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A simulation appraisal of performance of different HVAC systems in an office building

Milorad Bojić*, Novak Nikolić, Danijela Nikolić, Jasmina Skerlić, Ivan Miletić

Faculty of Mechanical Engineering at Kragujevac, University of Kragujevac, 34000 Kragujevac, Serbia

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ABSTRACT

The article reports on a simulation appraisal of energy consumption, energy costs and environment impact of three systems used for space heating, and space cooling of an office building in Kragujevac, Serbia. Three investigated systems are (1) a system with a natural gas boiler and convective baseboard heaters for water space heating and window air conditioners for air space cooling; (2) a system with a natural gas boiler and individual air reheaters for air space heating and a chiller plant for air space cooling; and (3) an air-to-air heat pump for air space heating, and cooling. The systems are modeled and simulated by using EnergyPlus software. After simulations, it is found that the first investigated system has the highest energy efficiency, the best economy, and the lowest environmental impact. That is because of the fact that the first system has water as a heating medium and uses predominantly natural gas as fuel. However, in future, when for generation the grid electrical energy requires less primary energy, and becomes decarbonized, the third system would be best to conserve energy resources and environment.

1. Introduction

In Serbia, the building sector consumes more than 50% of the consumed energy. Around 24% of the total building floor area is heated by electrical energy (14%) and natural gas (10%) [1]. Recent accelerated development of natural gas distribution grids in Serbia yields the higher use of natural gas for heating of buildings. In addition, because of recent very hot summers in Serbia, need for air conditioning of buildings is higher. Also, an intention of our country to become a member of the EU imposes an obligation for more efficient energy consumption and its reduction for 20% until 2020 [2]. As Serbia signed the Kyoto protocol, it should reduce emissions of CO_2, and other local pollutants such as SO_2, NO_x and particles. In addition, the Energy Performance of Buildings Directive of EU states that all buildings built after 31 December 2018 will have to produce their own energy onsite [3]. Because of these facts, when some office building is erected, it is essential to analyze its energy consumption, energy costs, and environmental impact for several systems for their heating and cooling, and to apply the system with the best energy efficiency, lowest energy operation costs and lowest impact to the environment.

In literature, there are many examples when different designs of heating and cooling systems are compared. In Ref. [4], ground-source heat pumps systems are compared with other heating options. In Ref. [5], heating options are discusses for eight-story wood-framed apartment building from life cycle primary energy use and carbon emission perspective. In Ref. [6], use of different gas engine heat pumps for residential and commercial buildings in various climate regions of Iran is discussed. In Ref. [7], different space heating fuel options for houses in northern New England are compared from costs and emissions perspective. In Ref. [8], performance and sustainability assessment of energy options are given for several building HVAC applications. In Ref. [9], life cycle assessment of different residential heating and cooling systems is investigated in four regions in the United States. In Ref. [10], the energy efficiency of variable refrigerant flow systems and ground source heat pump systems is compared for their use in office buildings. In Ref. [11], an application of multicriteria analysis in designing HVAC systems is presented for new and existing buildings. In Ref. [12], the performance of air-source heat pumps is studied for current and future offices when existing boilers and air-conditioning systems are replaced. In Ref. [13], calculations show that the CO_2 emissions related to district heating in residential buildings may be lower than that with heating based on electricity. In Ref. [14], the empirical results are given for energy, economic and environmental performance of the heating systems Greek multi-apartment and mixed-use buildings: a central oil-fired boiler, a unitary gas-fired boiler and unitary heat pumps.

This paper reports the analyses of three systems for space heating and cooling for an office building in Kragujevac, Serbia on their performance now and in the future when the electrical energy system in Serbia becomes decarbonized. The investigated systems are

* Corresponding author. Tel.: +381 34 330196.
E-mail address: bojic@kg.ac.rs (M. Bojić).

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Nomenclature

A	area of each heater (m^2)
C_{TOT}	total yearly operating costs (€)
COP	coefficient of performance
E_e	yearly consumption of electrical energy (J)
E_n	yearly consumption of natural gas (J)
E_{TOT}	total yearly energy consumption (J)
EIR	energy input ratio for space cooling
f_e	specific cost of consumption of electrical energy (€/GJ)
f_n	specific cost of consumption of natural gas (€/GJ)
g_e	specific carbon dioxide emission factor of electrical energy (kg/GJ)
g_n	specific carbon dioxide emission factor of natural gas (kg/GJ)
FF	ratio of the actual and the rated air mass flow-rate
P_f	actual electrical energy consumption of the variable flow-rate fan in the unit time (W)
P_k	electrical power of the compressor
PLR	ratio of actual and rated cooling load of the unit
R	primary energy consumption coefficient
S_{TOT}	total yearly carbon dioxide emission (kg)
Q_c	total heating (cooling) capacity (W)
q	heat rate exchanged between water and air (W)
R	coefficient of primary energy consumption
T	temperature (K)
U	coefficient of heat transfer (W/m^2 K)

the following: (1) the system with the natural gas boiler and convective baseboard heaters for space heating by hot water and the air conditioners for space cooling by cooled air; (2) the system with the natural gas boiler and individual air reheaters for heating by heated air and chiller plant for cooling by cooled air; and (3) the air-to-air heat pump for space heating by heated air, and space cooling by cooled air. The building and systems are modeled and simulated by EnergyPlus software. This article reports and discusses calculated data on energy consumption, energy costs and influence on the environment by these systems.

2. Description of the office building and its space heating and cooling

Toward modeling the office building and its system for space heating and cooling, this section describes the building model, building operation, and its three used heating and cooling systems.

2.1. Building model

The investigated office building shown in Fig. 1 has three floors. The first (ground) floor shown in Fig. 2 represents spaces for parking and storage of equipment. Other two floors have offices for business activities. The third floor is shown in Fig. 3. The entire building has 66 zones, of which 50 zones (office rooms) are conditioned (heated and cooled). Two zones are stairs and an elevator space that are not conditioned. The concrete building envelope is insulated by an 80 mm stiropore. U-values for the building envelope are in the range from 0.681 W/(m^2 K) to 1.153 W/(m^2 K). The percentage of the glazing area compared to the area of the overall building envelop is 11.5%. The windows are double glazed with the window U-value = 2.77 W/(m^2 K), and SHGC = 0.763. The building is not surrounded with any other building or object.

