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THE BENEFITS OF PARTIAL SUBSTITUTION OF FOSSIL FUEL BY ALTERNATIVE FUEL IN CEMENT PLANTS. CASE STUDY

The partial substitution of fossil fuels by alternative fuels is associated with economic benefits for the cement producers. This fact has been confirmed by their growing interest in such substitutions. In this paper, based on the energy balance, it was demonstrated for a selected cement plant that by co-combustion of fine coal with the PAS-r fuel the cement plant is able to save 3.03 $Mg \cdot h^{-1}$ of fine coal thanks to the use of 5.04 $Mg \cdot h^{-1}$ of the PAS-r fuel. An advantage worth emphasizing is the fact that waste co-incineration is a part of a sustainable development strategy. Energy recovery from waste also is an example of the use of renewable energy sources. The results of the present work allow concluding that the substitution of fossil fuels by alternative fuels is justified by both the environmental and economic objectives.

1. INTRODUCTION

The cement industry in Poland is in the seventh position compared to European cement producers in terms of production in volume. In 2015, our cement production was estimated at 15.6 million tones. Thanks to the technical modernization of the cement plants carried out since the beginning of the last decade, Poland is one of the technological leaders worldwide. The activities of the cement plants in Poland may be considered an example of a correctly implemented sustainable development strategy. At present, all cement plants operating in Poland practically have been completely modernized. One can say that 90% of cement plants have simply been rebuilt from scratch, replacing the old installations. Thanks to the modernization of flue gas cleaning systems, dust emissions have been significantly reduced. There are 14 cement plants in Poland belonging to 9 international concerns and cement producers. 98% of the cement production in Poland takes place in modern kilns with cyclone heat exchangers (mostly

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with calciners) [1], which represent the best available technique (BAT) in cement production [2].

The co-combustion process of waste fuel in a cement kiln is practically free of solid residues [3]. A high temperature existing in the kiln (gas temperature up to 2000 °C), the long residence time of the raw material charge during combustion (about 10 s) ensures effective combustion and destruction of harmful substances. This is particularly important in the case of substitution of fossil fuel by fuel derived from waste (RDF).

The mineral parts of the co-combusted waste are transformed into ashes at a high temperature and they consist of components rich in silicon compounds, easily built into the clinker structure [4]. In order to prevent a decrease of the strength parameters of the types of cement made from clinker produced by co-combustion with alternative fuels, the quality of alternative fuels used must be the subject of ongoing control [5].

The conditions in a cement kiln favor the combustion of RDF/SRF (solid recovered fuels) as secondary fuels, which explains, that these alternative fuels are increasingly used in the cement industry [3]. Bearing in mind the terminology, RDF is not standardized and its features (composition, contaminants, calorific value) are undetermined, while SRF is sampled and tested according to EU standards [6, 7]. Depending on the fuel composition, the alternative fuels may have a net calorific value (NCV) even more than 25 $MJ \cdot kg^{-1}$ but on average this value for many SRF tested in Poland is about 16–19 $MJ \cdot kg^{-1}$. The energy recovered during co-combustion of RDF/SRF calculated per biogenic carbon content is considered green energy.

The production of alternative fuels in Poland has gained particular importance in the face of new challenges forced by Polish law [8] and are dictated by the modern approach to waste management worldwide [9, 10]. Alternative solid fuels are formed as a result of the mechanical shredding step of the solid waste to the appropriate size required by the recipient (usually 30–40 mm). The grinding process, depending on the type of machine used, the type of waste applied, and the size of fragmentation needed is carried out in one or two stages. The waste fractions used to produce the fuel PAS-r type (used in our further analysis) are:

- paper, cardboard and cardboard packaging,
- plastic packaging, wood,
- textiles, upholstery fabrics, rags, cleaning cloths,
- tobacco refuse,
- cosmetics and household chemicals packaging,
- residual waste from municipal waste screening.

The wastes after the initial qualification, depending on the type, are screened in two stages on the feed conveyor and through it transported into the grinder hopper, where they are pre-shredded. After crushing, the waste is subjected to cleaning where metals (a magnetic separator) and ballast (i.e., interfering materials) such as debris, stone, and glass are removed by air separator. After crushing in the secondary shredder, a ready-made PAS-r fuel with granulation of 30 mm or 40 mm is obtained, depending on the sieve used. The finished product is picked up from the grinders by means of receiving conveyors and transported to the appropriate storage boxes (intermediate boxes for composing the final fuel). After performing the analysis and meeting the acceptance requirements, the final product/alternative fuel is directed to the cement plant and then burnt in rotary kilns. The calorific value of an alternative fuel always varies over time and depends on the characteristics of this fuel (i.e., humidity, the share of ash and organic compounds).

