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An environmental aspects of various types of heat sources in a single-family house

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Abstract: The article evaluates various types of heat source used for heating and ventilation in a typical single-family house. Additionally, the paper presents the ecological analysis of the proposed solutions according to The National Centre for Emissions Management (KOBiZE) standards. The analysis was carried out for commonly used heating systems such as a gas boiler with closed combustion chamber, an air-source heat pump (ASHP), a ground source heat pump (GSHP), a coal fired boiler and a wood fired boiler. Moreover, the paper describes the energy performance and energy balance of a typical single-family house. Ultimately, the ecological choice of heating system was presented.

Keywords: sustainability growth, ecological analysis, heat source for a detached house, environmental aspects
JEL codes: Q01, Q53

1. Introduction

The definition of sustainable development defines a degree of development that meets the needs and aspirations of the present without compromising the ability of future generations to meet their own needs. The concept was first presented in the report of the World Commission on Environment and Development, also known as the "Brudtland Commission" in April 1987 (Morżoł, 2006).

The concept of sustainable development refers to quality of human life; it about balancing of planes (Pawlowski and Pawlowski, 2004: 277):

- nature and environment (environmental conservation),
- technical (new technologies, preserving raw materials)
- economic (taxes, subsidies),

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- social (e.g. solution for the problem of unemployment),
- political (implementation and monitoring of strategies for sustainable development).

One of the elements of sustainable development is the effective use of resources (particularly natural). Among the actions leading to their use are following (Burchard-Dziubińska, Rzeńca and Splinter, 2014: 32):

- decoupling the economic growth from resource usage,
- introduction of a low carbon economy,
- increasing the share of renewable energy sources,
- actions aimed at promoting energy efficiency,
- development and implementation of new, environmentally friendly technologies.

It is worth noting that during the Summit of the European Council, which took place on 8-9 March 2007, an Action Plan which was designed to integrate climate and energy policy of the European Union States was adopted. Basic actions of this plan consisted of (Wysokińska and Witkowska, 2016: 61):

- reduction of 20% of greenhouse gas emissions by 2020 compared to 1990.,
- increasing the share of energy from renewable sources to 20% of the total average energy consumption of the EU in 2020.,
- rationalizing energy use and, consequently, reducing consumption by 20%,
- 10% share in the sales of transport biofuels in 2020.

The construction industry is one of the most important sectors that introduce the idea of sustainable development. Its significance in the national economy, participation in air emissions, energy consumption and waste production are noteworthy. It influences the environment in many areas, as shown in Table 1.

Table 1. Areas of the impact of construction on the environment

No.	Area
1	An energy consumption in the course of: - Construction - production of construction materials, transport associated with the construction, - Operation of a building (heating, air conditioning, ventilation, lighting) - approx. 25-40% of total energy consumption in OECD countries.
2	A flow of goods or building materials and products.
3	An increase in the amount of construction and demolition waste.
4	Additional waste connected with exploitation.
5	Consumption of natural resources during construction and operation (e.g. Water, wood, sand, etc.).
6	Air pollution as a result of - Producing materials (paints, varnishes, etc.) - Poor indoor air quality resulting from the use of harmful materials and other finishes - CO_2 emissions during operation.
7	Destruction of ecosystems - seizure of the space under construction and infrastructure.

Source: Belniak, Głuszczak and Zięba, 2013: 61.

For the purposes of building sector, the concept of sustainable development can be adapted, as according to (Marchwiński and Zielonko-Jung, 2014: 2) "a demand payment" of used resources at a given time, is difficult to achieve. Therefore, regarding the construction purposes, the definition of sustainable development accepts extraction and use of resources (as in large quantities), provided that these resources are renewable or exist in unlimited quantities in the Earth. In addition, the level of waste and pollution it is also acceptable, but may not exceed a level of tolerance of our planet.

The main problems associated with introduction of the concept of sustainable development in the construction industry is to reduce emissions of carbon dioxide and other gases into the atmosphere, to reduce the amount of construction waste and to prevent indoor air pollution. A detailed analysis on the impact of the construction industry on the environment includes primarily, energy consumption and CO_2 emissions, waste generation and pollution of internal environment. From the date of signature of the Kyoto Protocol in 1997, the countries that opted for its ratification, committed to reduce emissions of carbon dioxide, methane, nitrogen oxides and greenhouse gases (i.e. HFCs, PFCs and SF6). The treaty is regarded as the first step of the international community to act on improvement of the environmental protection.

