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Efficiency Assessment of the Production of Alternative Fuels of High Usable Quality within the Circular Economy: An Example from the Cement Sector

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Abstract: This article aims to present the mechanisms regulating the waste management system of one of the European countries that affect the cement industry. This publication analyses the possibility of using selected fractions of municipal and industrial waste as alternative fuels, including an analysis of ecological costs and benefits. The methodology includes the analysis of production data and the calculation of savings resulting from the use of alternative fuels. On this basis, ecological aspects were also indicated that should be taken into account when analyzing the profitability of the investment. Production data from an example Polish cement plant were used to analyze the research problem. Based on the guidelines of environmental standards and technical specifications, the parameters that PASr alternative fuels should meet were calculated in the company laboratory. This fuel type was then calculated in terms of emission intensity and production efficiency. The research results obtained in this paper study emphasize that the change in cement clinker production technology toward the use of waste raw materials and secondary fuels does not lead to an increase in heavy metal emissions to the extent that would justify qualifying cement as a material requiring systematic control of its harmful impacts on humans and the natural environment. The conclusions show that the use of alternative fuels reduces CO_2 emissions and production costs, without negatively affecting the efficiency and production volume. The average energy requirement for the production of 1 ton of cement is approximately 3.3 GJ, which corresponds to 120 kg of coal with a calorific value of 27.5 MJ per kg. Energy costs account for 30–40% of the total cement production costs. Replacing alternative fuels with fossil fuels will help reduce energy costs, providing a competitive advantage for cement plants that use it as an energy source. The presented considerations can provide an answer to all interested parties, including representatives of the executive and legislative authorities, on what path the sector should follow to fit into the idea of sustainable building materials and the circular economy.

Keywords: alternative fuels; cement sector; circular economy; environmental protection; resource recovery and recycling; sustainable construction

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1. Introduction

The growing awareness of resource depletion and climate challenges has further highlighted the enormous potential of alternative fuel production. Among the many economic sectors where innovations related to the circular economy are being introduced, the cement industry deserves special attention. It is expected that in the future, the cement industry, thanks to appropriate process solutions, will contribute to both saving natural resources and improving the quality of the environment, including reducing the amount of waste stored in landfills. The cement industry, which is a waste-free industry, plays an important role in the waste management system in European Union countries, including Poland. It uses (in recycling processes) significant amounts of waste and by-products (e.g., fly ash, blast furnace slag and Rea gypsum) as ingredients of raw material mixtures for the production of clinker, cement, and concrete [1,2]. In the process of co-processing, the cement industry uses waste that cannot be sent directly for recycling for various reasons. Due to economic unprofitability and the lack of a suitable market for products resulting from recycling, recycling is not the best choice for environmental reasons, causing an increase in the carbon footprint [3–5]. The cement industry has been operating in a circular economy for many years—waste is the basis for raw materials and fuels in the cement production process [6,7]. This allows for less extraction of raw materials and fossil fuels (coal). Waste managed in a cement plant does not go to a landfill, and so its potential is not wasted [8,9]. There is no problem with the ashes after burning the waste, as they go into the raw material mixture and constitute its valuable component. The industry has the opportunity to reduce its carbon footprint by reducing CO_2 emissions when co-firing biomass with alternative fuels, and part of the clinker (a cement component whose production requires the greatest amount of heat) can be replaced with waste from other industries (such as fly ash or blast furnace slag) [10–12]. The recovery of material that takes place in a cement kiln during the co-combustion of alternative fuels (RDF and waste tires) may be taken into account when setting municipal waste recycling rates at the municipal level. There are 10 cement plants in Poland equipped with a full production line (furnaces + cement grinding). Their production capacity is 16 million tons of clinker, and the cement production capacity is approximately 22 million tons per year. All plants co-burn waste fuels. The production of the so-called alternative fuels from waste for use in the cement industry is a big challenge for mechanical processing plants, as cement plants set increasingly higher requirements [13]. An important parameter is, for example, the calorific value, which should be >20 MJ/kg. Equally important is humidity < 15% and a heavy metal content <2500 mg/kg. Other parameters are the chlorine content, which should be <1%, a sulfur content < 1.5%, and an ash content < 15%. Moreover, the fuel should be in the form of shredded, solid waste with a granulation of no more than 40 mm and must constitute a homogeneous mixture [14–17]. Therefore, the waste treatment process must be organized in a way that meets these requirements.

This work aims to determine the possibility of using industrial waste and segregated municipal waste fractions for energy purposes. During the tests, the physical and chemical properties and the amount of waste intended for the production of alternative fuels were determined. The mass of alternative fuels used for combustion and the amount of pollutant emissions into the atmosphere during their co-combustion were determined. This research was based on data from one of the Polish cement plants for August 2023, i.e., the production volume, production efficiency, and percentage of use of alternative fuels in the mixture of fuel materials burned in the furnace.

Based on an analysis of the literature, it can be stated that research on the cement industry as an important link in the circular economy currently focuses on the problem of decarbonization, with a particular emphasis on the use of renewable energy sources. However, most articles omit the rarely discussed research problem concerning the analysis of the possibilities of using selected material fractions, including municipal and industrial waste, as alternative fuels. This topic was taken up by the authors and implemented by analyzing production data from a selected plant, taking into account the analysis of economic costs and benefits. To our knowledge, this is the first approach to this topic covering the assessment of the efficiency of alternative fuel production in the example of the cement sector and referring to the CCS/U technology (carbon capture and storage/usage) promoted in this sector. The considerations presented above introduce a new perspective in areas such as (I) sustainable construction, (II) recycled materials, (III) the circular economy, and (IV) alternative fuels.

Therefore, the presented research has many important implications, both theoretical and practical. At the same time, they fill a gap in the literature related to research not only on the circular economy and recycled materials but also constitute another step towards the dissemination of CCS/U technology, which is already perceived as an opportunity to build a new branch of the economy, contributing to the growth of employment and revenue in every market sector.

The article is divided into the following sections: Section 1 is an introduction to the topic. Section 2 reviews the literature on the use of alternative fuels in the cement industry. Section 3 describes the research methodology used to analyze the production process. Section 4 presents the methods of obtaining and processing waste into energy fuels for cement plants. Their profitability and effectiveness in implementing production processes were assessed. Section 5 contains conclusions from this research and prospects for the further development of analyses and research on this topic.