2. CONDITIONS AND RESTRICTIONS ON THE USE OF ALTERNATIVE FUELS IN A CEMENT PLANT

The specific environmental conditions existing inside a cement kiln and high sintering temperature of the cement clinker (i.e., bed temperature $T = 1450$ °C) allow also burning of other wastes described in the Waste List [11]. The calorific value of the substitutes for example of fossil fuels is presented in Table 1.

Table 1

List of fuel parameters for fossil coals and selected groups of wastes used in energy recovery processes [10]

Fuel	Moisture content [wt. %]	Ash content [wt. %]	Volatiles [wt. %]	Net calorific value [MJ·kg^{-1}]
Coal	3.2–19.1	3.5–26.9	28–35	21–28
Lignite coal	10.9–54.6	3.5–26.9	50–55	8.5–9.5
Waste wood	10–30	0.2–5	80–85	15–18
Paper and cardboard	15–25	10–15	85–88	11–14
Textiles	5–15	5–12	75–80	16–19
Waste tires	1–2	4–6	65–70	35–36
Plastics	1–5	1–7	90–96	13.7 (PVC) 21.8 (PET) 41.8 (PE)
Waste animal tissue	4–6	18–21	72–78	17.6–22.5
Sewage sludge after dewatering	73.2	34.8	83.11	1.6
Sewage sludge dried	7.4	34.3	82.38	11.9

Currently, in European Union countries, about 80% of the cement plants use alternative fuels. The highest level of substitution of fossil fuels with alternative fuels occurs in Austria and Germany (over 70% substitution by mass). In Poland, in 2014, the level of replacement of heat by alternative fuels in the cement plants was 30–50% of the thermal energy used for the production of clinker, while unit heat consumption for clinker burning is on average 3.46 MJ·kg^{-1}. Polish cement plants with consumption of ca. 1.3 million Mg per year of alternative fuels, plan to increase the consumption to 1.6 million Mg per year.

The progressive minimization of energy consumption from coal for clinker production is of economic importance for the producers, as the cost of fossil fuels constitutes the large share of total expenditure in the cement production cycle. The lower price of alternative fuel compared to fossil fuel allows one to allocate more funds for investments, new jobs and the modernization of the cement plant.

The key factors in a co-combustion process in any industrial installation are firing technique and corrosion. Another significant ecological factor is the emission of pollutants into the atmosphere. In the cement kiln, the decisive advantage in co-combustion of alternative fuels is their high energy recovery. This is directly related to the need to preserve the autothermal conditions of the combustion process. In order to ensure a stable co-incineration, it is necessary to ensure process conditions that allow keeping the temperature in the cement kiln above the flashpoint. In the current legal status, alternative fuels must have documentation of the tests carried out to determine the quality and suitability for the purpose of the co-firing process. The substitution of fossil fuel with alternative fuels may result in substantial savings of natural resources.

The dynamics of the decrease in the consumption of fossil fuel coal, as shown in Fig. 1, is a very positive phenomenon, considering the energy mix of Poland, where about 82% of energy is obtained from solid fossil fuels. The environmental benefit of partial substitution of fossil fuel by RDF/SRF is not only the reduction of the non-renewable fossil resources but also savings in the energy consumption necessary to extract and transport the coal fuel, as well as its shredding.

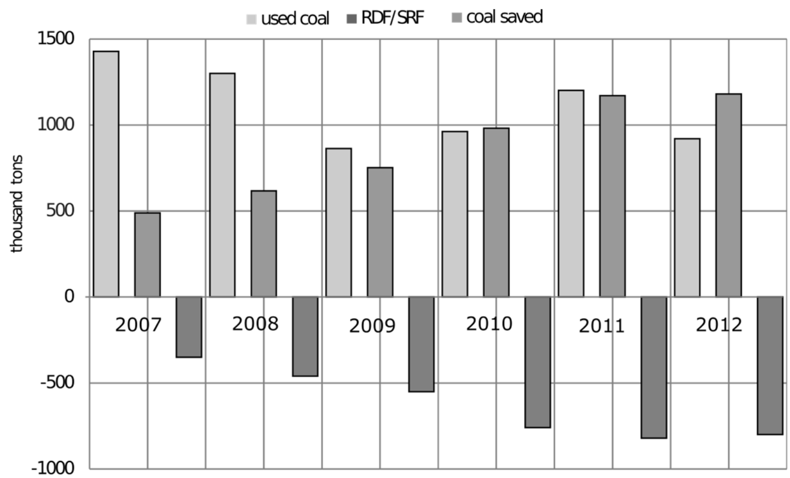

Fig. 1. Substitution of fossil fuels with alternative fuel in Poland adopted according to [1]

