Management of the atmospheric pollution mitigation through investment into modernization of heat generation units

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Abstract. The aim of the work was the investigation of the impact of particulate matter PM collection installations, and the type of fuel being used, on the emission into the atmosphere of particulate matter PM and gas pollutants that come from the operation of the energy installation in the food processing plant. The plant uses electricity from the grid for both production and social purposes. Thermal energy is produced locally using coal, and high-methane natural gas fired boilers. The heat generated is mainly used for technological purposes, in the form of steam supplied for individual production processes. The work presents results of pollutant emission measurements from the power equipment used during the period of time between years 2014 to 2017. The collected data are interpreted by means regression analysis and graphically presented. Annual emissions before and after installation of dedusting equipment at the plant were also compared.

1. Introduction

Advanced technologies and innovative solutions play a vital part in developed economies [1-3]. This is related to the increasing globalisation of the economy and wider access to markets [4-6]. Economic development entails increasing emissions of pollutants into the air [7,8]. Total control of emission is not feasible, and the costs of reducing emissions tend to increase along with increasing elimination [9,10]. As a result, a key problem for the institutions creating the protection policy is to reduce emissions to a level that ensures that harmful effects on vegetation, animals, and human health [9,10] are minimised.

The main threat to the state of the environment in Poland is the exceedingly high energy consumption of the economy and the basic energy carrier, i.e. coal [13]. According to the Ministry of Energy forecasts, in 2020 the share of renewable energy sources in gross final energy consumption will amount to approx. 13.8 percent. According to data from the Central Statistical Office, there are 1343 plants emitting particulate matter PM pollutants in Poland, including 1187 equipped with devices for reducing pollution, and there are 1847 devices emitting gaseous pollutants, unfortunately, only 252 of them have devices for reducing pollution, i.e. less than 14% [14-16]. Each energy installation operated by food processing industry companies releases gases and particulate matter PM into the air. Given the constant increase in pollution to the atmosphere, it has become necessary to introduce appropriate legal provisions [17]. The legal framework for the protection of atmospheric air for the
European Union (EU) is described in the MARPOL and LRTAP conventions and directives of the European Parliament and the Council of Europe. The most important goal of respecting these legal acts to meet the standards set by law is to reduce air emissions. Achieving this requires the efficient implementation of air protection programs and progress in the atmosphere quality management system at the national, provincial, and local levels [18].

In the countries of the European Union, the concept of sustainable development has been introduced, consisting of economic development that is associated with respect for the natural environment. An important element of this program is to ensure air quality, as it seems to be one of the most hazardous media, taking into consideration air’s movability which whereas may result in contamination of other areas. Unfortunately, despite numerous efforts, countries still emit large amounts of pollution. To improve the situation, the European Commission has adopted the “The Clean Air Policy Package” program. The concept focuses on reducing pollution by 2030. The document presents more stringent emission standards. Directives in force for EU member states contain limits for sulphur and nitrogen oxides, non-metallic organic compounds as well as ammonia and solid particles, namely PM10 and PM2.5. The negative effects associated with air pollution include above all an increase in mortality and a shorter life expectancy of citizens [19]. To improve the situation, the World Health Organisation (WHO) recommended values for maximum daily concentrations of fine particles: 25 μg/m³ for PM2.5 and 50 μg/m³ for PM10. Restrictions should not be exceeded more than three times a year in a given territory [20]. Not all countries have adopted the recommended procedures. In Poland, concentration of solid particles is one of the highest in the EU. The values for PM10 reach 200 μg/m³, and for PM2.5 up to 300 μg/m³. These amounts are eight and six times higher, respectively, than the recommendations of the World Health Organisation. In 2014, as many as 22 out of 28 EU member states exceeded the levels of air pollution. Proceedings were initiated against these countries for these deficiencies. Even by implementing pertinent directives, the problem of pollutant emissions is still relevant.