2. Literature Review of the Problem

The cement industry in Poland plays an important role in the management of waste from other industries, including power plants and metallurgy, and is the creator of the use of alternative fuels. Thanks to cement plants, approximately 1.5–2.0 million tons of waste is used as raw material for the production of alternative fuels, thanks to which this fraction is not disposed of in landfills [18]. The advantage of cement plants in the thermal transformation of waste is a very high temperature above 1400 °C, which ensures a safe method of waste disposal (by the Regulation of the Minister of Economy of 21 March 2002 on the requirements for the thermal transformation of waste). All substances produced as a result of the combustion of alternative fuels are incorporated into the clinker structures (they constitute approximately 4% of cement clinker) [19,20]. The cement industry and the ready-mix concrete industry are characterized by huge consumption of energy and raw materials; therefore, it is extremely important to find cheap and fully useful mineral materials that can fully replace the most expensive component in cement, Portland clinker, which is also waste from other industrial processes. One such raw material is fly ash that is precipitated in electrostatic precipitators and is waste from the combustion of hard coal [21,22]. The use of fly ash in the cement industry brings measurable ecological effects, one of the most important of which is the reduction of CO_2 emissions into the atmosphere. When producing fly ash cement by replacing 35% of Portland clinker with the addition of fly ash, CO_2 emissions will be reduced by 227 kg CO_2/ton of cement compared to the production of pure Portland cement with a Portland clinker content of 95% [23]. Fly ash is used as a mineral additive for the production of multi-component Portland cement; an active mineral additive and a micro aggregate for the production of ordinary and self-compacting concrete, for the production of high-value concrete; and a component of aerated concrete, road concrete and others. One of the activities that strongly supports waste management is the use of alternative fuels in cement plants [24–27]. The use of this type of fuel translates into a reduction in the production costs of cement plants as a result of lower energy costs by replacing some fossil fuels. Alternative fuels are properly sorted and processed waste containing energy. Such fuels are obtained from processed industrial and municipal waste. The ingredients of these fuels may be rubber waste, wood waste, paper, fabrics, plastics, used oils, solvents, paints, dried sewage sludge, and meat and bone meals. An alternative fuel may also be a single waste from a long list of waste, e.g., used car tires. Cement plants used 1180 thousand tons of alternative fuels in 2022, replacing 46% of the heat needed in the production process with energy from waste. Most of it was waste-based municipal fuels (RDF), the amount of which amounted to almost 1 million tons, which constituted over 80% of the total mass of fuels used [28,29]. The number of tires available as an alternative fuel in cement plants is limited and currently amounts to approximately 90,000 tons. Among the stream of alternative fuels, we can also distinguish plastics and rubber (3%) and sewage sludge (1%). The process of processing alternative fuels in a cement plant allowing for simultaneous energy and material recovery of waste is called co-processing. This process includes several recovery operations in one process: energy recovery, recycling/recovery of other inorganic materials, and possibly the recycling/recovery of metals and metal compounds [30]. Co-processing in a cement kiln is the best choice from an environmental, social, and economic point of view. The amount of alternative fuels and the level of heat replacement in the cement industry in Poland are systematically increasing. To reduce the ash content in the fuel, a fine mineral fraction must be separated in advance, which could be transferred to the combustible air fraction directed to the fuel at the final stage of separation [31–33]. Drum or grate screens work best to separate this fraction from municipal waste. If we intend to obtain fuel with the highest possible calorific value, we should use flammable fractions characterized by a high heat of combustion. In this case, it is worth using primarily plastics (PE, PP, etc.) and avoiding moist and low-calorie fractions. Hygroscopic materials include paper and cardboard, which also absorb moisture from kitchen waste, and therefore too high a share of this fraction in the fuel could reduce its calorific value [34]. The permissible chlorine content in the fuel cannot be exceeded, and so the fractions that contain the most chlorine, i.e., PCV, cannot be fed to it. This rule also applies to the contents of sulfur and heavy metals. When producing fuel from particular types of industrial waste, their heat of combustion and chlorine, sulfur, and heavy metal contents should be tested in the laboratory in advance to obtain the most complete information possible [35]. There is also a need to check whether the waste is suitable for use as an alternative fuel component and in what proportions to mix it so that the final product has the highest possible caloric value. Moreover, the contents of sulfur, chlorine and heavy metals must not be exceeded [36,37]. Shredding is also an essential process in the production of fuel from waste, and the use of preliminary shredding increases the efficiency of the separation of magnetic and non-magnetic metals and the light fraction emitted by the air separator. Currently, devices used in waste sorting and processing technologies allow a combustible fraction with high calorific value that is free of metals, ballast, and organics to be obtained [38]. This has a positive effect on the calorific value and improves the energy properties of the fuel. Of course, the better the quality of the fuel, the higher the price for the recipient. Therefore, cement plants, depending on the quality of the alternative fuel obtained (the most important criterion is the calorific value parameter), pay EUR 23/Mg. The costs of fuel production constitute a significant part of the operating costs of mechanical processing plants' municipal and industrial waste. However, reducing the waste stream sent to the landfill by one ton saves approximately EUR 46 (marshal's fee plus storage fee) [39]. In Poland, waste sorting plants are mainly associated with drum screens and the manual sorting of municipal waste. Unfortunately, their effectiveness is often low. Often, this type of investment is carried out only to change the waste code to "waste from mechanical waste processing" and to pay a lower marshal fee at the landfill. This practice will put an end to the Regulation of the Minister of the Environment of 8 January 2013, on the criteria and procedures for admitting waste to landfills of a given type (Journal of Laws of 2013, item 38), imposing restrictive conditions for storing residues after mechanical waste treatment [40]. Under the regulation, from 1 January 2016, it will not be possible to store waste with code 19 12 12. It designates waste originating from mechanical treatments in which the total organic carbon (TOC) content is >5% dry matter, the loss on ignition is >8% dry matter, and the heat of combustion is >6 MJ/kg dry matter. The calorific value of ballast from most Polish sorting plants, especially from those where the residue after separating secondary raw materials is not used to produce fuel from waste, exceeds the value specified in the regulation of 8 January 2024 [41,42]. These provisions will force the modernization of sorting plants in Poland, increasing their efficiency and, consequently, reducing the stream of waste going to landfills. This applies to most sorting plants of mechanical–biological municipal waste processing plants in Poland. There is still a lot of the high-calorie fraction in the ballast coming from Polish sorting plants.

A way to meet the restrictive provisions is to produce fuel for cement plants from the ballast fraction from the sorting plant, and in the future for thermal power plants, using additional devices that allow the separation of flammable fractions from the ballast that are desirable as components of such fuel. We can use an air separator or an automatic sorter to separate them. Then, a shredder should be placed in the technological line to obtain the appropriate fuel granulation—most often it is granulation below 40 mm. Optionally, this type of mixture can be enriched with other high-calorie fractions originating from industrial waste. Whether the plant agrees to such an investment is determined by the economic calculation, which is mainly influenced by the amount of waste processed annually [43]. Most often, mechanical waste processing plants producing alternative fuels process 40,000 tons a year 100 thousand Mg of municipal or industrial waste. Cement plants are interested in suppliers ensuring the maintenance of supplies of large amounts of fuel that meet the requirements and are reluctant to cooperate with small entities. Small sorting plants for mixed municipal waste have the option of establishing agreements with other plants and producing fuel in one of them. When investing in the construction or expansion of a mechanical waste processing plant with a technological line for producing fuel from waste, the seasonality of the cement plant's operation, the so-called downtime, must be considered [44–46]. This type of investment requires the construction of a hall for storing fuel from waste. Most plants producing alternative fuels in Poland also have laboratories to control the quality of the fuel obtained. The fuel properties of individual flammable types of waste are also examined in terms of the possibility of using them as fuel input from waste [47–49]. Waste fractions constituting input to alternative fuel must meet specific quality criteria so that the fuel obtained meets the requirements of the cement plant. Proper organization of the waste-to-fuel processing system is the basis for their effective acquisition and allows quality to be guaranteed [50–52]. When processing municipal and industrial waste, shredding and separation processes are used with magnetic, non-magnetic, and air metal separators and alternative automatic optical separators, which are increasingly used and allow high-quality fuels to be obtained [53,54]. The appropriate sequence of subsequent processes determines the effectiveness of waste processing into marketable secondary raw materials and alternative fuels from waste. Figure 1 shows a simplified diagram of the production process of PASr fuel.

