This extended research investigates and analyzes a typical multi-zone office building’s annual energy performance. The aim is to evaluate the HVAC system’s and HR unit’s performance in order to conduct the most efficient heating and cooling solution for temperate climate conditions. The energy performance of four HVAC system types (heat pump - air to air, gas - electricity, electrical and fan coil system) were analyzed, compared and evaluated on a virtual office building model in order to assess the total annual energy performance and to determine the efficiency of the HR unit’s application. Further, the parameters of an energy efficient building envelope, HVAC system, internal loads, building operation schedules and occupancy intervals were implemented into the multi-zone analysis model. The investigation was conducted in EnergyPlus simulation engine using thermodynamic algorithms and surface/air heat balance modules. The comparison and evaluation of the obtained results was achieved through the conversion of the calculated total energy demand into primary energy.

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# Energy Performance Modelling and Heat Recovery Efficiency Assessment

## Energy efficient HVAC system determination and Rotary Heat Exchanger's performance assessment

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**Impressum / Imprint**
Bibliografische Information der Deutschen Nationalbibliothek: Die Deutsche Nationalbibliothek verzeichnet diese Publikation in der Deutschen Nationalbibliografie; detaillierte bibliografische Daten sind im Internet über http://dnb.d-nb.de abrufbar.


Bibliographic information published by the Deutsche Nationalbibliothek: The Deutsche Nationalbibliothek lists this publication in the Deutsche Nationalbibliografie; detailed bibliographic data are available in the Internet at http://dnb.d-nb.de.


Coverbild / Cover image: www.ingimage.com

Verlag / Publisher:
LAP LAMBERT Academic Publishing
ist ein Imprint der / is a trademark of
OmniScriptum GmbH & Co. KG
Heinrich-Böcking-Str. 6-8, 66121 Saarbrücken, Deutschland / Germany
Email: info@lap-publishing.com

Herstellung: siehe letzte Seite /
Printed at: see last page
**ISBN: 978-3-659-78143-8**

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# Nomenclature

| | | |
|---|---|---|
| Ta | Air temperature | [°C] |
| G-Gh | Mean irradiance of global radiation horizontal | [$Wm^{-2}$] |
| G-Dh | Mean irradiance of diffuse radiation horizontal | [$Wm^{-2}$] |
| P | Air pressure | [hPa] |
| RH | Relative humidity | [%] |
| N | Cloud cover fraction | [-] |

# Acronyms

| | |
|---|---|
| SHGC | Solar heat gain coefficient |
| VAV | Variable air volume |
| DX | Direct expansion |
| PIU | Powered Induction Unit |

## Abstract

This extended research paper investigates and analyzes a typical multi-zone office building's annual energy performance for the location and climate data of central Belgrade. The aim is to evaluate the HVAC system's and HR unit's performance in order to conduct the most preferable heating and cooling solution for the typical climate of Belgrade city.

The energy performance of four HVAC system types (heat pump - air to air, gas - electricity, electrical and fan coil system) was analyzed, compared and evaluated on a virtual office building model in order to assess the total annual energy performance and to determine the efficiency of the HR unit's application. Further, the parameters of an energy efficient building envelope, HVAC system, internal loads, building operation schedules and occupancy intervals were implemented into the multi-zone analysis model. The investigation was conducted in EnergyPlus simulation engine using system thermodynamic algorithms and surface/air heat balance modules.

The comparison and evaluation of the obtained results was achieved through the conversion of the calculated total energy demand into primary energy. The research goal is to conduct the most preferable heating and cooling solution (Best Case Scenario) for temperate climate conditions of Belgrade city and outline major criteria in qualitative enhancement.

## 1. Introduction

The built environment evidently has the highest energy demand in the world, which is a contemporary problem of consideration. The connection between the energy demand and the increased $CO_2$ discharge to the atmosphere is a great motive to render a more efficient energy usage [1]. Therefore, the goal is finding an alternative solution in order to reduce the energy demand and losses. Numerous researches have been devoted in order to investigate the energy performance of buildings in the commercial sector [2-4]. Building energy efficiency and building performance topics were elaborated via investigations of existing office buildings and computational building models respectively [5]. Simulation-based building performance allows detailed assessment of energy consumption in buildings. Current energy consumption in the building sector is approximated to 40% of the total energy consumption in the world. Therefore, the primary parameters that mostly affect the commercial buildings energy performance are the heating and cooling requirements during the working hours. This paper elaborates the performance of four heating ventilation and air-conditioning (HVAC) system types and arguments the efficiency and importance of the Heat Recovery (HR) unit's application.

Studies have been conducted for energy performance assessment in the early design stages since energy simulation was not integrated into the decision-making process [6]. Numerous proposals have been applied in order to reduce the annual heating and cooling energy demand, as for example double skin facades which represent an additional skin on the outside wall of the building [7]. Thermal mass impact on the energy demand has also been analyzed in the function of occupant comfort to investigate the reduction of the energy requirements from the mechanical systems [5].

The motivation of the investigation was to find respectable answers for improvement of the current heating and cooling supply systems of inefficient office buildings in Serbia. Findings could be extended further for different building types and climatic conditions.

The purpose of the investigation is to analyze a medium multi-zone office building's annual energy performance for the location and climate data of central Belgrade. The reason for the investigation is to evaluate the HVAC system's and HR unit's performance in order to conduct the most preferable heating and cooling solution (Best Case Scenario) for the climate conditions of Belgrade city.

The aim was to determine the heating and cooling energy demand for preferable microclimatic conditions and offer methods for improvement. In this research the energy performance of a 300 [$m^2$] single level office building with an energy efficient envelope was analyzed and evaluated. Since indoor occupant comfort has to be maintained; the temperature, lighting comfort, humidity and air velocity were set in the simulation control for a sedentary work environment. Intervals of occupancy and HVAC operation were implemented in the multi-zone model. Finally, the average climate data was imported from Meteonorm 7 database for the location of central Belgrade [8].

Four HVAC systems were modelled and compared under the same conditions, referring to the climate data, internal loads, occupant schedules and energy efficient envelope with wall U-value of 0.25 [$Wm^{-2}K^{-1}$] and glazing U-value 1.0 [$Wm^{-2}K^{-1}$]. The HVAC system's and HR unit's performance was simulated in order to conduct the most preferable heating and cooling solution for the selected boundary conditions of indoor comfort parameters.

## 2. Methods

The admission of numerous aspects of interpretation plays a key role in energy performance assessment. A detailed energy simulation requires all phases of the project to be designed carefully and precisely, so the integrated parameters create an environment approximated to natural conditions. The interpolation of detailed hourly climate data is obligatory in the simulation, which is programmed to be conducted for an annual period in hourly time steps. The calibrated parametric model's construction properties, internal loads and Heating Ventilation and Air-Conditioning (HVAC) system properties have to form a tight dependence, thus the results will present less deviation from real conditions. The influence of each factor can be examined extensively and systematically utilizing a dynamic energy simulation engine as EnergyPlus, which allows flexibility of the thermal model and its properties.

The HVAC system and HR unit was the primary topic of consideration, since the heating and cooling loads require the highest amount of energy on an annual period in office buildings. The investigation involves the calculation of the building energy performance of four HVAC system types tested on a medium office building model. Four multi-zone models with identical envelope, internal loads and occupancy schedules were constructed with the application of the following HVAC systems:

a. **System 1:** Heat pump – air to air (Multi-zone model 1)
b. **System 2:** Gas and electricity (Multi-zone model 2)
c. **System 3:** Electrical (Multi-zone model 3)
d. **System 4:** Fan coil – Rooftop unit with chiller and boiler (Multi-zone model 4)

The methodology used in the investigation includes the following:

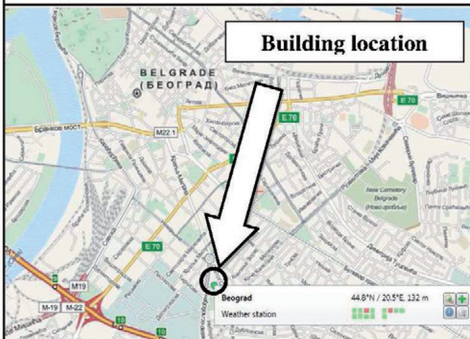
1. Modelling – designing a multi-zone building model with an energy efficient envelope, internal loads, occupancy schedules and HVAC system
2. Simulation – hourly time step calculation in EnergyPlus simulation engine, utilizing system thermodynamics and heat balance method, which operates with surface and air mass balance modules,
3. Comparative analysis and evaluation of the results.
4. Results outline major criteria for improvement from a synthesized, comparative and evaluative angle. The investigation concerns the following steps:
5. Designing a virtual single level multi-zone office building model according to the guidelines and functional disposition of office work spaces,
6. Implementation of climate and location data, envelope construction, internal loads and HVAC systems,
7. Run multiple simulations for an annual period,
8. Comparatively analyze and evaluate the annual energy performance of four multi-zone thermal models with different HVAC systems and assess the HVAC systems energy demand,
9. Assessment of the HR unit's efficiency.

## 3. Materials and multi-zone building model

### 3.1. Location and climate data

The parametric model was constructed as a single level multi-zone office building model according to the functional disposition of office work spaces with an area of 300 [$m^2$]. The location and climate data were imported from Meteonorm 7 – global climatological database for central Belgrade, as shown in tab. 1. [8]. The monthly average values of the climate data and annual Sun-path with building orientation are shown below in fig. 1 and tab. 2 [8]. In fig. 3 and fig. 4 average monthly air temperature and average monthly air relative humidity values can be seen.

