

Article

Conventional and Alternative Sources of Thermal Energy in the Production of Cement—An Impact on CO₂ Emission

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Abstract: The article evaluates the reduction of carbon dioxide emission due to the partial substitution of coal with alternative fuels in clinker manufacture. For this purpose, the calculations were performed for seventy waste-derived samples of alternative fuels with variable calorific value and variable share in the fuel mixture. Based on annual clinker production data of the Polish Cement Association and the laboratory analysis of fuels, it was estimated that the direct net CO₂ emissions from fossil fuel combustion alone were 543 Mg of CO₂ per hour. By contrast with the full substitution of coal with alternative fuels (including 30% of biomass), the emission ranged from 302 up to 438 Mg of CO₂ per hour, depending on fuel properties. A reduction of 70% in the share of fossil fuels resulted in about a 23% decrease in net emissions. It was proved that the increased use of alternative fuels as an additive to the fuel mix is also of economic importance. It was determined that thanks to the combustion of 70% of alternative fuels of calorific value from 15 to 26 MJ/kg, the hourly financial profit gain due to avoided CO₂ emission and saved 136 megatons of coal totaled an average of 9718 euros. The results confirmed that the co-incineration of waste in cement kilns can be an effective, long-term way to mitigate carbon emissions and to lower clinker production costs. This paper may constitute a starting point for future research activities and specific case studies in terms of reducing CO₂ emissions.

Keywords: alternative fuels; carbon dioxide reduction; financial benefits; cement industry



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1. Introduction

Cement manufacturing constitutes a significant source of anthropogenic CO₂ emissions both in the European Union and in the world [1]. The sector is responsible for approximately 5–9 percent of worldwide emissions [2,3]. In 2010–2019, carbon dioxide coming from the Polish cement industry constituted about 2–3% of the country's total CO₂ emissions [4,5]. Between 2010 and 2016, the CO₂ emission in the cement sector remained at an average level of 9.5 million tons, except for the increase to the level of 11.43 million tons in 2011, related to the record results in the construction industry in terms of the number of implemented projects. After 2016, a slow increase in the concentration of carbon dioxide from clinker production was observed, again to the level of 11.29 million tons in 2019, which was conditioned by economic growth. Based on the annual production of clinker and cement for this period [5], it can be estimated that circa 700–800 kg of CO₂ was emitted per ton of clinker produced and about 500–700 kg of CO₂ per one ton of cement produced.

In a cement plant, the calcination process plays an important role as concerns the environmental impact. It results from the fact that around 50–60% [6] of the CO₂ is liberated directly during the reaction of thermal decomposition of limestone. The combustion of fossil fuels in cement kilns contributes to about 40% of the carbon dioxide emissions [7],

while 10% of the CO₂ released comes from indirect emissions due to electrical power consumption, mainly during the grinding of cement and raw materials.

According to the EU climate policy, the cement industry is obliged to reduce the level of its CO₂ emissions by around 30% until 2030 with the target of reaching net-zero emissions by 2050 [8]. Therefore, improving energy and ecological efficiency currently constitute the industry priority objectives to meet the targets set by the European Union. In recent years, the key activities of the cement industry in terms of sustainable development and the EU requirements concerning the reduction of CO₂ emissions have been related to decreasing the use of energy and fossil fuels. The elimination of the wet process and the introduction of the dry method were the first steps taken to achieve energy efficiency. As a result, the modernization of cement plants enabled the reduction of specific heat consumption by almost 30–40%. In the wet process, the raw materials were introduced to the rotary kiln in the form of slurry with a moisture content of about 30–40% [9]. Therefore, the higher energy consumption was caused by the necessity of evaporating water from the raw materials. The specific heat consumption of the wet process exceeds 6 kJ per one kilogram of clinker. In turn, in the dry process, pre-heating and pre-calcining systems were incorporated. Dry kilns with a pre-heater consist of 4–6 vertical cyclones through which the raw meal passes down in the opposite direction of the moving hot exhaust gases [7]. As a consequence, the raw meal is partially pre-heated and pre-calcined. Such a system allowed reducing the unit heat consumption to a level below 4–5 kJ per kg of clinker. The pre-calciner is an additional furnace that calcines the materials after they have passed through the pre-heater but before they enter the rotary kiln. The pre-calciner chamber and the pre-heater account for approximately 40% of the fuel use, while 60% of the fuel is consumed in the rotary kiln. In addition, about 80–90% of the raw meal is calcinated [10]. An improvement of thermal efficiency and the reduction of CO₂ emissions in cement production were also achieved by the introduction of new types of cement with the limited share of clinker by the application of industrial by-products, e.g., granulated blast furnace slags or fly ashes as admixtures [11,12]. In 2016, approximately 4 million tons of industrial waste were used for cement manufacturing in Poland. Another effective way to lower production costs and carbon emissions from the clinker production process is the co-combustion of waste in cement kilns [13]. Until the 1980s, coal constituted the main primary energy source in clinker production, with a high emission factor of around 95 kg CO₂/GJ (at the calorific value of 22.70 MJ/kg) [14,15]. The reduction of carbon dioxide emissions from fossil fuel combustion in the rotary kiln was achieved by the application of fuels made from waste. Waste-derived fuels include a wide range of refuse materials (i.e., residues from MSW recycling, industrial/trade waste, sewage sludge, biomass waste, etc.) which have been processed to fulfill the guidelines and regulatory or industry specifications, mainly to obtain a high calorific value. Different terms and abbreviations are used for the fuel produced from waste, e.g., in Germany, it is labeled as SBS, EBS, or BRAM, and in Italy as CDR, CSS [16]. In other European countries, the fuel is referred to as an alternative fuel (AF) [17] or refuse-derived fuel (RDF) [18,19], while the European Committee for Standardization adopted the name solid secondary fuel (SRF) [20]. In the present work, the term alternative fuel will be applied to the fuel coming from waste. Alternative fuels are also subject to standard obligations related to CO₂ emission monitoring and reporting. However, according to the EU Emissions Trading System, a part of the fuel that constitutes the biogenic (or biodegradable) fraction is treated as CO₂-neutral and can be excluded from total emission [21–24]. So, replacing fossil fuels with alternative fuels brings about a number of economic benefits including fuel cost savings and lower fees for carbon dioxide emission.