2. Emissions in single-family housing

Air protection is one of fundamental and most important activities in the area of environmental protection. It is based on providing the best quality of air, mainly by (Lipińska, 2016: 71):
- maintaining the levels of substances in the air below the permissible levels, or at least at these levels,
- reducing the levels of substances in the air at least to the permissible limits, if they are not met.

One of the fundamental activities aiming to reduce emissions of air pollutants in single-family housing is to reduce the energy demand of a particular building. In existing buildings, the easiest way to achieve reduction of emissions is to conduct thermal modernization works (insulation of external envelope, replacement of windows and doors, better thermal transmittance “U-value”) and exchange of heat source (e.g. conversion of coal-fired boiler to biomass boiler). In newly constructed buildings, it is preferably to take into account the minimization of energy consumption of the building at the design stage; therefore, more and more houses are built in a passive standard (annual energy demand is less than 15 kWh/m^2). These houses are characterized with greater insulating parameters of external envelopes and application of innovative solutions to reduce energy consumption during operation.

This study focuses on the assessment of emissions associated with operation of a typical residential single-family building i.e. carbon dioxide (CO_2), sulfur dioxide (SO_2), nitrogen dioxide (NO_2), carbon monoxide (CO), dust and benzo[a]pyrene (B(a)P).

The purpose of this article is to present which of the analyzed heat sources emit into the atmosphere a smaller amount of impurities for a typical single-family house. In the building, there were used different heat sources: a gas boiler with a closed combustion chamber, an air-source heat pump, a ground source heat pump, a coal-fired boiler and a wood-fired boiler. The analysis was performed using specialized software – Audytor EKO v.1.0, in accordance with the standards of the National Centre for Emissions Management (KOBiZE).

3. Characteristics of the facility accepted for analysis

The object of research was a single-family house made of brick, two-storey without cellars, with a gable roof with (height - 8m, length - 16.2 m, width - 8 m), height of the storey in the light - 2.7 m, total height - 3.1 m. On the ground floor, there are a vestibule, hall, kitchen with window, living room, toilet, bathroom, pantry, and living room with dining area, utility room and garage. On the other hand, on the first floor there are three bedrooms, two bathrooms with window, two dressing rooms, a hall and utility room. The fundamental assumptions for the calculation are included in Table 2.

Table 2. The basic assumption for calculation

No.	Climate zone	III
1.	A design external temperature	- 20 °C
2.	An average annual external temperature	7,6 °C
3.	Location–a meteorological station	Racibórz-Studzienna
4.	Total heated floor area	179 m^2
5.	Total volume	479,5 m^3
6.	Window area	10,5 m^2
7.	Number of rooms	18
8.	The standard for determining the heat transfer coefficient U for building partitions	PN-EN ISO 6946
9.	The standard for the calculation of the design heat load Φ	PN-EN 12831:2006
10.	The standard for the calculation of the energy demand for heating Q_E	PN-EN ISO 13790

Source: Own elaboration

The building is located in the third Polish climate zone (PN-EN 12831: 2006) Construction barriers meet the standards specified in the Regulation of the Minister of Infrastructure of 12 April 2002. (Dz. U. of 2002 No. 75, item. 690, as amended). The outer walls are made of concrete blocks, polystyrene and plaster whereas internal walls of concrete blocks. The building is fully heated. Table 3 summarizes the number of rooms with its area and internal temperature. The calculation was made in accordance with applicable standards, using industry software designed to calculate the heat load - Auditor OZC 6.6 Pro.

Table 3. List of rooms

No.	Name of the room	Area [m^2]	Room temperature [°C]
1.	Vestibule	5,05	20,0
2.	Hall	3,34	20,0
3.	Bathroom	2,78	24,0
4.	Guest room	9,86	20,0
5.	Living room + dining area	30,80	20,0
6.	Kitchen	8,96	20,0
7.	Pantry	2,05	16,0
8.	Utility room	8,08	16,0
9.	Garage	31,06	12,0
10.	Hall	7,57	20,0
11.	Room	10,96	20,0
12.	Room	10,96	20,0
13.	Bathroom	4,23	24,0
14.	Dressing room	3,85	20,0
15.	Bathroom	4,77	24,0
16.	Dressing room	3,70	20,0
17.	Bedroom	23,21	20,0
18.	Utility room	7,81	20,0

Source: Own elaboration

For the above-accepted values, designed heat load was calculated. The calculation results are presented in Table 4. Thermal input of heating devices was determined in order to meet heating and ventilation needs. In addition, the seasonal demand for energy needed to heat the building was determined along with unit rate of seasonal heat demand.

