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DEVELOPMENT OF TECHNOLOGICAL LINE FOR SOLID RECOVERED FUEL PRODUCTION AND ITS UTILIZATION IN THE CEMENT INDUSTRY: THE CASE STUDY OF LITHUANIA

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This experimental research was purposed to investigate the production and energy potential of solid recovered fuel (SRF), obtained by extraction of prohibited materials, shredding and drying, from refuse-derived fuel (RDF) to use as an alternative fuel in the cement industry of Lithuania. The characteristics of the obtained RDF by separating the biological fraction from the mainstream of municipal solid waste (MSW) have been determined and compared with the criteria set by developing countries. According to EN15359, currently available RDF can't be called SRF and used as an alternative fuel in a cement kiln. The SRF production line by adding six additional technological units to the existing MBT line was developed. The calculation of the SRF production line was carried out and made 1.89 t/h. At the end of the production process of SRF from RDF, the moisture content (MC) of the obtained SRF decreased by 90 %. After the drying stage, the volume of SRF decreased by 19 %. The process of preparing SRF allowed increasing the net calorific value (NCV) by 22.1 % to 28.2 MJ/kg by reducing the MC. The obtained SRF had a high NCV, low MC, permissible Cl and Hg contents. Two scenarios of waste generation in the Alytus region until 2030 have been developed. Based on the waste generation scenarios results, the proposed SRF production line will provide 12 % of the additional fuel for clinker firing during the analyzed period. A cost analysis to assess the economic and environmental savings from the use of SRF was performed. The results showed that adding 12 % of SRF as a replacement fuel, equal to 1.86 t/h, to the coal used in the cement kiln would save 860 USD/h in coal costs. At the same time, it will emit 5.96 t/h of CO_2 into the atmosphere, and the net savings will amount to 1,131 USD/h

Keywords: SRF production, cement industry, RDF, MSW generation, RDF/SRF characteristics

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1. Introduction

Technological progress has allowed humanity to achieve independence from nature and qualitatively improve living conditions. However, most of the seized natural resources are used inefficiently and therefore are returned to the environment in waste. The variety and danger of the generated waste create a threat to the existence of the person himself. The amount of waste generated is growing from year to year, regardless of the population's standard of living. The growth of waste generation and accumulation forces governments to look for ways to solve these problems.

Waste that cannot be recycled is sent to incineration or a landfill, creating another environmental problem. After all, the accumulation of waste at landfills entails negative consequences today and in the future.

In developed and developing countries, the issue of reducing the amount of waste sent to landfills has been partially solved. The non-recyclable part of the waste is sent to the cogeneration power plant (CPP) to obtain heat or energy. However, after incineration of RDF, the bottom and fly ash are obtained, which must also be disposed of. At the same time, using waste as an alternative fuel in the cement industry will solve the current situation with waste and allow it to reach a circular economy. Using SRF as a substitute fuel in the clinker firing can help to reduce the consumption of non-renewable natural resources. A cement kiln is a significant ecological reserve, which can efficiently utilize non-recyclable materials. The uniqueness of the cement kiln lies in the high temperatures (1,200–1,450 °C) at which various types of waste can be burned without changing the quality of the finished clinker and without the formation of additional pollutants.

Therefore, waste disposal through alternative fuel production and using it in a cement kiln during clinker firing has economic and environmental benefits and is an urgent task.

2. Literature review and problem statement

MSW generation has been considered a major environmental problem in many countries, including Lithuania. According to the authors' statement [1], significant growth of urban citizens, improving the quality of life, use of inappropriate technologies and inadequate financing are considered the main challenges facing the waste management systems. Globalization and environmental problems in developing countries have achieved their peak, and solving these problems is a challenge for humanity. The authors' statement [2] focuses on the global problem of waste generation. The fact that MSW generation has increased significantly over the past decade and is steadily growing throughout the world is also evidenced by the data of the European Commission [3]. According to the authors [4], the waste generated is generally viewed as an inevitable by-product of economic activity. The paper states that the wrong choice of method of MSW disposal can become a serious environmental problem, especially when it comes to waste disposal at landfills. The forecasting of waste generation is considered, but issues related to the methods of processing and disposal of waste remain unresolved. However, under the statement [5], there is legislation about waste disposal that has established a hierarchy of available technologies for treating or managing wastes: prevention, minimization, reuse, recycling, energy recovery, and disposal. Landfilling is the last option for utilizing waste, and using it as alternative fuel ranks first. According to the statements, all this allows us to conclude that there is a complex global problem – waste generation.

