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Possibilities of RDF Pyrolysis Products Utilization in the Face of the Energy Crisis

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Abstract: The main goal of the study was to assess the possibility of practical use of products of pyrolysis of refuse-derived fuel (RDF), i.e., pyrolysis gas, biochar and pyrolysis oil, as an alternative to standard fossil fuels. The subject matter of the paper reaches out to the challenges faced by the global economy, not only in the context of the energy crisis, but also in the context of the energy transformation currently beginning in Europe. The increase in fuel and energy prices prompts countries to look for alternative solutions to Russian minerals. At the same time, the growing amount of municipal waste forces the implementation of solutions based on energy recovery (the amount of municipal waste per EU inhabitant in 2021 is 530 kg). One such solution is pyrolysis of RDF, i.e., fuels produced from the over-sieve fraction of municipal waste. In Poland, insufficient processing capacity of thermal waste conversion plants has led to significant surpluses of RDF (1.2 million Mg of undeveloped RDF in Poland in 2021). RDF, due to their high calorific value, can be a valuable energy resource (16–18 MJ/k). This issue is analyzed in this study.

Keywords: RDF; pyrolysis; steel and iron industry; sustainable production; energy crisis

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1. Introduction

The energy crisis that is currently affecting many countries around the world is largely due to the global economy's dependence on non-renewable fossil fuels such as coal, oil and natural gas [1]. Rising energy prices have contributed to the rising inflation, forcing some industrial plants to reduce or even stop production. Energy costs have also slowed down economic growth to such an extent that some countries are now heading for a deep recession. Production in Europe in particular, which consumes large amounts of gas in production processes, has suffered the most. These plants were forced to reduce their output because they could not afford to continue operating.

In addition to the energy crisis, the management of municipal solid waste is currently one of the biggest challenges, especially with regards to the environment [2]. The amount of municipal solid waste is increasing day by day all over the world [3] due to the continuous growth of industrialization, urbanization, consumerism, population growth and other factors [4]. Improper waste management has a negative impact on the environment [5], contributes to an increase in the amount of methane emitted into the atmosphere (which is one of the main factors responsible for global warming), causes deterioration of water quality and soil properties, and adversely affects human health [6]. Literature data show that since 2004 the world's largest producer of municipal solid waste (MSW) is China, which in one year collected six billion tons of unprocessed MSW in about 200 out of the 660 metropolises of the country. Improper management of MSW not only has a negative impact on the environment, but also poses a threat to public health and raises other socio-economic problems. Waste-to-energy (WtE) technologies such as pyrolysis, gasification, incineration and biomethanization [7] can convert MSW into usable energy (electricity and heat) in a safe and environmentally friendly way [8].

The results of literature research clearly prove that pyrolysis of municipal waste is a valuable source of secondary fuels, the wider use of which will contribute to further reducing the amount of landfilled waste, while increasing the diversification of fuel and energy sources in Poland [9,10].

On a national scale, it is not possible to convert all waste into RDF and, consequently, it is not possible to use them to the maximum extent in terms of energy [11]. An alternative to an incineration plant may be pyrolysis and waste gasification technology producing gas, the composition of which depends not only on the conditions of the process, but above all on the type of waste incinerated [12]. At present, the most problematic group of waste in terms of thermal conversion is plastic [13], rubber [14] and textile [14] waste. Spent railroad sleepers are also noteworthy, impregnated with creosote oil containing, among others, anthracene, fluorene, phenanthrene, benzo(a)anthracene and benzo(a)pyrene [15]. In addition to hydrogen, carbon monoxide and a small amount of methane, polycyclic aromatic hydrocarbons (PAHs) (Table 1) are also present in the composition of gas obtained as a result of thermal conversion of waste. The chemical composition of both pyrolysis gas and gas from waste gasification can be highly diverse, which translates into the impact of their combustion on the environment [16].

Table 1. PAH contents in the gaseous product after thermal conversion of municipal solid waste (MSW) and municipal solid waste co-incinerated with coal (MSW/Coal) in µg/g [16].

PAHs	**Process Temperature**									
	500 °C		600 °C		700 °C		800 °C		900 °C	
	Type of thermally converted fuel									
	MSW	MSW/Coal	MSW	MSW/Coal	MSW	MSW/Coal	MSW	MSW/Coal	MSW	MSW/Coal
2-ring	57.3	21.3	184.0	41.2	288.1	44.4	43.42	22.73	400.0	25.2
3-ring	671.8	67.26	1221.6	108.1	4283.7	257.9	5619.3	285.2	3078.9	884.5
4-ring	225.5	5.30	783.8	9.6	4040.6	15.2	1110.2	9.2	2002.3	1132.5
5-ring	14.4	0.52	98.9	0.2	835.4	4.9	100.1	0.1	235.8	70.9
6-ring	3.36	0.06	30.6	0.0	201.2	2.0	0.4	0.1	119.1	37.5
Sum	972.4	94.60	2319.0	159.2	9649.1	324.5	6873.4	317.5	5836.2	2150.8

Due to the energy crisis, many industries, including the iron and steel sectors, are facing economic problems and a loss of competitive advantage [17]. In connection with the above, numerous efforts are being made to increase energy efficiency of the metallurgical industry and thus reduce production costs, through, inter alia, the use of waste energy and alternative fuels (Figure 1) [18,19].

As revealed by literature sources, the iron and steel industries have great potential and opportunities to increase their energy efficiency, reduce carbon dioxide emissions and, as a result, promote sustainable development by replacing conventional fuels used in metallurgical processes with alternative fuels, including biomass (Figure 2) [20].