The main product of the analysed production plant is potato starch. There are five of the largest starch mills in Poland, located in Łomża, Łubon, Trzemeszno, Piła and Łobelz, and their share of the Polish market exceeds 70%. The processing capacity of these plants is about 1000-2400 tons of potatoes per day, whereas in small starch mills it reaches only about 300-800 tons. In the European Union, starch processing reaches about 3000-5000 tonnes of potatoes per day.

The production plant under analysis is located in north-eastern Poland. Analysed in the manuscript, the plant has a power installation whose use results in the emission of gases and particulate matter PM into the air. The plant uses electricity from the power grid for production and social purposes. Thermal energy, produced in a boiler room fired with fine coal and high-methane natural gas, is used to heat buildings and produce process steam for production processes. The boilers installation is equipped with a system of boiler operation control, including visual recording: pressure and temperature of water in front of the boilers, pressure and temperature of water behind the boiler, water inflow to the boilers, vacuum and temperature in the furnace chamber of the boilers, temperature of flue gases behind the boilers, oxygen content in flue gases. The analysed boiler house is operated all year round, 24 hours/day, i.e. the total operating time equals 8760 hours/year. Individual boilers are operated with variable heat load, depending on current technological needs. The production processes currently carried out in the plant do not require the full load of the power installation, however, for the purpose of analysing emissions to air, the maximum capacity of all boilers was assumed. All emitters in the analysed boiler room are equipped with appropriate stands for the measurement of gas and particulate matter PM emissions into the air.

The plant, in connection with currently used energy devices, is obliged to comply with the emission standards described in the Regulation of the Minister of the Environment of March 1, 2018 on emission standards for certain types of installations, fuel combustion sources and combustion equipment. Considering the production processes, the plant operates 12 technology emitters. The emitters belong to installations subjected to the Integrated Pollution Prevention and Control installation, which is required to obtain an integrated permit, in accordance with the Regulation of the
Ministry of the Environment of August 27, 2014, “On types of installations that may cause significant pollution of individual natural elements or the environment as a whole” [21]. In order to meet the required emission standards, in 2017 one coal-fired boiler was replaced with a new gas boiler, powered by a more ecological fuel, i.e. high-methane natural gas.

The first aim of the hereby work was to investigate the effect of particulate matter PM collection installations on the emission into the atmosphere of particulate matter PM and gas pollutants that originate from the operation of the energy installation. The analysed installation is an equipment of the Food Industry Company, which main product is potato starch. The analysis is based on data collected between years 2014-2017. The second goal was to investigate how the type of fuel affects emissions from the chosen installations.

2. Materials and methods

Materials for research were collected at the potato processing plant, which objective is to produce, among others potato starch, crystalline glucose, maltodextrin, glucose syrups, meal, potato flakes. The analysed plant produces more than 300 tons of finished products per day or 600 tons of finished products per day, assuming that the plant is operated for no more than 90 consecutive days in a given year. The technical specification of devices operated by the company and unit pollution emission ratios published in one of the KOBIZE (The National Centre for Emissions Management) reports were used for analysis.

### Table 1. Factors related to plant emissions [22-24].

| Group of factors | Physical sense                                                                 | Symbols |
|------------------|-------------------------------------------------------------------------------|---------|
| I                | Emission index per unit of fuel consumed [kg/Mg] or in the case of high-methane natural gas [kg/mln m$^3$] | W$_1$   |
| II               | Fuel consumption [Mg/year]                                                    | B       |
| III              | Calorific value of hard coal [MJ/kg] or in the case of high-methane natural gas [MJ/m$^3$] | W$_o$   |

In the analysis, group II (table 1.) includes the amount of particulate matter PM and gas pollutant emissions discharged into the air. The factor constituting group III (table 1.) shows the amount of fuel consumed for firing the steam boiler.