As shown in [6], the authors approve that the amount of waste available for energy recovery is much more significant than unsorted residual waste and argue that a better type of utilization is recycling materials and producing energy. It is claimed that there are materials recycling and collection technologies, which enhance the quality and quantity of recycled materials [7]. It can be assumed that waste and biomass materials can be used as sustainable renewable energy resources. Precisely this step will enable companies to save money, reduce greenhouse gas emissions, and decrease the consumption of non-renewable natural resources [8]. In [9], the focuses are that the disposal of MSW at landfills leads to landfill gas emissions and leachate formation. The prerequisites for creating alternative fuel from waste containing a biological fraction are stated. The authors propose to use RDF with a high content of organic fraction as an alternative fuel in a cement kiln. This paper does not consider the extraction process of the biological part of the waste from the main MSW stream since this fraction has the most significant adverse effect on the operation of the cement kiln and the quality of the finished clinker.

As it is shown in [10], in recent years, interest in burning the high-calorific fraction to obtain electricity has arisen in many countries worldwide. The reasons considered by the authors explain the increased interest in waste incineration for energy: depletion of natural resources, increased waste generated lack of landfill space, reduced greenhouse gases emissions, and reduced dependence on imported energy sources. However, there is no emphasis on what difficulties an enterprise may face when using waste as an alternative fuel. Such problems are considered in [11]: energy consumption, high product quality standards, and environmental concerns (reducing greenhouse gas emissions). The burning of fossil fuels is the leading cause of anthropogenic CO_2 emissions. According to the statement [12], the cement industry is a leader in consuming natural resources and the emission of gaseous substances into the atmosphere. A considerable amount of energy consumption and greenhouse gas emissions is described in the paper [13]. The work shows that about 0.8 tons of carbon dioxide are emitted into the atmosphere during one ton of cement production. The indicator of emitted CO_2 depends on the technology of clinker production, fuel, and cement produced. Depleting natural resources and rising fuel prices pushing cement plants to use alternative fuels during clinker firing are the main problems considered in the work.

The production and use of SRF in the cement industry as a replacement fuel can reduce greenhouse gas emissions compared to fossil fuel emissions, as described in [14]. The authors experimentally found that SRF is mainly (about 60 %) composed of paper, textiles, and wood – biogenic materials; the rest of SRF contains mixed plastics. In [15], it was checked that co-firing SRF with fossil fuels can bring economic and environmental benefits in reduced fossil fuel consumption and CO_2 emissions. According to the statement [16], every 5–10 % decrease in the cement production carbon dioxide intensity by 2050 could reduce emissions by around $0.4 \cdot 10^9$ t CO_2 and contribute to slowing climate change and global warming. According to this statement, when SRF is burned in a cement kiln, there is no by-product in the form of ash and harmful emissions – but experiences of European countries are not shown. However, the work [17] reviewed experiences of European countries showing that the use of fuel from waste for the cement industry can save companies a lot of money, provide controlled waste disposal, and reduce the consumption of non-renewable natural resources. However, issues related to the production of SRF from RDF by creating a production line remained unresolved.

Based on the analysis of the existing waste generation problem and disposal methods, the following can be determined. Notwithstanding that the topic of SRF production and use in the cement industry is sufficiently studied and relevant, but it is not used in Lithuania from a practical point of view. Issues related to fuel treatment and production processes remained unresolved. If resolved, high-quality fuel will be obtained, which can be used as an alternative fuel during clinker firing. Environmental and economic benefits will be achieved, such as reduced consumption of non-renewable solid fuels, savings in imports of solid fuels, reducing greenhouse gas emissions and less waste sent to CPP and landfills.

