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TECHNICAL AND ENVIRONMENTAL ASSESSMENT OF SELECTED HEAT PUMP CONFIGURATIONS. A CASE STUDY

Two heat pump systems with the highest energy performance indicators were chosen for an analysis. Those most efficient systems for heating and cooling are ground source heat pumps (GSHP) and the exhaust air heat pumps (EAHP). Consequently, two cases (case A and case B) with different pump configurations were related to a reference case R represented by gas-fired boilers covering heating needs and compression refrigeration units ensuring cooling needs. Technical assessment in the form of coefficients of performance as well as primary energy ratings were completed. An environmental impact taking into account CO_2, SO_2 and NO_x emissions of analysed heat pump systems was also evaluated.

1. INTRODUCTION

Environmental concern about global warming and local atmospheric pollution is the primary impetus for various clean energy technologies. There is a strong consensus among the scientists studying climate change problems that the global warming now observed is caused mainly by the combustions by-products. Thus, conventional energy systems are in large measure responsible for impending an environmental problem of global warming.

Renewable energy can be a certain measure of reducing the amount of fossil fuels combusted. One can notice the steadily rising energy prices and the risk of price shock observed lately makes renewable energy technologies more attractive than conventional ones. Another social and economic reason for the interest in clean energy is the growing demand for energy in general.

Application of heat pumps in heating, ventilating and air conditioning (HVAC) systems is broadly considered as a renewable energy technology. Also, a favourable

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environmental impact in the form of a reduction of CO_2, SO_2 and NO_x emissions is highlighted as an important factor of heat pumps usage. The best objective to demonstrate the benefits of application of heat pumps seems to be an educational institution building because then one can effectively teach a wide public about attractiveness of clean energy. Therefore, a school building has been chosen to study a feasibility of heat pump systems.

The heat pump concept is well established technology and its technical solutions are widely covered by the basic literature [1–4]. Additionally, specific concepts of air source and ground source heat pumps have gained quite considerable popularity in public but most applications are focused on small residential buildings which are illustrated in numerous literature references [5–13]. One can notice that technical, economic and ecological aspects of those small installations are not necessarily well applying to medium and big size buildings, as for example schools. Some distinguished examples of bigger heat pump installations can also be found in literature [14–17]. These literature examples show that the big size applications of heat pumps can give quite promising results and as the renewable energy installation can be the only heating and cooling source for the building without any need for an auxiliary heating or cooling. Furthermore, reduction of CO_2 emissions is highlighted as an important feature of environmental impact of the heat generation process in GSHP systems [18–20]. However, the issue of SO_2 and NO_x emissions related to operation of heat pumps in heating and cooling systems for building applications have not been widely analysed in the relevant literature.

The aim of this study was to investigate the energy saving potential as well as the environmental impact of using heat pumps systems for heating and cooling of buildings. Two cases of configurations of heat pumps have been analysed in the study, with highest performance indicators used in heating and cooling systems in a school building. Those most efficient heat pumps were ground source (GSHP) and exhaust air (EAHP) heat pumps. Those heat pump configurations hve been compared with a reference case represented by gas fired boilers producing hot water to cover heating needs and compression refrigeration units ensuring cooling needs. An environmental impact taking into account CO_2, SO_2 and NO_x emissions of analysed systems was assessed after calculations of the performance factors and primary energy consumptions.

2. DESCRIPTION OF THE SYSTEM

2.1. THE BUILDING CHARACTERISTICS

The school building under the study is a two-floor construction of 6100 m^2 total usable area. The building incorporates parts of various functions such as primary school, kindergarten, canteen, library and sports facility. Those areas require different indoor climate conditions. Thus, HVAC systems are chosen separately for specific areas. All rooms are equipped with a radiator type central heating system with design water temperature of 50 °C and the specific areas are served by separate air handling units which in independent way supply air of determined conditions.

The school building has been designed with a thermally efficient envelope. High thermal effectiveness is attained by applying very good insulation with the *U*-value of 0.17 $W/(m^2 \cdot K)$ for walls, 0.20 $W/(m^2 \cdot K)$ for roofs and 1.1 $W/(m^2 \cdot K)$ for windows. Additionally, some elements of passive solar techniques have been introduced to the architectural design. Thus, heating and cooling needs of the building are largely reduced without compromising the thermal comfort. Another technique of reducing the total heat demand has been a rejection of traditional natural ventilation that contributes considerably in design heat load without providing any proper indoor air quality. The main effectiveness criterion of the ventilation system is its capability of attaining CO_2 concentrations inside the building always below the level of 1000 ppm. The additional function of the ventilation system is supplementing air heating in winter and air cooling in summer.