Table 1. Location data

| **Location Data: central Belgrade** | **Program: Meteonorm 7** |
|---|---|
|  | Latittude 44.810˚<br>Longitude 20.473˚<br>Altitude 132 m<br><br>Climatic zone = III, 3<br>Radiation model = Default (hour)<br>Temperature model = Default (hour)<br>Temperature: New period = 2000-2009 |

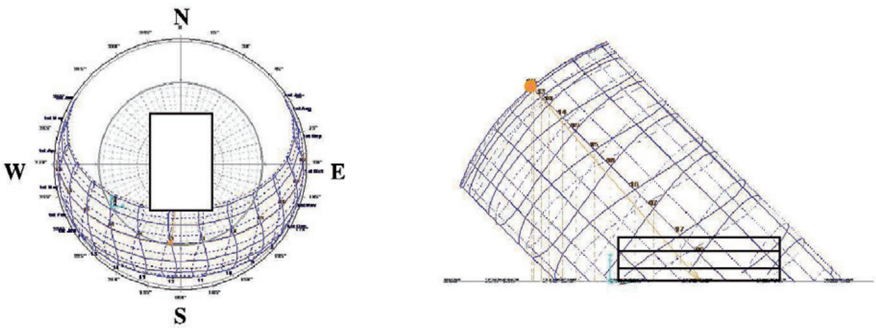



Figure 1. Annual Sun-path with building orientation

Table 2. Climate data – Average values for central Belgrade

| Month | Ta[°C] | G-Gh [Wm$^{-2}$] | G-Dh [Wm$^{-2}$] | P[hPa] | RH[%] | N |
|---|---|---|---|---|---|---|
| Jan | 1.6 | 52 | 30 | 997 | 75 | 6 |
| Feb | 3.7 | 88 | 47 | 998 | 69 | 6 |
| Mar | 8.5 | 137 | 65 | 998 | 60 | 5 |
| Apr | 13.6 | 184 | 85 | 998 | 58 | 5 |
| May | 18.8 | 232 | 117 | 998 | 58 | 5 |
| Jun | 21.7 | 250 | 122 | 998 | 60 | 5 |
| Jul | 23.6 | 259 | 104 | 999 | 57 | 4 |
| Aug | 23.4 | 233 | 97 | 998 | 59 | 4 |
| Sept | 17.8 | 172 | 76 | 998 | 66 | 5 |
| Oct | 13.7 | 113 | 53 | 998 | 70 | 5 |
| Nov | 8.4 | 63 | 35 | 998 | 71 | 5 |
| Dec | 2.9 | 47 | 25 | 997 | 77 | 6 |

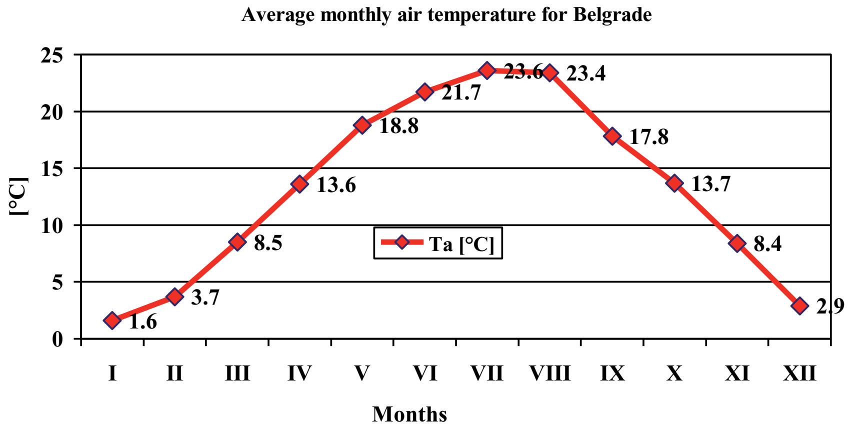



Figure 3. Average monthly air temperature for Belgrade

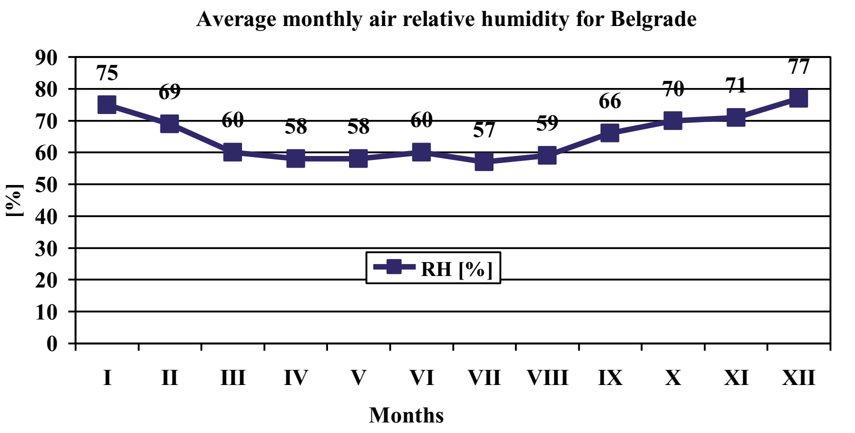



Figure 4. Average monthly air relative humidity for Belgrade

### 3.2. Modelling and simulation methodology

According to the model complexity and simulation process, four programs were used for this study, which are the following:

1. Autodesk Revit Arch. 2011 – 3D model design, function and construction [9],
2. Sketchup Make – Multi-zone thermal model construction [10],

3. Open Studio – Integration of multi-zone thermal model properties; construction materials, internal loads, occupancy and HVAC schedules [11],
4. EnergyPlus – energy simulation [12].

The investigation applies a complex dynamic simulation to determine detailed annual energy performance, since this type of simulation describes the function and behaviour of a parametric analysis model. Dynamic simulations are run in time intervals in order to create a realistic environment for detailed investigation of the energy demand.

The investigation was conducted on a virtual medium single level free-standing multi-zone office building, where the offices are positioned towards East, South and West separated by a central corridor. Each thermal zone was assigned with internal load properties typical for a medium office building. The thermal zones were formed and named according to their function in the building, as shown in tab. 3. The internal zone loads were set to typical medium office loads considering occupancy, electric equipment and lighting.

Table 3. Thermal zones and spaces

| Thermal zone | Space | Area [m$^2$] | Volume [m$^3$] | Thermal zone | Space | Area [m$^2$] | Volume [m$^3$] |
|---|---|---|---|---|---|---|---|
| Thermal zone 1 | Office 1 | 48.27 | 168.95 | Thermal zone 3 | Office 6 | 16.53 | 57.85 |
| | Office 2 | 48.27 | 168.95 | | Office 7 | 16.53 | 57.85 |
| | Office 3 | 48.27 | 168.95 | | Office 8 | 16.53 | 57.85 |
| Thermal zone 2 | Office 4 | 16.53 | 57.85 | Thermal zone 4 | Corridor | 60.00 | 210.0 |
| | Office 5 | 16.53 | 57.85 | | WC | 12.50 | 43.75 |
| Area sum [m$^2$] | | | 300 | Volume sum [m$^3$] | | | 1050 |

Zone-temperature set points were included according to the space functions in the multi-zone building model. The HVAC systems were applied for identical multi-zone models, thus four models were created with identical function, internal loads and construction. Obtained results are comparatively analyzed in terms of energy specific intensity, [kWha$^{-1}$] and [kWhm$^{-2}$a$^{-1}$].

The annual heating and cooling demand and HVAC energy performance are explored through the following steps:

1. Development of a simulation base multi-zone 3D model with assigned internal loads,

2. Export the multi-zone 3D model to Open Studio in order to implement an energy efficient envelope, assign material properties, thermal zone properties and typical interior loads for offices,
3. Implement each HVAC system in a separate but identical multi-zone model,
4. Run multiple simulations in EnergyPlus on annual basis using the climate data from Meteonorm 7 (Belgrade climate data) and calculate zone heating and cooling demands,
5. Implement for each HVAC system a HR unit connected to the outdoor air system,
6. Evaluate the energy performance of the building and evaluate the HR unit's efficiency.

### 3.3. Schedules and construction

The thermostat schedules were set to the following, tab. 4. The schedules for HVAC equipment operation, interior lights and occupancy intervals were also set up for the date, time and scale of the function. For the construction the ASHRAE 189.1 Climate zone 7-8 Construction Set was selected. The modified envelope layers consider the insulation of exterior walls and application of efficient window construction (double glazing with low-E layer). Modified construction layers are shown in tab. 5, and envelope surface properties are shown in tab. 6. The building envelope and window to wall ratio is shown in tab. 7.

Table 4. Thermostat schedules

| Schedule | Date | Time | Temp. setpoint |
|---|---|---|---|
| Office cooling setup schedule | 01.05 – 30.09 | Mon. to Fri. 7-18h | 24 $^0$C |
| Office heating setup schedule | 01.10 – 30.04 | Mon. to Fri. 7-18h | 21 $^0$C |

Table 6. Surface properties

| | **Construction** | **Reflectance [-]** | **U-factor with film [Wm$^{-2}$K$^{-1}$]** | **U-factor no film [Wm$^{-2}$K$^{-1}$]** |
|---|---|---|---|---|
| **SURFACE** | Exterior wall | 0.30 | 0.244 | 0.253 |
| | Ground floor slab | 0.30 | 1.627 | 2.692 |
| | Roof | 0.30 | 0.156 | 0.160 |
| | Window (Double-layer) | **Glass U-factor [Wm$^{-2}$K$^{-1}$]** | **Glass SHGC [-]** | **Glass visible transmittance [-]** |
| | | 1.00 | 0.290 | 0.271 |

Table 5. Modified construction set properties

| Exterior wall layers | Properties | Window layers | Properties |
|---|---|---|---|
| 120 mm<br>Fired clay brick | d = 0.1016 m<br>c = 0.89 $Wm^{-1}K^{-1}$<br>ρ = 1920 $kgm^{-3}$<br>Q = 790 $Jkg^{-1}K^{-1}$ | 6 mm<br>glass panel | Solar transmittance 0.4296<br>Solar reflectance 0.5204<br>Visible transmittance 0.4503<br>Conductivity 0.0089 $Wm^{-1}K^{-1}$ |
| 100 mm insulation | d = 0.1016m<br>c = 0.03 $Wm^{-1}K^{-1}$<br>ρ = 43 $kgm^{-3}$<br>Q = 1210 $Jkg^{-1}K^{-1}$ | 13 mm air gap | d = 0,0127 m |
| 200 mm<br>concrete block | d = 0.20 m<br>c = 1.11 $Wm^{-1}K^{-1}$<br>ρ = 800 $kgm^{-3}$<br>Q = 920 $Jkg^{-1}K^{-1}$ | Low E-layer | Hard coat<br>Insulated glass R= 2.45 |
| 19 mm wall air<br>space resistance | D = 0.019 m<br>R = 0.15 $m^2KW^{-1}$ | 6 mm<br>glass panel | Solar transmittance 0.4296<br>Solar reflectance 0.5204<br>Visible transmittance 0.4503<br>Conductivity 0.0089 $Wm^{-1}K^{-1}$ |
| 19 mm<br>gypsum board | d = 0.19 m<br>c = 0.16 $Wm^{-1}K^{-1}$<br>ρ = 800 $kgm^{-3}$<br>Q = 1090 $Jkg^{-1}K^{-1}$ | | |