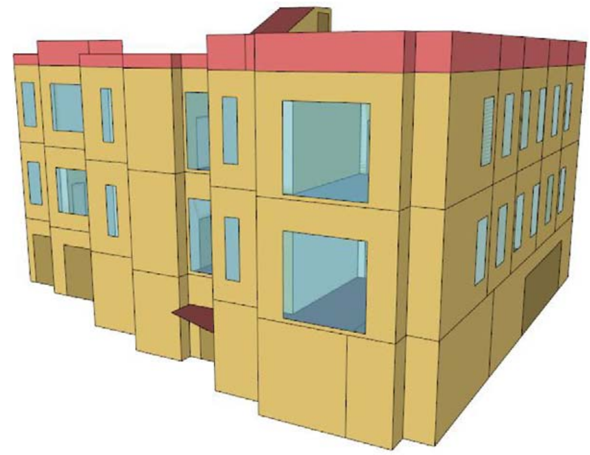

Fig. 1. Isometric view of the analyzed office building.

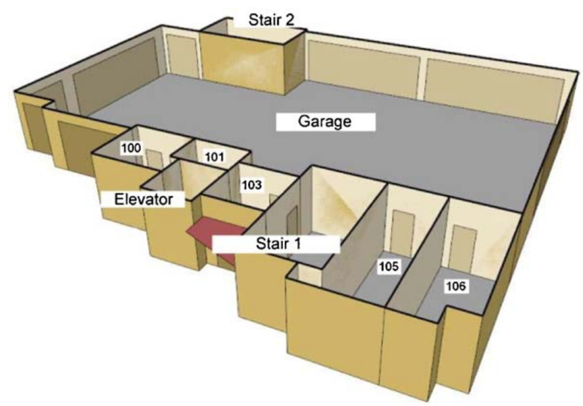

Fig. 2. Isometric cut of the first story of the office building.

2.2. Building operation

During a year, the offices are used only during weekdays from 9:00 to 17:00 h, when each office room is occupied by one person. Lighting is mainly used during afternoon and during night to pro-

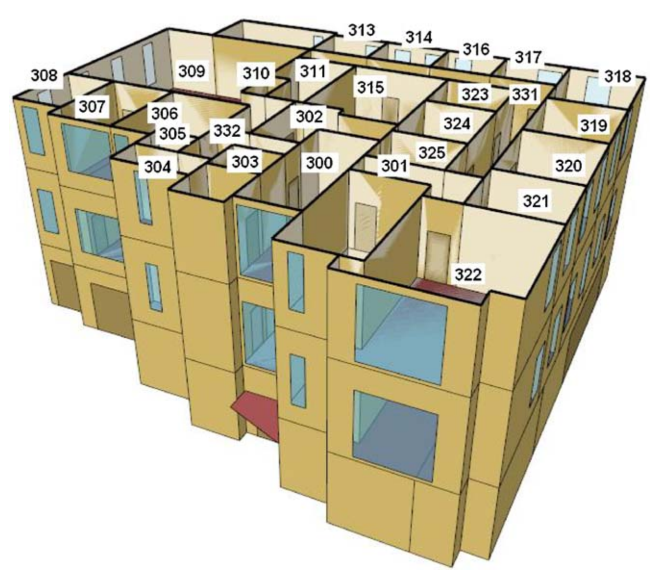

Fig. 3. An isometric view of the third story of the office building.

vide security. Air temperatures in the rooms that are heated are set to 20 °C and that are cooled to 24 °C. The infiltration is assumed to conform to the customary occupant behavior in Serbia.

The working period of the systems is from 15 October to 15 April for heating and from 15 April to 15 October for air conditioning, during the weekdays in the interval of 09:00–17:00 h. The value for the simulation time step is 15 min.

2.3. Heating and cooling systems

For the office building in Kragujevac, Serbia, three systems for space heating and cooling are analyzed by using EnergyPlus software: (1) the system with the natural gas boiler and the convective baseboard heaters for space heating by hot water and the air conditioners for space cooling by cooled air; (2) the system with the natural gas boiler and the individual air reheaters for heating by heated air and the chiller plant for cooling by cooled air; and (3) the air-to-air heat pump for space heating by heated air, and space cooling by cooled air.

The main components of these systems such as the boiler, the chiller, the window air conditioners, and the air-to-air heat pump are designed to address the rated capacity of space heating and space cooling. Other components of these systems such as the baseboard heaters, the fans, and the pumps are dimensioned by EnergyPlus software.

2.4. System 1 – convective baseboards with boiler on natural gas and window air conditioners

System 1 provides space heating during winter by hot water and space cooling during summer by cold air. The hot water is heated with the boiler on natural gas. It releases heat from the convective baseboards into rooms. The cold air is cooled by the window air conditioners.

Hot water convective baseboard heating with boiler on natural gas (system 1a) consists of a boiler on natural gas, convective baseboard heaters, a variable flow rate pump for transport of the working fluid, and pipes. The hot water convective baseboard heaters are put in each of the heated rooms. Its design in EnergyPlus means input of the detailed data about all its components. When the components are defined, we should do their accurate connection in order to get an accurate picture about the heating system. A schematic of the heating system is shown in Fig. 4.

The window air conditioners (system 1b) are put in every room that has space cooling. They have three components: a unit for the outside air, a fan, and a unit with an evaporator, a compressor and a condenser (ECC unit). The fan operates simultaneously with the

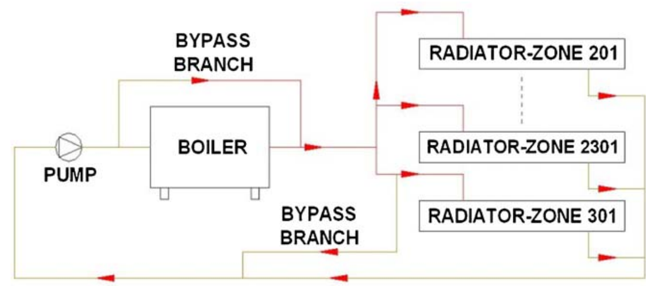

Fig. 4. The scheme of the heating system in the system 1with the natural gas boiler and convective baseboard heaters.

compressor. Design of this system (evaluation of the cooling energy and the rates of the air flow from the outside and the cooled rooms) is done by EnergyPlus software based on the previously calculated cooling needs also by using EnergyPlus. A schema of the space cooling system with the window air conditioners with all components and path flows of air is shown in Fig. 5.