In 2020, Cembureau, the European Cement Association, published a new carbon neutrality roadmap that outlines different routes and options for achieving a significant reduction in CO₂ emission [8,25]. According to the report, the future activities of the Polish and European cement industry towards reducing environmental impact and achieving EU

goals should focus on the further valorization of waste in the production process (i.e., the use of waste as an alternative fuel and a raw material in clinker production).

The scope of this work was to determine the direct CO₂ emission from co-combustion of the fossil fuel and alternative fuels. From the point of view of environmental protection, this constitutes an urgent issue to be addressed. The calculations were performed based on the amount of fuels needed for annual clinker production data and the CO₂ emission factor of the fuels. In the analyzed case, various configurations of fuel co-combustion were assumed; secondly, hard coal and alternative fuels were burned only in the main burner of the rotary kiln. Seventy samples of alternative fuels were analyzed to investigate how the quality parameters of various alternative fuels may affect the final amount of CO₂ emission. The modified parameters of the samples included the calorific value and the carbon content. In the literature, the correlation between AF parameters and the amount of CO₂ emissions has been poorly discussed. Previously, the researchers [26–28] have focused primarily on studying the changes of clinker reactivity resulting from the use of various alternative fuels in the production of cement. In this work, an economic effect achieved due to avoided CO₂ emission and the mass saving of the fossil fuel was additionally calculated.

2. Cement Manufacturing Process

The worldwide cement production in 2019 reached the level of 4 billion tons, this was an increase of approximately 50% as compared with 2005 production. Until now, China has been the largest cement producer by installed capacity manufacturing over half of the world's cement, with India as the second global producer [29]. World cement production in 2018, by regions and major countries, is presented in Figure 1. Since 2017, Poland has been the third-largest producer of cement in Europe, after Germany and Italy. Cement production in Poland in 2019 amounted to 19.0 million tons, which is 10% more than in 2017.

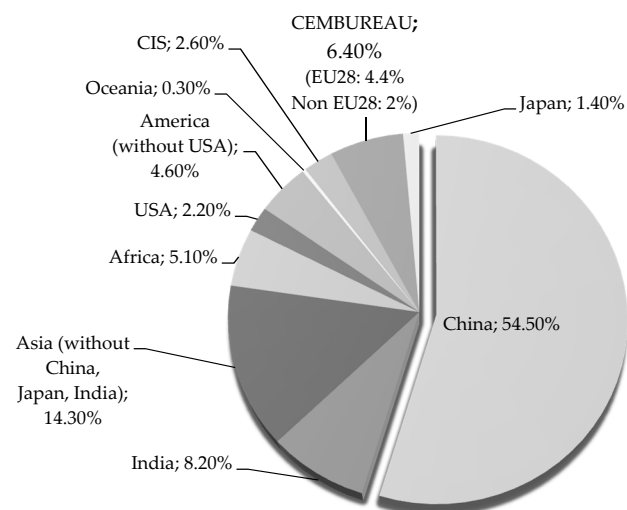


Figure 1. World cement production in 2018, by region and main countries.

Cement is a hydraulic binder, which means that after mixing with water it sets, hardens, and achieves proper strength characteristics, even in underwater conditions [30,31]. Due to its properties, cement is widely used as a binding material in the construction industry performing the role of a component of concrete mixtures, mortars, plasters, and many other products of construction chemistry. This finely ground material of gray color is produced by grinding clinker with calcium sulfate, being a setting time regulator (in the form of gypsum or anhydrite), and various ingredients such as granulated blast furnace slag, fly ash, or limestone (depending on the type of cement) in a cement mill [32]. Portland clinker is obtained by burning ground raw materials in a rotary kiln. The five stages which can be distinguished in the clinker production process occur in the following order:

(1) the dehydration process (heating and drying of the homogenized raw materials), (2) the calcination process (decomposition of raw materials into calcium oxide and carbon dioxide [33,34]), (3) the clinkerization process (formation of clinker phases: tricalcium silicate (C_3S), dicalcium silicate (C_2S), tricalcium aluminate (C_3A) and tetracalcium aluminoferrite (C_4AF)) and (4) the clinker cooling process. The cement manufacturing process, along with marked sources of pollutant emissions, is schematically displayed in Figure 2 [32].