The level of carbon dioxide emission to the atmosphere is limited in accordance with the content of the biogenic carbon content in the alternative fuel because this emission is considered zero. Each plant that meets the legal requirements related to combustion and co-combustion of waste fuels can reduce the amount of CO_2 emissions [12, 13].

The co-combustion of waste also can significantly reduce the emissions of nitrogen oxides [14]. These benefits promote the current and growing interest in substituting fossil fuels not only in the cement industry but also in the power industry, heating sector, steel industry and other industries [5].

Environmental and economic advantages associated with the use of RDF in cement kilns were described by Kara [4]. The author analyzed the benefits basing case study where self-made RDF partly substituted the main fuel, which was the petroleum coke. The purpose of our work is the benefits assessment of a cement plant working on black coal and partly substituting fossil fuel with an alternative fuel PAS type. In the analysis of the financial benefits, we present an alternative approach versus Kara [4]. Our work is, therefore, a voice in the discussion and confirms the multilateral benefits due to using RDF/SRF in the cement plant demonstrated by other authors.

3. MATERIALS AND METHODS

A case study was performed by the analysis of effects obtained by the substitution of fossil fuel with the alternative PAS-r type fuel. An example is given for the calculation based on real values obtained from the investigated cement plant. To calculate the energy effect, the substitution of 30% fine coal with an alternative PAS-r type fuel was assumed. The characteristics of the PAS-r type fuel (averaged values) are presented in Table 2.

Table 2

Characteristics of PAS-r fuel [15]

Net calorific value [MJ·kg^{-1}]	Moisture content [wt. %]	Ash content [wt. %]	Content of chlorine [wt. %]	Sulfur content [wt. %]	Bulk density [kg·m^{-3}]
24.38	3.19	7.98	0.42	0.23	100–300

Table 3

Data used to analyze the energy effect in the investigated cement plant (based on one rotary kiln)

Summary data in the year 2015	Value
Clinker production (total mass), Mg·year^{-1}	569 578
Working time, h·year^{-1}	7388
Productivity, Mg·d^{-1}	1850.28
Average calorific value of fine coal, MJ·Mg^{-1}	30 491
Average calorific value of alternative fuel (PSA-r type), MJ·Mg^{-1}	18 331
Heat demand to produce the total mass of clinker, MJ·year^{-1}	2 275 748 919
Amount of fine coal needed to produce the total mass of clinker, Mg·year^{-1}	74 635.7

According to studies carried out on a larger scale [15], the calorific value of PAS-r was estimated at a lower level: within 17.97–19.32 MJ·kg^{-1}. The calorific value of PAS-r fuel (assumed 18.33 MJ·kg^{-1}) used in the calculation presented below was based on the value given by the cement producer. The energy and mass balance were carried out on the basis of one rotary kiln in operation. Table 3 shows the total production of clinker in the investigated kiln per year, and parameters needed to calculate the result of replacing part of the coal by RDF fuel to produce this amount of clinker.

4. THE CALCULATION OF THE ENERGY AND MASS BALANCE IN CO-COMBUSTION IN A CEMENT PLANT. A CASE STUDY

The calculation was carried out in the following steps, which are presented below. In the first step, the heat demand necessary to produce the clinker per year in a single kiln was calculated, then the amount of the alternative fuel necessary to obtain this amount of heat was calculated. According to the data given in Table 3, the total heat demand Q_{C1} for the production of the clinker is calculated:

$$Q_{C1} = M_1 W_{o1} = 74\,635.7 \times 30\,491 = 2\,275\,748\,919 \text{ MJ·year}^{-1} \tag{1}$$

where: Q_{C1} – the total heat obtained from the conventional fuel combustion, MJ·year^{-1}, M_1 – the mass of the fine coal, Mg·year^{-1}, W_{o1} – the calorific value of the fine coal, MJ·Mg^{-1}.