The statistical analysis was aimed at presenting the correlation r, between the emission of gaseous and particulate pollutants and the dependent variables (W$_1$, W$_2$). The correlation coefficient r was intended to facilitate determination of the potency of the emissions of pollutants resulting from the combustion of energy fuels that were discharged into the ambient air, for a specific fuel consumption or for the chemical energy introduced into the fuel. The determination factor R$^2$, calculated on the basis of r, was supposed to additionally determine the strength of influence of factors from particular groups.

Markings used:
- $E_p$ – average particulate matter PM emissions during the year [t],
- $E_{CO2}$ – average CO$_2$ emissions per year [t],
- $E_{NO2}$ – average NO$_2$ emissions per year [t],
- $E_{CH4}$ – average CH$_4$ emissions per year [t],
- B – fuel consumption by a given steam boiler [Mg/year],
- E – amount of energy produced [MWh/year],
- $W_o$ – calorific value of hard coal [MJ/kg] or in the case of high-methane natural gas [MJ/m$^3$] throughout the year,
- W$_1$ – emission factor per unit of fuel consumed [kg/Mg] or in the case of high-methane natural gas [kg/mln m$^3$].
The statistical study of the data included establishing linear regression equations. The general formula was adopted to describe the emissions of pollutants by the plant in consideration of many factors:

\[ y = b_1x_1 + b_0 \]  

(1)

\( y \) – explained variables \([W_1, W_2]\),
\( x_1 \) – explanatory variables in the studies \([\text{PM, CO}_2, \text{NO}_2, \text{CH}_4]\),
\( b_1 \) – directional coefficient,
\( b_0 \) – fixed quantity.

The amount of energy produced:

\[ E = W_0 \cdot B \]  

(2)

Emission factor per unit of fuel used:

\[ W_1 = \frac{E_{\text{p}}/E_{\text{CO}_2}/E_{\text{NO}_2}/E_{\text{CH}_4}}{B} \]  

(3)

The emission factor for the chemical energy introduced into the fuel:

\[ W_2 = \frac{E_{\text{p}}/E_{\text{CO}_2}/E_{\text{NO}_2}/E_{\text{CH}_4}}{B \times W_o} \]  

(4)

Basing on the data received from the food processing plant, the impact of individual boilers on pollutant emissions was analysed.

Equipment operated at the plant:

1. Steam boiler - CDK DUKLA SALAVI
   - Fuel- had coal:
     - calorific value \([W_o]\): 23.365 MJ/kg
     - total sulphur content: 0.41%
     - ash content – 9.71%
   - nominal heat power – 6.7 MW
   - thermal power in fuel – 8.5 MWt
   - thermal efficiency - 72%
   - coal consumption during the year [B]- 11449.3 Mg/year
   - boiler operation time - 8760 h (continuous operation)
2. Steam boiler - OR-16-025
   - Fuel- had coal:
     - calorific value \([W_o]\): 23.365 MJ/kg
     - total sulphur content: 0.41%
     - ash content – 9.71%
   - nominal heat power – 13.75 MW
   - thermal power in fuel – 16.8 MWt
   - thermal efficiency - 79%
   - coal consumption during the year [B]- 22723.4 Mg/year
   - boiler operation time - 8760 h (continuous operation)
3. Gas boiler - Viessmann Vitomax HS
   - Fuel - mine gas:
     - calorific value \([W_o]\): 31.0 MJ/Nm\(^3\)
     - total sulphur content: 40 mg/m\(^3\)
   - nominal thermal power – 5.15 MW
   - thermal power in fuel – 5.42 MWt
   - thermal efficiency - 95%
   - natural gas consumption during the year [B]- 5.515 mil m\(^3\)/year
   - boiler operation time - 8760 h (continuous operation).
3. Results

The information collected concerning the gas and particulate matter PM emissions of the energy installation of the selected production plant. In the analysis of the research, the amounts of energy produced, and the emissions of air pollutants produced from the combustion of fuels were shown. The cooperation with the plant facilitated the presentation of a number of observations related to the emission of pollutants from the power equipment in use. In 2014, 2015, and 2016, three hard coal-fired boilers were operated in the analysed plant. In 2017, the company additionally used a boiler fired with high-methane natural gas. On the basis of the data obtained from the analysed plant, the relationship between the average emissions of pollutants resulting from the combustion of energy fuels (input data set: year, average particulate matter PM emissions, fuel consumption, and calorific value) in relation to the emission factor per unit of used fuel and the emission factor for chemical energy introduced in the fuel.