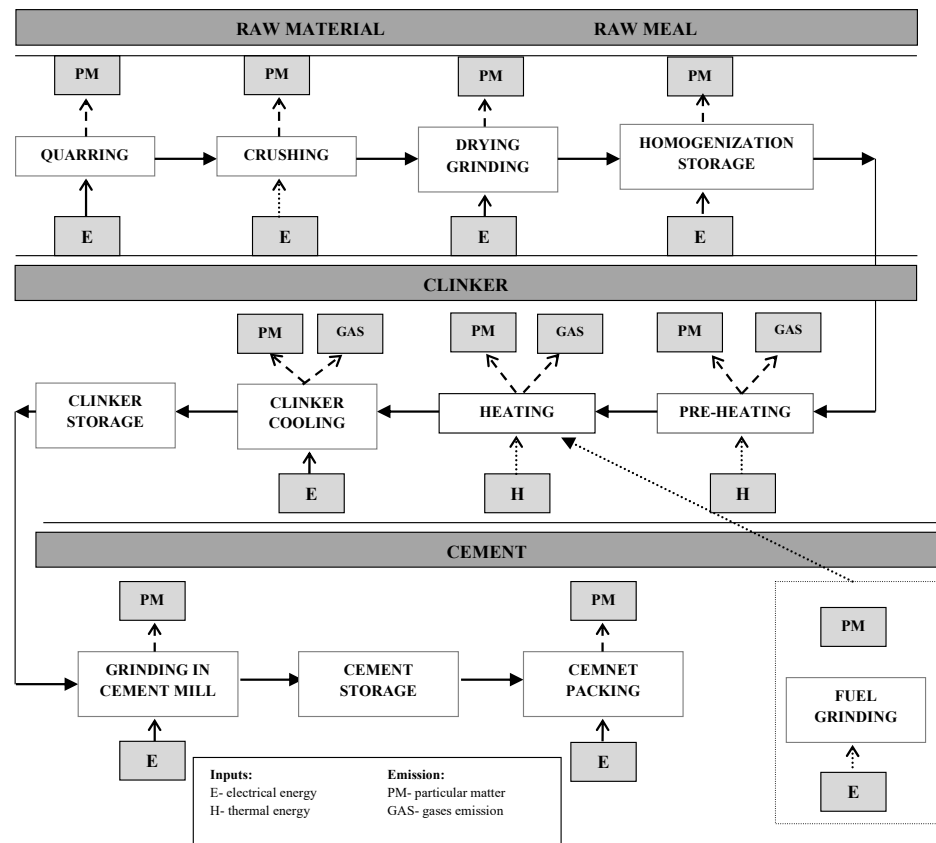


Figure 2. Flow chart of cement manufacturing.

3. Materials and Methods

In the present work, 70 alternative fuel (AF) samples, understood as “solid secondary fuel” according to the EN 15357:2011 standard, were analyzed to determine the potential reduction of direct CO_2 emission from the co-firing of waste-derived alternative fuels. Samples were derived by Cement Plant, Poland. The types of fuels covered in the study are mixtures of non-hazardous high-calorie waste such as plastics, paper, textiles, and tires, coming from the mechanical treatment of waste (for example sorting, crushing, compacting, pelletizing) [17]. An analysis of AF quality parameters was performed in the Department of Environmental Monitoring, Central Mining Institute. The samples tested were initially dried at the temperature of 313 K. The dried samples were ground with the application of a knife mill (LMN-100, TESTCHEM); the nominal grain diameter in the prepared sample did not exceed 2 mm. The test samples were obtained by grinding with the use of a cryogenic mill (6870, SPEX SamplePrep LLC, Metuchen, NJ, USA). The total carbon content in the samples was determined by means of the high-temperature combustion method with IR detection (HELIOS CHS 900, ELTRA), in accordance with standard EN 15407:2011. The calorific value and the heat of combustion were determined using the calorimetric method (C 5000 IKA WERKE), based on the PN-EN 15400:2011 standard. The results of the tests of AF samples are presented in Figure 3.

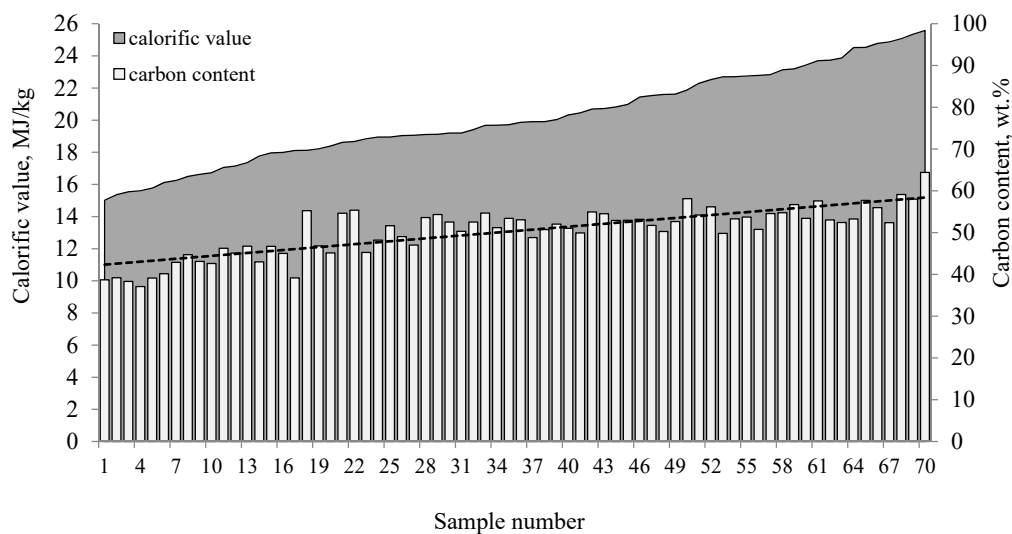


Figure 3. Parameters of alternative fuels.

The total emission of CO₂ coming from the co-combustion of coal and alternative fuels in a cement kiln was calculated using the following equation [35]:

$$E_{CO_2, fuel} = Z \cdot EF_{CO_2} \tag{1}$$

where:

$E_{CO_2, fuel}$ is CO₂ emission from the combustion process by type of fuel in Mg CO₂ per hour;
 Z is the amount of fuel combusted mass converted into the energy content of this fuel in TJ per hour;

EF_{CO_2} is the CO₂ emission factor in Mg CO₂/TJ.