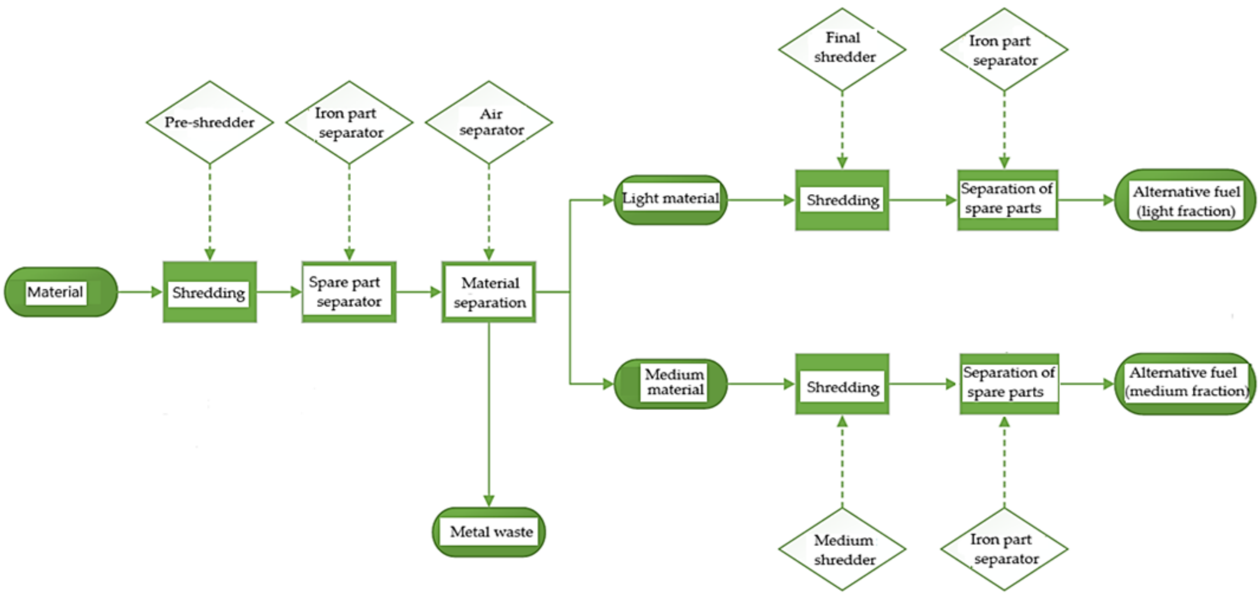

Figure 1. Simplified diagram of the PASta fuel production process.

The article, based on a literature review, gives a fresh look at the process of burning cement clinker in a rotary kiln, presenting unique possibilities for the simultaneous recovery of energy and inorganic material from waste. This method of waste management was analyzed in various aspects: the availability and quality of waste fuels on the market, legal requirements in the field of environmental protection, infrastructure and technical solutions, safety issues and their impacts on the product and process, environmental benefits, climate protection, etc. This paper presents the cement sector and analyzes all these conditions to responsibly use waste-based fuels and be adequately prepared for changing legal or market requirements in the short term, as well as those related to the goals set by politicians for 2050.

After a literature review, it was found that alternative fuels for clinker production are poorly used in the Polish cement industry. This is because Polish law is not fully specific in this respect and there is a lack of knowledge on how to use this technology. With this in mind, the authors present a compendium of knowledge regarding environmental requirements, technical specifications of devices, methods of obtaining alternative fuels, and assessing the profitability of their use.

The analysis presented in this way may allow us to indicate a further path for the transformation of the cement sector not only in Poland but also in other countries of the European Union. Although the analysis includes a selected case study, it should be noted that all operating cement plants in the European Union are an important link in the circular economy that can replace part of traditional fuels with alternative fuels produced from waste in the coming years until emission neutrality is achieved by 2050.

3. Materials and Methods

The amount of industrial and municipal waste generated systematically increases with the development of industry and the increase in the consumption of material goods. Waste generated from both sectors, by the principles of sustainable development, should be subject to rational management, taking into account the possibility of recycling or recovering the energy contained in the waste. Both unprocessed waste and waste processed into alternative fuel can be burned. The greatest ecological benefits, i.e., saving natural resources, reducing the amount of waste deposited in landfills, and reducing CO_2 emissions, are brought by the co-combustion of processed waste into alternative fuel in existing production systems (e.g., cement kilns and power boilers). Co-combustion of alternative fuels requires meeting several legal requirements regarding their combustion conditions and emission standards specified for waste combustion installations and the co-combustion of alternative fuels. Meeting emissions standards is possible by using substitute fuels with strictly defined quality parameters and calorific values.

The main goal of this article is to provide knowledge about the effective use and management of industrial waste for energy purposes in the cement plant sector.

The research work focused primarily on the following:

- Determining the size of the waste management market in Poland;
- Determining the possibilities of using various alternative fuels in the cement sector;
- Identifying problems that need to be solved to organize an effective production system while taking into account environmental regulations and currently applicable standards;
- Identifying ways to support the development of alternative fuels in the cement industry so that the waste management system in Poland becomes a closed-circuit economy by EU regulations.

To reduce emissions in the cement clinker production process, the authors carried out field research aimed at modifying the raw material mix and changing the fuel used. The research covered aspects related to the following:

1. The use of a mineralizer (fluorite) in the production of clinker to reduce the sintering temperature;
2. Maximizing the consumption of the so-called neutral biomass, mainly in the form of meat and bone meal and dry sewage sludge, as a substitute for hard coal;
3. The use of rubber dust (used, finely cut tires);
4. The use of alternative raw materials for the production of Portland clinker that contain significant amounts of non-carbonate lime, such as lime fly ash from the combustion of brown coal, post-carbide lime produced during the production of acetylene, granulated blast furnace slag, or the so-called soda lime;
5. The impact of alternative fuel dryers for drying using waste heat generated during clinker cooling;

6. Oxygen dosing to the clinker kiln burner to improve combustion efficiency.

The following research methods were used in this research:

- Data analysis based on data obtained from the cement plant;
- Expert interviews with production technologists;
- Analytical work (qualitative and quantitative analyses);
- An analysis of the current scientific literature.

Research was conducted on waste management methods for industrial purposes within the framework of the principles of the circular economy.

The subject of the authors' research is the assessment of the use of waste of various origins for the production of alternative fuels for cement plants. As part of the work carried out, the composition of waste, physical and chemical parameters, its production process, and legal and environmental requirements were determined. The research was carried out in the company laboratory. Using the equipment of the cement plant, the desired composition of the waste fraction with the required quality for use by EU directives and the permissible range of contamination was sought. The result of this research is to obtain the required parameters of the alternative fuel type PASr and to assess its effectiveness when used by the cement plant. The cost of producing such fuel, the cost of CO_2 emissions, and the costs of implementation by the plant were calculated.

4. Results and Discussion

4.1. Qualitative Analysis of Alternative Fuels

An important step in using alternative fuels as fuel in cement production is to carry out laboratory tests determining the parameters of alternative fuels important for the combustion process, such as the calorific value and moisture content, but also the contents of harmful elements and chemical compounds. Additionally, laboratory analyses help determine the optimal composition of the fuel mixture in the process of co-combustion of coal and alternative fuels. When examining a sample, considerable attention is paid to the number of so-called ballasts, i.e., the contents of ash and moisture, a high concentration of which hurts the fuel's calorific value and increases the ignition temperature. Another important parameter is the chlorine content because, during the combustion of alternative fuels, molecular chlorine is formed from waste, which contributes to faster wear of the cement kiln installation elements through their corrosion. Table 1 shows the calculations for the tested parameters of PASr fuel.