3. The aim and objectives of the study

The aim of the study was to investigate the potential for SRF production from RDF and use it in the clinker firing as a replacement fuel for the Lithuania cement plant by using the extraction of prohibited materials, shredding and drying process so that the prepared fuel complies with the European standard. Using the SRF production process as an alternative fuel in the clinker firing is still a comparatively new and topical direction but is practically not used in full. This will make it possible to use the SRF production process as an alternative fuel in the clinker firing.

To achieve this aim, the following objectives are accomplished:

– to determine the main characteristics of RDF and SRF and to prove that the ash obtained after the incineration of SRF contains crystalline phases;

– to develop an SRF production line, which will be supposed to produce an alternative fuel for a cement plant, taking into account the operation of the existing CPP;

– to develop two scenarios of MSW generation until 2030;

– to investigate the economic and environmental feasibility of production and utilization of SRF in the cement industry.

4. Materials and methods

4. 1. The research area

The research area is the Alytus mechanical-biological treatment (MBT) plant, located in Alytus city and cement plant of Lithuania. Scenarios of waste generation were developed based on the data from waste generation reports in the Alytus region. An SRF production line was developed based on the literature data and taking into account the technological and apparatus capabilities of the Alytus MBT plant. During two seasons, 2020–2021, morphological and granulometric studies of the RDF fraction were carried out on the territory of the Alytus MBT plant. Preparation of samples for the analysis and detection of the parameters of the analyzed materials was conducted within the laboratories of the Lithuanian Energy Institute.

4. 2. RDF and SRF testing

According to [18], RDF is a non-defined term and refers to waste that has not undergone proper processing. RDF is mainly incinerated to obtain heat or energy. SRF is a fuel produced from non-hazardous waste following EU standards. SRF is sampled and tested according to EU standards. Only fuels produced following EN15359 may be referred to as "SRF". The characteristics of RDF and SRF were determined to prove that SRF has better quality than RDF in accordance with:

– granulometric composition – CEN/TS 15415:2006;

– moisture content (MC) – EN 15414-3:2011;

– volatile matter (VM) – EN 15402:2011;

– ash content (AC) – EN 15403:2011;

– chlorine content (Cl) – EN 15408:2011;

– mercury content (Hg) – LST EN 16175-1:2016;

– net calorific value (NCV) – EN 15400:2011;

– SEM-EDS analysis of ash – was performed on ZEISS EVO MA10 microscope at an accelerating voltage of 20 kV. Bruker AXSX Flash 6/10 detector can display all the elements present in the specimen at an overall accuracy of about 1 % and detection sensitivity down to 0.1 % by weight;

– Crystalline phase analysis of ash after incineration of SRF was carried out on Bruker D8 Advance diffractometer with CuKα radiation at 40 kV in 2Θ (5°÷70°) interval at a scanning step of 0.02°.

4. 3. Development of SRF production line

Taking into account the technological process, equipment at the Alytus MBT plant and based on the literature data, a technological line for the production of SRF was developed. The SRF production line has six additional units of equipment. Each piece of equipment has an essential role in preparing SRF from RDF.

To not disrupt the operation of the Kaunas CPP, the amount of waste for the cement plant should be about half of the waste incinerated at the Kaunas CPP. For the calculation of the flow rates of the SRF production line, eq. (1)–(5) are used:

$$SRF_{FR}=RDF_P-Z_1-Z_2-Z_3-A_{MC}, \tag{1}$$

$$Z_1=(RDF_P\cdot x)/100\ \%, \tag{2}$$

$$Z_2=[(RDF_P-Z_1)\cdot y]/100\ \%, \tag{3}$$

$$Z_3=[(RDF_P-Z_2)\cdot q]/100\ \%, \tag{4}$$

$$A_{MC}=[(RDF_P-Z_3)\cdot MC_L]/100\ \%, \tag{5}$$

where SRF_{FR} – flow rate of the SRF production line (t/h); RDF_P – flow rate of some part of incinerated waste (2.7 t/h); Z_1, Z_2, Z_3 – flow rate of produced RDF after extraction of materials (inert, ferrous, non-ferrous metal) (t/h); x, y, q – amount of extracted materials on each stage of separation (%), MC_L – amount of moisture lost (%), A_{MC} – flow rate of RDF after moisture loss (t/h).