2.5. System 2 – space air heating by a boiler on natural gas and separate reheaters of air and air space cooling

System 2 consisted of two parts where one (the space air heating by the boiler on natural gas and separate reheaters of air) operated during winter and one (the air space cooling) operated during summer.

Air space heating with the boiler on natural gas and separate air repeaters (system 2a) requires use of the natural-gas-fired boiler. This heating system shown in Fig. 6 uses two cycles of the working mediums. The first cycle has the heated water as a working medium and the second cycle has the heated air as a working medium. In the first cycle, after the water heating in the boiler, the hot water is sent to the main heater, to the heater of the outside air, and to the separate heaters, where the hot water releases heat. Then, the hot water returns again to the boiler for its heating. The hot water is transported by the pump (of variable flow rate) through the pipes.

In the second cycle, the heated air is a mixture of the used air taken from the rooms and of the outdoor air taken from the outdoor. The heated air is transported and heated in three devices: the heater of the outdoor air, the main heater, and the separate heaters of the heated rooms. The fan transports the heated air through the air channels to the rooms.

Space cooling system by cold air (system 2b) has the following parts: a chiller, a pump (of variable flow rate), a main cooler, and a cooler for the outside air. Here, there are cycles of two working

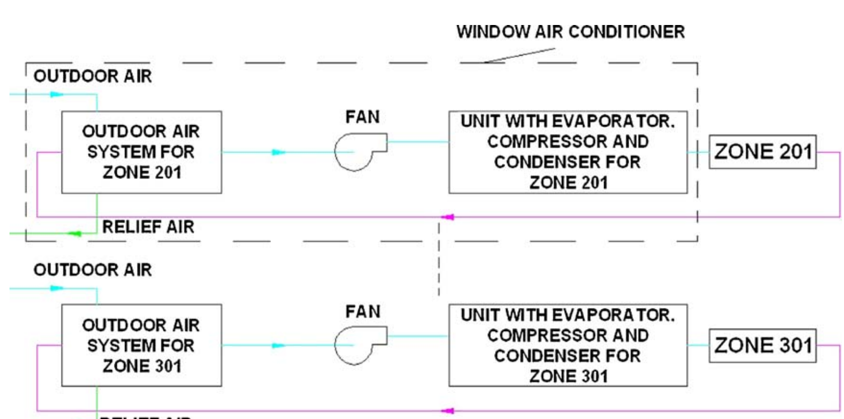

Fig. 5. The scheme of the air conditioners for space cooling in the system 1.

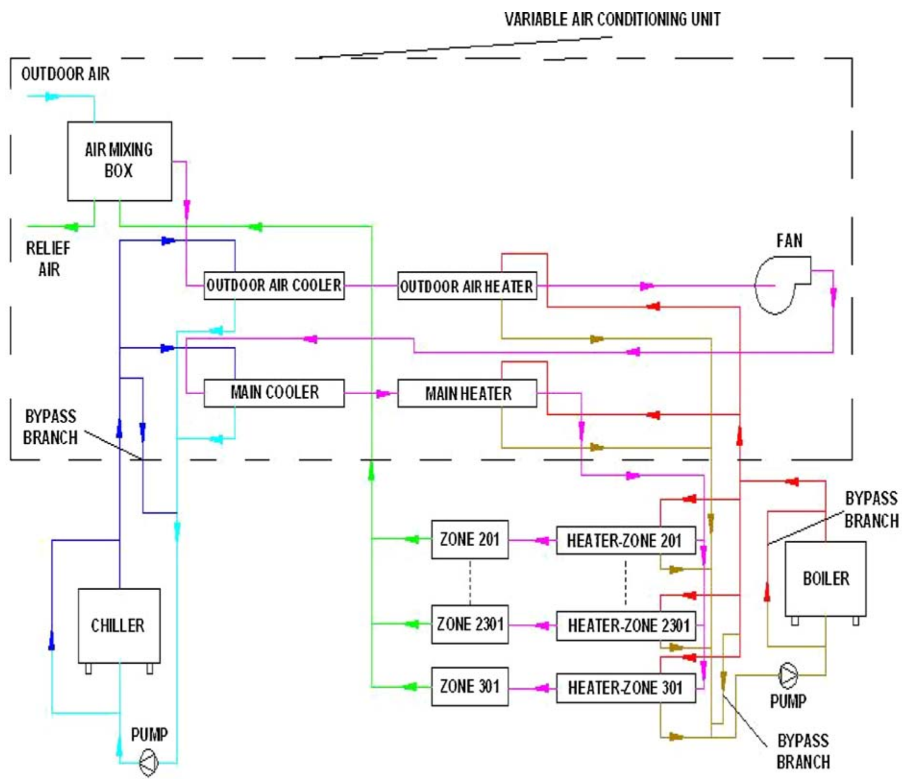

Fig. 6. The scheme of the system 2 with the natural gas boiler and individual air reheaters for air space heating and the chiller plant for air space cooling.

mediums: water and air. Forced by the pump, the chilled water circulates from the chiller to the main cooler and the cooler for the outside air. By using the fan, the air circulates from the cooler to each of the cooled rooms.

It should be noted that the components such as the fan, the main heater, and the main cooler, the heater and the cooler of the outside air as well as the unit for the outside air are inside the unit for air conditioning, while separate heaters are put in each room that is heated.

2.6. *Air-to-air heat pump for space heating and space cooling (system 3)*

System 3 consists of an air-to-air heat pump that operates during entire year: for space air heating and for air space cooling. The fan operates simultaneously with compressor.