Table 7. Window-area, wall-area and window-wall ratio

| | Total | North (315 to 45 deg) | East (45 to 135 deg) | South (135 to 225 deg) | West (225 to 315 deg) |
|---|---|---|---|---|---|
| Gross wall area [$m^2$] | 264.80 | 84.00 | 48.40 | 84.00 | 48.40 |
| Window area [$m^2$] | 88.19 | 25.20 | 14.52 | 33.95 | 14.52 |
| Window to wall ratio [%] | 33.30 | 30.00 | 30.00 | 40.42 | 30.00 |

## 3.4. HVAC system types and equipments

### *3.4.1. Heat pump system*

The heat pump system has gained great attention in application in recent years due to rising energy prices. A heat pump can provide a substantially greater amount of heat according to the energy that it consumes. "Heat pumps are designed to move heat from one fluid to another. The fluid inside the home is air and the fluid outside is either air or water. In the summer, heat from the inside air is moved to the outside fluid. In the winter, heat is taken from the outside fluid and moved to the inside air." [13]

"The most common type of heat pump is the **air-source heat pump**. Most heat pumps operate at least twice as efficiently as conventional electric resistance heating systems in Climate Zone 4. They have typical lifetimes of 15 years, compared to 20 years for most furnaces." [13] The operation principle of an air source heat pump is presented in fig. 5.

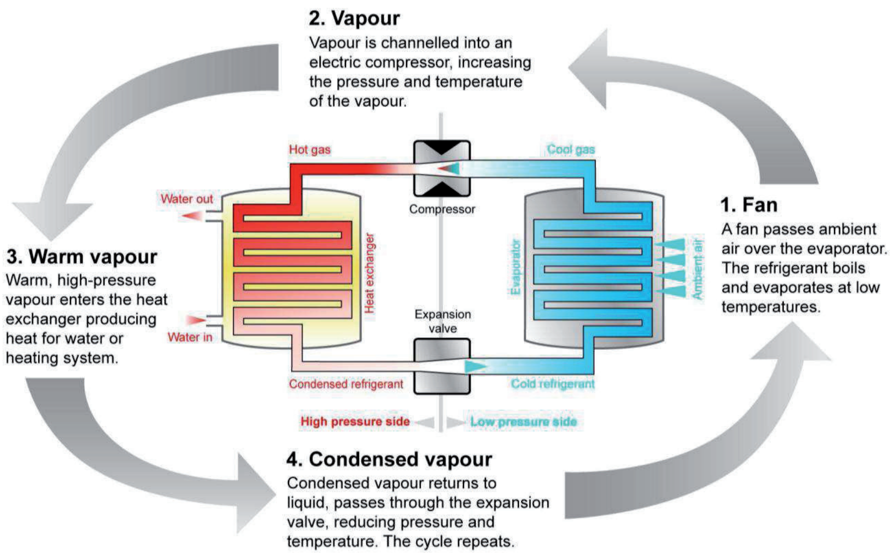



Figure 5. Heat pump cycle - air source [14]

The complete cycle consists of two sides; low pressure and high pressure side. Condensed vapour returns to liquid and passes through the expansion valve where pressure and temperature are reduced, followed by the evaporator process where with a fan ambient air is passed over the refrigerant. Through this process the refrigerant evaporates and is channelled into the electric compressor, increasing its pressure and temperature. Afterwards the warm, high-pressure vapour enters the heat exchanger producing heat for water or heating system. Finally when heat is exchanged the condensed vapour returns to the beginning of the cycle and the process starts over.

“In a **ground water heat pump open loop system**, fig. 6, water is pumped from a well through an isolation heat exchanger and is returned to the aquifer through an injection well. The heat pumps reject (cooling) and absorb (heating) heat from the groundwater through the heat exchanger and a closed piping loop in the building. This arrangement protects the heat pumps from the groundwater if the quality is suspect. Any required cleaning can be easily done at the stainless-steel heat exchanger. Use of injection well disposal ensures the water table level is not adversely affected.” [15]

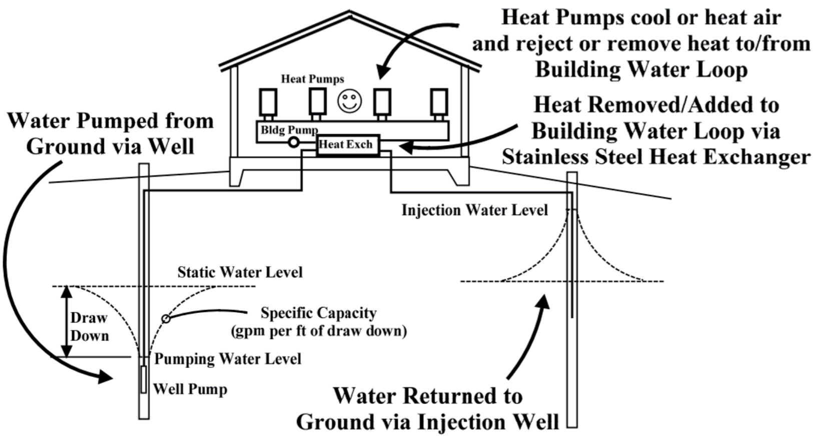



Figure 6. Ground water heat pump - open loop system [15]

“The **ground loop of a closed loop system** is formed by a network of pipes located underground and outside the building footprint as shown in fig. 7. Depending on the energy load and particulars of the site the loops may be installed in either a vertical or horizontal configuration for closed loop system.” [16]

“The primary function of the ground loops is to collect heat from or dispose heat to the ground. This is achieved by circulating a working fluid through buried or submerged pipes (closed loop systems). In heating mode, the heat pump transfer heat collected in the ground loop into the building. In cooling mode, the process is reversed and heat from the building is transferred to the ground loop for disposal.” [16]

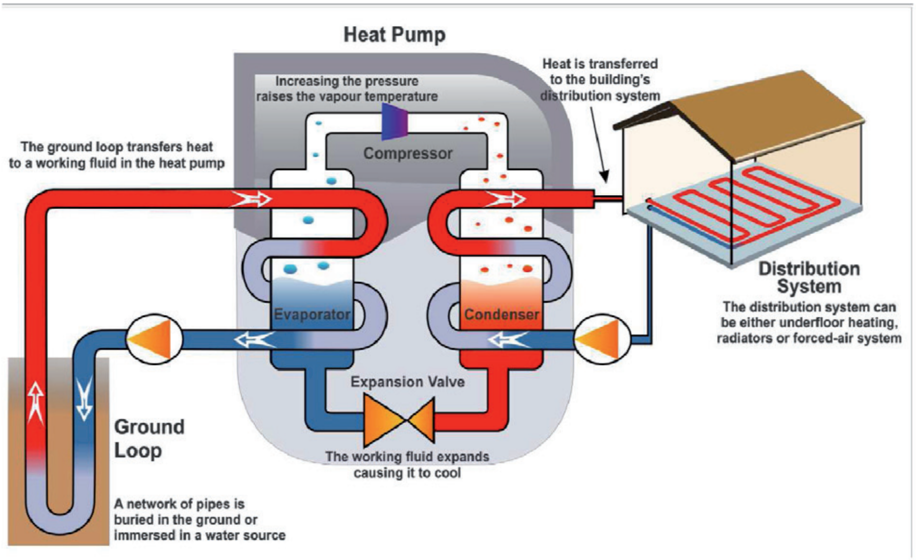



Figure 7. Ground loop heat pump – closed loop system [16]

"The distribution system delivers or removes heat to/from a building. One of the most efficient methods for space heating is to lay pipes in the buildings concrete floor through which warmed water from the heat pump is circulated. Alternative methods include radiators or forced air systems." [16]

In the EnergyPlus simulation the following heat pump air to air system was applied. The system consists of cooling coil direct expansion (DX) single speed, heating coil DX single speed, electric heater, variable speed fan and setpoint manager node for single zone reheat. The system supplies 4 thermal zones of a complete volume of 1050m$^3$. The heat pump air to air system loop is shown in fig. 8.