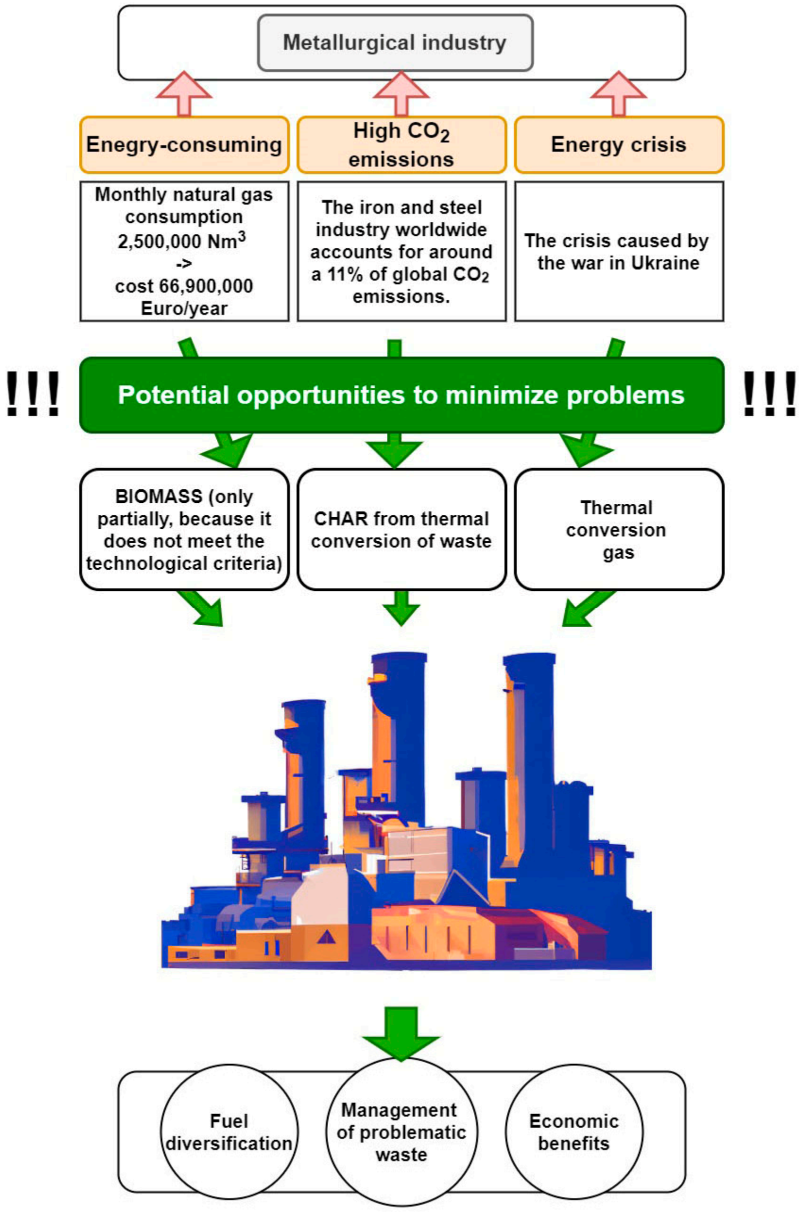

Figure 1. Potential opportunities to improve energy efficiency of the metallurgical industry [20].

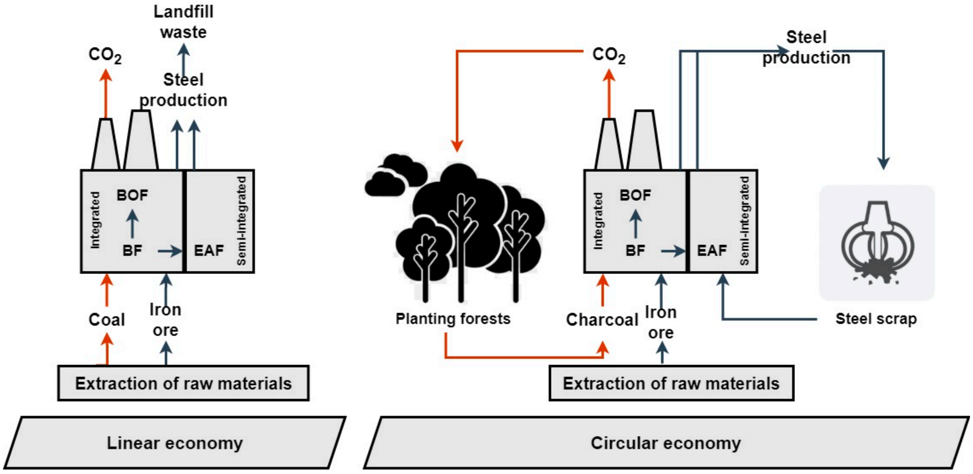

Figure 2. The idea of linear and circular economy in the metallurgical sector [8].

2. Theoretical Background

2.1. Energy Potential of RDF

RDF is a type of alternative fuel produced from MSW. Their calorific value is estimated at about 16–18 MJ/kg [21]. The process of producing RDF consists of separating combustible substances (rubber, paper, plastics, wood, etc.) from the municipal waste stream by sorting [10]. Thanks to pelletization, RDF is characterized by a homogeneous particle size, but the diverse composition of these fuels may cause high variability of their physico-chemical properties. It is worth noting, however, that the Polish waste segregation system primarily uses mechanical-biological waste treatment plants, thanks to which adverse variability of the composition is reduced and a good input material for the production of RDF is obtained. The fraction selectively separated from the solid waste stream is characterized by increased stability of the material composition, and the impact of the waste collection site is negligible (Figure 3) [22,23].

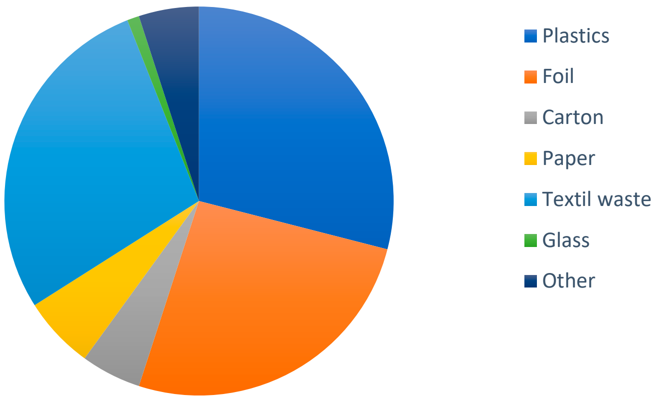

Figure 3. Typical composition of alternative fuels produced from mixed municipal waste in Poland [24].

Research by the authors of the publication [24] showed that the composition of 12 samples of alternative fuels was dominated by combustible components, such as plastics, wood, textiles, paper and cardboard, which together accounted for 94% of the mass of RDF. Other components found in the fuels were non-flammable and their presence negatively affected the calorific value of RDF. Producers and consumers of alternative fuels want the non-flammable fraction to constitute the lowest possible percentage of the fuel mass. This fraction should not be present in the alternative fuel, but often contaminates it as a result of bonding with other waste [24]. For comparison, Figure 4 shows the composition of solid recovered fuel (SRF)/refuse-derived fuel (RDF) in selected European countries. Composition studies were conducted between 2009 and 2019 and the results were averaged for all the countries [25]. Differences in the composition of fuels produced from waste may result from different waste management models in the individual countries. The culture and the ways of disposing of waste can also have an impact, as well as, for example, the way products are packed and the type of material used for this purpose.