Table 1. Parameters of the alternative fuel type PASr.

PASr Fuel Parameters	
State of Matter	**Constant**
Ash content, %	<15
Grain size (max), mm	30
Moisture content, %	<15
Bulk density, kg/m^3	200–600
Flash point, °C	>65
Calorific value, MJ/kg	>19
Auto-ignition temperature, °C	>120
Estimated quantity of main ingredients, %	Plastics 35 Paper Fabrics 20 Rubber 10 Wood 5
Sulfur (S), %	<0.50
Chlorine (Cl), %	<1.00
Mercury (Hg), ppm	<2

Table 1. *Cont.*

PASr Fuel Parameters	
State of Matter	**Constant**
Chromium (Cr), ppm	<100
Nickel (Ni), lead (Pb), copper (Cu), cobalt (Co), manganese (Mn), ppm	<2000
Cadmium (Cd), thallium (Tl), ppm	<10

Source: Our own study based on [18].

4.2. Consumption of Alternative Fuels in a Cement Plant

This part of the research and analysis presents fuel consumption in one of the Polish cement plants, including alternative fuels. Detailed data from one sample measurement month are presented in Table 2. The following fuel materials were used as fuel to power the furnace: coal, diesel and heating oil (used only when starting the furnace), ash with a high carbon content separated from fly ash, and high and medium caloric fractions of the alternative fuel type PASr. PASr HCV and PASr calciner fuels are fuels from external suppliers, while fuels with the note ZPPA are fuels from the on-site alternative fuel production platform. Figure 2 additionally shows the percentage of fuels fed to the furnace in the cement plant in the examined period of July 2023. An important observation is the fact that coal constituted only about 23% of all fuels fed.

Table 2. Sample data on the consumption of fuels fed to the furnace in a cement plant for the period of July 2023.

July 2023											
	Material	**Wear [t]**	**Calorific Value [GJ/t]**	**The Amount of Energy Used [GJ)]**	**Emission Factor [kgCO$_2$/GJ]**	**Biomass Content [%]**	**Energy from Biomass [GJ]**	**Biomass Emission Rate [kgCO$_2$/GJ]**	**CO$_2$ Savings [t]**	**Fuel Utilization Rate [%]**	**Biomass Heat Consumption Rate [%]**
Traditional fuels	Coal	4113.55	25.9	106,537	93.8	0,00	0.00	93.80	0.00	23.11	0.00
	Heating oil	6.37	43.01	274	74.1	0,00	0.00	74.10	0.00	0.06	0.00
Sum		4119.92	68.91	106,811	167.90	29.7	0.00	167.90	0.00	23.17	0.00
Alternative fuels	Ash *	881.90	15.67	13 816	110.73	0.00	0.00	110.73	−234.36	3.00	0.00
	PASr HCV	319.18	27.86	8 891	86.39	28.20	2507.46	62.03	282.21	1.93	0.54
	PASr calciner	2970.74	19.52	57 994	82.98	42.90	24,879.74	47.38	2690.16	12.58	5.40
	PASr ZPPA	5912.18	19.17	113,354	56.52	36.10	40,920.87	36.12	6534.50	24.59	8.88
	PASr calciner ZPPA	8200.46	19.52	160,089	82.98	42.90	68,678.34	47.38	7425.95	34.73	14.90
Sum		18,284.46	101.74	354,144	419.60		136,986.42	303.63	16,698.45	76.83	29.72
Total		22,404.38	170.65	460,955.00	587.50		136,986.42	471.53	16,698.45		29.72

Source: Our own study based on [18]. * Ash with high carbon content separated from fly ash.

Important data from the point of view of assessing the effectiveness of the use of alternative fuels are the fuel utilization rate, the biomass heat consumption rate, and CO_2 savings. The scope of these data is presented in Table 1. The calculated CO_2 savings of 16,698.5 tons means that if alternative fuels were not provided and coal was burned instead, carbon dioxide emissions would be higher by almost 16,700 tons, which would increase fees for CO_2 emissions. CO_2 savings with ash were negative because ash with a high carbon content separated from fly ash was used, and therefore carbon dioxide emissions were not reduced.

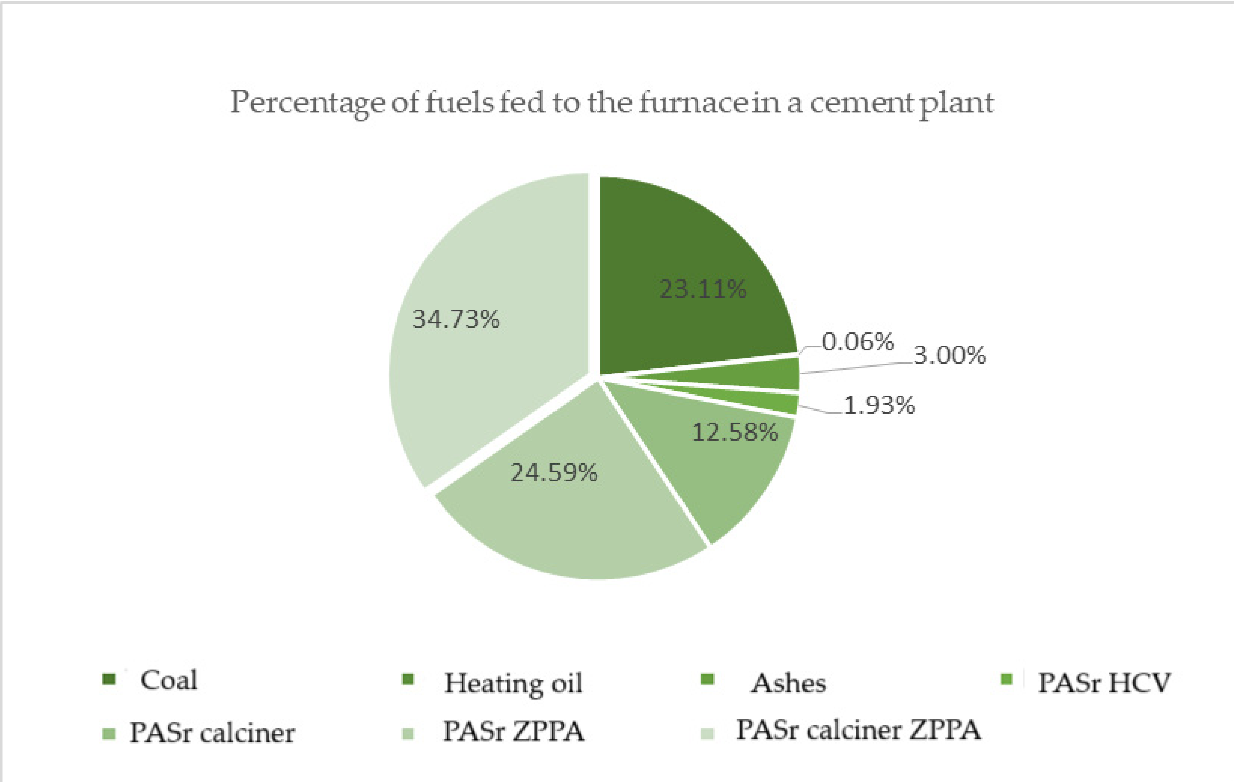

Figure 2. Percentage of fuels fed to the furnace in a cement plant (July 2020). Source: Our own study based on [18].