The carbon dioxide emission factor from fuel combustion expressed in megatons of CO₂ emitted per unit of calorific value is calculated according to equation [35]:

$$EF_{CO_2} = \frac{3.664 \cdot C}{Q} \tag{2}$$

where:

EF_{CO_2} is the CO₂ emission factor in Mg CO₂/TJ;

3.664 is a molecular weight ratio of CO₂ to C;

C is carbon content of combusted fuel in %;

Q is calorific value in TJ/Mg.

The total emission from the combustion process was a sum of CO₂ emissions from all fuels used, i.e., from coal and alternative fuels.

The calculation was performed for several scenarios with various shares of alternative fuels. The fuel mix composition data are presented in Table 1.

Table 1. Share of energy coming from conventional and alternative sources.

Fuel Type	Options										
	1	2	3	4	5	6	7	8	9	10	11
Coal	100%	90%	80%	70%	60%	50%	40%	30%	20%	10%	0%
Alternative fuel	0%	10%	20%	30%	40%	50%	60%	70%	80%	90%	100%

For the purpose of this work, the following assumptions were made as listed below:

(a) The yearly average heat demand for the production of clinker equals 45×10^9 MJ. The value was calculated from the annual clinker production data for the period of 2010–2018, published in the Polish Cement Association report [4], and using the following Equation (3):

$$H_d = M_c \cdot H_s \quad (3)$$

where:

H_d is the average CO₂ total heat demand to produce clinker in MJ per year;

M_c is average capacity of cement kiln in Mg per year;

H_s is specific heat consumption per ton of clinker in MJ/Mg.

The results of the Polish Cement Association report are summarized in Figure 4. As seen, the specific heat consumption per ton of clinker ranged from 3677 to 3828 MJ/Mg. Thus, it was calculated that with an average capacity of cement kiln of about 12×10^6 Mg of clinker, it is necessary to provide approximately $44\text{--}46 \times 10^9$ MJ of heat.

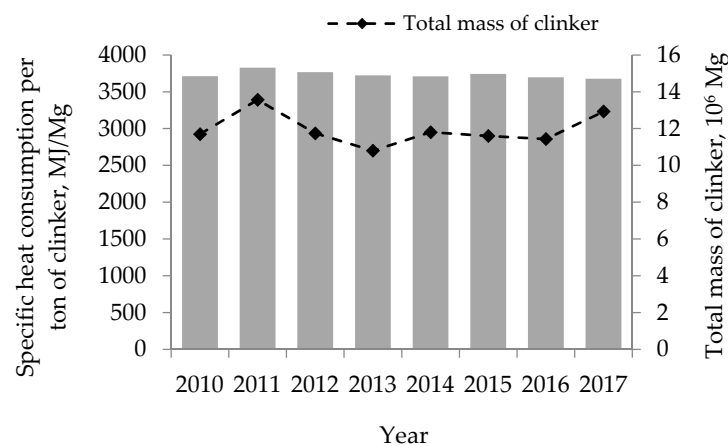


Figure 4. Clinker production data for the period of 2010–2018, Poland.

(b) The rotary kiln is operated for about 8000 h annually.

(c) The fuel mix is combusted only in the main burner.

(d) The calorific value and the carbon content of coal are 28.81 MJ/kg and 76.2%wt., respectively [36]. The quality parameters of coal are unchanged in the calculations.

(e) The quality parameters of alternative fuels (i.e., calorific value and carbon content) are not constant. The calorific value of AF samples tested varies within a comparatively wide range, from the highest value of about 25.58 MJ/kg to the lowest one of 15.02 MJ/kg.

(f) In the performed calculation, it was assumed that the biogenic fraction in alternative fuel samples will be 30% [37,38].

(g) The price of CO₂ emission allowances is 30.04 €·Mg⁻¹ [39].

4. Results and Discussion

4.1. Alternative Fuels Characteristic

The results of the qualitative analysis (see Figure 3) indicate differences between individual samples of alternative fuel, which may result from the heterogeneous composition of the waste stream used for fuel production. Alternative fuels are mainly produced from mixed streams of municipal solid waste, including different shares of plastic, paper, textile, or rubber. A typical composition of AF regarding its different components is presented in works [20,40–42]. The selected groups of wastes are characterized by various physical-chemical parameters [43,44]. Plastics have a very high calorific value, even exceeding 40 MJ/kg, due to a low content of ash and moisture, while paper and wood has the calorific value of about 11–20 MJ/kg. For comparison, the heating value of coal is about 28 MJ/kg. The share of a given fraction in the alternative fuel determines its calorific value.

The calorific value of the tested AF samples ranges from 15.02 MJ/kg to 25.58 MJ/kg, while the carbon content changes from 37.09% to 64.42%. The average carbon content in the alternative fuels with the following calorific values: 15–16 MJ/kg, 16–17 MJ/kg, 17–18 MJ/kg, 18–19 MJ/kg, 19–20 MJ/kg, 20–21 MJ/kg, 21–22 MJ/kg, 22–23 MJ/kg, 23–24 MJ/kg, 24–25 MJ/kg, and 25–26 MJ/kg is equal to 38.49%, 42.70%, 45.57%, 48.66%, 51.64%, 52.63%, 53.18%, 53.23%, 54.65%, 54.83%, and 60.51%, respectively. As shown in Figure 3, the higher carbon content in individual AF samples does not always correspond with a higher calorific value. For example, the carbon content in sample 18 (with the calorific value of 18.12 MJ/kg) is about 55.24%, and in samples 67 (with the calorific value of 24.87 MJ/kg) and 68 (with the calorific value of 25.07 MJ/kg) the carbon content is 52.38% and 59.11%, respectively.