Proper technical solution of the building architecture and its HVAC system can considerably reduce all heating and cooling needs for the central heating and the ventilation system. The total annual heating load of the building consists of central heating and ventilation requirements. The building central heating needs 481 200 kWh while the ventilation heating requires 330 800 kWh. A significant part of ventilation heat can be recuperated by a two stage recovery arrangement combining cross flow heat exchangers and exhaust air heat pumps. The annual cooling load of the building cannot be calculated in such a straightforward way as it is a case with heating load because the ventilation system operates up to 12 hours per day in the cooling season that is much shorter than heating season with an irregular function during hottest months of July and August. The cooling load simulation for the reference year conditions gives the value of 96 500 kWh. The cooling can be supplied to air handling units by central refrigeration system or exhaust air heat pumps.

2.2. REPRESENTATION OF THE HEAT PUMPS' SYSTEM

The performance of heat pumps used in the building heating and cooling installations is affected by several factors, as:

- Climate – annual heating and cooling loads and maximum peak demand.
- Temperatures of heat source and heat sink.
- Auxiliary energy consumption (pumps, fans and supplementary heating or cooling devices).
- Construction of heat pump units.
- Heat pump sizing in relation to heating and cooling loads.
- Operational characteristics and control system of heat pump units.

Technical and economic performance of a heat pump is closely related to characteristics of the heat source. An ideal heat source has high and stable temperatures during heating season and it is fully available. Different heat sources have been analysed for a specific application in the school building. The following heat sources have been assessed in the study: ambient air, exhaust air, underground water and ground-soil. The ambient air is the most common heat source for heat pumps. However, ambient air source heat pumps attain much lower seasonal performance factors than heat pumps of other sources. This is mainly due to the fall of both capacity and coefficient of performance with decreasing outdoor temperature as well as a relatively high temperature lift and an energy needed for de-frosting operation. In general, air-to-air and air-to-water heat pumps seem to be not particularly suitable for complex heating, ventilating and air conditioning installations. Thus, the evaluation concentrates on GSHPs. Three types of ground source heat pumps have been considered: (1) one with the ground heat exchanger in the form of horizontal coils, (2) another with vertical U-tube arrangements and (3) last one with water wells as heat source. The horizontal coils concept has been abandoned because of the lack of sufficient area of the site. Neither the idea of water wells proves to be a practical solution due to the necessity of having several water extraction and injection wells on the building site.

Hence, the GSHP with the vertical heat exchanger is chosen as a heating or a cooling source for the building. During heating season, the GSHP extracts heat from the ground through the ground heat exchanger and supplies it to central heating and ventilation installations. It is also possible to operate the GSHP in such a manner that a cooling effect is produced. The fluid circulating in the ground heat exchanger is used then as a heat sink for the condenser while the evaporator cools the cooling water delivered to air handling units.

Another heat source that is considered in this particular building is exhaust air in the ventilation system. The exhaust air heat pump (EAHP) is basically heat recovery device in the air handling unit (AHU). During heating season the EAHP extracts heat from the exhaust air and heat the outside air. During the cooling season, the heat pump operates in a revers mode to cool and possibly dehumidify outside air entering the air handling unit. The exhaust air then cools the condenser coil at a lower temperature than the ambient air temperature. The AHU is additionally equipped with a recovery heat exchanger and in this way the overall recovery process is more efficient.

Those two heat pump types (GSHP and EAHP) have been chosen as the most efficient solutions to be used in two different configurations (case A and case B) for heating and cooling the building. Figure 1 illustrates the case A representing the GSHP system that delivers heat to central heating installations and heating coils in air handling units during heating season.

During cooling season the GSHP system operates in a reverse mode supplying cold water to AHUs. In this case one needs only GSHP units coupled with the ground heat exchanger (GHE) to cover all heating and cooling demands of the building. Both

GHE and GSHP units are sized for design heating demand of central heating and ventilation because design cooling demand is always lower in local climate and thus only some of GSHP units are required to cover the whole cooling load.