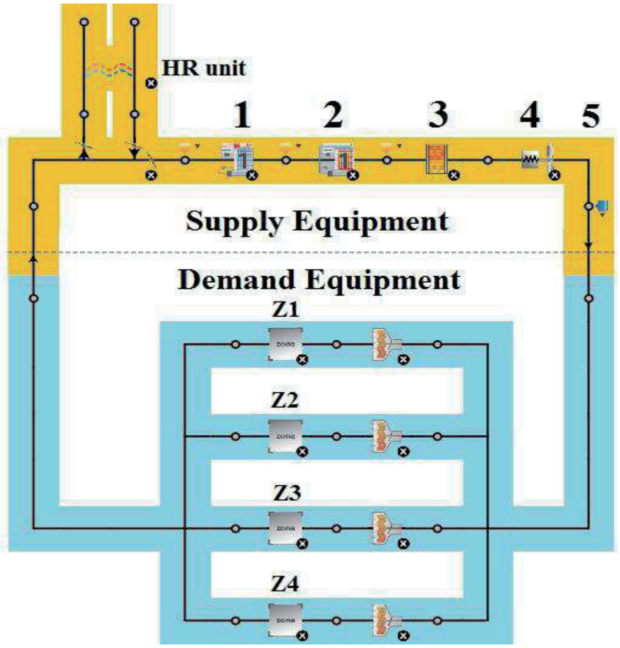



Figure 8. Scheme 1 - System 1 – Heat pump (air to air)
1. Coil cooling DX single speed,
2. Coil heating DX single speed,
3. Coil heating electric,
4. Variable speed fan,
5. Setpoint manager single zone reheat

### *3.4.2. Gas heating system*

#### *3.4.2.1. Direct gas-fired air heating systems*

"Direct gas-fired air heating systems are a class of equipment utilized primarily in industrial and commercial environments to provide for worker comfort. These systems have gained widespread use due to the fact that they are inexpensive to build, maintain, and operate compared to other furnace types of comparable heating capacity. The feature that differentiates a direct gas-fired heating system from other types of heating equipment is its burner system. A "trough" or "line" burner is installed directly in the supply air stream. Combustion products are introduced into the building space during operation." [17]

A direct gas-fired air heating systems is presented in fig. 9. "The key advantages are simplicity and efficiency. No heat exchanger is required. This eliminates component installation and maintenance costs. The primary disadvantage is the introduction of waste products into the airstream. Carbon Monoxide and Nitrogen Dioxide are the primary pollutants. These are limited to no more than 5.0 PPM for CO and 0.5 PPM $NO_2$. A direct gas-fired air heating system may be used in an industrial or commercial application for any or all of the following purposes:

1. Make-up air heating – air is introduced to a building to replace air being exhausted,
2. Space heating – a unit provides primary or supplementary heating to a building space,
3. Space pressure control – building or room pressurization is held within a range." [17]

#### *3.4.2.2. Gas fired heating coils*

"A direct fired heater is a style of heater in which a burner provides hot gasses that transfer their heat energy to a process liquid or gas flowing directly through coils installed inside the heater vessel. Direct fired heaters can utilize radiant and/or convection heat transfer sections, and can be configured in many different ways depending on the requirements." [19]

"Gas fired heating coils are designed for inclusion in air handling units to provide a high efficiency gas fired heating section. They may also be used for replacing steam and hot water coils in existing units and plenum systems to enable changeover from central boiler plant to decentralized gas fired systems." [20]

In the EnergyPlus simulation the following gas heating coil system was applied. The system consists of cooling coil DX single speed, gas heating coil, variable speed fan and set point manager single zone reheat. The system supplies 4 thermal zones of a complete volume of $1050 m^3$. The gas heating coil system loop is shown in fig. 10.

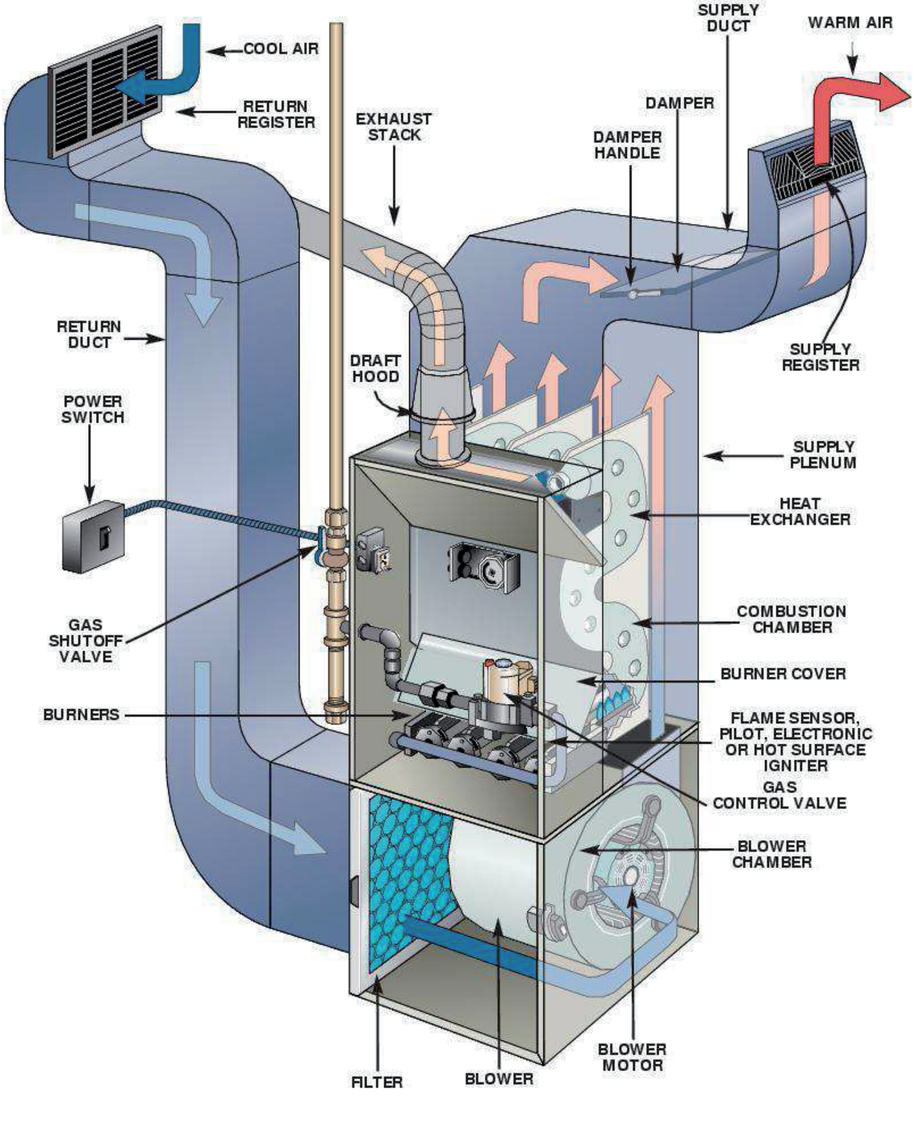



Figure 9. Gas air heater [18]

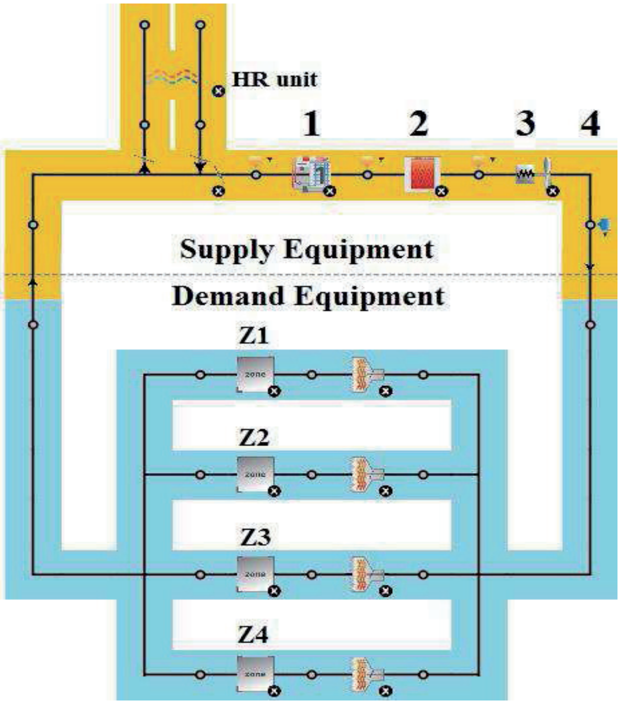



Figure 10. Scheme 2 - System 2 – Gas and electricity

1. Coil cooling DX single speed,
2. Gas heating coil,
3. Variable speed fan,
4. Setpoint manager single zone reheat

***3.4.3. Electric system***

An electric heater is a device for heating rooms that converts electric current to heat by means of resistors that emit radiant energy. Resistors may be composed of metal-alloy wire, non-metallic carbon compounds, or printed circuits. Heating elements may have exposed resistor coils mounted on insulators, metallic resistors embedded in refractory insulation and encased in protective metal, or a printed circuit encased in glass. Fins may be used to increase the area that dissipates the heat. [21]

### *3.4.3.1. Electric forced-air heater*

An electric forced-air furnace uses a blower unit to blow air over electrically-heated coils. The warm air is then distributed through the home through ducts. These units can be used with heat pumps or central air conditioners. [22] The electric forced air heater can be seen in fig. 11 including all specified elements.

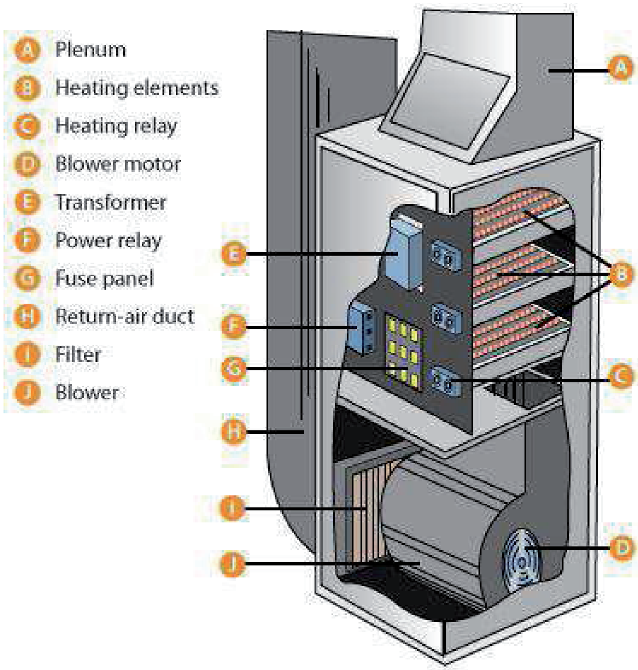



Figure 11. Electric forced-air heater [22]

In the EnergyPlus simulation the following electric heating coil system was applied. The system consists of cooling coil DX single speed, electric heating coil, variable speed fan and set point manager single zone reheat. The system supplies 4 thermal zones of a complete volume of 1050m$^3$. The electric heating coil system loop is shown in fig. 12.