4.2. Mass Balance in Co-Combustion of Coal and Alternative Fuel

The analyzed case demonstrated that for the production of 12 thousand Mg of clinker per year, with a unit heat consumption of 3732 MJ/Mg, an amount of 194.31 Mg of coal per hour is needed. Figure 5 shows the quantity of alternative fuel necessary to obtain the required amount of heat, i.e., about 5.6 TJ per hour, with varying levels of coal substitution.

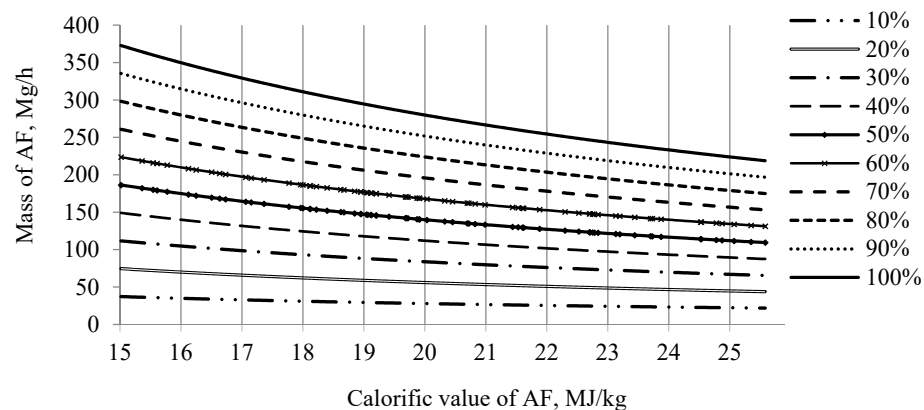


Figure 5. The mass of the alternative fuel is required for the production of clinker. The substitution of coal with alternative fuels was: 10%, 20%, 30%, 40%, 50%, 60%, 70%, 80%, 90%, and 100%.

As can be seen in Figure 5, an hourly demand for alternative fuels decreases with the increase in calorific value. Assuming complete substitution of coal with the fuel of the AF type, the necessary amount of an alternative fuel with a calorific value of 15–19 MJ/kg is 300–400 Mg/h, while for an alternative fuel with a calorific value of 19–26 MJ/kg—it is 200–300 Mg/h. The effect of calorific value on the amount of the alternative fuel consumed is less noticeable at the consumption of 70–80% coal in the clinker production. For example, at 20% co-combustion of AF, the difference between the amount of the low-calorie and high-calorie fuels is 31 Mg/h, while at 80% substitution by AF the difference is 123 Mg/h. It was calculated that the thermal deficit due to the reduction of coal burning to 40% makes that 2–3 times more alternative fuel must be mass transported into the rotary kiln than in the case of the conventional fuel, while with a 20% reduction it is 5–8 times more. This indicates that the alternative fuel storage area must be located significantly higher or the frequency of fuel supply increased as compared to coal.

In this study, the mass savings of coal achieved due to a partial replacement with alternative fuel are presented in Table 2. Based on the results, it can be estimated that the substitution of coal with alternative fuels at the level of 70% means that the savings for the cement producer may exceed 55 million euros per year. It should be noted that to calculate the total financial profit, it is necessary to deduct the costs of alternative fuel from the value given in Table 2. The price of alternative fuels is much lower compared to the costs associated with coal, which makes these fuels more cost-effective [45,46].

Table 2. Economic benefits of substituting coal with alternative fuel (AF).

Share of Heat from AF Fuels	Mass Saving of the Coal	Cost Savings
	Mg·h ⁻¹	€·h ⁻¹
10%	19.43	923
20%	38.86	1847
30%	58.29	2770
40%	77.72	3693
50%	97.15	4617
60%	116.58	5540
70%	136.02	6463
80%	155.45	7387
90%	174.88	8310

4.3. CO₂ Emission Balance

According to Equation (2) and qualitative data of coal sample (see Section 3) the CO₂ emission factor of coal was calculated as

$$EF_{CO_2} = \frac{3.664 \cdot 0.762}{0.0288} = 96.94 \frac{\text{Mg CO}_2}{\text{TJ}} \quad (4)$$

The emission factor for all AF samples tested was calculated in a similar way, the results are summarized in Figure 6. The determined factor values of alternative fuel ranged from 77.22 Mg CO₂/TJ to 111.78 Mg CO₂/TJ (the average value being 91.91 Mg CO₂/TJ). Uncertainty estimates for CO₂ emission factors for the fossil fuel and alternative fuels were 1.5% and 3–4%, respectively. As can be seen, the factor value of some AF samples exceeds the emission factor from the combustion of coal. Higher emission factor values were recorded for sixteen fuel samples (numbered 8, 11, 13, 18, 21, 22, 25, 28, 29, 30, 32, 33, 35, 36, 42, and 50), mainly with a low calorific value of below 20 MJ/kg and a high carbon content (>52%). The ratio of carbon content and calorific value varied from 26.93 to 30.49 for these selected samples of AF, while for coal it was 26.47. According to [10], the emission factor for hard coal (for the year 2019), calculated based on the national average calorific value, is 94.70, i.e., the ratio of carbon to the calorific value is 25.85. This means that the most effective way to achieve a low CO₂ emission factor will be to use alternative fuels with a ratio value below 25–26.