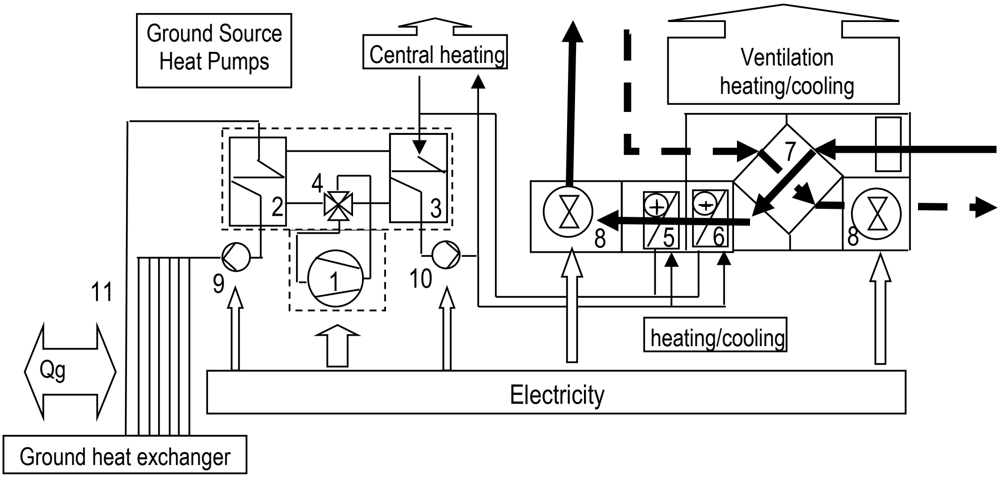

Fig. 1. GSHP configuration, the case A: compressor (1), evaporator (2), condenser (3), four-way valve (4), heating coil (5), cooling coil (6), cross flow heat exchanger (7), fan (8), brine circulation pump (9), heating/cooling water pump, vertical ground heat exchanger (11)

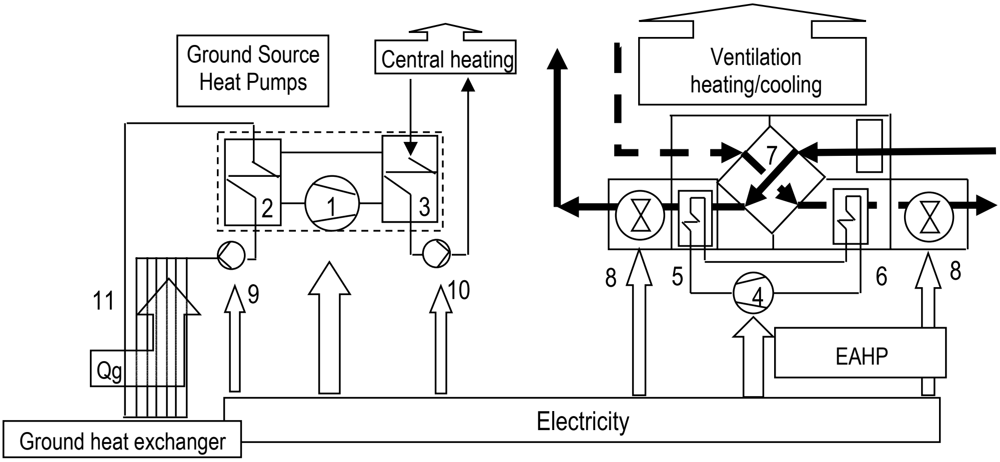

Fig. 2. GSHP and EAHP configuration, the case B: compressor (1), evaporator (2), condenser (3), four-way valve (4), air side condenser (5), air side evaporator (6), cross flow heat exchanger (7), fan (8), brine circulation pump (9), heating water pump (10), vertical ground heat exchanger (11)

Figure 2 shows another configuration of heat pumps designated as the case B. At this time, the GSHP supplies heat just to central heating installations whereas air handling units incorporating EAHPs can heat or cool ventilation air. In this case, both types of heat pumps, GSHP and EAHP, operate independently using fully their characteristics. The GSHP capacity is much lower than in the case B because heating and cooling demands of the ventilation system is covered by the EAHP. Also, the ground heat exchanger, one of the most costly items of the GSHP system, can be proportionally smaller.

3. EVALUATION OF HEAT PUMPS PERFORMANCE

The main task of the presented analysis is to compare heat pumps arrangements in terms of their thermal performance as well as CO_2, SO_2 and NO_x emissions illustrating an environmental impact of the system. After finding the most thermally and environmentally efficient heat pumps system, this solution will be related to the reference case (case R) represented by gas-fired boilers and a central cooling plant in the form of vapour compression units.