2.2. Legal Background of Energy Recovery from RDF

Thanks to the departure in the EU from the linear economy model to the circular economy (CE) and the implementation of the "zero waste" idea, all of the EU countries are striving to stop landfilling municipal waste [26]. Changes in waste management are expected to have a beneficial impact on the economy, the environment and the health of residents of EU countries. One of the main documents introducing changes in waste management is the "Circular Economy Package" (2015), which implements long-term measures to reduce landfilling and to increase the reuse and recycling of waste [27].

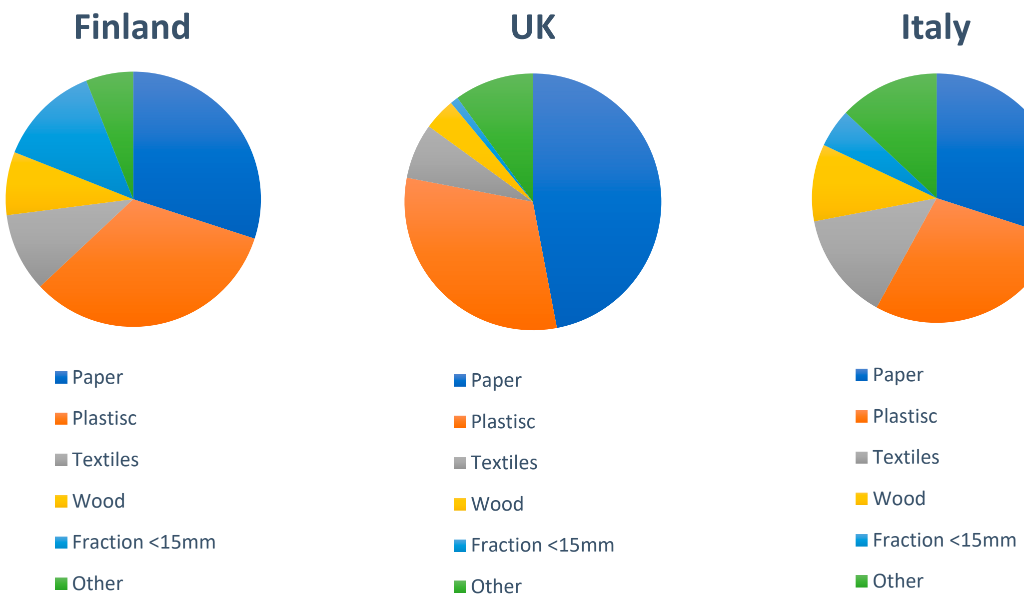

Figure 4. Typical compositions of samples of SRF/RDF commercially produced from municipal solid waste (Finland, UK, Italy) [25].

In Poland, appropriate legislative measures were also taken, convergent with the EU legislation and with the Regulation of the Minister of Economy (in force since 1 January 2016) which prohibit, among other things, the landfilling of high-calorific waste, i.e., waste with a combustion heat above 6 MJ/kg of dry matter (Figure 5) [28]. Although legal solutions to minimize the problem of waste storage have already been introduced and are in force, RDF have not obtained the status of "fuels" yet. These materials are still categorized as waste identified with code "19 12 10". Additionally, until now, neither the EU nor the Polish legislator has clearly defined what parameters RDF should have [29]. The lack of top-down unification of RDF parameters results in great freedom in determining the requirements of various industries or enterprises regarding these fuels. For example, the main clients for RDF (cement plants) approach these requirements very rigorously, setting fuel specifications at a very high level (Table 2).

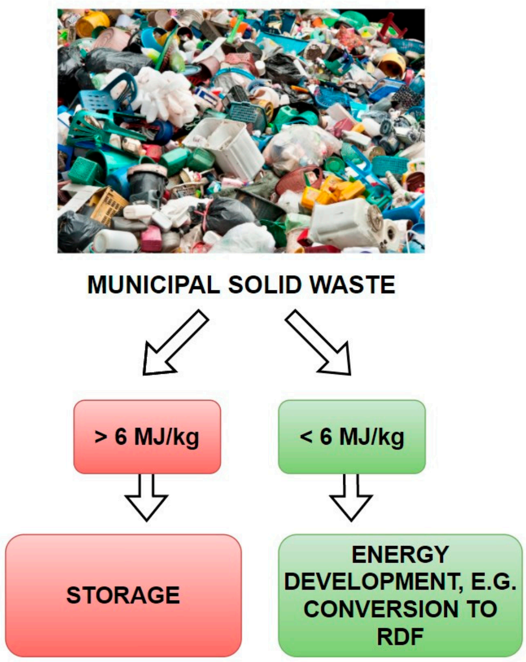

Figure 5. Waste management in terms of calorific value [24,28,29].

Table 2. Required specifications of RDF (19 December 2010), ODRA S.A. cement plant.

Parameters	Units	Acceptable Limits Values
Total moisture content	%	≤18.0
Total sulfur content (operating condition)	%	≤0.5
Chlorine content (dry state)	%	≤0.7
LHV (operating condition)	GJ/Mg	≥20.0

Taking into account the amount of municipal waste produced each year in Poland (about 13.7 million tons, year 2021), the part suitable for thermal conversion accounts for 21.5% (2.7 million tons) (GUS data source). Cement plants burn only about 1 million tons per year (very restrictive calorific value standards > 18–20 MJ/kg), which means that other consumers, for example heating plants, are unable to consume all the fuel that is produced [24]. The constant increase in the amount of municipal waste also causes an increase in the production of fuel from waste. The need to manage the newly created waste fuel may be noticed in the extraction of fossil fuels, which in turn will have an impact on the climate and energy economy [30].