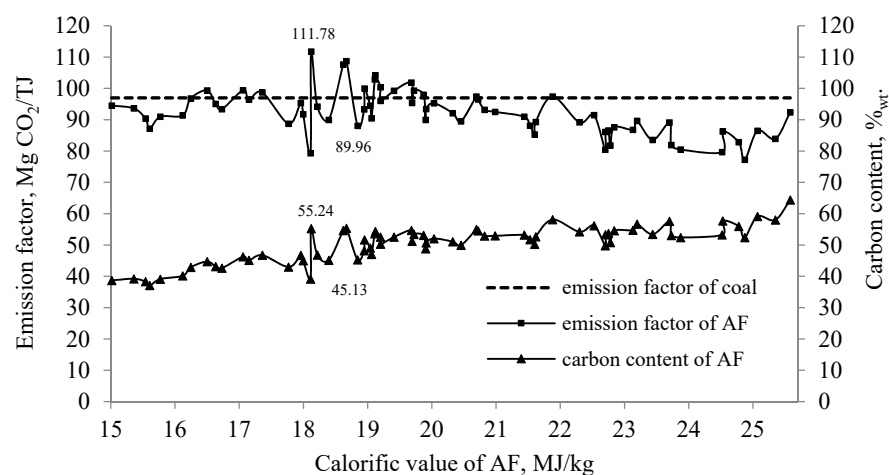
**Figure 6.** CO₂ emission factor of alternative fuel samples tested.

Figure 7 illustrates the avoided emission of CO₂ resulting from the co-combustion of coal with 30% biogenic carbon-containing alternative fuels. According to the data of the Polish Cement Association, the content of biomass in alternative fuels burned in Polish cement plants in 2008–2016 ranged from 25 to 36% [47].

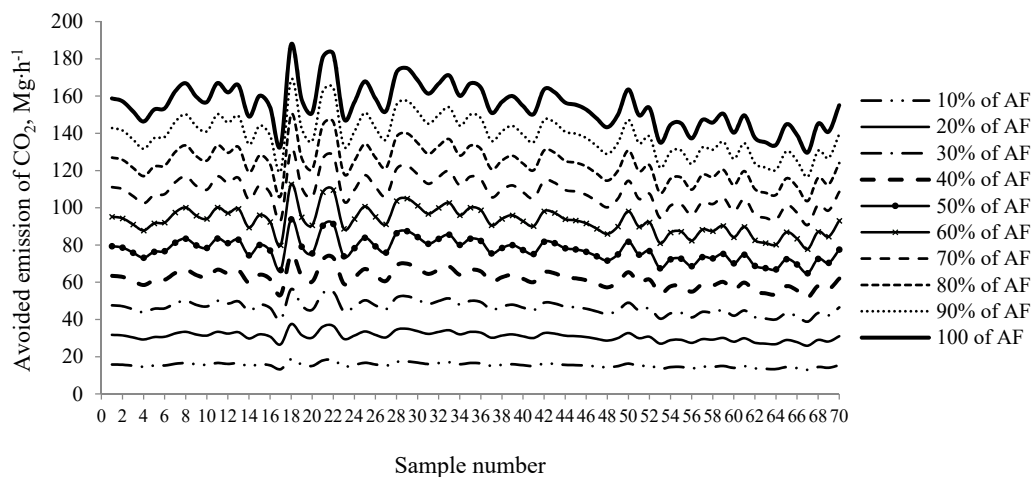


Figure 7. Avoided CO₂ emission from biomass fraction.

Biogenic carbon emission comes from the waste of biological origins such as residues or waste streams from forestry and timber processing, agriculture, pulp, and paper as well as sugar industries [45,48]. The biogenic fraction in a given fuel is determined by appropriate laboratory tests specified in European standards, i.e., the manual sorting method (MS), the selective dissolution method (SDM), or the radiocarbon method (14C-Method) [21,40].

In accordance with the Intergovernmental Panel on Climate Change guidelines, the emission of biogenic carbon in the form of carbon dioxide from the incineration process is regarded as climate-neutral since carbon is generated by the natural cycle, and can be excluded from the total amount of CO₂ emissions [49,50]. The majority of case studies assumed that the amount of CO₂ absorbed by growing forests through the photo-synthesis process is equal to the emission from the combustion process [51,52]. However, in recent years, there has been a more and more common belief that biomass fuels should not be considered carbon neutral when forest energy resource management is not carried out sustainably [53–55]. In this work, it was assumed that carbon dioxide emissions from biomass fraction can be considered carbon neutral.

As can be seen in Figure 7, a co-firing of coal with 30% of alternative fuels allows one to avoid about 40–59 Mg of CO₂ emission per hour, while with 80% and 100% of AF even 104–150 Mg of CO₂ or 130–188 Mg of CO₂ per hour, respectively. The curves show slight decreases in the amount of avoided emission with the increases in calorific value of the alternative fuel samples (the samples are numbered from the lowest to the highest calorific value), particularly with high coal to AF substitution. It can be related to the fact that a necessary amount of a high-calorific AF to supplement the thermal deficit is lower than that of a low-calorific fuel. The irregular trend of the curves and the occurrence of peaks are related to the variability of quality parameters in the analyzed fuel samples, especially the carbon content. For example, the carbon content of fuels with a calorific value of about 18 MJ/kg varies from 39.17% to 55.36%.

Table 3 shows the financial benefits resulting from the avoided fees for CO₂ emissions. In the analyzed case, the cost of CO₂ avoided ranges from 465 euros per hour for the lowest reduction of coal combusted to 4185 euros per hour (assuming 90% combustion of the alternative fuel). On an annual basis, these costs will amount to several million euros. Of course, the greater the biogenic fraction share is, the greater the profit. With the share of the biogenic fraction at the level of 60%, the savings in Table 3 will double. The financial benefits will also depend on the price of carbon dioxide emission allowances of the Emission Trading System (EU ETS) [39]. From the beginning of 2020 to mid-March, the prices for the emission of 1 Mg of CO₂ were at the level of 22–26 euros. At the end of March 2020, the prices of CO₂ emission allowances dropped significantly, even to 14 euros. Currently, the exchange price of CO₂ emission allowances reaches the level of 28–30 euros.