4.3. Percent Change in the Alternative Fuel Use Rate

Based on the production data presented in Table 3, Figures 3 and 4 were prepared to show the dependence of the clinker production volume and production efficiency on the alternative fuel use rate on individual days in July 2023.

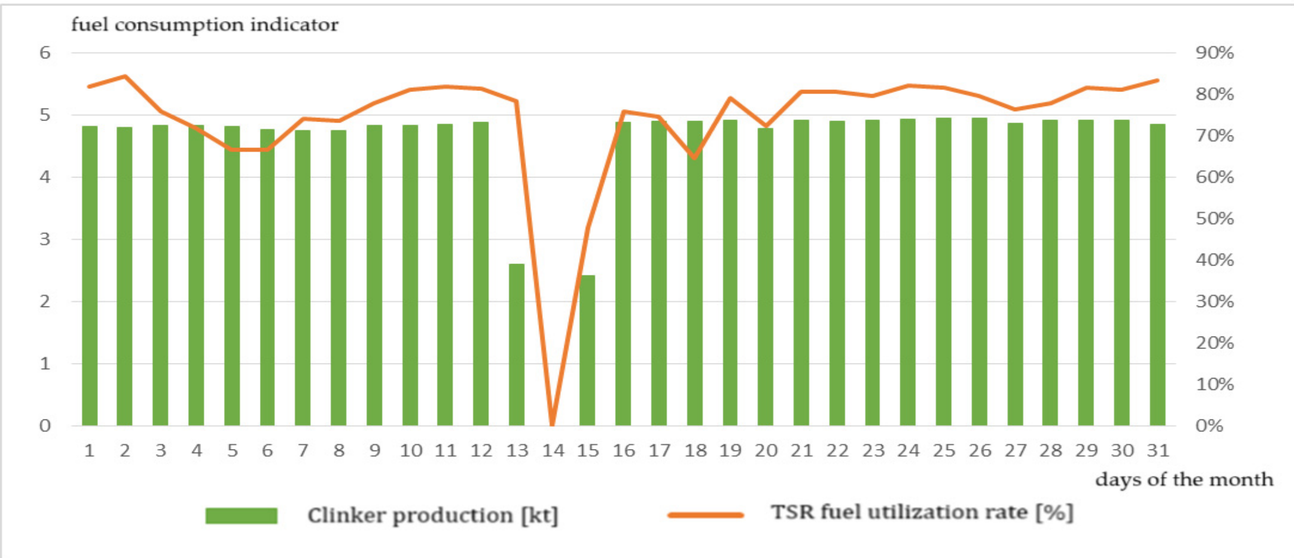

Figure 3. Dependence of the clinker production volume on the use of alternative fuels (July 2023). Source: Our own study based on [18].

Table 3. Daily fuel production and consumption in July 2023.

July		Clinker Production				Main Burner			Calciner				
Time	**Furnace Operating hours, h**	**Clinker Production, t**		**Coal, t**	**Starting Oil, l**	**PaSr ZPPA, t**	**Coal, t**	**PaSr HCV, t**	**PaSr Kalcynator ZPPA, t**	**Sludge Sewage, t**	**Ash, t**	**Heat Consumption, MJ/t**	**TSR Fuel Gauge, %**
44,013	24	4824	201	99.60		20,866	4.90	40,674	1.60	0.00	30.30	335,700	81.90
44,014	24	4803	200	70.90		21,723	7.40	32,417		0.00	28.00	291,100	84.30
44,015	24	4825	201	121,90		20,609	14.10	34,970	0.90	0.00	22.50	326,700	75.80
44,016	24	4826	201	13,890		16,972	20.00	34,400	14.90	0.00	23.40	326,200	71.80
44,017	24	4816	201	18,410		34.63	1.70	39,113	75.50	0.00	30.8	323,900	66.60
44,018	24	4762	198	17,250			19.00	40,456	94.10	28.56	14.20	338,400	66.70
44,019	24	4744	198	14,930		92.76	4.30	41,793	42.30	29.51	23.50	350,300	74.10
44,020	24	4753	198	15,270		15,119	3.70	39,338	0.40	27.78	22.30	351,000	73.70
44,021	24	4833	201	12,530		17,329	0.80	36,365	0.60	25.68	32.40	328,300	77.80
44,022	24	4840	202	97.60		15,688	8.00	39,573	10.70	27.94	28.90	325,300	81.20
44,023	24	4843	202	96.30		17,585	5.20	38,254	2.60	27.01	32.00	323,800	81.90
44,024	24	4879	203	11,190		18,328	0.90	43,088		30.42	23.50	348,900	81.40
44,025	13	2591	202	64.10		10,056	6.70	21,769	0.10	15.37	12.50	354,400	78.40
44,026	0		0	0.10	412,400			0.00	0.00	0.00	0.00		0.00
44,027	15	2416	168	11,750	350,500	71.95	53.10	12,044	0.10	8.50	16.00	389,300	47.90
44,028	24	4888	204	11,820		17,990	19.70	35,571	1.70	25.12	22.20	328,200	75.90
44,029	24	4897	204	14,310		16,892	4.60	36,874	1.80	26.04	21.60	333,600	74.70
44,030	24	4894	204	15,000		13,409	40.80	28,934	1.40	20.43	30.10	309,700	64.70
44,031	24	4915	205	12,030		18,193	2.40	37,997	0.60	26.83	35.20	333,000	79.00
44,032	24	4787	199	12,730		16,157	16.20	32,570	0.20	0.00	24.90	303,000	72.30
44,033	24	4918	205	10,880		19,420	1.20	40,076	0.50	0.00	23.40	320,600	80.50
44,034	24	4905	204	10,440		19,639	5.80	41,029		0.00	23.50	326,200	80.70
44,035	24	4914	205	11,540		19,565	1.60	40,332	0.60	0.00	28.80	328,300	79.70
44,036	24	4935	206	10,440		19,953	0.30	43,327		0.00	26.40	332,600	82.10
44,037	24	4943	206	10,920		19,650	0.10	43,647	0.50	0.00	27.40	335,000	81.50
44,038	24	4944	206	11,910		20,163	1.20	40,595		0.00	37.70	334,600	79.60
44,039	24	4870	203	12,590		18,398	9.10	36,074	7.30	0.00	50.70	32,870	76.40
44,040	24	4918	205	10,820		17,792	9.90	33,808	1.90	0.00	54.90	303,300	77.80
44,041	24	4918	205	93.10		19,897	0.30	31,627	0.50	0.00	46.90	287,300	81.50
44,042	24	4918	205	93.10		19,416	10.40	36,047	0.30	0.00	34.10	302,500	81.10
44,043	24	4852	202	89.80		19,787	1.80	38,246	0.10	0.00	53.60	318,300	83.40
Sum	700	4852		353,000	762,900	490,530	27,520	109,1008	26,120		88,190		
Mean	22.55	470,570	194,97	11,387	381,450	16,915	9.17	35,194	1005	10.30	28.44	327,940	76.83

Source: Our own study based on [18].