Table 4. The energy performance of designed building

No.	Type of data	Value
1.	Design heat load of a building Φ_{HL}	16,28 kW
2.	Seasonal energy demand for heating $Q_{H,nd}$	74,26 GJ/rok
3.	Item indicator of seasonal heat demand E_{AH}	115,2 kWh/(m^2·rok)

Source: Own elaboration

As is apparent from the values shown in Table 4, to meet the heating needs of the designed building, the heat source should have a heating power of 16.3 kW and above. In order to achieve results similar to real conditions, the demand for heat in each month should be taken into account; the values including also loss caused by permeation through the envelope and ventilation are presented in Table 5.

Tabel 5. Energy balance for a single family house

No.	Month	No. of days	Temp.	Q_D	Q_{ve}	$Q_{H,nd}$	$L_{H,m}$
		day	°C	GJ/rok	GJ/rok	GJ/rok	h
1.	January	31	-0,1	5,86	10,86	13,86	744
2.	February	28	-0,8	5,50	11,25	13,82	672
3.	March	31	5,4	4,09	7,85	8,58	744
4.	April	30	8,8	2,94	6,04	4,65	720
5.	May	31	13,6	1,62	3,61	1,05	634
6.	June	30	16,0	0,98	2,53	0,34	0
7.	July	31	17,7	0,56	1,79	0,03	0
8.	August	31	17,8	0,54	1,75	0,03	0
9.	September	30	14,4	1,36	3,23	1,11	496
10.	October	31	9,2	2,75	5,60	5,13	744
11.	November	30	2,3	4,93	9,55	11,60	720
12.	December	31	-0,5	5,99	11,08	14,06	744
13.	seasonal	365	8,7	37,12	75,15	74,26	6218

Source: Own elaboration

where:

$L_{d, m}$–a number of days in the month,

$T_{em, m}$ - an average external temperature in the month during heating season,

Q_D–a heat loss through building envelope,

Q_{ve}- an energy loss caused by air ventilation.

$Q_{H, nd}$ - a total heat demand,

$L_{H, m}$–a number of hours of heating the room in a month.

Analyzing the values presented in the table 5, it can be noted that the greatest amount of energy should be supplied to a single-family house from October until April, due to the fact that in these months there is the lowest external temperature. The average values vary -0.8 ° C to 9.2°C.

4. Efficiency of heating systems

The results of heating system efficiency calculations, powered by different sources of heat, are presented in the following parts of the article.

4.1 Case no. 1 –a gas boiler with closed combustion chamber

In this case, it is assumed that the building will be heated by a gas boiler with closed combustion chamber. The central heating is made of panel radiators, with central and local regulation. The parameters of the system are 70/50 °C, the system is without a heating water buffer cylinder. In order to calculate the annual consumption of energy, the average seasonal total efficiency of heating system should be calculated in accordance with the Regulation of the Minister of Infrastructure and Development of 3 June 2014 (Dz.U. 2014 poz. 888). It is expressed by the formula:

$$\eta_{H,tot} = \eta_{H,g} \cdot \eta_{H,e} \cdot \eta_{H,d} \cdot \eta_{H,s} \quad (1)$$

where:

$\eta_{H,tot}$ – average seasonal total efficiency of the heating system,

$\eta_{H,g}$ - average seasonal efficiency of heat from the energy source or energy supplied to the heat source,

$\eta_{H,e}$ - average seasonal efficiency of regulation and use of heat in the heated space,

$\eta_{H,d}$ - average seasonal efficiency of heat transfer from the heat source to the heated space,

$\eta_{H,s}$ - average seasonal efficiency of the heat accumulation in the capacitive elements of the heating system.