Table 2 contains information on the amount of energy produced, and Table 3 contains values of unit emission factors W1.

Table 4 contains emission factor values for the chemical energy introduced in the fuel [t/Mg] or for high-methane natural gas [t/m³]. Data on the emission of air pollutants generated from the combustion of fuels in the analysed plant are presented in Table 5.

| Boiler type                        | Energy produced [TJ/year] |
|-----------------------------------|---------------------------|
| Steam boiler- CDK DUKLA SALAVI     | 267.51                    |
| Steam boiler - OR-16-025          | 530.93                    |
| Gas boiler - Viessmann Vitomax HS | 170.97                    |

| Emissions of pollutants          | Thermal coal | High-methane natural gas |
|----------------------------------|--------------|--------------------------|
| Carbon dioxide [t/TJ]            | 97.5         | 56.10                    |
| Methane [t/TJ]                   | 7.5          | 0.13                     |
| Nitrous oxide [t/TJ]             | 0.447        | 0.03                     |

| Emissions of pollutants          | Coal-fired boilers [t/kg] | Boiler fired with high-methane natural gas [t/m³] |
|----------------------------------|----------------------------|-----------------------------------------------|
| Carbon dioxide [t/year]          | 0.000097500               | 0.000047490                                  |
| Methane [t/year]                 | 0.000007500               | 0.000000106                                  |
| Nitrous oxide [t/year]           | 0.000000447               | 0.000000025                                  |

| Emissions of pollutants          | Steam boiler- CDK DUKLA SALAVI | Steam boiler- OR-16-025 | Gas boiler-Viessmann Vitomax HS |
|----------------------------------|---------------------------------|-------------------------|---------------------------------|
| Carbon dioxide [t/year]          | 26082.51                        | 51765.89                | 9591.14                         |
| Methane [t/year]                 | 2006.35                         | 3981.99                 | 21.37                           |
| Nitrous oxide [t/year]           | 119.58                          | 237.33                  | 5.13                            |
Figure 1 shows a comparison of emissions of boilers fired with different fuels. A boiler fired with high-methane natural gas emits far fewer pollutants than a boiler fired with hard coal. Data for the preparation of the graph was provided by the analysed production plant.

\begin{figure}
\centering
\includegraphics[width=\textwidth]{figure1.png}
\caption{Emissions of air pollutants from the plant tested on the example of a coal-fired boiler and a boiler fired with high-methane natural gas.}
\end{figure}

In the course of the study the emission factor per unit of fuel used and the emission factor per chemical energy introduced in the fuel have been also analysed.

Based on the input data set for each of the analysed pollutants (particulate matter, CO\textsubscript{2}, NO\textsubscript{2}, CH\textsubscript{4}), the following were determined: regression statistics based on the average emission and emission factor per unit of fuel used and regression statistics based on the average emission and emission factor per chemical energy introduced in the fuel (multiple of R, R\textsuperscript{2}, matched R\textsuperscript{2}, standard error). The coefficients determining the significance of the hypothesis were then calculated on the basis of the average emission and the emission factor per unit of fuel consumed (coefficients, standard error, tStat, value - p).

Table 6 shows regression models of dependent variables.

On the basis of formulae obtained from statistical analysis, the relationship between substance emissions and the selected indicators can be interpreted. The results in Table 6 justify the significant impact of pollutant emissions resulting from the combustion of different energy fuels on the specific fuel consumption or on the chemical energy introduced in the fuel.