Basing on the heat demand for the annual production of the clinker, the quantitative demand for the alternative PAS-r fuel was calculated. Assuming the amount of heat 2 275 748 919 MJ·year^{-1} needed to produce 569 578 Mg·year^{-1} of clinker, the potential necessary amount of the alternative fuel (PAS-r type) was calculated:

$$M_2 = \frac{Q_{C2}}{W_{o2}} = \frac{2\,275\,748\,919}{18\,331} = 124\,144 \text{ Mg·year}^{-1} \tag{2}$$

where: Q_{C2} – the total heat obtained from the PAS-r fuel combustion, MJ·year^{-1}, M_2 – the mass of the PAS-r fuel, Mg·year^{-1}, W_{o2} – the calorific value of the PAS-r, MJ·Mg^{-1}.

In the next step, the hourly heat consumption was calculated with the full replacement of fine coal, and then the effect of the amount of the fine coal saved would be estimated.

The potential hourly consumption of fossil fuel (assuming 100% fine coal combustion) is:

$$M_{h1} = \frac{M_1}{t} = \frac{74\,635.700}{7388} = 10.1 \text{ Mg·h}^{-1} \tag{3}$$

where: M_{h1} – the hourly consumption of fine coal, Mg·h^{-1}, M_1 – the mass of fine coal, Mg·year^{-1}, t – the kiln's working time during the year, h·year^{-1}.

Alternatively, the hourly consumption of the PAS-r fuel (assuming 100% combusted fuel of the PAS-r type) is:

$$M_{h2} = \frac{M_2}{t} = \frac{124\,144}{7388} = 16.8\ \text{Mg·h}^{-1} \tag{4}$$

where: M_{h2} –the hourly fuel consumption of the PAS-r, Mg·h^{-1}, M_2 – the mass of the PAS-r fuel, Mg·year^{-1}.

Assuming, that the conventional fuel used so far will be replaced by 30% of the alternative PAS-r type fuel, the energy balance starting from the hourly fuel demand was calculated. Thus, in the next step, the benefits of replacing conventional fuel by 30% of alternative fuel were calculated. Therefore, the savings of the conventional fuel with the assumption of 70% coal combustion are as follows:

$$M_{h1\,\text{red}} = 0.7 M_{h1} = 0.7 \times 10.1 = 7.07\ \text{Mg·h}^{-1} \tag{5}$$

Therefore, the mass saving ($M_{h2\,\text{red}}$) of the fine coal is:

$$M_{h2\,\text{red}} = M_{h1} - M_{h1\,\text{red}} = 10.1 - 7.07 = 3.03\ \text{Mg·h}^{-1} \tag{6}$$

In the next step, the thermal deficit, Th_{def} was calculated with the limitation of the coal burning to 70%, which was estimated as follows:

$$Th_{\text{def}} = M_{h2\,\text{red}}\, W_{o1} = 3.03 \times 30\,491 = 92\,387.73\ \text{MJ·h}^{-1} \tag{7}$$

The thermal deficit must be supplemented by the alternative fuel combustion heat. Thus, the necessary use of PAS-r fuel (with the calorific value of 18 331 MJ·Mg^{-1}) is equal to:

$$\frac{Th_{\text{def}}}{W_{o2}} = \frac{92\,387.73}{18\,331} = 5.04\ \text{Mg·h}^{-1} \tag{8}$$

The calculation steps taken in the example made it possible to estimate fossil fuel savings under realistic cement kiln operating conditions.

The saving of the fuel translates into economic effects. The cement plant due to partial substitution of the conventional fuel by SRF may calculate profits depending on the current relationship between fossil and SRF fuel prices. But the financial affairs of enterprises are their strictest secrets and the purchase prices of fuels are included. In business practice, such a large recipient as a cement plant obtains much more favorable fuel prices than those given in price lists or presented in response to individual inquiries. There are also significant fluctuations in fuel prices not only in individual years but also months. Assuming only specific estimates based on the obtained data, the calculations given below do not reflect the actual financial profits of the cement plant due to partial substitution of conventional fuel into SRF fuel, and they will be surely higher.

The profits due to avoided CO_2 emissions with the assumption of a specific share of biogenic carbon (biomass) in the alternative fuel used should be added to this amount. For example, according to the data in force in 2015, in the calculations should be included:

- the price of emission allowances P_{ea} for 2015 varied from 6.25 to 8.75 €·Mg^{-1} (7.5 €·Mg^{-1} on average, currently ca. 28 €·Mg^{-1}).
- CO_2 emission factor E_f in 2014 assumed for reporting according to the Emission Trading Scheme for fine highly calorific coal was 94.05 kg·GJ^{-1} (94.05 × 10^{-6} Mg·MJ^{-1}).