Those comparative studies are based on simulation model written within the Matlab platform. The simulation covers the building and its heating demand for central heating and ventilation, performance of central heating and ventilation installations and the operation of the heat pumps. The performance of the heat pump unit is usually characterized by a well-known indicator called the unit coefficient of performance, COP_u, that is defined in heating mode as the ratio of heat produced by a heat pump to electrical power delivered to compressor.

$$\mathrm{COP}_u = \frac{Q_H}{P_c} \tag{1}$$

Nevertheless, the system coefficient of performance, COP_s gives a broader picture of heat pump systems taking into account auxiliary energy to run brine circulation pumps or additional fans. For the GSHP, the COP_s takes the form of

$$\mathrm{COP}_s = \frac{Q_H}{P_c + P_{cp}} \tag{2}$$

where Q_H is the heating capacity of the GSHP, P_c the compressor power and P_{cp} the power of circulation pumps. The COP_s for the exhaust air heat pump, the EAHP, is assumed to have the same value as COP_u because the combined fans power in the air handling unit with the EAHP is in the similar range as in the conventional AHU.

The final analysis carried out for all three the cases (R, A, B) has been focused on energy ratings of the described systems. The ratings have been performed according to the European Standard EN 15603:2008 [21] taking into account different forms of energy such as delivered energy, primary energy and auxiliary energy. For the baseline situation of the case R when all heating needs are covered by gas boiler, the delivered energy is calculated as:

$$E_{\text{del}} = \frac{E_{HV}}{\eta_t} \tag{3}$$

where E_{HV} is the energy needed for heating and ventilation, η_t the total efficiency of the system. The primary energy is calculated then as:

$$E_{\text{prim}} = E_{\text{del}} F_g + E_{\text{aux}} F_{el} \tag{4}$$

where F_g is the primary energy factor for gas heating, F_{el} the primary energy factor for electricity and E_{aux} is the auxiliary electrical energy. According to the European Standard CENITC 228:2007, the following values of those factors have been taken for the study: $F_g = 1.1$ and $F_{el} = 3.0$ [22]. The delivered energy for the GSHP and the EAHP is determined by the following formula:

$$E_{\text{del}} = \int_0^{\tau} \frac{P_C}{\text{COP} - 1} d\tau \tag{5}$$

where P_c and COP is integrated throughout the heating season. The primary energy for both types of heat pumps is calculated as:

$$E_{\text{prim}} = \left(E_{\text{del,GSHP}} + E_{\text{del,EAHP}} + E_{\text{aux}}\right) F_{el} \tag{6}$$

In addition to primary energy rating, also carbon dioxide rating has been performed as stated by the standard EN 15603:2008. The combined environmental impact of all greenhouse gases compounds is commonly normalized to the specific effect of CO_2 and all emissions are expressed in CO_2 equivalents. For the purpose of this study, the emissions are just expressed in the mass of CO_2. Emission factors for heat production with gas boiler, EF_h and electricity production, $EF_{el,}$ representative in the local energy production market are introduced in order to calculate actual emissions. The following values are currently used in Poland: EF_h = 0.202 kg CO_2/kWh and EF_{el} = 0.812 kg CO_2/kWh according to [23]. Similarly to CO_2, SO_2 and NO_x emissions are being evaluated for considered systems with the values relevant to electricity production: $EF_{el}(SO_2)$ = 6.0 g/kWh and $EF_{el}(NO_x)$ = 2.5 g/kWh [23].

In the cooling mode, heat pump units operate reversely and both ground heat exchanger fluid and exhaust air serve as cooling media for condensers whereas evaporators deliver cooling effect to the ventilation system. All above described formulas are then changed by replacing the heating capacity of the heat pump system (Q_H) by the cooling capacity (Q_C). A common practice in describing performance of heat pump system is to use an average or a reference value of COP. In this study, the coefficients of performance are calculated on an hour-by-hour basis throughout the heating or cooling season and then are weighted for a given time period, e.g. a day or a month. Thus, COP values take into account an actual heating or cooling demand of the building.

All the relevant models and formulas have been put into the Matlab simulation program specially constructed for this study.

4. RESULTS AND DISCUSSION

In order to evaluate an environmental impact of heat pumps performance one should first make a proper technical appraisal of the systems. It takes into account calculations of the following items: the coefficients of performance as well as delivered and primary energy attributed to heat pump arrangements.