Using information provided in the Regulation (Dz.U. 2014 poz. 888), the partial average values of seasonal efficiency were established, these are: $\eta_{H,g}$ = 0.87, $\eta_{H,e}$ = 0.90, $\eta_{H,d}$ = 0.96, $\eta_{H,s}$ = 1.0. Introducing the value to the formula (1) the seasonal average efficiency of a system for the heating is obtained, which is

$$\eta_{H,tot} = 0,75. \quad (2)$$

4.2. Case no. 2 – an air-water heat pump

In this case, it was assumed that the building is heated by the air-water heat pump. The building is equipped with a floor heating, with central and local regulation. The parameters of the installation are 55/45 ° C, the installation is equipped with a heating water buffer cylinder. Average partial values of seasonal efficiency are: $\eta_{H,g}$ = 2.70, $\eta_{H,e}$ = 0.89, $\eta_{H,d}$ = 0.96, $\eta_{H,s}$ = 0.95. Whereas the total average seasonal efficiency of the system with air-source heat pump is

$$\eta_{H,tot} = 2{,}19. \tag{3}$$

4.3. Case no. 3 –a glycol-water heat pump

In this case, it is assumed that the building will be heated by glycol-water ground heat pump. As in the case no. 2, the floor heating is used, with central and local regulation. The parameters of the installation are 55/45 ° C, the installation is equipped with a heating water buffer cylinder. Average partial performances are: $\eta_{H,g}$ = 3.50, $\eta_{H,e}$ = 0.89, $\eta_{H,d}$ = 0.96, $\eta_{H,s}$ = 0.95. This translates to an average seasonal total efficiency:

$$\eta_{H,tot} = 2{,}84. \tag{4}$$

4.4. Case no. 4 –a coal fired boiler

In this case, it was assumed that the building will be heated by a traditional coal boiler. Similarly as in the case no.1, the central heating system is made of radiators, with central and local regulation. The parameters of the system are 70/50 °C, the system is not equipped with a heating water buffer cylinder. Average partial performances are: = 0.82, = 0.90, = 0.96, = 1.00. Anaverage seasonal efficiency is:

$$\eta_{H,tot} = 0{,}71. \tag{5}$$

4.5. Case 5 –a wood fired boiler

In this case, it was assumed that the building would be heated with a wood-fired hot water boiler. As in the cases no. 1 and 4, it was made of panel radiators, with central and local regulation. The parameters of the installation are 70/50 °C, there was no heating water buffer cylinder. Average partial performances are: $\eta_{H,g}$ = 0.65, $\eta_{H,e}$ = 0.90, $\eta_{H,d}$ = 0.96, $\eta_{H,s}$ = 1.00. An average seasonal efficiency is

$$\eta_{H,tot} = 0{,}56. \quad (6)$$

5. An analysis of emission of harmful substances into the atmosphere by various heat sources

An analysis of emissions harmful compounds of the proposed solutions will be based on determination of emissions of individual compounds emitted into the atmosphere during operation of the heating system in the building. It was assumed that the demand for the final energy used by the auxiliary devices of the heating system would be covered by conventionally produced electricity. The calculations have omitted energy requirements needed for the preparation of hot water. The analysis was performed using specialist software - Auditor EKO v.1.0. Table 6 summarizes the energy consumption for the analyzed cases.

Table 6. A consumption of particular energy sources

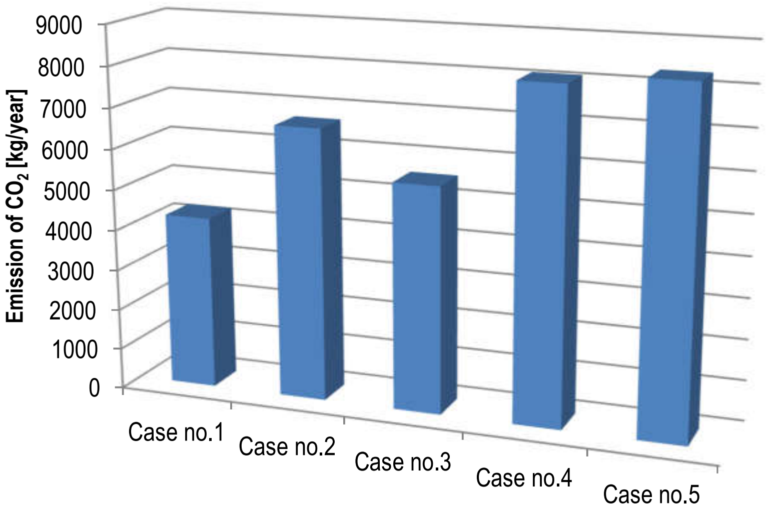
FUEL	CASE	CONSUMPTION
ELECTRICITY	Caseno.1	433,64 kWh
	Caseno.2	4 721,33 kWh
	Caseno.3	3 842,37 kWh
	Case no.4	433,64 kWh
	Case no.5	433,64 kWh
NATURAL GAS	Caseno.1	1 342,16 m^3
HARD COAL	Caseno.4	2,36 Mg
WOOD	Caseno.5	6,35 m^3