2.3. Processes of Thermal Conversion of Municipal Waste

In order to prioritise environmental concerns, European legislation mandates Member States to adhere to progressively rigorous rules pertaining to waste management and the mitigation of pollutant emissions. The objective of this initiative is to reduce the amount of trash that is disposed in landfills by promoting the utilisation of thermal waste conversion techniques for the recovery of materials and energy [31]. Thermochemical conversion methods like as pyrolysis and gasification have been found to result in reduced emissions of pollutants into the atmosphere as compared to combustion [32]. Moreover, these methods are considered economically feasible for the treatment of municipal or industrial waste. In recent years, there has been a growing recognition of the significance of pyrolysis and gasification techniques in mitigating the environmental consequences associated with combustion processes and the generation of power from waste materials. The employment of these methodologies facilitates significant adaptability in the utilisation of primary resources and also facilitates the acquisition of chemical energy in the shape of hydrocarbon products, alongside electrical power. The widespread adoption of waste-to-energy technology has the potential to reduce reliance on fossil fuels. According to a study conducted in the United States [33], the substitution of 0.4 tons of coal used for electricity production can be achieved by recovering each ton of municipal waste. It is anticipated that the widespread use of these technologies in the United States will result in a significant decrease in coal consumption, estimated to be approximately 100 tons year [33].

The circular economy model incorporates the utilisation of energy derived from trash, resulting in the neutralisation of the energy balance for several waste materials. The utilisation of the latent energy present in waste materials should be harnessed in order to fulfil energy demands, specifically for the generation of heat and electricity. The economic and environmental justification for harnessing the potential of garbage has been documented [34].

It is important to acknowledge that, in accordance with the relevant waste management hierarchy, the process of energy recovery takes precedence above recycling and composting. Hence, it is imperative to take into account the categorization of trash that is neither economically viable or technically unfeasible for recycling and composting (as seen in Figure 6) [26,35,36].

To release energy stored in waste, various methods of thermal conversion are used: incineration, pyrolysis, torrefaction and gasification (Figure 7) [37].

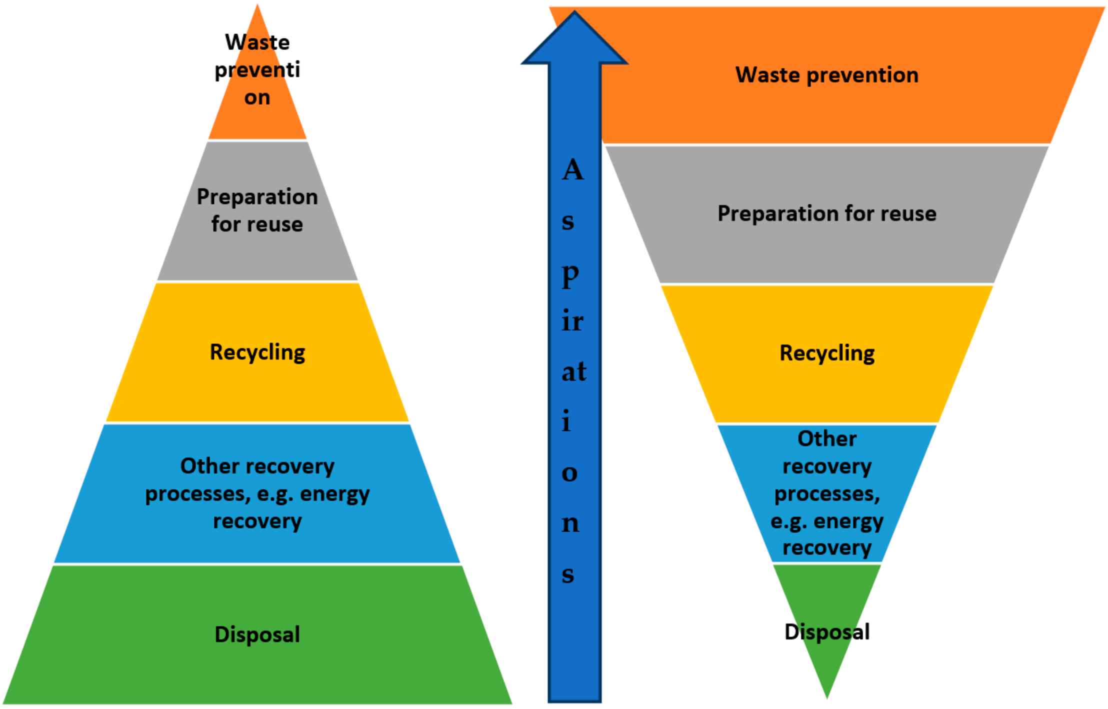

Figure 6. Waste management hierarchy [28].

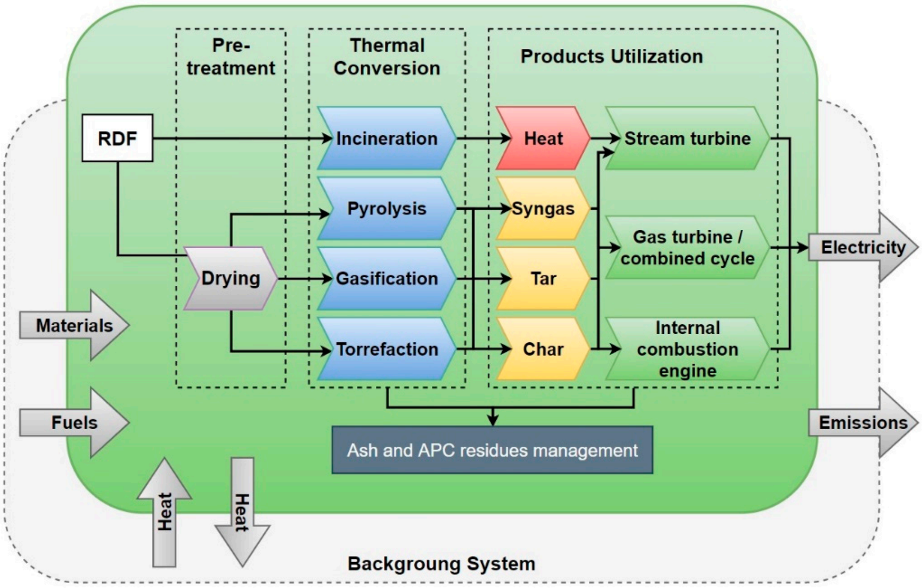

Figure 7. Methods of thermal conversion of waste [38].