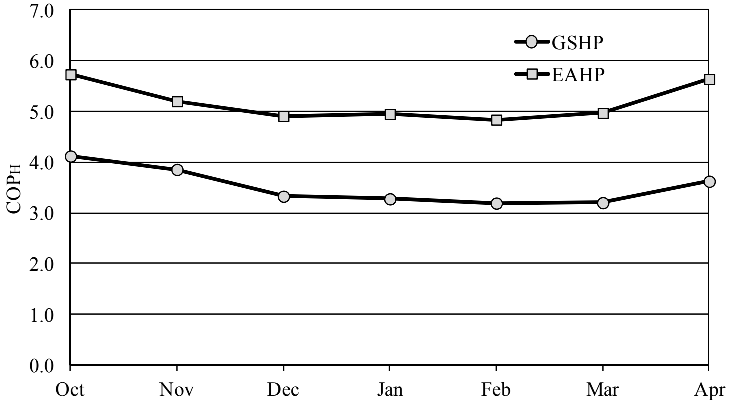

Fig. 3. Heating coefficients of the performance

Figure 3 shows monthly normalised values of unit COP_H in the heating mode for the ground source heat pump (GSHP) and for the exhaust air heat pump (EAHP). The COP_H values for the GSHP vary from 4.12 in October to 3.20 in February with the heating seasonal average of 3.35. The COP_H values for the EAHP change from 5.73 in October to 4.84 in February with the heating seasonal average of 5.15. It is quite evident that during the heating season, the performance of EAHP is more energy efficient than the performance of GSHP.

The COP_C values for the GSHP vary from 5.60 in May to 4.80 in July with the cooling seasonal average of 5.00. The COP_C values for the EAHP change from 4.80 in

May to 3.90 in July with the cooling seasonal average of 4.25 (Fig. 4). Throughout the cooling season, the GSHP performance is more efficient than the EAHP performance due to the change of source and sink temperatures. The values of overall system performance factors, COP_s, are in general lower by 10–15 % than in the case of unit COP due to the need of auxiliary energy for circulation pumps.

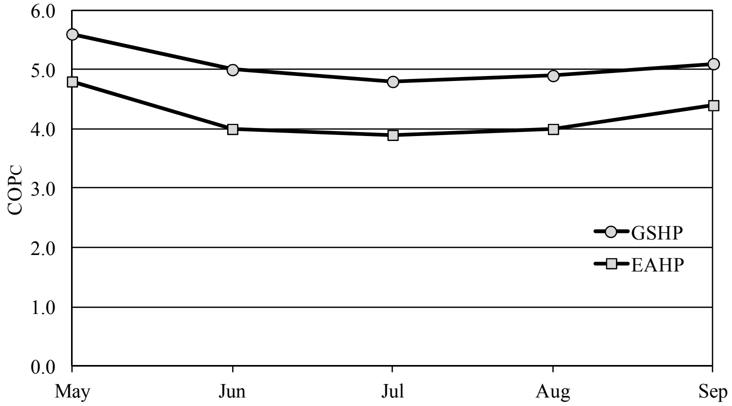

Fig. 4. Cooling coefficients of the performance

It is worth mentioning that the GSHP and EAHP attain the best thermal performances of all heat pumps usually operating in heating and ventilation systems. Therefore, those applications seem to be the best cases for examining their primary energy ratings and their CO_2, SO_2 and NO_x emissions.

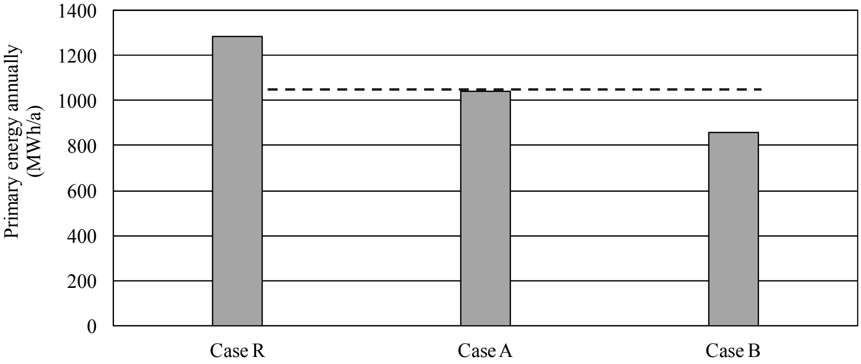

Fig. 5. Annual primary energy usage

Figure 5 shows the annual consumption of primary energy for all three cases. The case R represented by a standard solution of gas-fired boilers and a central cooling plant in the form of vapour compression unit consumes more primary energy than the two cases with heat pumps arrangements (cases A, B). The case B with the ground source heat pump serving the central heating system and the exhaust air heat pump assisting the ventilation system has better primary energy rating than the case A with the ground source heat pump covering all needs of central heating and ventilation.