The air-to-air heat pump contains a unit for outside air, fan, an ECC unit, and an additional natural gas heater. This system provides both the space heating and cooling of the rooms to the investigated building. The working medium is a mixture of the outdoor air and the used air. By using the fan, the mixture is directed to the unit with the evaporator, the compressor, and the condenser and if it is necessary, to the additional heater. After that the air is directed to the rooms that are either heated or cooled. When the dry bulb-thermometer temperature of the outdoor air is below the temperature when the compressor operates, the additional natural gas heater is activated. A schema of the system is shown in Fig. 7.

3. Mathematical models

For the modeling of different systems for space heating and cooling, the used mathematical model is that of the used software EnergyPlus. In addition, some relationships are given that are used to obtain the simulation results.

3.1. *Used software*

To simulate thermal behavior of the office building and have accurate calculation results, software EnergyPlus version 3.0 is used. This program is very useful tool for modeling of energy and environmental behavior of buildings. In the software, it is possible to input how people use building during its space heating and cooling. In this direction, the complex schedules of heating and cooling can be defined together with schedules for use of lighting, internal energy devices and occupancy in the building. The influence of the solar radiation, shadowing and infiltration is also taken into consideration [15,16].

The mathematical model used in this research is that embaded in EnergyPlus [16]. Some details and used coefficients are given in Appendix A to this paper. Then, modeling of general components is described such as boiler, pumps, convective baseboard heaters, air heaters, and fans. Models of complex systems are explained such as window air conditioners (system 1b), air space heating with boiler on natural gas and separate air reheaters (system 2a), space cooling system by cold air (system 2b), air-to-air heat pump for space heat-

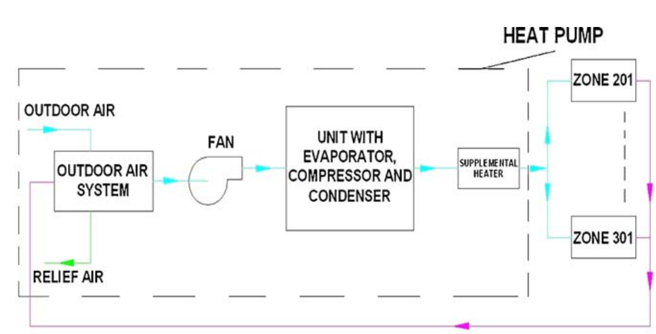

Fig. 7. The schema of the air-to-air heat pump for space heating and space cooling in the system 3.

Table 1
Monthly averages for Kragujevac, Serbia [17].

Months	Average low(°C)	Average high(°C)	Average precipitation(cm)	Mean number of precipitation days(days)
January	−3.8	3.8	4.11	11.6
February	−1.7	6.7	3.87	10.4
March	1.4	11.8	4.44	10.6
April	5.5	17.3	4.94	12.2
May	10.1	22.0	7.38	13.1
June	13.0	25.0	8.47	12.9
July	14.2	25.0	6.8	9.3
August	13.7	27.2	5.33	9.3
September	10.7	23.9	4.48	8.1
October	6.3	18.2	3.82	8.6
November	2.4	11.5	4.82	10.3
December	−1.6	5.6	4.76	12.3

Remarks: Climatological information is based on monthly averages for the 30-year period of 1961–1990; mean number of precipitation days = mean number of days with at least 1 mm of precipitation; precipitation includes both rain and snow.

ing and cooling, ECC unit during space heating and space cooling, and system for treatment of outside air.

As the result of this simulation, the yearly energy consumption of natural gas E_n and yearly energy consumption of electrical energy E_e are obtained.

3.2. Weather

The city of Kragujevac lays on Balkan Peninsula in state of Serbia, south of its capital city of Belgrade. Its average height above sea-level is 185 m. Its latitude is 44°02N, and longitude 20°56E. The city has a moderate continental climate with distinct seasons (winter, spring, summer, and autumn). To familiarize with the Kragujevac climate, Table 1 gives the average low and high temperatures, mean precipitation and mean number of precipitation days for each month during entire year [17]. The epw file used in the simulation is generated by Meteonorm software [18]. To simulate it is taken that the heating devices are usually in operation from 15 October to 15 April next year that is valid in practice for entire Serbia. In these simulation, it is also taken that the cooling devices are in operation is from 15 April to 14 October.

3.3. Primary energy consumption

The total yearly primary energy consumption of an investigated system is calculated by using the following equation

$$E_{TOT} = E_n + E_e R \quad (1)$$

here, E_n stands for yearly consumption of natural gas, E_e stands for yearly consumption of electrical energy, and R stands for the primary energy consumption coefficient. This coefficient is defined as the ratio of total input energy of the energy resources (hydro, coal, oil and natural gas) and the final produced electric energy. Its value for Serbian energy mix for electrical energy production is $R = 2.154$ [19].

3.4. Operating costs

The total yearly operating costs to run a system are calculated by using the following equation

$$C_{TOT} = f_n E_n + f_e E_e \quad (2)$$

here, f_n stands for the specific cost of consumption of natural gas (in €/GJ), and f_e stands for the specific cost of consumption of electrical energy (in €/GJ). The operating costs data are determined by using the monthly prices for electric energy and natural gas charged by the national distribution enterprises in Serbia. The price of electric energy is defined for the high consumption tariff (for household) as the simulated systems operate during weekdays from 09:00 to 17:00 h, while the price of natural gas is defined for the natural gas with energy value of 34538 kJ/m^3, for households [20,21]. These prices given in Table 2 do not include the fix monthly costs present in each bill.

Table 2
The prices of energy in Serbia on April 20, 2009 [19,20].

Final energy	Consumption	Price
Electric energy	0–350 kWh	9.22 €/GJ
	350–1600 kWh	13.82 €/GJ
	Over 1600 kWh	27.65 €/GJ
Natural gas	–	8.9 €/GJ

3.5. Carbon dioxide emission

The total yearly carbon dioxide emission during a system operation is calculated by using the following equation

$$S_{TOT} = g_n E_n + g_e E_e \quad (3)$$

here, g_n stands for specific carbon dioxide emission factor of natural gas (kg/GJ), g_e stands for specific carbon dioxide emission factor of electrical energy (kg/GJ). The emission factors are given in Table 3. The data for yearly carbon dioxide emission are obtained when values of the consumption of the final energy are multiplied by the emission factors.