The thermal conversion techniques depicted in Figure 7 are employed globally in diverse combined heat and power facilities to generate both electricity and heat [27]. However, it is important to note that each of these processes exhibits variations in parameters, including atmospheric conditions (namely the presence of oxygen), operating temperature, reactor system, and other factors. The assessment of end products and intermediate products is conducted to ascertain their quality. The temperature of a thermal process is mostly influenced by the appropriate design of the plant, the kind of reactor, and the input materials [39,40]. In underdeveloped nations, the practise of pre-treating trash is typically not observed in the context of incineration, as untreated municipal waste is commonly utilised as a primary input. Tables 3–6 in the cited literature [9,41–44] provide a comprehensive analysis and comparison of the various approaches employed for the thermal conversion of waste. Without a doubt, combustion is the prevailing mechanism of thermal conversion [45]. The technique described is well recognised and may be easily initiated and implemented in various regions, thanks to the prevalence of technology and the existence of ubiquitous infrastructure [27]. Nevertheless, combustion has numerous drawbacks in comparison to pyrolysis or gasification techniques [46].

Tables 3–6 present a comparative analysis of the primary benefits and drawbacks associated with pyrolysis and gasification methods, as indicated by reference [47].

Table 3. Comparison of advantages and disadvantages of the pyrolysis process [48–50].

PYROLYSIS	
✓	✗
• The sole thermochemical process capable of producing liquid, solid, and gaseous fractions suitable for immediate utilisation in diverse power plants; • A process with high flexibility, ability to control parameters (temperature, pressure, dwell time) so as to obtain the desired product; • Complete destruction of toxins (furans and dioxins); • The process is suitable for the disposal of many types of plastics and other waste groups; • Environmentally friendly—low NO_X and CO_2 emissions; • Less exhaust gas; • [Higher efficiency of energy recovery from] waste compared to other methods of disposal; • Energy recovery rate of up to 80%.	✗ High initial investment costs; ✗ The need for fuel with a high calorific value is driven by the necessity for processed waste, particularly plastics, to possess a high calorific value in order to ensure the quality of the secondary fuels derived from them; ✗ High water content in liquid oily products; ✗ Technology little known to the "average person", which raises concerns about its use.

Table 4. Comparison of advantages and disadvantages of the gasification process [41,48,49,51].

GASIFICATION	
✓	✗
✓ High energy efficiency of the process and reduction of pollutant emissions; ✓ The resulting syngas is easy to purify compared to flue gas treatment after conventional waste incineration; ✓ Waste gasification technologies using cogeneration systems based on reciprocating engines enable their use in existing waste management systems; ✓ Reduction of waste volume by up to 95%; ✓ The possibility of using the method to manage various groups of waste.	✗ Tar production; ✗ High initial investment costs; ✗ Poor availability of infrastructure with reactors for waste gasification; ✗ Corrosion of metal pipes during reaction; ✗ Higher power consumption; ✗ The amount and composition of syngas from gasification depending on the type of waste, gasifying agent, temperature, pressure and method of gasification.

Table 5. Comparison of the benefits and drawbacks of the torrefaction process [52–54].

TORREFACTION	
✓	✗
✓ Torrefaction products are biochar and torgas, ✓ Torrefied raw material has very low moisture (1–6%), higher calorific value and energy density, better abrasion and more uniform characteristics, lowering waste volume by 30% and keeping up to 90% of the basic energy in biochar., ✓ The possibility of using the method to manage various groups of waste, ✓ Torgas produced can be used to dry torrefied waste/fuel (torgas contains around 10% of the energy present in the initial material), ✓ Financial analyses encourage the construction of heating plants adapted to torrefied RDF combustion, showing high return on investment.	✗ The torrefaction technology has not yet reached commercial status and is still at the stage of research and testing in pilot installations, ✗ High ash content in the fuel, ✗ High initial investment outlays,

Table 6. Comparison of advantages and disadvantages of the combustion process [55–57].

COMBUSTION	
✓	✗
✓ Technology widely known and used on a massive scale, high availability of boilers and infrastructure, ✓ The technological process does not raise objections from society due to its universality, ✓ Combustion reduces up to 90% of the volume of the burned material.	✗ Combustion releases carcinogenic compounds such as dioxins and furans, as well as increases the emissivity of greenhouse gases and other air and atmosphere pollutants., ✗ The need to adapt an expensive exhaust gas treatment system, ✗ The greatest source of low emission is heat production (the combustion of low-quality fuels in boilers). ✗ Combustion wastes resources whose re-use saves more energy and reduces the amount of pollution generated, ✗ High initial investment outlays, ✗ Highly energy-intensive process.

The concept underlying the pyrolysis process is the heat decomposition of organic matter [58], specifically in the case of refuse-derived fuel (RDF), in the absence of oxygen. This process yields gaseous, liquid, and solid byproducts (Figure 8) [59].

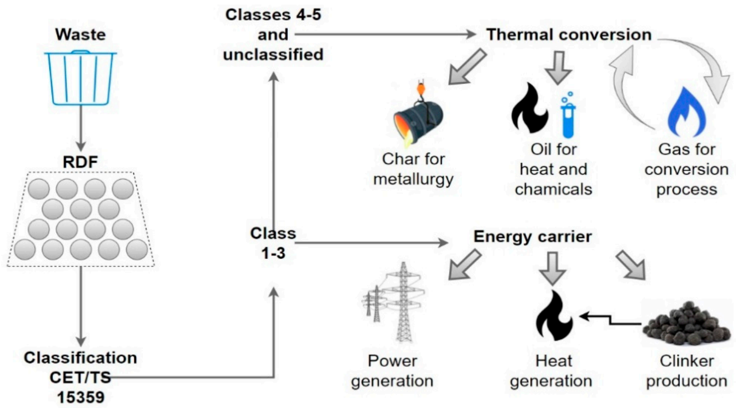

Figure 8. Diagram of the RDF pyrolysis process [60].

3. Possibilities of Using RDF Pyrolysis Products

Today, both Polish and global heavy industry (including the power generation sector) is characterized by high energy intensity, in addition to high pollutant emissions [42]. Given that improving energy efficiency is one of the priorities of the EU's energy policy, particular emphasis is placed on all forms of fuel and energy saving [61]. When it comes to Poland, there are many opportunities to save energy with relatively small financial resources. One solution is to use pyrolysis gas from the thermal conversion of RDF to fire metallurgical furnaces without the need for their pre-treatment, which in the case of polycyclic aromatic hydrocarbons (PAHs) is extremely problematic and expensive [16,62,63].