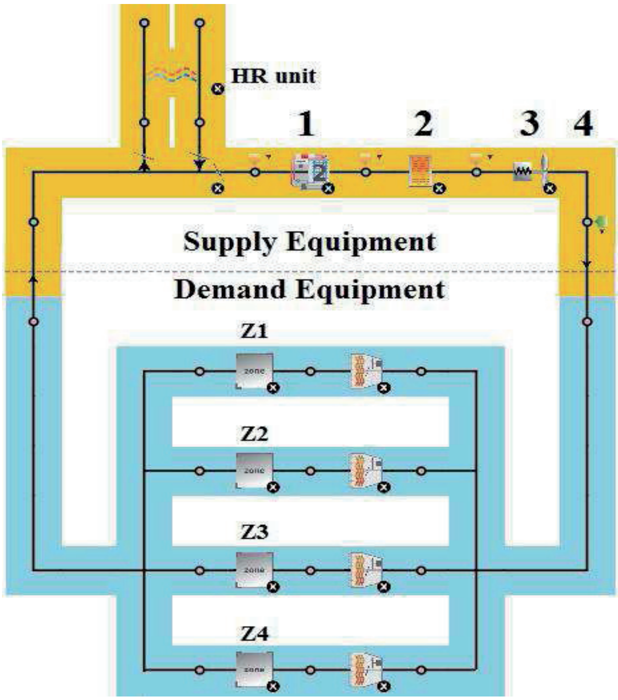



Figure 12. Scheme 3 - System 3 – Electric

1. Coil cooling DX single speed
2. Coil heating electric
3. Variable speed fan
4. Setpoint manager single zone reheat

### *3.4.4. Fan coil system*

"Fan coil systems consist of multiple fan coil units, a piping system, chiller, and boiler. The fan coil units themselves are comprised of a finned-tube coil, an insulated drain pan under the coil to collect condensate, a fan to move air through the coil, filters, and a cabinet to house these components. Typically fan coils are either located above ceilings or ducted to ceiling diffusers, or under windows using console units." [23]

"The chiller may be air-cooled (available in either a single packaged unit, or in various split configurations), or water-cooled in a split configuration utilizing a cooling tower. Water-cooled chillers are more efficient because they reject heat to the wet bulb temperature of the outside air, while air cooled chillers reject heat to the normal dry bulb temperature of the outside air. Water-cooled chillers require maintenance of the cooling tower. For this reason we do not usually recommend water-cooled chillers for smaller systems." [23]

**Two pipe systems**, fig. 13:

"A two-pipe fan coil system consists of fan coil units with single coils, which are connected to two pipes (one supply pipe and one return pipe) that either provide hot water or chilled water throughout the building. A building with a two-pipe system is either entirely in a heating mode or entirely in a cooling mode. It is not possible to cool some rooms while heating others.

A two-pipe system is usually operated in the heating mode in the winter and the cooling mode in the summer. In the spring and fall it is not uncommon to have alternating hot and cold spells, or cold mornings with warm afternoons. This would require that the Owner either tolerate some temperature swings or switch the mode of the system. For example, suppose a warm day was encountered in October, when the system was in the heating mode. The Owner could either accept the lack of air conditioning for a few hours or days, or manually switch the system from heating to cooling. Automatic switchover is not recommended as it can lead to unnecessary cycling.

Two pipe systems cannot handle simultaneous heating and cooling, and are not acceptable where there are internal rooms with high internal gains, such as computer rooms.

Two pipe systems are less complicated in the sense that there are fewer pipes, coils, valves and controls." [23]

**Four pipe systems**, fig. 14:

"A four pipe system has fan coil units with separate heating and cooling coils, as well as separate pairs of heating and cooling pipes. Hot water or chilled water is always available. The system is able to instantly switch from the heating mode to the cooling mode, or vice versa, and can provide heating to some rooms while simultaneously providing cooling to other rooms. It is very flexible." [23]

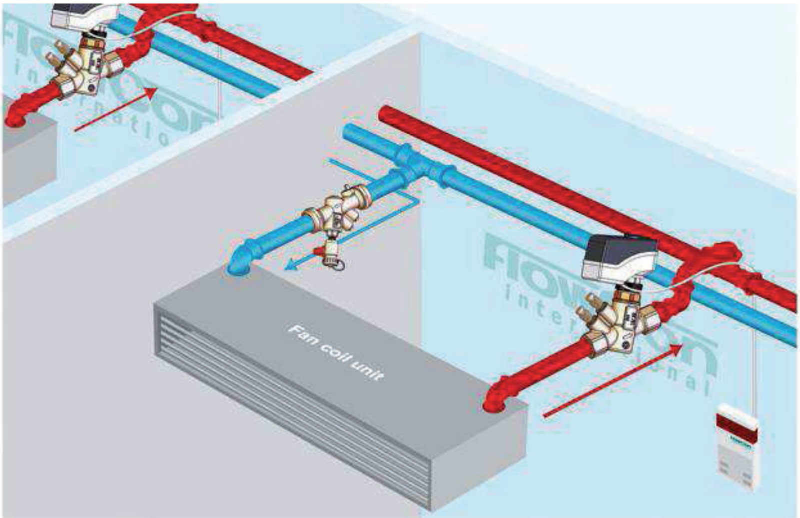



Figure 13. Fan coil - two pipe systems [24]

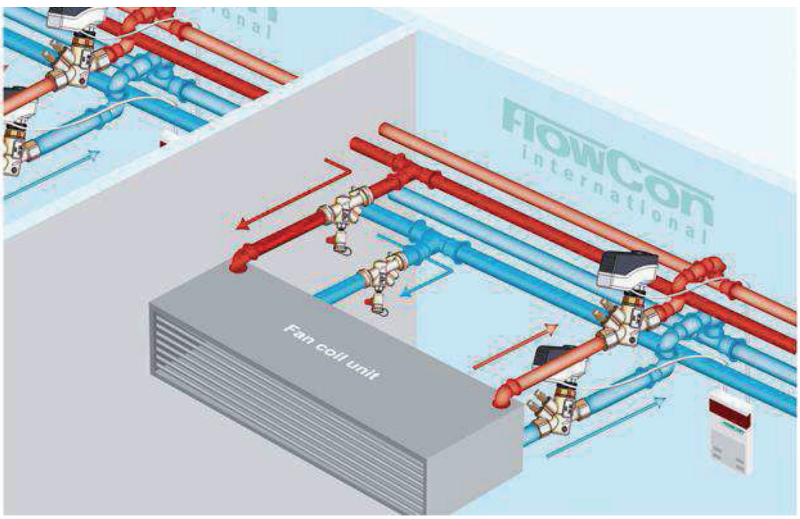



Figure 14. Fan coil - four pipe systems [24]

In the EnergyPlus simulation the following fan coil system was applied. The system consists of cooling coil water loop - variable speed pump, electic chiller, coil heating water loop - variable speed pump, gas boiler, variable speed fan and set point manager single zone reheat. The system supplies 4 thermal zones of a complete volume of 1050m$^3$. The fan coil system loop is shown in fig. 15.

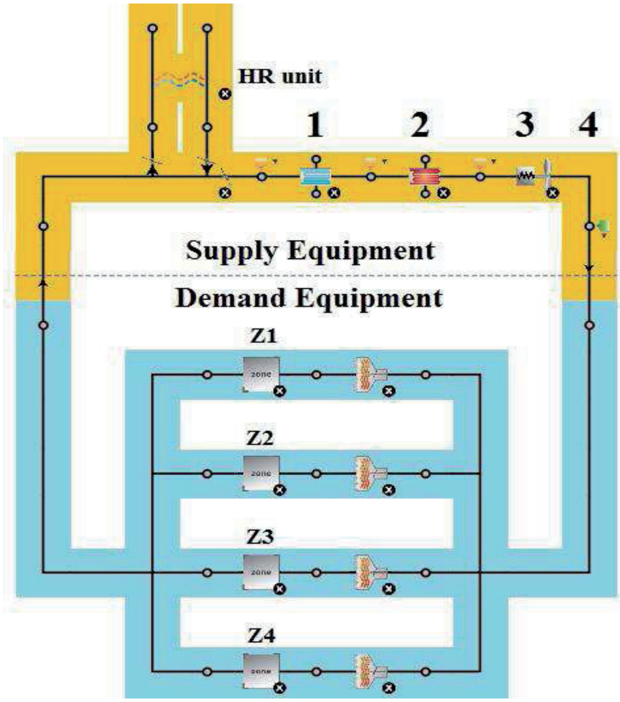



Figure 15. Scheme 4 - System 4 – Fan coil

1. Coil cooling water – Pump / variable speed, electric chiller
2. Coil heating water – Pump / variable speed, gas boiler
3. Variable speed fan
4. Set point manager single zone reheat

## 4. Building energy performance results and discussion

### 4.1. Primary simulation – without the heat recovery unit

Four HVAC systems have been modelled according to the system type and supply fuel. The systems consist of the following supply and demand equipments assigned to each multi-zone model, as shown in tab. 8. The schemes of the four HVAC systems are show in the appendix. For detailed setup of the HVAC systems' mechanical elements, professional sources were used [25, 26].