4. Results and discussion

This section reports the results of the simulation of annual operation of three systems that provide space heating and cooling to the investigated office building. These systems are (1) the system with the natural gas boiler and convective baseboard heaters for heating and the air conditioners for cooling; (2) the system with the natural gas boiler and individual air reheaters for heating and chiller plant for air cooling; and (3) the air-to-air heat pump for heating and cooling. The operation of the office building is evaluated according to its energy consumption, operating cost, and pollutant emission. Then, these results are discussed to reach some conclusions on which of system is better to realize today and in future.

Table 3
The greenhouse gas emission factors for the electric energy and natural gas.

GHG emissions	Emission factor (kg/GJ)	
	Electric energy	Natural gas
Carbon dioxide (CO_2)	206.53	56.1

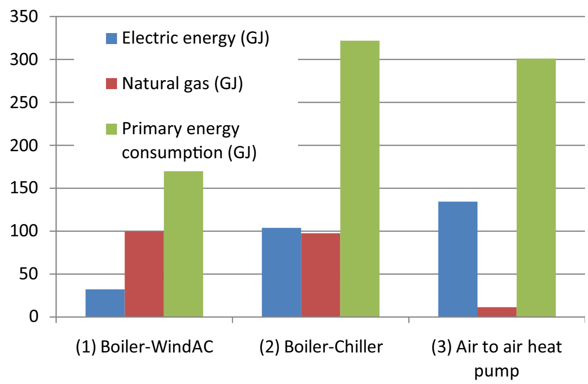

Fig. 8. The yearly final and primary energy consumption of the analyzed systems for $R = 2.15$.

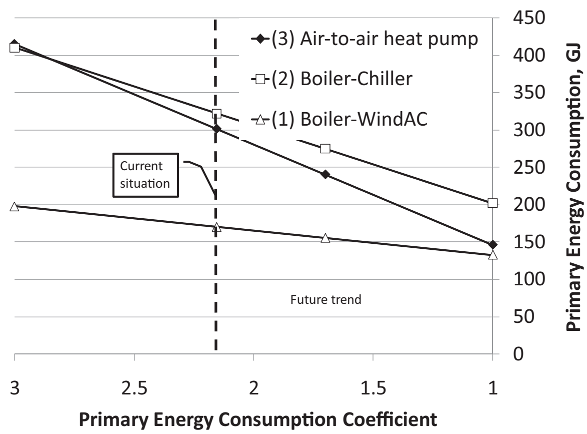

Fig. 9. Primary energy consumption vs. primary energy consumption coefficient R.

4.1. Results

The results are simulation data on the energy consumption, operating costs, and pollutant emissions for each of all three systems when separately installed in the investigated building. The energy consumption data are presented by using Figs. 8 and 9. In Fig. 8, the annual values for consumptions of electrical energy, natural gas, and primary energy are shown for all three simulated systems. Then, the primary energy consumption coefficient is $R = 2.15$. In Fig. 9, the annual primary energy consumption is shown as a function of R for all three simulated systems.

The operating costs obtained by the simulations are shown in Fig. 10 for all three simulated systems. The figure gives the total yearly operating costs and yearly operating costs for use of electrical energy for heating, electrical energy for cooling, natural gas for heating.

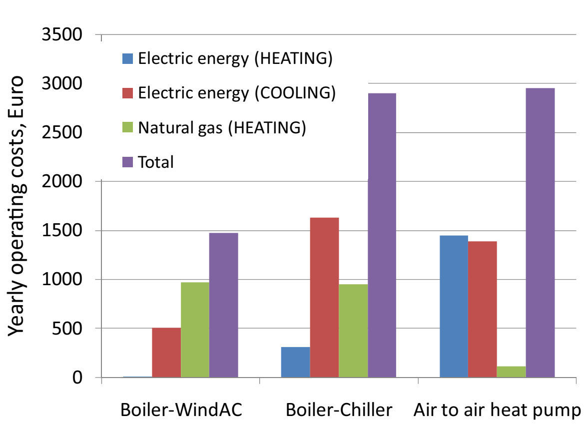

Fig. 10. The yearly operating costs of the analyzed systems.

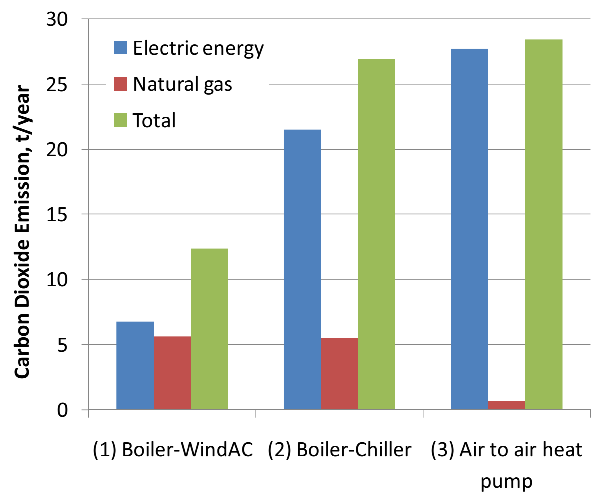

Fig. 11. The yearly carbon dioxide emission of the analyzed systems for $R = 2.15$.

The pollutant emissions relates to carbon dioxide emissions. These yearly data are shown for three simulated systems in Fig. 11 for $R = 2.15$. In Fig. 12, the yearly carbon dioxide emission is shown as a function of the yearly carbon dioxide emission coefficient for electrical energy.

4.2. Discussion

By using Figs. 8–12, the operations of three selected systems are analyzed, discussed regarding the energy, economy and environmental standpoints.