The issue of management of RDF pyrolysis products deserves attention, as evidenced by the interest of both waste management and metallurgical companies, among others, due to the following [64,65]:

- The possibility of managing the surplus RDF;
- The possibility of managing environmentally harmful plastic waste, such as polyethylene (PE), polypropylene (PP), polyvinyl chloride (PVC), polystyrene (PS) [66], textile and rubber wastes, as well as gaseous products of thermal conversion of these wastes;
- The possibility of reducing the consumption of natural gas for heating furnaces, which will translate into economic benefits [20,67].

The products of RDF pyrolysis are currently used mainly for energy generation purposes (Figure 9) [46].

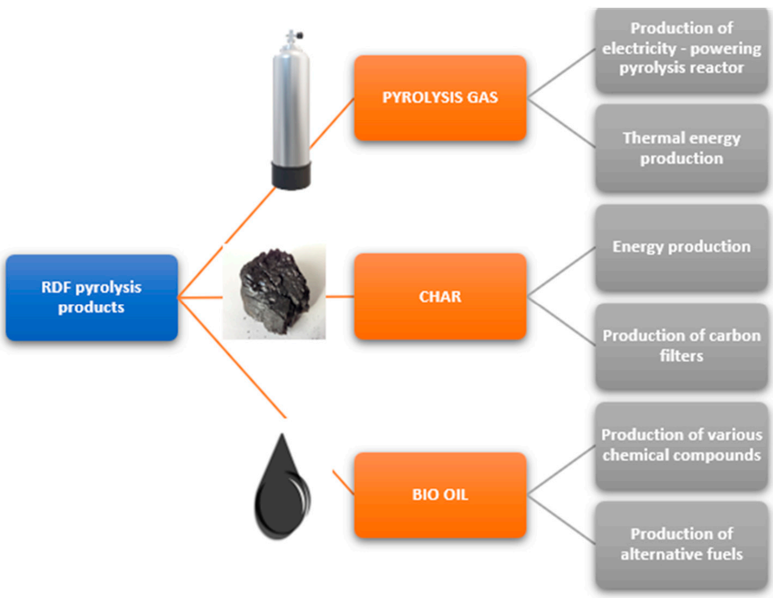

Figure 9. Uses of RDF pyrolysis products [24,24,62,68–70].

The gas fraction produced at higher temperatures, without a catalyst, is characterized by a high calorific value of about 28 MJ/m^3. So high calorific value makes this gas an attractive fuel which can be used not only in industrial boilers, but also in gas engines and turbines, enabling the production of electricity and heat [71]. At the same time, gas obtained after the catalytic process can be used to produce methanol, hydrocarbons, ammonia or liquid fuels by Fischer–Tropsch synthesis. Pyrolysis gas may also be a potential source of hydrogen due to its significant content [72]. This aspect can have a significant impact on the environment, as about 95% of H_2 comes from fossil fuels, and the share of this product in the energy market is increasing due to the growing demand for zero fuel emissions. Therefore, hydrogen obtained in this way can play an important role in the petrochemical, electronic, metallurgical and transportation industries. In addition, mention should be made of the potential use of pyrolysis gas as a fuel in integrated gasification combined cycle (IGCC) boilers, where its environmentally friendly nature could contribute to reducing the cost of gas purging equipment [73,74].

Biochar and pyrolysis oil can be used as energy raw materials or as base substances for the production of various chemicals [75–77]. Oil produced by RDF pyrolysis can be a good base for the production of substances such as styrene, benzene, toluene, xylenes (BTX) and naphthalene derivatives [24,60,69–71]. Biochar, which is a solid carbonized product of thermochemical conversion of municipal waste, is currently a popular alternative to expensive activated carbon due to its properties, especially in adsorption applications [42]. At the same time, this solid product from the pyrolysis of municipal waste can be a valuable fuel due to its relatively high calorific value (18–30 MJ/kg) (Figure 10) [42,78].

Taking into account the calorific values (Figure 10) featured by the individual RDF pyrolysis products, it can be seen that this factor determines their use in the industry [10,74,75]. The energy crisis caused by the armed conflict between Russia and Ukraine, the increase in fuel prices and the diversification of fuel suppliers are very important factors that affect the management of pyrolysis gas, biochar and bio-oil [76].

The products of pyrolysis vary in calorific value and composition due to different parameters [79], including feedstock type, reactor system, gas dwell time, heating rate, exposure time, temperature, pressure ranges, catalyst activity (if any), and the presence of hydrogen gas or hydrogen compounds [80].

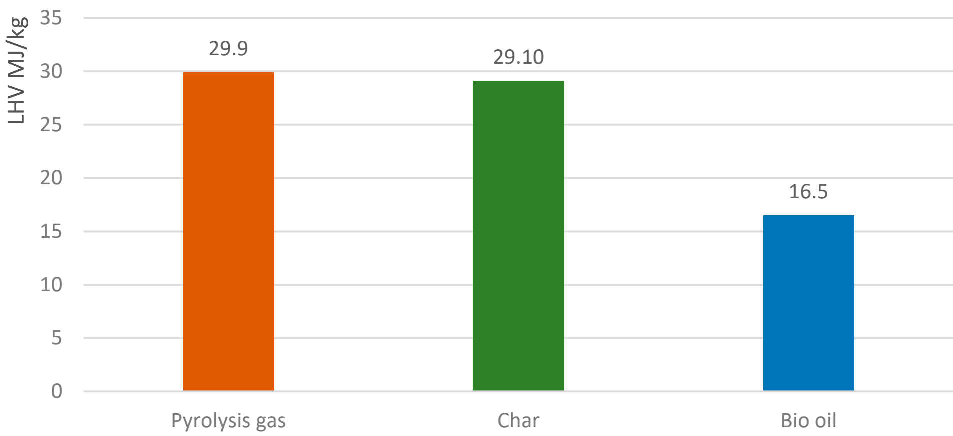

Figure 10. Comparison of calorific values of the individual RDF pyrolysis products [10,81,82].

The metallurgical industry is one of the key industries in developed countries [83]. Iron and steel production plays a key role in the global market economy. The world leader in iron and steel production is China, which supplies more than 50% of all raw materials in the metallurgical industry to the world market [84]. Metal products are the leading industrial material in almost every industry. Steel is of great importance for industry, urbanization and transport [34]. At the same time, the metallurgical industry is one of the most energy-intensive and polluting industries in the world [85]. These problems are met by the idea of a circular economy and the EU's "Green Steel for Europe" program [86], the aim of which is to decarbonize the steel industry [87], improve energy efficiency [88], achieve carbon neutrality and implement sustainability [89,90]. The transformation of the iron and steel industries is a long and complex process (Figure 11) [91]. Each mill has its own specificity of production, which involves individual adaptation of solutions to unique, already operating, process lines [92].

