4 CONCLUSIONS

With the developing technology and increasing world population, energy consumption is increasing rapidly. Meeting this need from exhaustible energy sources has led human beings to use energy efficiently and to produce systems and solutions that will contribute to energy savings. Air conditioning constitutes an important part of energy consumption. Today, studies are carried out to minimize energy consumption in buildings.

With the developing technology, the variety of mechanical air conditioning systems that can be applied in buildings is increasing. Considering the advantages and disadvantages of the systems that can be applied, energy consumption can be minimized by choosing the appropriate and correct system for the building.

In this study, operating convenience, operating costs and initial investment costs of six different mechanical air conditioning systems were examined. As a result of the energy analysis, annual fuel consumption and annual energy costs for each alternative system are given in Tab. 6. As a result of the quantity measurements, the initial investment costs of these systems are shown in Tab. 7.

According to the results obtained from the studies, in general, air source systems can be operated with less energy cost than water source systems. High energy costs arise in all-air systems and water source heat pump systems. Although the operating cost of all-air systems is high, they have a very low cost compared to other systems in terms of investment cost. Since the fresh air, heating and cooling needs of the spaces are met by the supply air in the All-air system solution, it requires more shaft and suspended ceiling space than other systems. When criteria such as initial investment costs, operating costs, ease of operation and manufacturing speed are taken into account, air source systems are a more advantageous solution.

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