The fractional composition of RDF was used to calculate the percentage of materials in SRF. To comply with the requirements, during treatment, RDF loses fine fractions, metals and some part of moisture. Calculations were done as follows, Eq. (6), (7):

$$SRF_{fr}=C\cdot RDF_{fr}, \tag{6}$$

where SRF_{fr} – amount of SRF materials produced from RDF (%); C – conversion ratio; RDF_{fr} – amount of each material in the composition of RDF: plastic, paper, textile, and other (%). The conversion ratio can be calculated by using eq. (10):

$$C=(100\ \%-MC_{RDF})/\Sigma RDF_{fr}, \tag{7}$$

where MC_{RDF} – moisture content of RDF (%).

4. 4. Forecasting MSW generated

As previously mentioned, scenarios of waste generation were developed based on the data from waste generation reports in the Alytus region. In Scenario I, the very rapid growth of waste generation is projected per capita in 2030. These data will be very rough estimates, as they do not include many other essential factors. For the calculation of waste generation by Scenario I, eq. (8) was used:

$$WG=WG_{pr.year}+1/4\times GDP_{prog}, \tag{8}$$

where WG – municipal waste generation (t); $WG_{pr.year}$ – municipal waste generation in the previous year (t); 1/4 – increase in GDP value; GDP_{prog} – gross domestic product.

The obtained data will be very rough estimates, as they do not include many other essential factors.

In the development of Scenario II in which the average level of MSW generation in Lithuania will remain at the current level until 2030, the amount of waste generated was calculated using eq. (9)

$$WG = WG_{pr.year} + 1/9 \times GDP_{prog}. \quad (9)$$

The total amount of RDF generation for both scenarios was calculated using eq. (10):

$$RDF_{gen} = (MSW_{gen} \times 31\,\%)/100\,\%, \quad (10)$$

where RDF_{gen} – amount of RDF generated (t);
MSW_{gen} – amount of MSW generated (t);
31 % – amount of MSW sent to the CPP.

4. 5. Environment and economic benefits

To investigate economic and environmental feasibilities associated with the production of SRF for use as an alternative fuel during clinker firing ("Akmenes cementas", Lithuania), a visit was conducted to the cement plant to obtain the necessary information. As a result, a calculation was proposed, according to which it is suggested to use 12 % of SRF as a replacement for the main fuel (coal) that is used at the cement plant in Lithuania today. The proposed calculation option is based on literature, actual data and data obtained from the cement plant. In the course of the calculation, an assessment was made of the volume of replacement of SRF, the cost savings for the purchase of the main fuel (coal), the savings in greenhouse gas emissions and net cost saving.

5. Results of research on the quantity and quality of SRF produced for the cement industry as an alternative fuel

5. 1. Characteristics of RDF and SRF

The RDF that was obtained after the separation of MSW generally is larger than 80 mm in size, it is obtained by sieving and followed by recycling the plastic, metal, paper and derived materials. The RDF composition formed after the separation of MSW at the Alytus MBT plant is given in Table 1. The table presents the results (average values) obtained during the study period.

Table 1

Relative proportion of materials after mechanical-biological (MB) separation

Fractions	After separation input (%)
Soft plastic	33.55
Hard plastic	3.09
Multilayer	2.761
Polystyrene	0.752
Textile	39.62
Diapers	2.513
Paper	13.4
Wood	1.984
Metal	0.926
Fine fraction (d<20 mm)	1.455
Total	100

After extracting the biological fraction from MSW by mechanical separation, RDF was obtained. At first, the granulometric composition of RDF was determined. Based on the results of the measurements, the granulometric composition of RDF was calculated (Fig. 1).