The metallurgical industry is currently intensifying its efforts to reduce CO_2 emissions [93]. At the same time, large-scale research is being carried out to reduce the use of fossil fuels or eliminate them altogether [94].

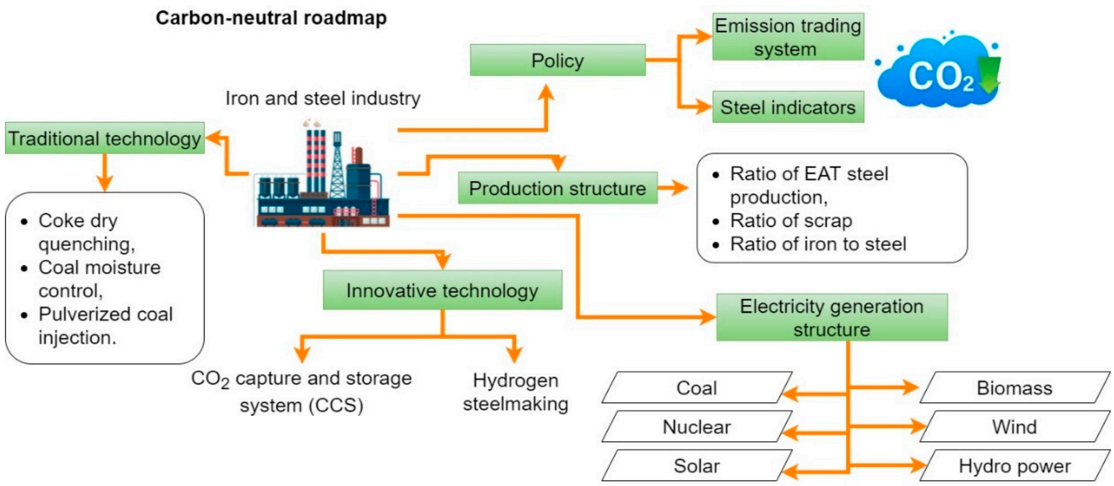

Figure 11. The path to decarbonization of the metallurgical industry [95].

The products of RDF pyrolysis show great potential for substituting conventional fuels. Countries such as Brazil show that it is possible to use biochar in the metallurgical industry. As much as 75% of total production of biochar in these countries goes to the iron and steel industries. In order for biochar to be used in metallurgy, it must meet strictly defined requirements, similar to those that characterize conventional fuels [96].

Biochar can replace conventional fuels in several stages of iron and steel production. Figure 12 shows the potential pathways for biochar to be introduced into the iron and steel production process [43]. Biochar can replace bituminous coal and coke in, among others:

- coke ovens;
- sintering processes;
- blast furnace processes;
- carbonization of liquid steel.

The metallurgical industry, as one of the most energy-intensive industries, consumes huge amounts of gaseous fuels. Just one of the mills operating in Poland consumes 2,500,000 Nm^3 of natural gas per month. The monthly costs incurred by the company are EUR 5,575,000. In 2022, during the deepest energy crisis in recent years, the price of natural gas reached a staggering price of EUR 2.63 (the mean EUR: PLN exchange rate in 2022 was 1:4.68). Steelworks are trying to cut production costs by switching to coke oven gas supplied from coking plants. Unfortunately, the price of this gas has also increased almost 3 times (0.21 EUR). Taking into account the calorific value of gas from the pyrolysis of RDF, which varies from 20 to even 30 MJ/m^3 [10,26,44,97], one can consider the use of pyrolysis gas for pre-heating furnaces before the plastic processing of metals [20]. Figure 13 compares the calorific values of conventional gaseous fuels with those of pyrolysis gas obtained from the pyrolysis of RDF.

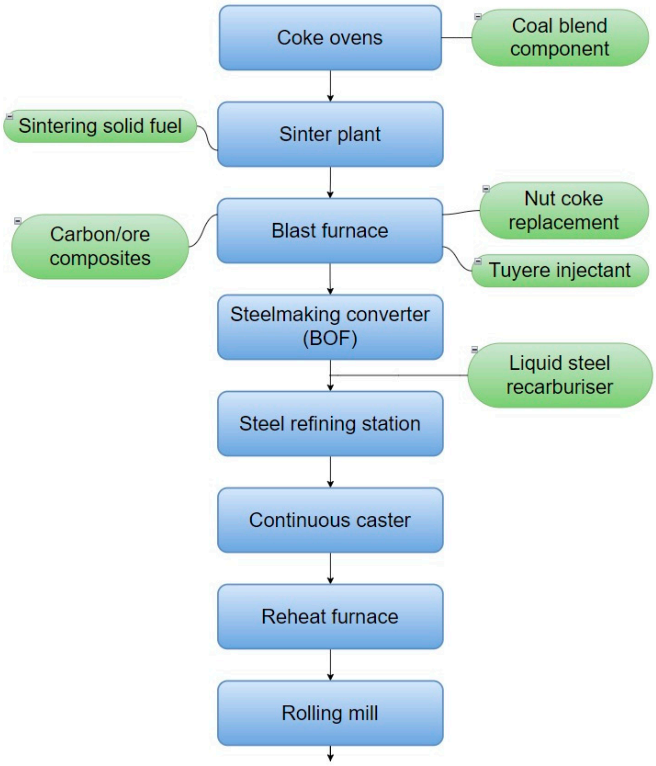

Figure 12. Biochar applications in metallurgy [95].