In the analyzed case, each increase in the share of heat from alternative fuels by 10% means on average about 15 Mg per hour of additional CO₂ emissions avoided.

Table 3. The financial benefits resulting from the avoided fees for CO₂ emissions.

Share of Heat from AF Fuels	Avoiding CO ₂ Emission (30% of Biomass)	Benefits of Fees from Avoided Emission of CO ₂	
	Mg CO ₂ ·h ⁻¹	€·h ⁻¹	€·year ⁻¹
10%	15.48	465	3,720,268
20%	30.96	930	7,440,536
30%	46.44	1395	11,160,804
40%	61.92	1860	14,881,072
50%	77.40	2325	18,601,341
60%	92.88	2790	22,321,609
70%	108.36	3255	26,041,877
80%	123.84	3720	29,762,145
90%	139.32	4185	33,482,413
100%	154.80	4650	37,202,681

Figure 8 presents the total gross and net emissions of CO₂. The gross emission is related to the Mg of CO₂ emitted from coal and the alternative fuel together, while net emission takes into account a zero-emission factor from the biodegradable fraction in AF. The calculations were made on the assumption of two different biogenic fraction contents in fuels, namely 30% and 60%. The higher content of the biogenic fraction was assumed based on the results of fuel characteristics from various cement plants, presented in work [20,21]. The mean gross emission factor, at the 10% alternative fuels share in the mix, was 540.21 Mg CO₂ per hour, and at the 90% alternative fuels share—it declined to the level of 518.71 Mg CO₂ per hour. Uncertainty estimates for the emissions measurement of gross carbon dioxide were on the order of 4–5%. For comparison, to obtain 5.6 TJ·h⁻¹ of heat, 194.31 Mg of coal per hour is needed, which corresponds to the total emission from coal combustion of about 542.90 Mg CO₂. As can be observed in Figure 8, the replacement of coal with AF has undoubtedly resulted in a reduction of fuel emissions, particularly when the emission from biogenic fraction was considered carbon neutral. It means that the use of biomass and biomass by-products as alternative fuels can be classified as limiting CO₂ emission. The mean net emission factor ranged from 524.73 Mg CO₂ per hour up to 379.38 Mg CO₂ per hour. It was found that each successive 10% increase in the share of heat from alternative fuels (with the biogenic fraction of 30%) contributed to the reduction of the net emission level by each subsequent 3–4%, in relation to the emission from the combustion of coal alone. In the case of 90% coal and 10% alternative fuels, the average level of net emissions from all samples is 524.73 Mg CO₂, and with 80% coal and 20% alternative fuels it is 506.56 Mg CO₂, whereas with 70% coal and 30% alternative fuels it is 488.39 Mg CO₂. With regard to alternative fuels with a twice higher share of the biogenic fraction, each 10% replacement of coal will reduce emissions by about 6%, compared to coal emission. With the lowest share of alternative fuels (10%), the net emission varied from 505.90 Mg CO₂ per hour to 513.64 Mg CO₂ per hour, while with the higher share of alternative fuels (90%), the minimum net emission was 209.91 Mg CO₂ per hour and the maximum was 279.56 Mg CO₂ per hour. Based on the results, it was found that with the full substitution of coal, the average gross emission of CO₂ from all samples is 30% higher than the net emission (Figure 8j), while with 20% substitution of coal the difference is 6% (Figure 8b).