Source: Own elaboration

After analyzing the results summarized in the table 6, it can be concluded that the electricity consumption in the cases no. 1, 4 and 5 is the same, because it is associated with the operation of auxiliary equipment of the installation (circulation pumps, etc.). In turn, the highest electricity consumption concerns cases no.2 and 3; this is due to the fact that the heat pump is an electric equipment, and therefore it is the only source of energy needed to heat the building. In other cases (no. 1, 4 and 5) in addition to electricity, the devices additionally consumed: case no. 1 - 1343 m^3 of natural gas, case no. 4 - 2360 kg of coal and in the case no.5 - 6.35 m^3 of wood.

The following figures (Fig. 1 ÷ 5) present the emission of harmful pollutants, i.e. carbon dioxide, sulfur dioxide, nitrogen dioxide, carbon monoxide, particulate matter, and B (a) P by the heat source.

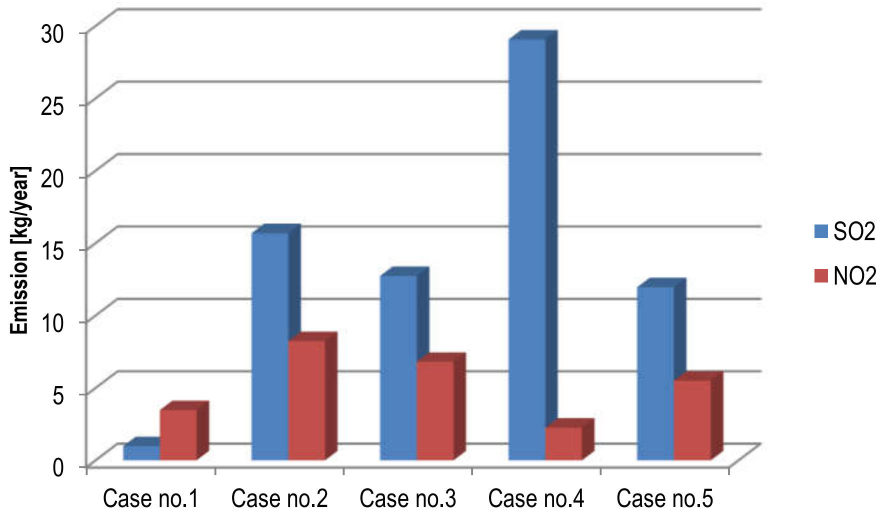
Figure 1. Carbon dioxide emissions



Source: Own elaboration

The above chart demonstrates the emission of carbon dioxide into the atmosphere for individual cases of heat sources. It can be noticed that the gas boiler emits the least of carbon dioxide (slightly more than 4,200 kg/year), the next is a ground source heat pump - a little more than 5,500 kg/year. Then, followed by an air-source heat pump (6690 kg/year), the coal-fired boiler (about 8100 kg/year) and a wood fired boiler (8340 kg/year).