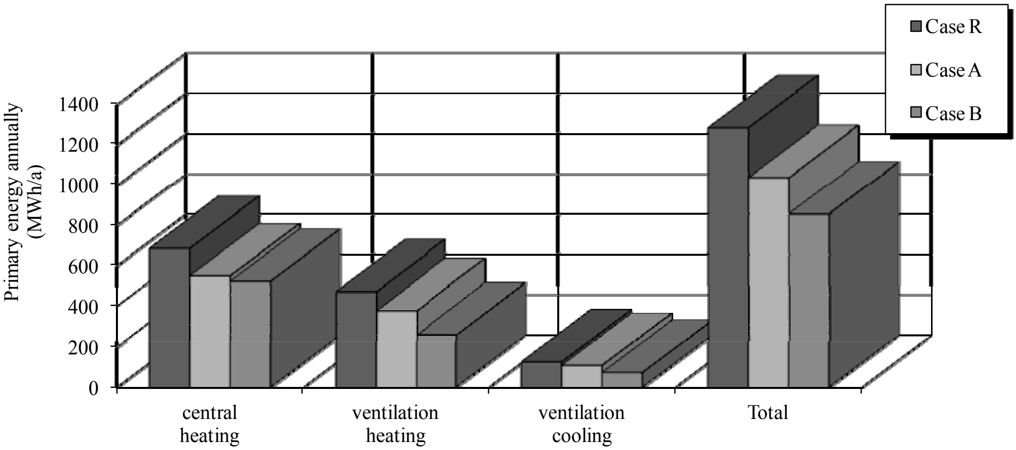

Fig. 6. Break-up of primary energy usage (cases R, A, B)

Figure 6 illustrates how primary energy usage is allocated to specific installations, central heating, ventilation heating and ventilation cooling. The smallest differences among the cases can be observed in ventilation cooling and in central heating between the cases A and B. Altogether the trend in partitions is similar to the total usage with the case R having the highest primary energy usage and the case B the lowest usage in central heating, ventilation heating and ventilation cooling.

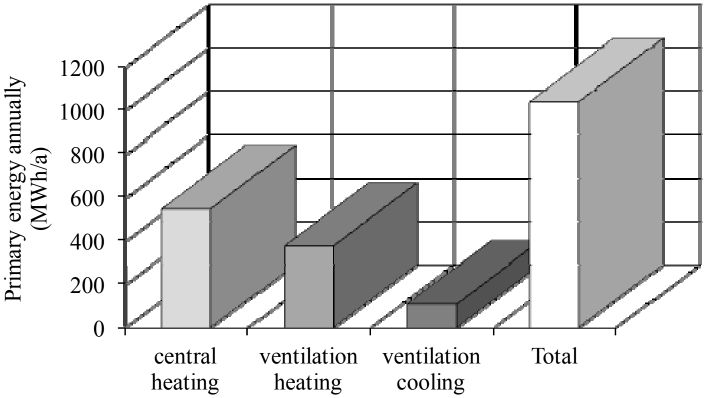

Fig. 7. Break-up of primary energy in the case A

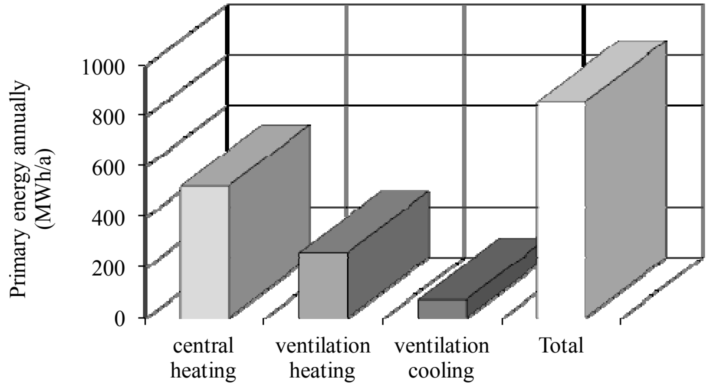

Fig. 8. Break-up of primary energy in the case B

Figures 7 and 8 show the break-up of primary energy usage in the case A, and case B, respectively. One can notice that the central heating always consumes more primary energy than the ventilation heating and cooling together. This phenomenon comes from the specific characteristics of building thermal performance. The proportion could be changed but the total usage of primary energy would be always lower in the case B than the case A.