Energy consumption will be analyzed and discussed by comparing all types of energy consumption in each of three HVAC systems. From Fig. 8, it may be found out that the first system spends around 25% of electrical energy and 75% of natural gas, the second system 52% of electrical energy and 48% of natural gas, and the third system spends 92% of electrical energy and 8% of natural gas. In addition, from Fig. 8, it may be concluded that in case of Serbia today (when $R = 2.15$), the annual consumption of the electrical energy for space heating and cooling is the lowest for the system 1 ($E_e \approx 30$ GJ/year) and the highest for system 3 ($E_e \approx 130$ GJ/year). On the other hand annual consumption of natural gas is the lowest for the system 3 ($E_e \approx 15$ GJ/year) and the highest for the system 1 ($E_n \approx 100$ GJ/year). Consequently, the system 1 has the smallest annual consumption

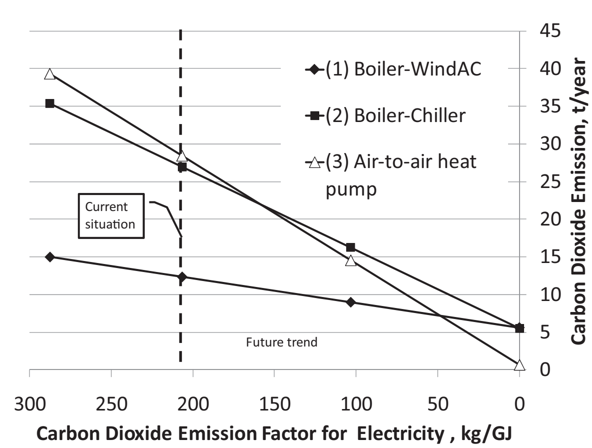

Fig. 12. Carbon dioxide emission vs. carbon dioxide emission factor for electricity.

of the primary energy ($E_{TOT} \approx 170$ GJ/year) as it has the highest consumption of natural gas for heating and lowest consumption of electrical energy for cooling, while the system 3 has very high annual consumption of primary energy ($E_{TOT} \approx 300$ GJ/year).

In future, it may be assumed that the development of the electrical energy generation in Serbia would go toward larger use of renewable energy sources and consequently lower value of R. In Fig. 9, it is shown that a decrease in R would yield a decrease in the primary energy consumption of each of applied systems. For instance, E_{TOT} of the third system will decrease and approach to that of the first system to around 140 GJ/year.

Economy analysis of operation of these systems refers to comparison of their operating costs regarding all types of used energy, and type of performed service (heating, cooling, and total). These comparisons of economy performance of all three systems are based on data given in Fig. 10. For use of natural gas for heating, the annual operating costs are the lowest for the system 3 (around 210 €) and very high for the system 1 and 2 (around 945 €). For use of electrical energy for heating, the annual operating costs are the lowest for the system 1 (around 0 €), higher for system 2 (315 €), and the highest for the system 3 (around 1420 €). For use of electrical energy for cooling, the annual operating costs are the lowest for the system 3 (around 520 €) and very high for the system 3 (around 1360 €), and the highest for system 2 (1630 €). For heating, the annual operating costs are the lowest for the system 1 (around 470 €), higher for the system 3 (around 1550 €), and the highest for system 2 (around 1680 €). For cooling, the annual operating costs are the lowest for the system 1 (around 85,000 €), very high for the system 3 (around 1370 €), and the highest for system 2 (1630 €). Finally, the total annual operating costs are the lowest for the system 1 ($C_e \approx 1470$ €), very high for system 2, and the highest for system 3 (around 2940 €).

The environmental analyses refer to comparison of calculated carbon dioxide emissions of the systems as a consequence of their operation. From Fig. 11, it may be concluded that in case of Serbia today (when $g_e = 206.53$ kg/GJ), the annual CO_2 emission due to use of the electrical energy for space heating and cooling is the lowest for the system 1 (around 6.5 t/year) higher for the system 2 (around 22 t/year) and the highest for system 3 (≈27.5 t/year). On the other hand, the annual CO_2 emission due to consumption of natural gas is the lowest for the system 3 (≈1 t/year), higher for the system 2 (around 5 t/year) and the highest for the system 1 (≈5.5 t/year). Consequently, the system 1 has the smallest annual CO_2 emission ($S_{TOT} \approx 12$ t/year) as it has the highest consumption of natural gas for heating and lowest consumption of electrical energy for cooling, while the system 3 has the highest annual CO_2 emission ($S_{TOT} \approx 28$ t/year).

In future, it may be assumed that the development of the electrical energy generation in Serbia would go toward decarbonized electrical energy at the national electrical energy grid consequently lower value of g_e. In Fig. 12, it is shown that a decrease in g_e would yield a decrease in the annual CO_2 emissions for each of applied systems. Consequently, when electric energy production in Serbia is decarbonized, this would make that third system goes $S_{TOT} = 0$ kg/GJ, while first and second system would go to $S_{TOT} = 6$ kg/GJ.

Finally, the analysis of three systems points out that now in Serbia the first system is the most efficient, the most economic and the system with the lowest negative impact on the environment. That is because of the fact that the first system has water as a heating medium and uses predominantly natural gas as fuel. In Serbia, electrical energy use still has very high energy, and environmental impact compared to use of natural gas in the first and second system. When, in future, the generation of the grid electrical energy becomes decarbonized, the third system would be best to conserve resources and environment.

5. Conclusion

This paper reports the results of the simulation of annual operation of three systems that provide space heating and cooling to the investigated office building. These systems are (1) the system with the natural gas boiler and convective baseboard heaters for heating and the air conditioners for cooling; (2) the system with the natural gas boiler and individual air reheaters for heating and chiller plant for air cooling; and (3) the air-to-air heat pump for heating and cooling. The simulation tool is EnergyPlus. The buildings are in Kragujevac, Serbia. The operation of the office building is evaluated according to its energy consumption, operating cost, and pollutant emission. Then, these results are discussed to reach some conclusions on which of system is better to realize today and in future.

It is found that the system 1 has the smallest annual consumption of the primary energy as it has the highest consumption of natural gas for heating and lowest consumption of electrical energy for cooling, while the system 3 has very high annual consumption of primary energy. In future, it may be assumed that the development of the electrical energy generation in Serbia would go toward larger use of renewable energy sources, the total energy consumption of the third system will decrease and approach to that of the first system. Economy analyses of operation of these systems show that the total annual operating costs are the lowest for the system 1, very high for system 2, and the highest for system 3. The environmental analyses show that the system 1 has the smallest annual CO_2 emissions as it has the highest consumption of natural gas for heating and lowest consumption of electrical energy for cooling, while the system 3 has the highest annual CO_2 emission. When electric energy production in Serbia is decarbonized, this would make that third system has the negligible CO_2 emissions lot less than that of the first and second system.