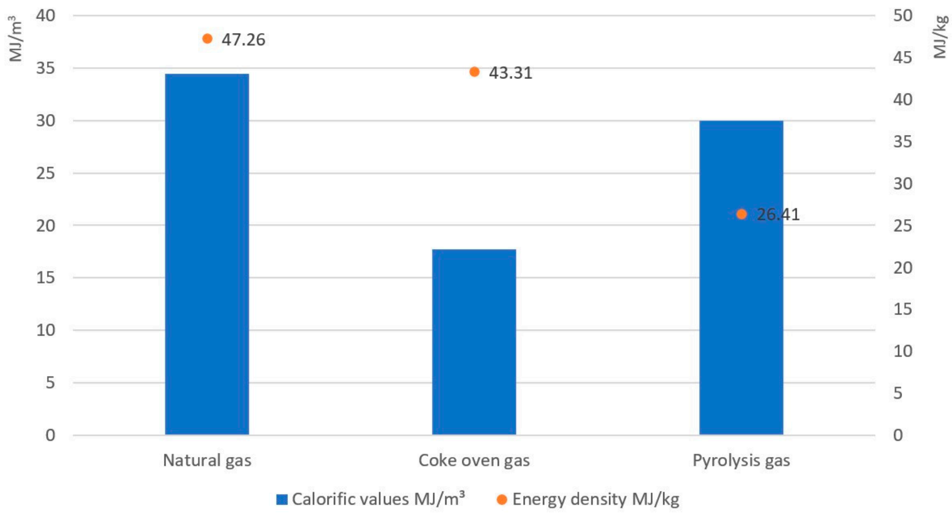

Figure 13. Comparison of the calorific values of conventional gaseous fuels with those of pyrolysis gas [9,10].

According to Szwaja et al. [67], it is possible to use gas obtained from thermal conversion (in this case from the torrefaction of biomass) for energy purposes in the metallurgical industry. The authors [20] proposed a concept of using torgas for firing pusher furnaces in the process of co-combustion with natural and coke-oven gases. The paper has shown that, despite low calorific value of torgas (6 MJ/Nm^3), its energy use offers economic benefits and, additionally, biochar is produced during the process, which can be used at other stages of iron and steel production. The use of gases from the thermal conversion of waste, for example pyrolysis, where the calorific value is much higher than in the case of torgas, may contribute to reducing the consumption of natural gas, which will ultimately allow the diversification of fuel and energy sources, while bringing measurable economic and environmental benefits [20,67].

4. Analysis of Strengths and Weaknesses of Generating Energy from RDF Pyrolysis Products

As suggested by numerous literature sources, the pyrolysis of RDF seems to be a promising solution [9,58]. The management of surplus RDF production has economic, environmental and social benefits. The use of RDF pyrolysis products for energy purposes, like any process, shows not only advantages but also disadvantages [47,98,99]. An analysis of these strengths and weaknesses is presented in Table 7.

Table 7. Strengths and weaknesses of using RDF pyrolysis products as energy sources [47,98,99].

Strengths	Weaknesses
(1) The generation of energy from the pyrolysis products offers environmental benefits: • More waste managed instead of landfilled; • Lower emissions of pollutants compared to conventional combustion; • Reduced production and use of conventional fossil fuels. (2) Pyrolysis is a very flexible process. By controlling the parameters of the process, you can get larger quantities of a more desirable product. (3) Pyrolysis is also suitable for the disposal of various types of waste, which is very beneficial considering diverse morphological compositions of RDF. (4) The pyrolysis plant does not require a large area, which enables integrating it into the existing infrastructure of the steelworks or other plant. (5) The conversion of RDF is in line with the ideas of circular economy. In addition, the products of RDF pyrolysis can be further used for generation of energy, which brings the metallurgical industry closer to carbon neutrality. (6) Continuous and intensive research on the pyrolysis process and the possibilities of managing its products enrich the world of science and bring the economy and industry closer to the introduction of pyrolysis for use on an industrial scale. (7) Finding new applications for pyrolysis products. Proposal to use pyrolysis gas and biochar for energy purposes, reducing the consumption of conventional fuels. (8) Possibility of co-financing investments from domestic sources (the National Fund for Environmental Protection and Water Management may co-finance up to 50% of eligible investment costs—up to PLN 50 million of non-returnable aid). Significant reduction of investment costs, which has a positive effect on the willingness to manage post-process products of the RDF pyrolysis. (9) The calorific values of pyrolysis gas and biochar are sufficient to treat them as attractive alternative fuels that can reduce process costs and bring the steel industry closer to carbon neutrality.	(1) RDF consists of a processed over-sieve fraction from the municipal waste stream. This involves additional processes (grinding, drying, pelletization) that the waste must undergo before it is delivered to the pyrolysis reactor. (2) The chlorine and sulfur contents in RDF, under certain process conditions, may corrode the plant, which may shorten the lifetime of the reactor, which will result in greater expenditures on maintenance. (3) Unknown investment costs: due to the lack of a pyrolysis plant operating on an industrial scale, investment and maintenance, and also profits, are just estimates at this stage, which discourages local governments and investors from building new pyrolysis systems. (4) Insufficient processing capacities of thermal waste disposal plans and lack of investment financing from the EU. (5) Lack of knowledge of the technology by the public, which may result in social reluctance at the stage of consultations or plans for the construction of infrastructure. Public opposition may effectively block or delay the finalization of the investment. (6) Low environmental awareness of the society, which may result in a lack of understanding of the need to obtain new sources of alternative fuels (a perception of no need to build new infrastructure for thermal conversion of waste). (7) Frequent incomprehensible changes in the law, too short time to implement changes, very high environmental standards to meet in a short time—all this gives rise to uncertainty that discourages companies from investing in new, prospective technologies.

5. Summary and Conclusions

The energy transformation taking place in Europe, additionally stimulated by the energy crisis resulting from the geopolitical situation and Russia's military operation against Ukraine, is a platform for the implementation of new solutions and technologies. One such solution is to replace fossil fuels with alternative ones. The use of RDF is in this case an example of a solution that allows for efficient use of industrial and municipal waste, thus reducing the amount of waste deposited in landfills and at the same time reducing the demand for fossil fuels. This approach meets global trends in this area and is in line with the policy of sustainable development. RDF produced from the over-sieve fraction of waste can be used in many industries. The metallurgical industry looks particularly attractive in this case, as it seems to be the most absorbent industry for alternative fuels in the coming years. This is due to both technological conditions, production costs incurred by metallurgical companies, as well as the volume of production and the volume of demand for fuels. The use of biochar or, for example, gases from the thermal conversion of waste makes economic sense in this case [20]. Despite the investment and adaptation costs that the company must incur in the initial phase of technological transformation, in the long run it may bring measurable benefits to the steel industry, which will significantly compensate for the costs incurred. Already a 20% share of energy produced from biochar would give measurable effects in the form of a significant reduction in the relationship between the amount of carbon dioxide from non-renewable fossil fuels and the amount of carbon dioxide from alternative sources. These are arguments for the implementation of new technologies and the use of alternative fuels in the metallurgical industry. Reducing CO_2 emissions will have a positive impact on climate change by limiting the greenhouse effect, which will bring measurable benefits to the entire society [100].

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