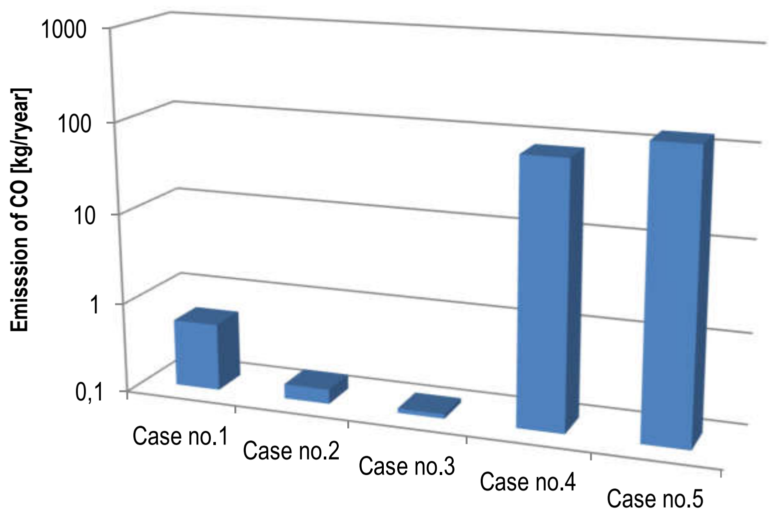
Figure 2. Emissions of sulfur dioxide and nitrogen dioxide



Source: Own elaboration

Figure 2 presents emissions of sulfur dioxide and nitrogen dioxide for each source of heat. In the case of sulfur dioxide, the best option appears to be a gas boiler, which emissions do not exceed 1 kg/year. Then the wood fired boiler (less than 12 kg/year), the ground source heat pump (12.7 kg /year), the air-source heat pump (15.7 kg/year) and the coal-fired boiler (29.1 kg/year). However, in the case of nitrogen dioxide, the emissions is slightly different - the fired -boiler coal (2.26 kg/year), the gas boiler (3.47 kg/year), the wood -fired boiler (5.50 kg /year), the ground source heat pump (6.81 kg/year) and air-source heat pump (8.23 kg/year).

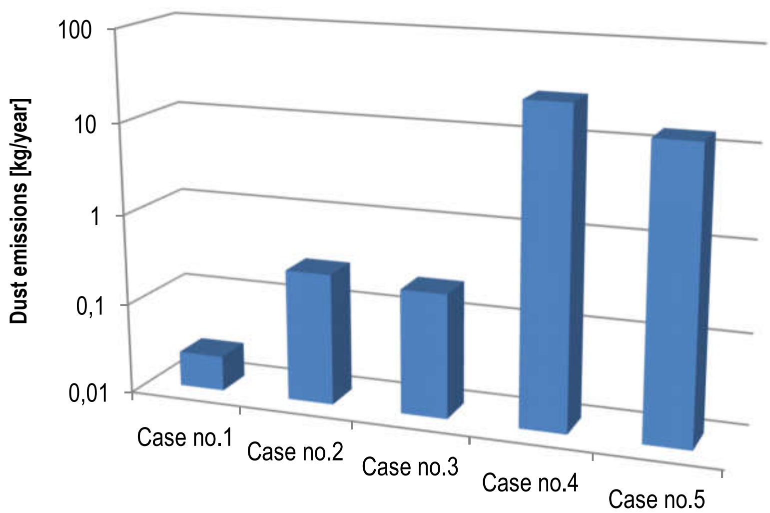
Figure 3. Carbon monoxide emissions



Source: Own elaboration

In the case of carbon monoxide emissions (Figure 3), the best solution appears to be the ground source heat pump, which emissions were 0.11 kg / year; then the air-source heat pump (0.14 kg / year), the gas boiler (0.56 kg / year), the coal-fired boiler (80 kg / year) and the wood-fired boiler (136 kg / year).

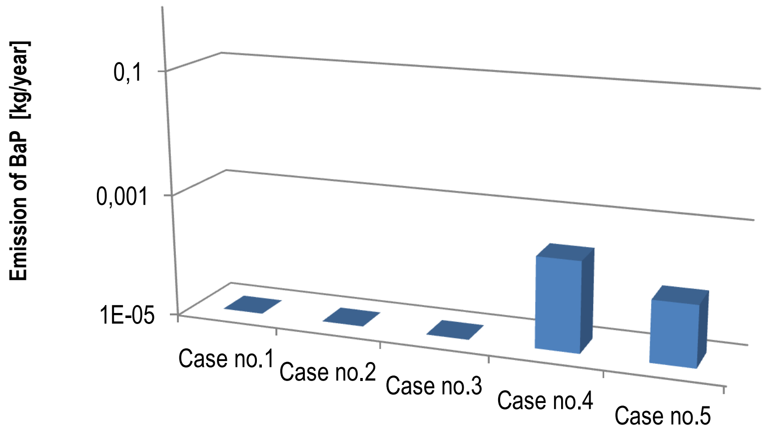
Figure 4. Dust emissions



Source: Own elaboration

Analyzing the dust emissions (Figure 4) the best solution was successively:the case no.1 (0.024 kg /year), the case no.3 (0.23 kg /year), the case no.2 (0.28 kg /year), the case no.5 (14.58 kg / year) and the case no. 4 (28.82 kg / year).