Finally, the analysis of three systems points out that now in Serbia the first system is the most efficient, the most economic and the system with the lowest negative impact on the environment. That is because of the fact that the first system has water as a heating medium and uses predominantly natural gas as fuel. Later, when the electrical energy of the grid requires less primary energy for generation, and becomes decarbonized, the third system would be best to conserve energy resources and environment.

To select and install some of these systems in the office building, it is also necessary to know the investment costs, maintenance costs, reliability and other factors, which are not included in this study.

Appendix A.

A.1. Models of general components in heating and cooling systems

Models of general components such as boiler, pumps, convective baseboard heaters, air heaters, and fans are used as given in EnergyPlus. However, to function properly in simulation, they need realistic data. In this simulation, they use the following data.

Boiler is used in the systems 1 and 2. Boiler model needs the rated thermal efficiency (=0.8), and the rated and maximum water temperatures (81 and 100 °C), at the exit from the boiler, respectively. The used fuel is natural gas.

The pump (of variable flow rate) transports the hot water in the heating systems 1 and 2, and chilled water in the cooling system 2. The pump model needs the value of the pressure drop (22,000 Pa) to transport hot water to baseboard heaters, and (36,700 Pa) to transport chilled water inside the chiller system. Then, the model needs the value (0.9) of efficiency of the pump motor. This pump may operate between its minimum value (0 kg/s) and the maximum value of the flow rate.

Model of hot water convective baseboard heaters needs values of the maximum flow rate of hot water through these heaters and value of product of coefficient of heat transfer and area of each heater (*UA*). They are obtained from the design calculation of the heaters.

The modeled air heaters are all water-to-air heat exchangers used in the system 2a. Their model requires the values for the maximum flow rate of the water through each of heaters, their heating capacity, as well as the values of product of the coefficient of heat transfer and the surface size (*UA*). Assumed temperatures of water at the entrance and exit of each heater are 82.2 and 71.1 °C, and that of air at the entrance and exit of each heater 16.6 and 32.2 °C, respectively.

Model of single-speed fan located inside air conditioner (system 2) needs total efficiency (=0.5). The fan handles the pressure drop during air transport of 75 Pa. The fan located inside the air–air heat pump (system 3) has the total efficiency of 0.7, and handles the pressure drop during air transport of 3750 Pa. The efficiency of fan motors is 0.9.

A fan with variable flow rate located inside the heating system requires data inputs that define the fan availability, the fan efficiency (=0.7), the motor efficiency (=0.9) and handle the pressure drop required to transport air to the heated or cooled rooms (=3750 Pa). The actual electrical energy consumption of the fan in the unit time is given as [5]:

$$P_f = P_{f,r}(C_1 + C_2FF + C_3FF^2 + C_4FF^3 + C_5FF^4) \quad (A1)$$

where C_1, C_2, C_3, C_4, C_5 are the dimensionless coefficients with values of 0.351, 0.309, −0.541, 0.872, and 0, respectively, $P_{f,r}$ is the rated power of the fan, and *FF* stands for the ratio of the actual and the rated air mass flow rates through the fan.

A.2. Model of window air conditioners in system 1

In the software, the ECC unit of the window air conditioner system is described by two equations: one for the actual total cooling capacity and one for the energy input ratio. The actual total cooling capacity is given as:

$$Q_c = y_{c1}y_{c2}Q_{c.r} \quad (A2)$$

where y_{c1} stands for the total capacity temperature modifier factor, y_{c2} is the total capacity flow modifier factor, and $Q_{c,r}$ is the total rated cooling capacity. The total capacity temperature modifier factor is $y_1 = a_1 + a_2(T_{wbi}) + a_3(T_{wbi})^2 + a_4(T_{ci}) + a_5(T_{ci})^2 + a_6(T_{wbi})(T_{ci})$. The values of the coefficients a_1, a_2, a_3, a_4, a_5, and a_6 are 0.943, 0.00954 K^{-1}, 0.000684 K^{-2}, −0.0110 K^{-1}, 0.00000525 K^{-2}, and −0.00000972 K^{-2}, respectively. The total capacity flow modifier factor is $y_2 = b_1 + b_2FF$. The values of the coefficients b_1 and b_2 are 0.8 and 0.2, respectively [5]. Here, T_{wbi} is wet bulb temperature of the air entering the cooling coil of the unit, and T_{ci} is dry bulb temperature of air entering the condenser of the unit. This is the flow across the cooling coil. On the other side the energy input ratio (energy input/cooling output) of this unit is given as:

$$\mathrm{EIR}_c = z_{c1}z_{c2}COP_r^{-1} \quad (A3)$$

here z_{c1} – the temperature modifier of EIR (function of temperature), z_{c2} – the flow-rate-ratio modifier of EIR (function of the flow rate ratio) and COP_r is the rated coefficient of performance of the unit (the adopted value is 3). The functions are the following: $z_{c1} = d_1 + d_2(T_{wbi}) + d_3(T_{wbi})^2 + d_4(T_{ci}) + d_5(T_{ci})^2 + d_6f(T_{wbi})(T_{ci})$ and $z_{c2} = e_1 + e_2(ff) + e_3(ff)^2$. Here, coefficients d_1, d_2, d_3, d_4, d_5, and d_6 have values of 0.342, 0.0349 K^{-1}, −0.000624 K^{-2}, 0.00498 K^{-1}, 0.000438 K^{-2}, and −0.000728 K^{-2}, respectively. The coefficients e_1, e_2, e_3 have values 1.16, −0.181 and 0.0256, respectively [5]. Here, $ff = 0.85 + 0.15$ (*PLR*) where *PLR* is ratio of actual and rated cooling load of the unit. In addition, the simulation of the ECC unit requires data on the unit availability. Under the rated conditions, it is assumed that the air enters the unit with the temperatures of dry and wet bulb thermometer of 26.7 °C and 19.4 °C, and that the air enters the condenser with the temperatures of dry and wet bulb thermometer of 35 °C or 23.9 °C, respectively.