Table 8. HVAC system equipments

| Equip. | SYSTEM 1 - Heat pump (air to air) | SYSTEM 2 – Gas and electricity |
|---|---|---|
| **Supply equipment** | 1.Coil cooling DX single speed<br>2.Coil heating DX single speed<br>3.Coil heating electric<br>4.Variable speed fan<br>5.Setpoint manager single zone reheat | 1. Coil cooling DX single speed<br>2. Coil heating (gas boiler)<br>3. Variable speed fan<br>4. Setpoint manager single zone reheat |
| **Demand equipment** | **Zone 1** Air terminal single duct VAV with electric reheat<br>**Zone 2** Air terminal single duct VAV with electric reheat<br>**Zone 3** Air terminal single duct VAV with electric reheat<br>**Zone 4** Air terminal single duct VAV with electric reheat | **Zone 1** Air terminal with gas reheat<br>**Zone 2** Air terminal with gas reheat<br>**Zone 3** Air terminal with gas reheat<br>**Zone 4** Air terminal with gas reheat |
| **Equip.** | **SYSTEM 3 - Electrical** | **SYSTEM 4 - Fan coil** |
| **Supply equipment** | 1. Coil cooling DX single speed<br>2. Coil heating electric<br>3. Variable speed fan<br>4. Setpoint manager single zone reheat | 2. Coil cooling water<br>- Pump variable speed, electric chiller<br>3. Coil heating water<br>- Pump variable speed, gas boiler<br>4. Variable speed fan<br>**5.** Set point manager single zone reheat |
| **Demand equipment** | **Zone 1** air terminal single duct parallel PIU reheat<br>**Zone 2** air terminal single duct parallel PIU reheat<br>**Zone 3** air terminal single duct parallel PIU reheat<br>**Zone 4** air terminal single duct parallel PIU reheat | **Zone 1** Air terminal single duct VAV with reheat<br>**Zone 2** Air terminal single duct VAV with reheat<br>**Zone 3** Air terminal single duct VAV with reheat<br>**Zone 4** Air terminal single duct VAV with reheat |

The simulation was performed for a period of one year, 8760 hours with hourly time steps. The primary simulations were run without the HR unit and the obtained results are shown below in fig. 16-23 as a proportional representation and annual sum of building energy demand. Numerical results are shown in tab. 9-12. The absolute values of monthly energy demands are shown from a proportional aspect for an annual period, in order to compare the energy demands of interior loads, fans, heating and cooling. In all four cases the highest annual energy demand was recorded for heating.

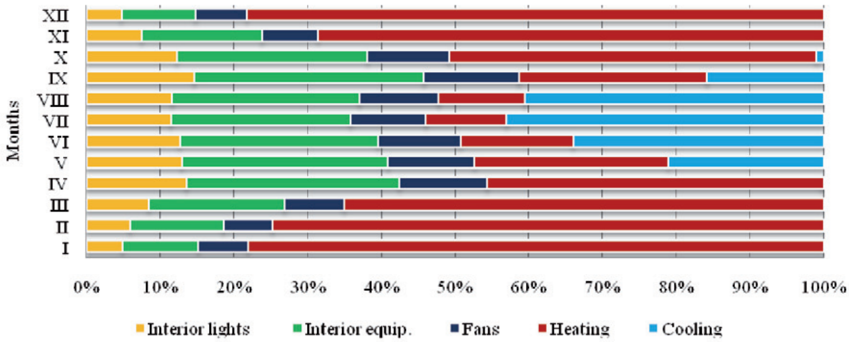


Figure 16. Monthly energy performance proportion – System 1 – Heat pump

For each multi-zone model the absolute value of interior lighting and equipment was set to constant intensity during working hours for every month, yet the proportional monthly energy demand presented a significant deviation. For system 1 (heat pump – air to air), fig. 16, in the summer period the constant loads (interior lights and equipment) were approximated to 40% of total monthly consumption, while the winter period presented close to 20%. The highest heating energy requirement was recorded for January, February and December, nearly 78% of total monthly demands. In contrary, the peak demand for cooling was slightly above 40% in July.

The obtained heating load for the heat pump shows an annual energy demand of 22 [GJ] from total 39.4 [GJ], which is 55% from total annual demand, fig. 17.

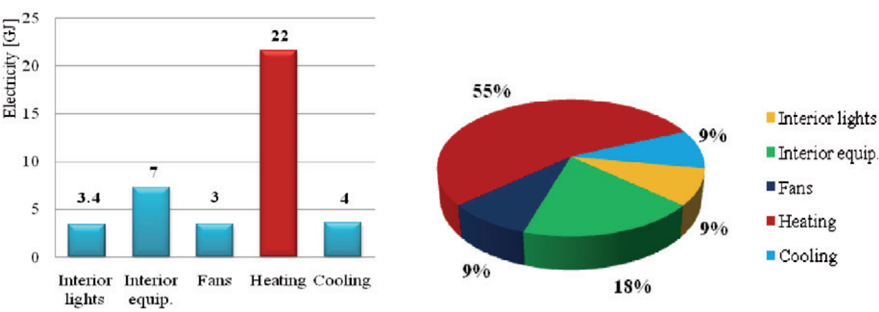


Figure 17. Annual energy demand – System 1 - Heat pump (air to air)

Tab. 9 shows the annual demand and peak values for the heat pump – air to air without the HR unit. Nevertheless, the heating energy demand can be reasonably lowered, with the attachment of the HR unit to the outside air loop system, which will be elaborated in the following section.

Table 9. Building Energy Performance – Heat pump (air to air)

| | **Int. light: elec. [MJ]** | **Int. eq.: elec. [MJ]** | **Fans: elec. [MJ]** | **Heating: elec. [MJ]** | **Cooling: elec. [MJ]** |
|---|---|---|---|---|---|
| Annual sum | 3,385 | 7,276 | 3,454 | **21,597** | 3,639 |
| Min. of months | 259 | 558 | 247 | 279 | - |
| Max. of months | 292 | 623 | 428 | 4,843 | 1,102 |

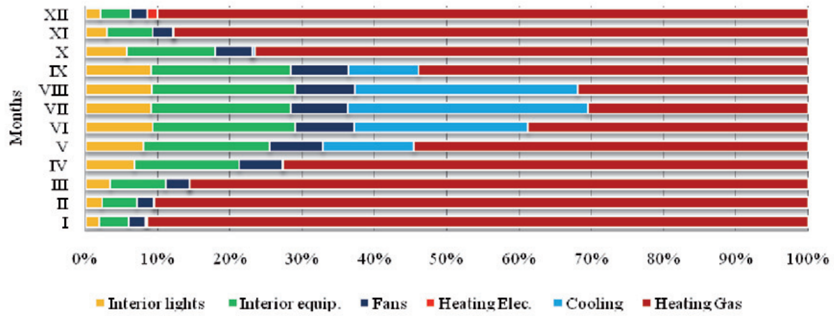



Figure 18. Monthly energy performance proportion – System 2 – Gas and electricity

The absolute value of interior lighting and equipment for system 2 (gas-electricity), fig. 18, presents only 2% of the energy requirement in the winter period, while in the summer period it rises to nearly 9%. The heating energy demand presented drastic values in the winter period with a peak demand of 92%. The peak value for cooling in the summer period reached close to 32%.

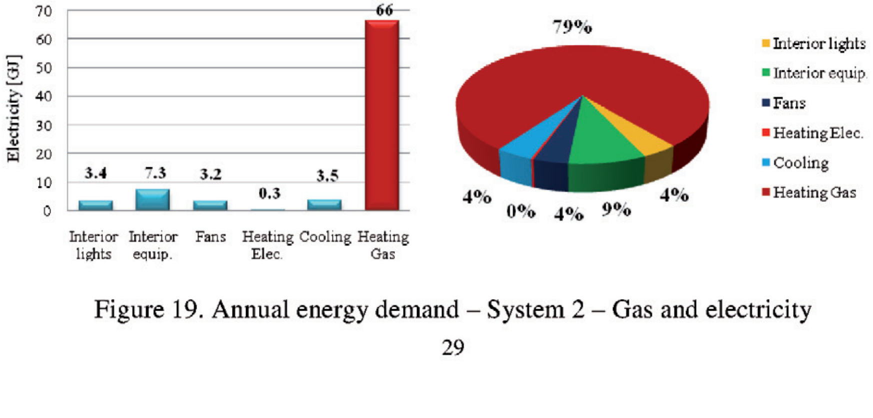



Figure 19. Annual energy demand – System 2 – Gas and electricity

The heating load for system 2 supplied with gas and electricity requires the highest amount of energy among the four compared systems. The heating load is three times higher in comparison with the heat pump. The obtained heating load for system 2 (gas-electricity) shows an annual energy demand of 66 [GJ] from total 83.7 [GJ], which is 79% from the total annual demand, fig. 19. Tab. 10 shows the annual demand and peak values for system 2 without the HR unit.

Table 10. Building Energy Performance – Gas and electricity

| | Int. light: elec. [MJ] | Int. eq.: elec. [MJ] | Fans: elec. [MJ] | Heating: elec. [MJ] | Cooling: elec. [MJ] |
|---|---|---|---|---|---|
| Annual sum | 3,385 | 7,276 | 3,235 | **66,264** | 3,515 |
| Min. of months | 259 | 558 | 247 | 983 | 39 |
| Max. of months | 292 | 623 | 335 | 13,768 | 1,070 |

The monthly energy performance for system 3 (electrical) is presented below in fig. 20 and 21.

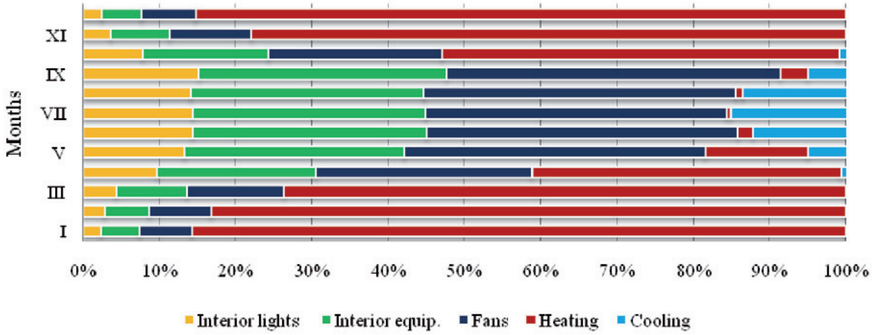



Figure 20. Monthly energy performance proportion – System 3 – Electrical

The absolute values of internal loads for system 3 (electrical), fig. 6, show 2% of the energy requirement in the winter period, while in the summer period it rises nearly to 14%. The heating energy demand has shown a peak demand of 85% in January. The peak value for cooling in the summer period reached close to 15%, while the fans require from May until September close to 40% of total monthly energy.