Figure 5. Benzo[a]pyrene emissions



Source: Own elaboration

When assessing the results, shown in Fig. 5, regarding the emissions of benzo(a) pyrene it can be noticed that only in the cases with coal-fired boiler and wood-fired boiler the emission into the atmosphere occurred. The wood -fired boiler emitted 0.0003 kg/year, while coal-fired boiler 0.0001 kg/year.

6. Summary

One of the important aspects of sustainable development in the residential construction sector, is to, pay special attention to the energy consumption of the building, and thus the emission of harmful substances into the atmosphere during the whole construction process. Air protection is one of the most important measures to protect the environment.

In this study, the analysis of environmental solutions for a variety of heat sources in a single-family house was performed. The following heating systems were taken into consideration: a gas boiler with closed combustion chamber (case no. 1), an air-source heat pump (case no.2), the ground heat pump (case no.3), the coal-fired water boiler (case no.4) and a wood fired water boiler (case no.5). The analysis was carried out according to ecological standards of the National Centre for Emissions Management (KOBiZE). Below there are conclusions derived from the analysis regarding the emissions of :

- CO_2 – the best solution was to use a gas boiler with closed combustion chamber, whose emissions were slightly more than 4,200 kg / year, while the worst was wood-fired boiler 5 (8340 kg / year),
- SO_2– in this case, the best solution was a gas boiler and its emissions do not exceed 1 kg / year. The worst was the coal-fired boiler that emits 29.1 kg / year ,
- NO_2–in the case of nitrogen dioxide emissions, the coal-fired boiler will emit 2.26 kg / year, while the worst was the air-source heat pump (8.23 kg / year),
- CO – the best solution turns out to be the ground source heat pump, which emissions were 0.11 kg / year, the worst was the wood-fired boiler (136 kg / year),
- Dusts–the gas boiler with closed combustion chamber emitted the least (0.024 kg / year), while the most emissions was in the case of the wood fired boiler (28.82 kg / year),
- B(a)P –emissions of Benzo[a]pyrenewas only in the case of the coal-fired boiler and wood-fired boiler, 0.0003 kg/ year for coal fired boiler and 0.0001 kg / year for wood fired boiler.

The purpose of this article was to present emissions from various sources of heat typical for single-family residential construction. It was found that in most cases, the biggest emissions characterizes coal-fired boiler. Unfortunately, it is also one of the most frequently used sources of heat in single-family housing, especially in buildings constructed prior to 2000. The lowest emission of harmful substances into the atmosphere characterizes a gas boiler with a closed combustion chamber.

It should also be noted that, the case with the heat pump indirectly emits pollution into the atmosphere, because it is powered by electricity, which in turn is produced in the conventional manner by power plants fired by coal and lignite.

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Aspekty środowiskowe różnych rodzajów źródeł ciepła w domku jednorodzinnym

Streszczenie

W artykule przeprowadzono analizę emisji zanieczyszczeń przez różne rodzaje źródeł ciepła, wykorzystywanych do ogrzewania i wentylacji dla typowego domku jednorodzinnego. W pracy analiza emisji proponowanych rozwiązań została przeprowadzona zgodnie z standardami Krajowego Ośrodka Bilansowania i Zarządzania Emisjami (KOBiZE). Analizę wykonano dla najczęściej używanych systemów grzewczych w budownictwie mieszkaniowym jednorodzinnym: kotła gazowego z zamknięta komorą spalania, powietrznej i gruntowej pompy ciepła, kotła wodnego opalanego węglem oraz kotła wodnego opalanego drewnem. Ponadto przedstawiono charakterystykę i bilans energetyczny typowego domku jednorodzinnego. Ostatecznie zaproponowano najbardziej ekologiczne rozwiązanie systemu grzewczego dla typowego domku jednorodzinnego.

Słowa kluczowe: zrównoważony rozwój, analiza ekologiczna, źródło ciepła dla domu jednorodzinnego, aspekty środowiskowe