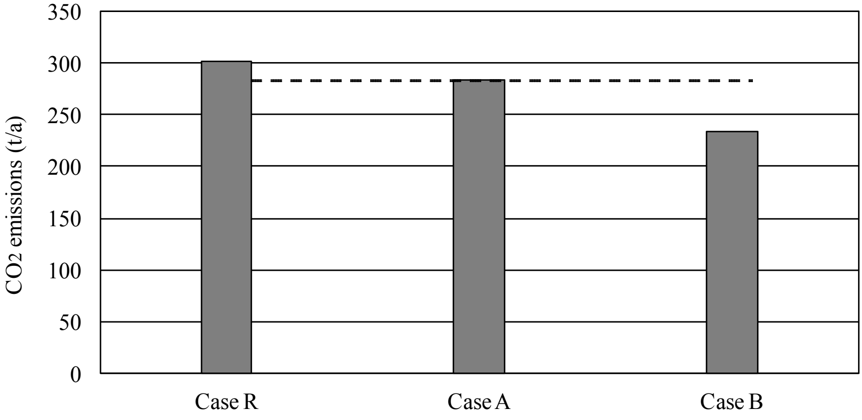

Fig. 9. Annual CO_2 emissions

The completion of primary energy ratings allows evaluation of CO_2, SO_2 and NO_x emissions in the considered cases. Figure 9 illustrates that annual CO_2 emissions in both solutions with heat pumps, the cases A and B, are lower than the reference solution, the case R, with gas boilers and ordinary refrigeration units. The arrangement with the GSHP and the EAHP (case B) has distinctively lower emissions than the arrangement with only the GSHP system. These reductions of emission in the analysed heat pump arrangements come from the fact that heat pump units of very high coefficients of performance have been used in the system. The positive effect would be even better if the electricity production was transformed to cleaner less carbon intensive methods.

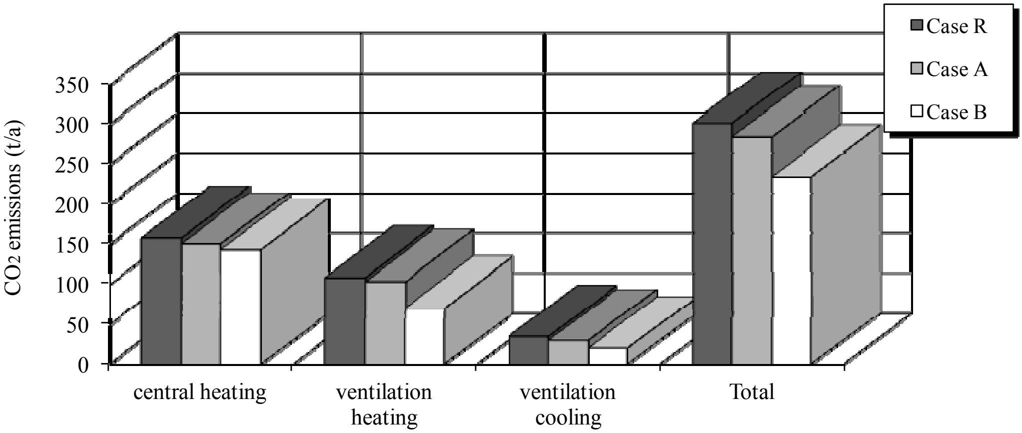

Fig. 10. Break-up of CO_2 emissions

Figure 10 illustrates CO_2 emissions allocated to specific installations, central heating, ventilation heating and ventilation cooling. The smallest differences among the cases can be observed in central heating. Ventilation heating in the cases R and B demonstrates comparable emissions. The best result with ventilation heating is obtained in the case B due to the application of the EAHP with a very high coefficient of performance. Ventilation cooling presents emission proportions similar to ventilation heating.

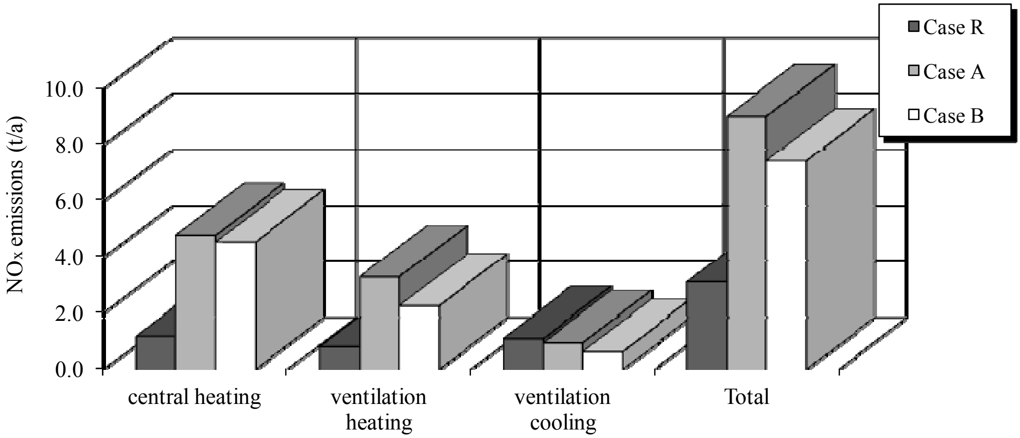

Fig. 11. Break-up of NO_x emissions

Figure 11 depicts NO_x emissions allocated to specific installations: central heating, ventilation heating and ventilation cooling. The situation is then very different from that with CO_2. NO_x emissions are distinctively lowest in the reference case R with gas boilers and refrigeration units. Traditional central heating and ventilation heating with gas boilers represent much smaller emissions than installations with heat pumps. Ventilation cooling renders similar emissions among all cases since the same compression cooling method based on electricity is used.