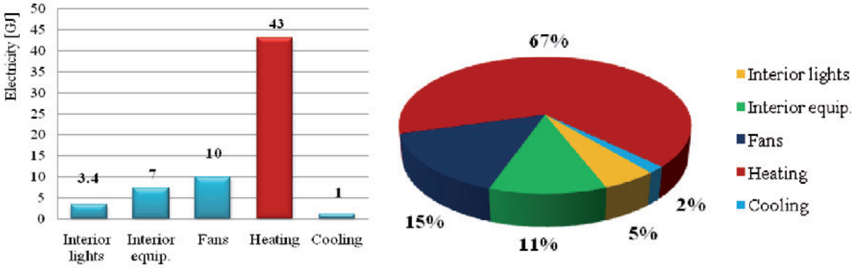



Figure 21. Annual energy demand – System 3 – Electrical

The obtained heating load for system 3 (electrical) presented an annual energy demand of 43 [GJ] from total 64.4 [GJ], which is 67% from the total annual demand, fig. 21. Tab. 11 shows the annual demand and peak values for system 3 without the HR unit.

Table 11. Building Energy Performance – Electricity – Electrical system

| | Int. light: elec. [MJ] | Int. eq.: elec. [MJ] | Fans: elec. [MJ] | Heating: elec. [MJ] | Cooling: elec. [MJ] |
|---|---|---|---|---|---|
| Annual sum | 3,385 | 7,276 | 9,880 | **43,158** | 1,076 |
| Min. of months | 259 | 558 | 766 | 11 | - |
| Max. of months | 292 | 623 | 859 | 10,572 | 308 |

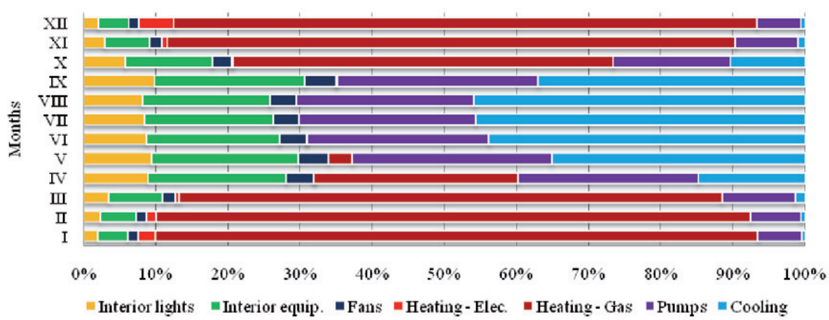



Figure 22. Monthly energy performance proportion – System 4 – Fan coil

The absolute value of internal loads for system 4 (fan coil), fig. 22, presented 6% of the energy requirement in the winter period, while in the summer period it rises nearly to 30%. The heating energy demand has shown a peak demand of 83% in

January. The peak value for cooling in the summer period reached close to 46%, while the fans require close to 24% of the total monthly energy.

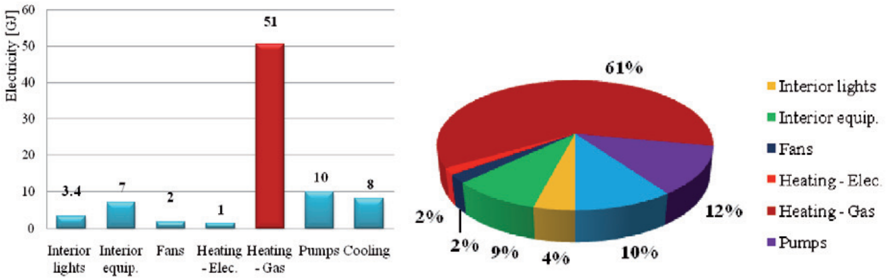



Figure 23. Annual energy demand – System 4 – Fan coil system

The simulated heating load for system 4 (fan coil) resulted in an annual energy demand of 52 [GJ] from total 82.4 [GJ], which is 61% from the total annual energy demand, fig. 23. The annual energy demand with peak values for system 4 is shown in tab. 12 without the HR unit.

Table 12. Building Energy Performance – Electricity – Fan coil system

| | **Int. light: elec. [MJ]** | **Int. eq.: elec. [MJ]** | **Fans: elec. [MJ]** | **Pumps: elec.[MJ]** | **Heating: gas [MJ]** | **Cooling: elec. [MJ]** |
|---|---|---|---|---|---|---|
| Annual sum | 3,385 | 7,276 | 1,752 | 10,039 | **52,079** | 8,150 |
| Min. of months | 259 | 558 | 121 | 787 | - | 60 |
| Max. of months | 292 | 623 | 217 | 904 | 12,438 | 1,594 |

The fan coil system has a higher energy demand since it operates with two coil loops; heating coil loop connected to the boiler and the cooling coil loop connected to the rooftop chiller. Both loops have a separate electric pump which has an energy demand of 10 [GJ] annually. The answer to the high heating demand of 52 [GJ] is the gas supplied boiler. In comparison with the previous gas heater, HVAC system 2, the result is lower for 14 [GJ], although system 2 had one coil loop with only one variable speed pump in operation.

## 4.2. Evaluation and comparison of the HVAC systems' primary energy performance; secondary simulation – with heat recovery unit

### *4.2.1. Heat recovery unit operation principle*

"A heat recovery unit allows the internal air renewal of the premise, maintaining and recovering the energy used for air conditioning.

The main objective of a heat exchanger or heat recovery system is the recovery of the energy by transferring the heat of the air that is extracted from the inside of a premise to the air that is driven outside, as shown in fig. 24.

A heat recovery unit is basically composed of a directly driven fan, an exhauster and a heat exchanger, all perfectly assembled and joined inside a thermal and noise insulated structure. The internal extraction air circuit pass by the exchanger without mixing with the circuit of the external driven air.

Through heat exchanger ventilation it is possible to recover a high percentage of the energy used for the premise acclimatization that otherwise would waste." [27]

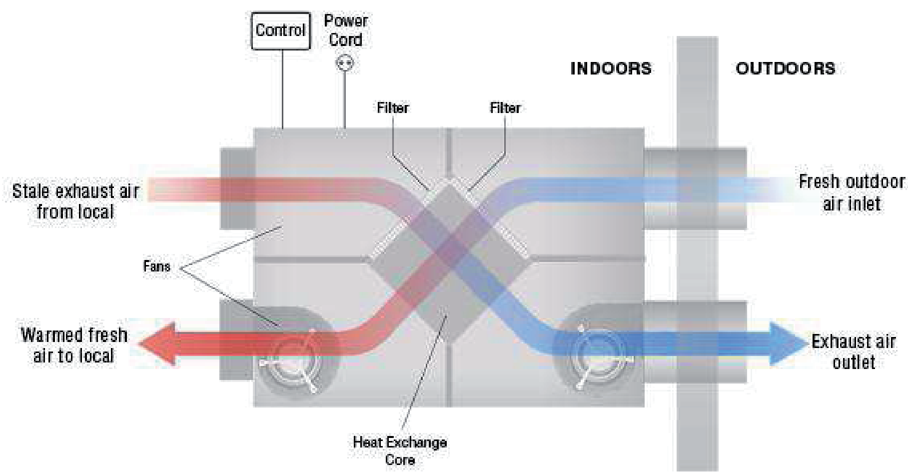



Figure 24. Heat recovery unit [27]

Advantages of ventilation with heat recovery include [28]:

- Increasing comfort and air quality due to constant air renewing. Used oxygen is replaced; the $CO_2$ level remains low. Toxins are removed

- Humidity is reduced to an ideal level
- Warmth remains inside the building, pollution and noise stay outside
- Fresh air from outside is filtered and preheated. Also available with separately available F7-filter to remove pollen
- Substantial reduction of additional heat demand leading to lower heating costs
- High efficiency levels in returning heat to the building
- Meets the requirements of EU Energy Directive

### *4.2.2. Rotary regenerative heat exchanger*

"Rotary regenerative heat exchangers, fig. 25 and 26 are used for heat recovery, and are designed to transfer heat (non-hygroscopic version), or to transfer humidity (hygroscopic version) while simultaneously maintaining the ability to transfer heat from the outlet air to the inlet air. The heat or humidity transfer takes place in the rotor, one half of which reaches into the hot outlet air flow and the other half into the cold inlet air flow. As the rotor turns, the heat-exchange surface of the heat exchanger passes in turn through the outlet and inlet air flow, and thus heat or heat and humidity transfer is enabled. Rotary regenerative heat exchangers are, due to their design and mode of operation, among the most efficient pieces of equipment. Rotary regenerative heat exchangers are mainly used as components of air-handling unit assemblies for inlet and outlet ventilation air.

The designation of rotary regenerative heat exchangers is based on the rotors' diameter range. The heat exchanger's size is determined by the air discharge in relation to the rotor's pressure loss and efficiency." [29]

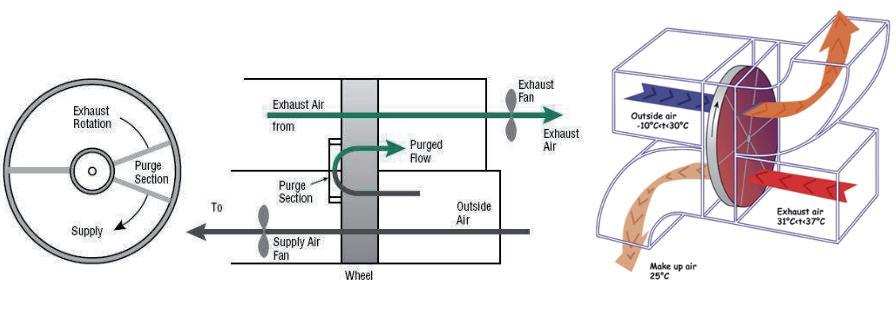



Figure 25. Rotary heat exchanger [30]

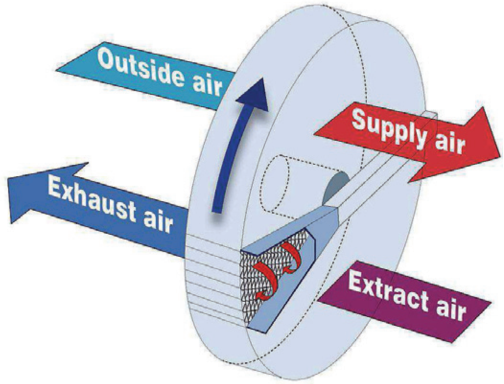



Figure 26. Rotary heat exchanger [31]

### *4.2.3. Comparative analysis of the HVAC systems' primary energy performance*

The second phase refers to the Heat recovery – Rotary heat exchanger unit's connection to the outdoor HVAC system air loop in EnergyPlus with the following properties shown in tab. 13.