Using the result obtained in equation (7), the calculated benefits of fees for avoiding CO_2 emissions $E_{CO_2\,av}$ under assumption that the content of biogenic carbon in PAS-r fuel C_{bio} is ca. 45% (it varies from 30 to 60%) are as follows:

$$E_{CO_2\,av} = Th_{def} E_f C_{bio} = 92\,387.73 \times 94.05 \times 10^{-6} \times 0.45 \approx 3.91\ \mathrm{Mg \cdot h^{-1}} \tag{9}$$

Thus, the benefit from avoided emission of CO_2 $B_{CO_2\,em}$ is

$$B_{CO_2\,em} = E_{CO_2\,av} P_{ea} = 3.91 \times 7.5 = 29.33\ € \cdot \mathrm{h^{-1}} \tag{10}$$

the price of high-calorific fine coal in 2015 was on average 83 €·Mg^{-1}, the price of alternative fuel SRF/RDF was in 2015 approximately 18 €·Mg^{-1}.

Based on the previous results given in (6) and (8), the expected benefits of partial substitution of the conventional fuel by SRF fuel F_{ben} are as follows:

$$F_{ben} = F_{CO} - F_{RDF} = 3.0 \times 83 - 5.04 \times 18 = 160.77\ € \cdot \mathrm{h^{-1}} \tag{11}$$

where F_{co} – purchase costs of fossil fuel replaced by RDF, F_{RDF} – purchase costs of PAS-r fuel.

Thus, the total benefit (profit) is around 190 €·h^{-1}.

5. RESULTS AND DISCUSSION

The problems regarding the kiln energy and mass balance are very important as they can limit the SRF/RDF substitution rate, and, in some cases, technological modifications and process parameter adjustments are required. It is a specific task for kiln operators to define the real possibility of substitution by evaluating the quality and thermal characteristics of the RDF as the basic parameters to define the compatibility at fixed substitution ratios [16].

Energy costs account for 30–40% of the total costs of cement production. Therefore, the substitution of alternative fuels for fossil fuels will help to reduce energy costs, providing a competitive edge for a cement plant using this source of energy. The presented result of the energy and mass balance calculation was obtained based on the average results from a 12-month work period of a cement kiln producing 569 578 tons of clinker per year and the amount of fine coal needed to produce the total mass of clinker is 74 635.7 Mg per year. The analyzed case showed that by co-combustion of fine coal with the PAS-r fuel the cement plant management is able to save 3.03 $Mg\cdot h^{-1}$ of fine coal thanks to the use of 5.04 $Mg\cdot h^{-1}$] of the PAS-r fuel. The resulting financial profits due to the partial substitution of the conventional fuel by the alternative one will depend on the current relation between the prices for the fossil fuel and those for the SRF. An additional benefit for the cement plant is the reduction of fees for the greenhouse gas emissions, in accordance with the applicable legal procedures, because the SRF contains certain portions of biogenic carbon. Assuming data from 2015, the total benefit for the cement producer could be around 190 $€\cdot h^{-1}$.

The economic benefits do not include all the advantages of fossil fuel co-firing. The use of the co-combustion of alternative fuel in the cement kiln implements the strategy of the production of green energy and a decrease in landfill deposition, in a perspective of the Zero Carbon Landfill and an increase in the landfill lifetime [17]. RDF from MSW could be a strategic component of an integrated waste management system to reach the recycling and reduction targets for combustible materials going to landfill [4]. Recently (after 2014), the new responsibilities for the EU member states appeared in the implementation of the strategy of the so-called circular economy (zero waste for Europe). The cement industry in Poland is a positive example of the implementation of the strategy of a circular economy. The evidence for this is the growing level of substitution of fossil fuels by RDF/SRF. The observed increase in the demand both for the consumption and production of alternative fuels is in the interest of local communities, as it is conducive to generating new jobs.

6. CONCLUSIONS

The energy and mass balance carried out in the present work showed that the substitution of fossil fuels by SRF is highly profitable for cement producers due to the saving of more expensive conventional fuels, and thus reducing the production costs. The benefits of reducing environmental protection fees are also important. Another important environmental benefit resulting from the use of alternative fuels from waste is also the reduction of the waste being deposited at landfills. The co-incineration of RDF/SRF is a part of a sustainable development strategy. Energy recovery from waste is an example of the use of renewable energy sources (RES). The results and discussion presented in this paper allow one to conclude that the substitution of fossil fuels with alternative fuels is justified by both the environmental and economic objectives.

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