The latter environmental impact factor, i.e. SO_2 emissions is portrayed in Fig. 12. Emissions in the case R for central heating and ventilation heating are practically nonexistent because of SO_2 free gas burning boilers. On the other hand, electricity production is quite SO_2 intense and all heat pumps and refrigeration units signify considerable SO_2 emissions.

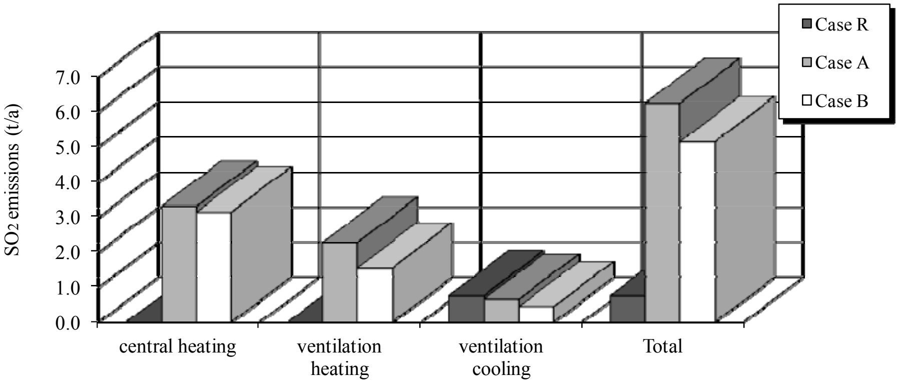

Fig. 12. Break-up of SO_2 emissions

The presented method of analysing the primary energy usage and assessing the CO_2, SO_2 and NO_x emissions in heat pump systems used for heating and cooling the buildings is so far not covered in the relevant literature. Therefore, it is worth popularizing this approach in heat pumps applications as well as other systems considered to be based on renewable energy.

5. CONCLUSIONS

The presented study has focused on evaluating an energy saving potential as well as an environmental impact of using heat pumps systems for heating and cooling of buildings. Two heat pump systems with the highest energy performance indicators have been chosen for analysis. Those most efficient systems for heating and cooling are the ground source heat pump (GSHP) and the exhaust air heat pump (EAHP). Subsequently, the two cases A and B with different pump configurations have been related to a reference case R represented by gas-fired boilers covering heating needs and compression refrigeration units ensuring cooling needs. In order to assess the environmental impact of the systems, the technical appraisal of the considered cases has been completed. The outcome of that appraisal has been a presentation of primary energy ratings for three systems. One can notice that the biggest primary energy usage is in the case R and the smallest in the case B, indicating that heat pump systems are more energy efficient than the traditional solution with gas-fired boilers and central refrigeration units. Also, the configuration with ground source and exhaust heat pumps has better primary energy ratings than the configuration with only the ground source heat pump.

A similar trend can be noticed with CO_2 emissions but the differences among the cases are much smaller. It is worth mentioning that heat pumps in the analysed building have lower CO_2 emissions because they are very energy efficient units. Most of heat pump systems used in buildings are not so efficient and therefore, CO_2 emissions could be higher than in traditional solutions.

A completely different picture has come from the analysis for NO_x and SO_2 emissions.The traditional system in the case R releases over twofold less NO_x than systems with heat pumps. The situation with SO_2 emissions is even more acute since the reference system R emits six times less SO_2 than the ground source heat pump system in the case A and almost five times less than the GSHP and the EAHP in the case B. The only source of SO_2 in the case R is ventilation cooling produced by typical compression refrigeration units which consume a little more electricity than the heat pumps. Altogether, the gas boilers are much cleaner as far as NO_x and SO_2 are concerned than the heat pumps which are supposed to be clean energy source. The reason for that unfavourable situation is a specific electricity production mix occurring in Poland. The only remedy for achieving a more benign environmental impact of heat pumps operation could be a process of introducing less carbon intensive methods of electricity production.

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