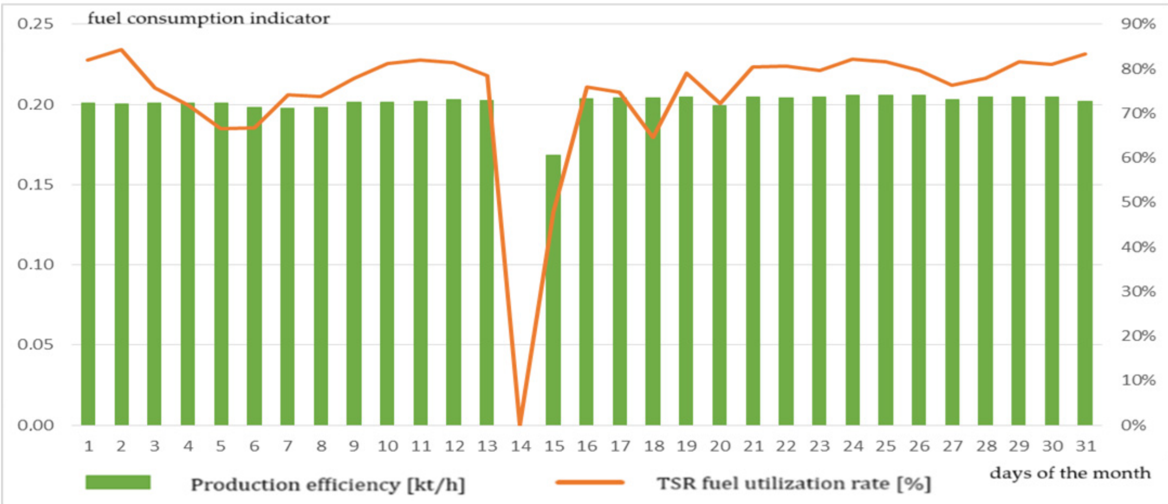

Figure 4. Dependence of the clinker production efficiency on the use of alternative fuels (July 2023). Source: Our own study based on [18].

Figures 3 and 4 show that both the production volume and production efficiency are relatively constant, while the percentage of alternative fuels fed to the furnace is more diverse. The decrease in fuel consumption is particularly noticeable in the periods from 2–7 and 16–18 July. This is because alternative fuel does not have a constant calorific value and when a fraction with a lower calorific value is fed to the furnace, the share of coal is increased to maintain performance at a constant level. However, on other days, the percentage share of alternative fuels remained at a similar level. On 14 July, the furnace was not working. Table 3 shows daily fuel production and consumption in July 2023.

Similarly, measurements were performed in August 2023, the results of which are presented in Figures 5 and 6.

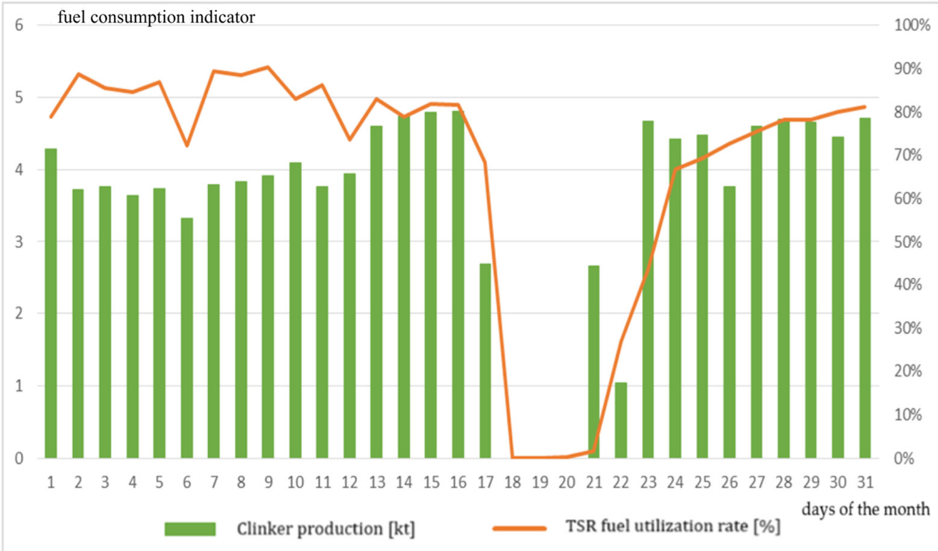

Figure 5. Dependence of the clinker production volume on the use of alternative fuels (August 2023). Source: Our own study based on [18].

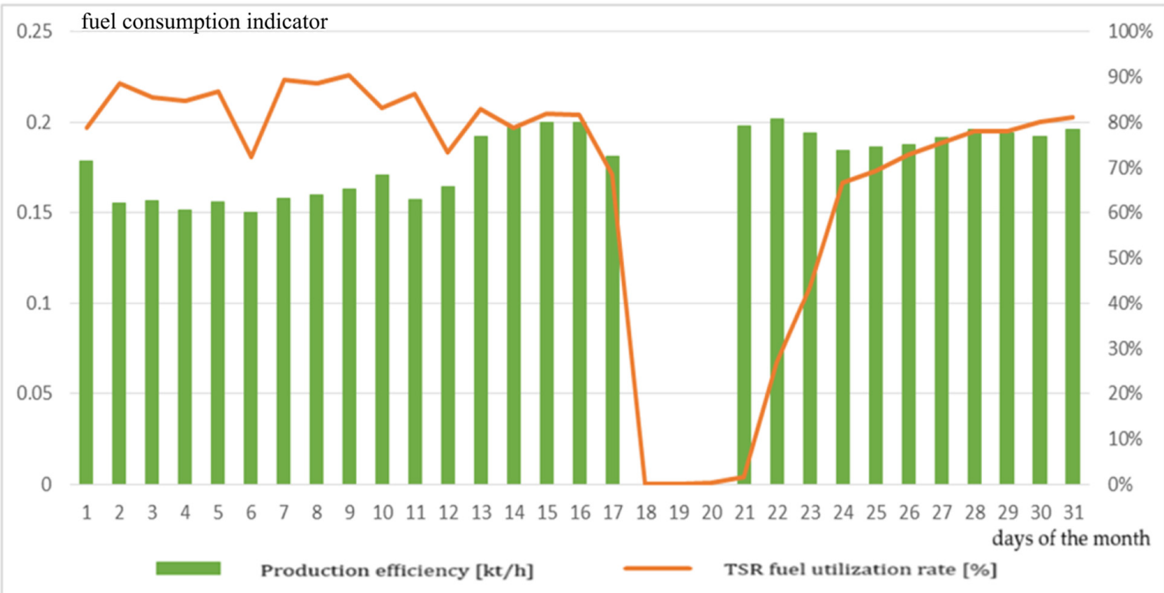

Figure 6. Dependence of the clinker production efficiency on the use of alternative fuels (August 2023). Source: Our own study based on [18].

Figures 5 and 6 show that both the production volume and production efficiency are relatively constant in the period from 2–12 August, but a lower production volume and efficiency can be observed than in the later days of this month, although as the charts show, this is not caused by the supply of alternative fuels. After analyzing the data presented in Figures 5 and 6, there was no decrease in production efficiency when increasing the share of alternative fuels dosed into the furnace. Due to the extensiveness of the work in question, the daily production and consumption of fuels in August 2023, based on which calculations and analyses were made, were not presented.