Table 13. HR – Rotary Heat Exchanger air to air sensible and latent

| | |
|---|---|
| Supply air flow rate | Auto sized |
| Sensible effectiveness at 75% heating air flow | 0.81 |
| Latent effectiveness at 75% heating air flow | 0.73 |
| Sensible effectiveness at 75% cooling air flow | 0.82 |
| Latent effectiveness at 75% cooling air flow | 0.73 |
| Heat exchanger type | Rotary |

Annual energy performance results of the four HVAC systems were converted into primary energy according to the HVAC systems' supply fuel and fuel production technology. The conversion factor for electricity, for the Serbian power plant supplied by 'lignite' coal equals approximately $f_{prime}$= 3.5. The conversion factor for gas is $f_{prime}$= 1.1 [32]. The conversion factor refers to the production technology and transportation efficiency of energy. Gas has a low conversion factor, because it is excavated on site and after minor treatment transported directly to the user. On the contrary, power plant using lignite coal for electricity production in Serbia operates with conversion factor between $f_{prime}$= 3.0 – 4.0. Tab. 14 shows the converted total annual primary energy demand for each HVAC system, applied to the identical multi-zone building models.

The result for the gas supplied HVAC system, due to its very low conversion factor has the least primary energy demand of 37.45 [$MWha^{-1}$], close to the primary energy demand of the highly efficient heat pump supplied by electricity. The HR unit's efficiency shows a slight deviation among each system. Although the proportional deviation is low, the absolute deviation in significant. For example, as shown in tab. 14, the proportional deviation between the heat pump and the fan coil system is 0.8%, however the absolute deviation is approximately 20 [$MWha^{-1}$], 42%.

Tab. 15 shows the primary energy demand for the heating and cooling loads and the percentage of these loads in comparison with the total annual energy performance.

Table 14. Total annual primary energy demand of multi-zone office building

| **SYSTEM 1**<br>**Heat pump** | **SYSTEM 2**<br>**Gas and electricity** | **SYSTEM 3**<br>**Electrical** | **SYSTEM 4**<br>**Fan coil** |
|---|---|---|---|
| **Primary energy without HR unit** | | | |
| 127 [$kWhm^{-2}a^{-1}$] | 124 [$kWhm^{-2}a^{-1}$] | 209 [$kWhm^{-2}a^{-1}$] | 218 [$kWhm^{-2}a^{-1}$] |
| ∑ 38,255 [$kWha^{-1}$] | ∑ 37,451 [$kWha^{-1}$] | ∑ 62,965 [$kWha^{-1}$] | ∑ 65,588 [$kWha^{-1}$] |
| **Primary energy with HR unit** | | | |
| 87 [$kWhm^{-2}a^{-1}$] | 84 [$kWhm^{-2}a^{-1}$] | 135 [$kWhm^{-2}a^{-1}$] | 151 [$kWhm^{-2}a^{-1}$] |
| ∑ 26,351 [$kWha^{-1}$] | ∑ 25,332 [$kWha^{-1}$] | ∑ 40,670 [$kWha^{-1}$] | ∑ 45,585 [$kWha^{-1}$] |
| **Primary energy reduction with HR unit** | | | |
| 31.5% | 32.3% | 35.4% | 30.7% |

Table 15. Annual heating and cooling loads primary energy

| **SYSTEM 1**<br>**Heat pump** | **SYSTEM 2**<br>**Gas and electricity** | **SYSTEM 3**<br>**Electrical** | **SYSTEM 4**<br>**Fan coil** |
|---|---|---|---|
| **Heating and cooling demand without HR** | | | |
| ∑ 24,566 [$kWha^{-1}$] | ∑ 20,248 [$kWha^{-1}$] | ∑ 43,006 [$kWha^{-1}$] | ∑ 24,746 [$kWha^{-1}$] |
| 64% of the total energy requirement | 54% of the total energy requirement | 68% of the total energy requirement | 38% of the total energy requirement |
| **Heating and cooling demand with HR** | | | |
| ∑ 12,785 [$kWha^{-1}$] | ∑ 8,581 [$kWha^{-1}$] | ∑ 20,693 [$kWha^{-1}$] | ∑ 23,787 [$kWha^{-1}$] |
| 48% of the total energy requirement | 34% of the total energy requirement | 51% of the total energy requirement | 32% of the total energy requirement |

Heating and cooling demands without the HR unit show a relatively high percentage of 64% for the heat pump, 54% for the gas-electricity, 68% for the electrical system and 38% for the fan coil. The importance of the HR unit is significant since it lowers these demands drastically, from 64% to 48% for the heat pump, from 54% to 34% for the gas-electricity and finally from 68% to 51% for the electrical system. The Fan Coil system was specific because the HVAC system operation requires a constant energy supply, so the heating and the cooling demand was lowered the least, from 38% to 32%.

The evaluation of the HVAC systems indicates that the most efficient system among the compared for heating and cooling would be the heat pump (air to air) and the gas-electricity, since the primary energy need for these systems with the HR unit application is approximately equal. However, the simulation presented that a multi-zone office building with heat pump HVAC system demands three times less heating energy, compared to the gas-electricity HVAC system from previous calculations, shown in tab. 9 and 10. In further research an economic evaluation will present a more detailed comparative overview of the mentioned systems.

The calculations also consider the HVAC systems' energy intensity as shown in tab. 16, without and with the application of the HR unit. This comparative analysis increases the importance of HR unit application, resulting in lower energy requirement for HVAC system operation. Tab. 17 shows the conversions from tab. 16 into primary energy for the operation of the four HVAC systems.

Table 16. Utility use per total floor area

| HVAC System | Without HR, annual HVAC energy demand [$kWhm^{-2}a^{-1}$] | With HR, annual HVAC energy demand [$kWhm^{-2}a^{-1}$] |
|---|---|---|
| **Heat pump** | 21.15 | 15.56 |
| **Gas and electricity** | 6.65 Electricity, 62.72 Gas<br>∑ 69.37 | 6.21 Electricity, 26.59 Gas<br>∑ 32.8 |
| **Electrical** | 51.24 | 29.50 |
| **Fan coil** | 23.56 Electricity, 48.36 Gas<br>∑ 71.92 | 29.16 Electricity, 31.91 Gas<br>∑ 61.07 |

Table 17. Primary energy use for HVAC operation per total floor area

| HVAC System | Without HR, HVAC energy intensity [$kWhm^{-2}a^{-1}$] | With HR, HVAC energy intensity [$kWhm^{-2}a^{-1}$] |
|---|---|---|
| **Heat pump** | 74.03 | 54.46 |
| **Gas and electricity** | 23.28 Electricity, 68.99 Gas<br>∑ 92.27 | 21.73 Electricity, 29.25 Gas<br>∑ 50.98 |
| **Electrical** | 179.34 | 103.25 |
| **Fan coil** | 82.46 Electricity, 53.19 Gas<br>∑ 135.65 | 102.06 Electricity, 35.10 Gas<br>∑ 137.16 |

The heat pump HVAC system with HR unit requires the least annual energy for operation (15 [$kWhm^{-2}a^{-1}$], primary 54 [$kWhm^{-2}a^{-1}$]), while the fan coil HVAC system with HR unit required the most (61 [$kWhm^{-2}a^{-1}$], primary 137 [$kWhm^{-2}a^{-1}$]) among the four designed systems.

From the comparative analysis the presented results indicate that for central Belgrade location and climate parameters a similar multi-zone office building with similar functional disposition, envelope construction and glazing properties requires the least amount of energy for the HVAC operation if the Heat Pump (air to air) system is applied.

The analysis indicates that the most preferable solution for a medium office building between (200-400 [$m^2$]) would be the application of the heat pump (air to air) powered HVAC system with HR unit with an annual operating energy demand of 15.56 [$kWhm^{-2}a^{-1}$]. Although the climate parameters and internal loads are variable, the same method can be applied for further investigation.

## 5. Final remarks and conclusion

Dynamic energy performance simulations are useful in order to assess and analyze the energy demands of a building, underlining the importance of decision-making in the early stages of design. Therefore, engineering decisions in further stages of improvement and optimization can be precise.

The paper has elaborated a topic of applying the computational approach in evaluation of the annual energy performance on a multi-zone office building model with typical internal loads, in order to assess the total annual energy demand of the building and HVAC system operation. An evaluative study was conducted for the HR unit's performance in order to analyze its efficiency on an annual heating and cooling period. From the comparative analysis the presented results indicate that for central Belgrade location and climate a similar, according to the analyzed, multi-zone office building between (200-400 [$m^2$]) would have the most efficient preformance if the heat pump HVAC system with HR unit is applied, since the annual HVAC operational energy demand is approximately 15 [$kWhm^{-2}a^{-1}$]. The heat pump HVAC system's energy intensity is significantly lower compared to the gas-electricity (33 [$kWhm^{-2}a^{-1}$]), electrical (30 [$kWhm^{-2}a^{-1}$]) and fan coil (61 [$kWhm^{-2}a^{-1}$]) system from the simulations. The heat pump HVAC system's operational energy intensity per floor area is approximately 55% lower compared to the gas-electricity, 50% lower compared to the electrical and finally 74% lower compared to the fan coil.

Although the climate parameters and internal loads are variable, the same method can be applied for further investigation. The paper has elaborated the importance of energy simulation in the first stages of a developing project.

Further investigations include validation of a similar office building for the same location. Future goals will be developed in the direction of comfort analysis to optimize annual building energy performance in the function of microclimatic conditions.

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