A.3. Model of air space heating with boiler on natural gas and separate air reheaters (system 2a)

The main heater, heater of outside air, separate air reheaters, and fan with variable flow rate are components located in system 2a. They are discussed in the section for general components.

A.4. Model of space cooling system by cold air (system 2b)

In the software, the chiller is described by the following equations. The electrical power of the compressor is given as [5]:

$$P_k = k_1k_2k_3\left(\frac{Q_{c,r}}{COP_r}\right) \quad (A4)$$

where k_1 stands for the function of ratio of the full loads, k_2 stands for the function of the power ratio, k_3 stands of function of capacity ratio, $Q_{c,r}$ is the rated capacity of cooling, *COP* is the coefficient of performance of the chiller. The functions are $k_1 = C_1 + C_2PLR + C_3PLR^2$, where C_1, C_2, C_3 have values 0.0330, 0.686 and 0.282, respectively; $k_2 = C_1 + C_2\ k_3 + C_3\ k_3{}^2$, where C_1, C_2, C_3 have values 2.33, −1.98 and 0.612, respectively; $k_3 = C_1 + C_2\Delta_{temp} + C_3\Delta_{temp}^2$, where C_1, C_2, C_3 have values 0.995, −0.0460 and −0.00136, respectively, Δ_{temp} is temperature difference defined by the following expression

$$\Delta_{temp} = \frac{T_{ci} - T_{ci,r}}{TRC} - (T_{w,e,o} - T_{w,e,o,r}) \quad (A5)$$

where T_{ci} is the temperature of air at the entrance to the condenser, $T_{ci,r}$ is the rated temperature of air at the entrance to the condenser, *TRC* is the coefficient of the temperature increase, $T_{w,e,o}$ is the temperature of water at the exit of the chiller evaporator, $T_{w,e,o,r}$ is rated temperature of water at the chiller exit.

In addition, the simulation of the unit requires the rated capacity of cooling, and the rated flow rate. Further data entered to the software are the chiller *COP* (=3.2), the minimum, maximum, and optimal ratio of the actual load and the rated load of the chiller (0, 1, 0.65, respectively), the temperature of air at the entrance at the condenser cooled by air (35 °C), the temperature of water at the exit of the chiller (6.67 °C), and the coefficient of increase of the temperature (2.78 °C).

The fan and the unit for the outdoor air are described when the components for the heating system are described.

A.5. Model of air-to-air heat pump for space heating and cooling (system 3-ECC Unit during space heating)

In the software, the ECC unit is described by the two equations. The heating power is given as:

$$Q_h = y_{h1}y_{h2}Q_{h,r} \quad (A6)$$

here y_{h1} is function of temperature, y_{h2} is function of the flow rate ratio, and $Q_{h,r}$ is heating capacity under the rated conditions. The functions are the following: $y_{h1} = a + b(T_{db,o}) + c(T_{db,o})^2 + d(T_{db,o})^3$, with values of the coefficients *a*, *b*, *c* and *d* of 0.759, 0.0276 K^{-1}, 0.000149 K^{-2} and 0.00000350 K^{-3}, respectively, and $y_{h2} = a + b(ff)$, with values of the coefficients *a* and *b* of 0.84 and 0.16, respectively [5]. $T_{db,o}$ is the temperature of the dry bulb thermometer of air at the entrance in external part of the unit. In addition, the energy input ratio is given as:

$$\mathrm{EIR_h} = z_{h1} z_{h2} COP_r \quad \text{(A7)}$$

here z_{h1} is function of temperature, z_{h2} is function of flow rate ratio, and COP_r is rated *COP* (the adopted value is 2.75). These functions are the following: $z_{h1} = a + b(T_{db,o}) + c(T_{db,o})^2 + d(T_{db,o})^3$, with the following coefficient values *a*, *b*, *c* and *d* of 1.193, $-0.0300\,K^{-1}$, $0.00104\,K^{-2}$ and $-0.0000233\,K^{-3}$, respectively, and $z_{h2} = a + b(ff) + c(ff)^2$, with coefficient values *a, b* and *c* of 1.38, −0.434, and 0.0512, respectively [5]. Quantity *ff* is obtained from (5) as for the window air conditioners.

In addition, the simulation of the unit requires the following data. Under the rated conditions, the temperatures of the dry and wet bulb thermometers in the outer air are 8.33 and 6.11 °C, and the temperatures of the dry and wet bulb thermometers in the air at the entrance to the unit are 21.1 and 15.6 °C. The temperature of the dry bulb thermometer in the outside air below which the compressor is turned off is −8 °C. The temperature of the dry bulb thermometer in the outside air above which the defrosting system is turned off is 5 °C.

A.6. Model of air-to-air heat pump for space heating and cooling (system 3-ECC Unit during space cooling)

The ECC unit is described by identical five functions of the performances to the functions defined for window air conditioners, however, with different values of coefficients. For the y_{c1} function values of the coefficients a_1, a_2, a_3, a_4, a_5 and a_6 are 0.767, $0.0108\,K^{-1}$, $-0.0000415\,K^{-2}$, $0.00135\,K^{-1}$, $-0.000261\,K^{-2}$ and $0.000457\,K^{-2}$; for the y_{c2} function values of coefficients b_1 and b_2 are the same as for the window air conditioners; for function z_{c1} values of the coefficients d_1, d_2, d_3, d_4, d_5 and d_6 are 0.297, $0.0431\,K^{-1}$, $-0.000749\,K^{-2}$, $0.00598\,K^{-1}$, $0.000482\,K^{-2}$ and $-0.000956\,K^{-2}$; and for the function z_{c2} values of the coefficients *a*, *b* and *c* are 1.16, −0.182 and 0.0256.

In addition, the simulation of the unit requires to assume COP_r (=3) of the system under the rated conditions. Under the rated conditions, the air enters the unit with the temperatures of the dry and wet bulb thermometers of 26.7 °C and 19.4 °C and that the temperatures of the dry and wet bulb thermometers in the front of the condenser are 35 °C or 23.9 °C.

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