4.4. CO_2 Capture and Storage or Use (CCSU–Carbon Capture and Storage/Use)

CCS/U technology has the greatest potential when it comes to reducing CO_2 emissions in the cement industry. CCS is a technology for reducing CO_2 emissions from industrial sources by separating and capturing this gas from exhaust gases for storage. One such technology that can be used in the cement industry is post-combustion CO_2 capture, which does not require significant modifications to the furnace system and can be used in both new and existing furnace systems. In this method, CO_2 capture can take place in the chemical absorption process, using the membrane method, or through physical absorption or mineral carbonation. Currently, the most advanced research is on chemical absorption—pilot studies are being conducted in several industrial sectors. These works show that the chemical method is highly effective in removing CO_2 from the exhaust stream. The development of the membrane method depends on whether it is possible to develop high-performance membranes with gas separation efficiency. The mineral carbonation process may be an interesting solution in the cement industry due to the possibility of returning the used sorbent to the cement furnace system as a raw material. The speed of the reaction requires an improvement through the appropriate preparation of the materials used in this method. Work is underway on a modified version of this process, which could take place in the cyclone heater of a rotary cement kiln [18]. Another technology for capturing CO_2 is combustion in oxygen instead. Oxygen is supplied to the air for fuel combustion, which facilitates the separation of the CO_2 stream from the waste gases. Current research results on this technology in terms of its use in industry cement assume a modification consisting of locating the combustion process in oxygen only in the decarbonizer. However, the capture efficiency in this case is lower and is approximately 60–70% compared to the 85–95% efficiency obtained when burning in smoldering throughout the furnace system. In turn, the technology of capturing CO_2 before the combustion process (pre-combustion) has a very limited application in the cement industry because it only covers CO_2 from the fuel, and, as we know, in the production of cement, more CO_2 emissions come from raw materials. The emission of selected pollutant indicators into the atmosphere when using alternative and conventional fuels is presented in Table 4.

Table 4. Emissions of selected pollutants to air, %.

Type Emissions	Emission Measurement Pollution with No Use of Alternative Fuels	Emission Measurement Pollution When Using PASr Fuel
Dust	8.005	2.245
NO_x	172.436	144.298
SO_2	2.686	0.528
CO	88.865	87.949
HCl	3.39	1.430

Source: Our own study based on [18].

The implementation of CO_2 capture on an industrial scale is associated with very high investment and operating costs for cement plants. In 2020–2030, it is possible to launch several projects, which will bring a small global reduction in CO_2 emissions. Only after 2030, can this reduction method be used on a larger scale, but it is estimated that in 2050, it may cover only 10–15% of the global cement production. Transporting and storing large amounts of CO_2 are still unsolved problems, primarily because there is no appropriate, sufficient infrastructure but also due to the high costs and social acceptance [22]. The captured CO_2 would be transported to an underground storage facility and permanently stored in a geological formation. A more preferred solution is to use the captured CO_2 in various chemical reactions, e.g., by reacting with hydrogen, in the production of polymers, or in solvent or methanol synthesis. Research focuses on a comprehensive approach to this reduction method—hydrogen would come from water electrolysis carried out using renewable energy. The second component of electrolysis, oxygen, could be used in the combustion process in a cement kiln. The Skyline project was implemented on an industrial scale in one of the cement plants—waste gases containing CO_2 are passed through a tower with a NaOH solution and the reaction produces sodium bicarbonate. Research projects are also being carried out involving the use of microalgae to capture and manage the CO_2 stream in the photosynthesis process. A significant disadvantage of this technology is the need to provide a large amount of space for the algae farm. A small part of the captured CO_2 can also be used in the food industry. It is currently difficult to predict how the technology for using captured CO_2 will develop on an industrial scale in the future. The use of CCS/CCU technology in the cement industry would, on the one hand, reduce CO_2 emissions but would also result in a significant increase in energy consumption. The key factor will be the very high costs associated with its implementation. Some of the technologies described are still at an early stage of development. The cement industry in Europe supports the concept of an emission reduction target by 2050 and is conducting research toward achieving this target. It is ready to develop and implement technologies such as CCS/CCU in the future. However, the higher the CO_2 emission reduction goals, the more expensive the reduction technologies become. At this stage, much will depend on the extent to which the industry will be supported, mainly through appropriate legal facilities, in its efforts to achieve reduction targets.

Based on the research performed, it was found that burning alternative fuels from biomass, the basic raw material in Poland, significantly reduced production costs. Assuming, for example, the average amount of clinker produced in July 2023, i.e., 141,171 tons, as a constant production volume for all months in 2023, and the loss of 1% TSR bio would involve a cost of almost EUR 138,000 per year, and it would be almost EUR 460,771 million per year in 2024.

To sum up, the implementation of CCS/U technology can reduce the costs for the entire economy resulting from EU ETS fees unless the prices of CO_2 emission allowances are relatively low. In such a case, the benefits of introducing CCS/U technology are achieved by both the cement industry and many other industries, including in particular the construction sector. Beneficial effects also occur for the volume of consumption, investment, and employment. At low prices of emission allowances, savings due to the reduced demand for emission allowances are lower than the costs associated with the operation of CCS/U technology.

4.5. CO_2 Emission Cost Analysis and Trend

Due to the cement production technology used, this industry is a source of greenhouse gas emissions. The share of the cement industry in global greenhouse gas emissions is approximately 3%, which is 1.4 billion tons of CO_2 equivalents. The share of CO_2 emissions from the cement industry accounts for 5% of global CO_2 emissions resulting from human activities. This part of the research indicates possible directions for reducing these emissions [34]. The authors assessed the costs of CO_2 emissions and the resulting liabilities to the EU. The costs of using alternative fuels for the analyzed cement plant were compared and the savings resulting from their use were indicated. The results are shown in Figure 7.

The authors conclude that there are four ways to reduce CO_2 emissions. Firstly, clinker production technology should be developed to reduce energy consumption during production. The proposed solution will reduce it by 40%. Secondly, the cement portfolio should be reduced by replacing clinker with additives. The authors suggest replacing 25–30% of the clinker with ashes, slags, or lime flour [55]. As a result, 4 million tons of CO_2 will be released into the atmosphere. Thirdly, the use of alternative fuels should be increased. The authors' research results allow us to conclude that with the Polish possibilities of a circular economy, it is possible to replace 70% of the heat from fossil fuels with alternative fuels. Fourthly, products with a beneficial impact on the carbon footprint should be introduced, e.g., UHPC concrete, which allows the consumption of building materials to be reduced during the implementation of the investment. The cement industry should reduce CO_2 emissions through the following:

- Improving production processes;
- Improving the efficiency of cement kilns;
- Replacing the energy-intensive wet method with dry and semi-dry methods;
- Modernizing the cement plant to reduce electricity consumption and, consequently, reduce CO_2 emissions from power plants:
- Concentrating on greater production in more efficient plants through the valorization of waste in production processes;
- Using waste as alternative fuels and thus eliminating disposal by storage and combustion in incineration plants, resulting in reduced gas emissions in greenhouses;
- Using waste as a raw material in the production of clinker;
- Optimizing the cement composition;
- Reducing the amount of clinker per ton of cement by using, for example, granulated slags blast furnace, fly ash, natural pozzolana, etc., as cement ingredients, thus reducing CO_2 emissions;
- Improving the quality of products, which increases durability, thus improving the efficiency of cement use;
- Recovering thermal energy from production processes and using it to produce energy electricity that is then used in technological processes, thus reducing electricity production and related CO_2 emissions.