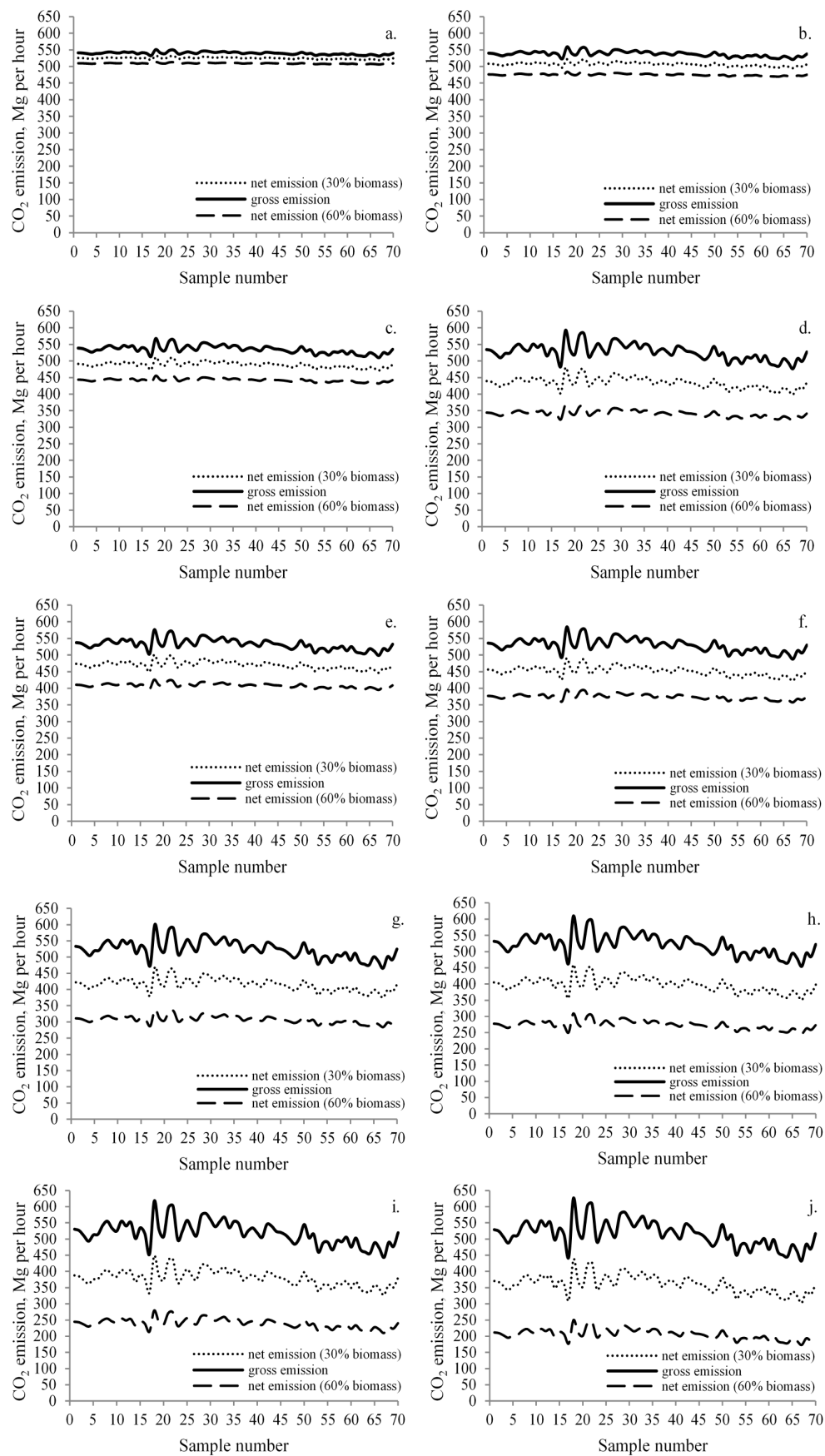


Figure 8. The amount of CO₂ emitted from co-combustion of coal with (a) 10%, (b) 20%, (c) 30%, (d) 40%, (e) 50%, (f) 60%, (g) 70%, (h) 80%, (i) 90, and (j) 100% alternative fuel.

According to the methodology used for EU-ETS benchmarks, a limit value for clinker production is 766 kg CO₂ per Mg clinker [56]. Based on the results shown in Figure 8, gross fuel emission is on average at the level of 353 kg CO₂ per Mg of clinker (with the production of 12 million Mg of clinker per year and the working time of 8000 h). Substitution of 50% and 70% coal with alternative fuels of 30% biomass content resulted in the reduction of fuel emissions to the level of 301 kg CO₂ and 277 kg CO₂ per Mg of clinker (net emission), respectively. This is about 30–40% of the emission benchmark of 766 kg CO₂ per Mg of clinker. It means that approximately 60–70% of CO₂ emissions can come from the calcination process (process emission).

A slight decline of the total net emissions is observed with the increase in the calorific value of the alternative fuels, particularly at the high level of coal substitution with AF (Figure 8h–j). For example, in the case of a 70% share of alternative fuels with the emission factors below 96 Mg CO₂/TJ (Figure 6), the average net CO₂ emission from samples with a calorific value of 16–17 MJ/kg is 413 Mg CO₂/hour, while for samples with a higher calorific value in the range of 21–22 MJ/kg and 24–25 MJ/kg, the emissions are 407 Mg CO₂/h and 386 Mg CO₂/h, respectively. For the sixteen remaining samples with the emission factor above 96 Mg CO₂/TJ, the net emission was in the range of 430–470 Mg CO₂/h and was only about 13–23% lower than the emission coming from 100% coal combustion, regardless of the calorific value.

5. Conclusions

The paper discusses the issue of using alternative fuels in clinker burning systems. The performed calculations showed the environmental and financial benefits of using alternative fuels as coal substitutes in cement manufacturing.

The estimated emissions were determined using the CO₂ emission factor for coal of 96.43 Mg CO₂. The calculation reveals that the net emission of CO₂ was reduced by about 25%, which was achieved by the co-combustion of 70% alternative fuels with a CO₂ emission factor below 96.43 Mg CO₂. In the case of fuel samples with a CO₂ emission factor above 96.43 Mg CO₂, the decline in emissions was slight, about 18%. In the analyzed case, an increase in the share of alternative fuels by each 10% resulted in a saving of coal mass by 19.43 Mg per hour, which generates savings of about 923 euros. In turn, the 10% reduction of coal burned means that about 0.56 TJ/h of thermal deficit must be supplemented with alternative fuel. This requires the burning of about 28–37 Mg of AF with the calorific value <20 MJ/kg and about 22–27 Mg of AF with the calorific value <20 MJ/kg within an hour. The total savings of approximately 1388 euros per hour were calculated for each 10% increase in alternative fuels. The cost reduction resulted from both the mass savings of the coal and the co-combustion of alternative fuels with the 30% biogenic fraction content.

It has been proven that substituting coal with alternative fuels is one of the most prospective solutions, in terms of environmental protection and mitigating climate change. Co-combustion of AF reduces the consumption of high-emission fuels, thus enabling the fulfillment of the obligations stipulated by the Paris Agreement of 2015, i.e., the achievement of the carbon neutrality targets to combat global climate change. At the same time, alternative fuels produced based on waste contribute to the implementation of the idea of a circular economy through using materials otherwise destined for landfills.

Balancing off the cement plant's environmental impact constitutes an urgent issue, particularly with the progressive maximization of energy consumption from waste-derived alternative fuels, and undoubtedly requires further detailed research. Future studies should focus on assessing the impact of the morphological composition of waste characterized by high heterogeneity on the amount of CO₂ emissions coming from the combustion process.

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