All regressions performed in the calculations are statistically significant. The greatest influence is exerted by formulas \( y=0.18x-0.000000000000045 \) for index W1 and \( y=0.0058x+0.000000000000014 \) for index W2, with determination factor amounting to 100% and \( y=0.00000026x+0.12 \) for index W1 and \( y=0.000018x+0.017 \) for index W2, with R\textsuperscript{2} amounting to 96%.

On the basis of the analyses carried out for each of the examined emissions (particulate matter CO\textsubscript{2}, NO\textsubscript{2}, CH\textsubscript{4} emissions), it was found that for the emission factor per unit of fuel used, the value-p is lower than 0.05 for x1. This means that \( \beta_1 \) is statistically significant, i.e. the average emission value affects the emission factor per unit of fuel used. Moreover, for each of the emissions tested (particulate matter PM, CO\textsubscript{2}, NO\textsubscript{2}, CH\textsubscript{4}) it was found that for the emission factor for the chemical energy introduced in the fuel the value-p is lower than 0.05 for x1. This means that \( \beta_1 \) is statistically significant, i.e. the average emission value affects the emission factor per unit of fuel used.
| Indicator | The diagram equation | R2 [%] | The essence of regression |
|-----------|----------------------|--------|--------------------------|
| $W_1 = \frac{E_{CO_2}}{B} [\frac{kg}{Mg}]$ | $y = 0.000015x + 5.35$ | 36.6 | Important |
| $W_1 = \frac{E_{NO_2}}{B} [\frac{kg}{Mg}]$ | $y = 0.000062x + 2.89$ | 41 | nportant |
| $W_1 = \frac{E_{CH_4}}{B} [\frac{kg}{Mg}]$ | $y = 0.0000026x + 0.12$ | 96 | nportant |
| $W_1 = \frac{E_p}{B} [\frac{kg}{min m^3}]$ | $y = 0.8x - 0.000000000000045$ | 100 | nportant |
| $W_2 = \frac{E_p}{B \times W_o} [\frac{g}{Mg}]$ | $y = 0.000042x + 0.39$ | 81 | nportant |
| $W_2 = \frac{E_{CO_2}}{B \times W_o} [\frac{g}{Mg}]$ | $y = 0.0000066x + 0.23$ | 36.6 | nportant |
| $W_2 = \frac{E_{NO_2}}{B \times W_o} [\frac{g}{Mg}]$ | $y = 0.0000026x + 0.12$ | 41 | nportant |
| $W_2 = \frac{E_{CH_4}}{B \times W_o} [\frac{g}{Mg}]$ | $y = 0.000018x + 0.017$ | 96 | nportant |
| $W_2 = \frac{E_p}{B \times W_o} [\frac{kg}{min m^3}]$ | $y = 0.0058x + 0.000000000000014$ | 100 | nportant |

4. Conclusions

The main purpose of the observation was to show the amount of particulate matter PM and gas emissions produced by boilers of various fuel types, power, or efficiency. The analysed company constantly strives for less air pollution. For this purpose, coal-fired boilers are replaced by gas-fired boilers. As a result, despite the continuous increase in production at the plant, a decreasing trend in emissions of carbon dioxide, methane and nitrogen oxides can be observed. In the case of coal boilers, the plant management invests in modern dedusting installations. The heat energy produced in the plant is used mainly for technological purposes, in the form of thermal steam supplied to individual production processes, but also to heat buildings.

The least harmful to the environment is the heat energy produced in the plant by a gas-fired boiler, a more ecological fuel, i.e. high-methane natural gas, where the emissions are about 50% lower than those of a coal-fired boiler with the highest nominal heat output.

The second important benefit of converting the installation to a more ecological one is the higher boiler efficiency and the gas boiler is able to produce more energy than a steam boiler at the same time, compared to the installed heat output.

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