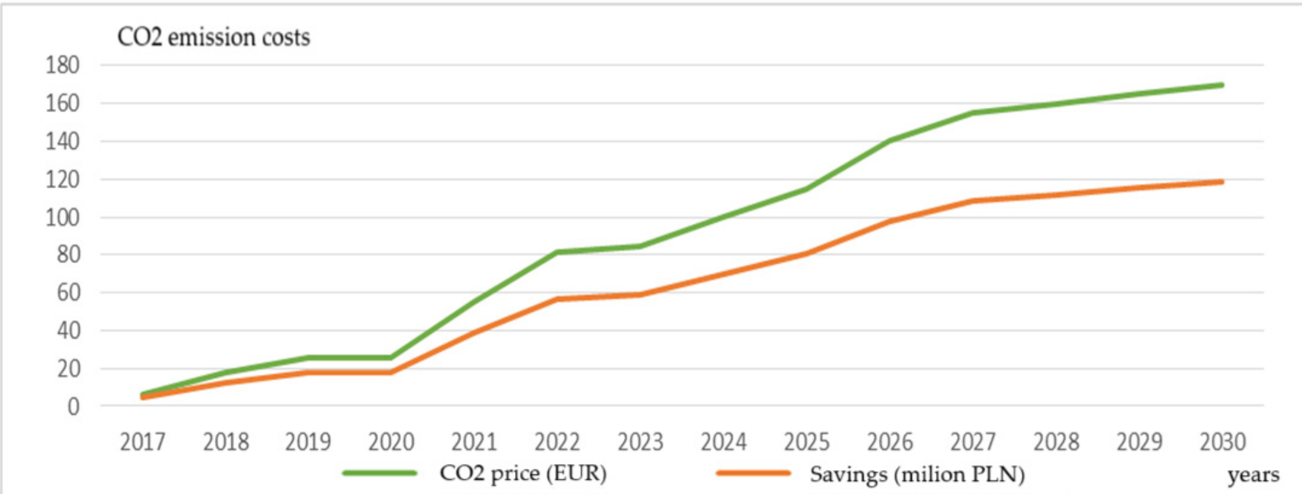

Figure 7. CO_2 emission costs in 2017–2030. Source: Our own study based on [18].

In 2001, CO_2 emissions per 1 ton of clinker were 988 kg. Today, they are 807 kg, i.e., after 23 years we are talking about an 18% reduction in emissions. The allocation will be much lower. It is said to be 680 kg and will decrease by 2% every year. Still, rising electricity prices and rising CO_2 emission costs will impact production costs. Therefore, the large-scale introduction of alternative fuels and CO_2 capture and its management and use are the directions of future work. By 2050, the economy is expected to be CO_2 neutral, and breakthrough technologies will be introduced that are not currently available.

5. Conclusions

The combustion of alternative fuels is becoming more and more popular and will be used more and more widely, due to both the saving of energy resources and the possibility of utilizing the growing mass of waste. The use of substitute fuels not only brings economic benefits but also reduces the emissions of certain gases, which are particularly dangerous for the environment. These concern the reduction in dioxin emissions for certain types of waste. The presented research confirmed that the combustion of substitute fuels can also reduce NOx emissions. This is very important because, unlike sulfur dioxide, reducing nitrogen oxide emissions from the combustion of conventional fuels encounters greater technological difficulties and requires large investment outlays. Combustion tests confirmed the belief that regardless of the nature of the calciner's reducing properties, further effects can be achieved by the co-combustion of substitute fuels. The obtained results require confirmation in subsequent studies and tests using various types of substitute fuels. Co-firing of substitute fuels in existing installations brings significant economic benefits and ecological through the following:

- An increase in revenues due to the lower price of fuels from waste in comparison with fossil fuels;
- A reduction in reported CO_2 emissions (saving CO_2 emission limits granted for a given production sector);
- An increase in the level of waste recovery.

The use of processed waste as an alternative fuel in co-combustion processes reduces the consumption of natural fuels, limiting the amount of waste deposited in landfills, as well as reducing the amount of gas emissions into the atmosphere that would be emitted during the combustion of unprocessed waste in incineration plants. With rising prices of primary fuels, energy obtained from waste is a very attractive alternative for industry, and reducing the amount of waste deposited in local landfills is beneficial to the condition of the environment, which we should keep in good condition for future generations.

In the context of conditions related to waste management in cement plants, it is necessary to pay attention to the following aspects:

- The need to ensure the possibility of obtaining appropriate amounts of ashes for technological purposes from volatile and blast furnace slags. According to estimates, the annual demand for blast furnace slag may range from approx. 2.2 million Mg/year to approx. 3.1 million Mg/year and fly ash from 1.1 to 1.5 million tons (depending on the volume of clinker and cement production).
- When using a 62% heat equivalent from the combustion of solid secondary fuels in 2023, the average content of a biogenic component at the level of a 40% indicator reduction in CO_2 emissions due to the combustion of a mixture of coal dust and secondary fuel was approx. 87 kg CO_2/Mg clinker, which constitutes approx. 10% of the total emissions for firing Portland clinker. In a plant with the most advanced technology of the linearization process using solid secondary fuels in Poland, the use of these fuels is 88.5% equivalent heat and an emission reduction of 124 kg CO_2/Mg clinker is documented, i.e., approx. 14% of the total emissions resulting from the burning of Portland clinker.
- The possibility of obtaining alternative fuels for the needs related to clinker production (RDF) must be ensured in the amount of approx. 1.8 million Mg/year in 2021 to approx. 3.1 million Mg/year in 2050 (the demand for alternative fuels will depend on the volume of clinker production and the share of alternative fuels in the energy balance of the clinker burning process).

Future research directions should include techniques, i.e., technological directions, that could contribute to reducing carbon dioxide emissions from cement plants. These are as follows:

- Removal of carbon dioxide from the system (CCS) through the use of post-combustion techniques (removal of CO_2 after the combustion process—this method is the most popular and often used in industry, especially in power plants powered by fossil fuels);
- Hydrogen technologies;
- Low-temperature heat recovery, e.g., for electricity production;
- Other technologies that are currently being researched (under the "New Energy" program of the National Center for Research and Development).

To sum up, it should be categorically emphasized that the cement sector, not only in Poland but throughout the European Union, requires the cooperation of all market participants, i.e., investors, architects, designers, contractors, and manufacturers of construction products, to be transformed into a low-emission sector. The cement sector is focused not only on production and sales but also on a very wide design area set by standards that determine the use of low-emission products. Therefore, all market participants must understand the idea of decarbonization to change the entire construction industry, which in the European Union, is responsible for 36% of CO_2 emissions. Only then will full transformation and the introduction of a circular economy be possible.

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Abbreviations

AWDF	solid fuel produced from animal waste, mainly from slaughterhouses
CCS/U	carbon capture and storage/usage
PASr	solid fuel produced by grinding waste such as paper, cardboard, foil, plastic packaging, etc., to a granulation of 0–40 mm or 0–70 mm
PASi	solid fuel produced by mixing sawdust or tobacco dust sorbent with waste paints, varnishes, etc.
RDF	solid fuel produced from a flammable fraction of municipal waste, which is briquetting (briquette size: 32 × 32 cm)
BRAM	solid fuel produced from household waste and industrial waste with similar characteristics to those mentioned earlier; this fuel is used in combination with conventional fuel and constitutes approximately 10% of the mixture
INBRE	solid fuel produced from flammable fractions of municipal waste
PAP	liquid fuel produced as a result of the homogenization process of liquid flammable waste, e.g., fuel oils, solvents, paints, etc.
Ppm	parts per million, a unit expressing the concentration of the components of a given substance in a solution
PASr HCV	a high-calorie fraction of alternative fuel used in the Kujawy cement plant from external suppliers (calorific value above 20 MJ/kg)
ZPPA	alternative fuel production plant
TSR	alternative fuel use rate
TSR bio	biomass heat consumption rate

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