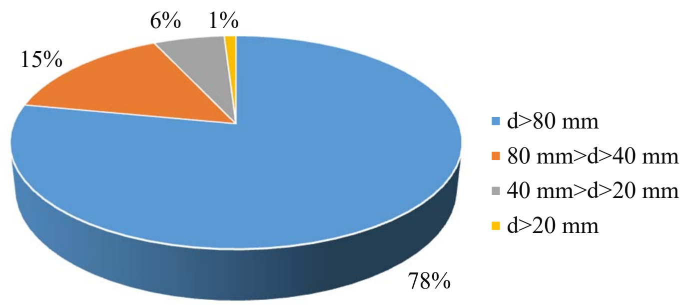


Fig. 1. Granulometric composition of the obtained RDF

The results presented show that the analyzed material is dominated by a fraction with a size d>80 mm and reaches 78 %. The remaining 22 % are a fraction of 80 mm>d>40 mm – 15 %; fraction size 40 mm>d>20 mm – 6 %, and a fraction with a size of d<20 mm – 1 %.

After carrying out morphological and granulometric analysis and preparing the SRF composition (extraction of prohibited materials, shredding, drying), the main characteristics of RDF and SRF were determined. Table 2 presents the main characteristics of RDF and SRF.

Table 2

Characteristics of RDF and SRF fractions

Composition of RDF/SRF (%)		
Fraction	Annual average	
	RDF	SRF
Plastic (%)	40.41	29.1
Paper (%)	13.48	9.7
Textile (%)	41.15	29.6
Wood (%)	2.01	1.4
Metal (%)	1.07	–
Glass (%)	0.4	–
Fine fraction (%)	1.47	–
Total	100	70
Moisture content (%)	30.06	3
Ash content (%)	7.1	4.7
Volatile matter (%)	76	88
Chlorine content (%)	0.14	0.09
Mercury content (mg/kg^{-1})	0.04	0.02
Net calorific value, MJ/kg	22.0	28.2

RDF was shredded in an SM 300 mill to obtain SRF. Fig. 2 presents SRF produced from RDF.

Fig. 2. SRF produced from RDF

According to the data presented in Table 2, the MC of RDF is high enough for RDF to be considered as a fuel. The main factors for common humidity are the season and the materials of which RDF consists.

By selecting alternative fuels for use in the cement industry, the most important criteria are the percentage of MC and NCV. The MC of SRF produced from RDF is within acceptable limits – 3 % to consider SRF as an alternative fuel by clinker firing. The MC significantly reduces the NCV of the fuel and it can be seen in Table 2. The NCV was determined in an IKA C6000 automatic bomb calorimeter in adiabatic mode. The NCV was determined in two test sub-samples. The sample is tested in a pellet form. The prepared sample was being pressed with a hydraulic press at a force of about 10 tons having a diameter of about 13 mm and a mass of (1.0±0.2) g.

The VM value of SRF is higher than in RDF and constitutes 88 % and 76 %, respectively. This difference can be explained that shredded materials have better flame stability and improved carbon burnout.

The NCV of RDF was on average 22.0 MJ/kg. Due to high MC (30 %), RDF can be used only to produce heat or energy at the CPP. Pretreated and prepared SRF has a lower value of MC (3 %) and respectively higher NCV (28.2 MJ/kg) and can be used as a replacement fuel in the cement industry.

The main problem that arises from the use of SRF by cement kilns is the chlorine content. The chlorine compounds and alkaline metals during carbonization create salts. These salts create micro-cracks in the concrete and the compressive strength decreases [19]. Cl_{RDF}=0.14 % to Cl_{SRF}=0.09 %; Hg_{RDF}=0.04 mg/kg^{-1} to Hg_{SRF}=0.02 mg/kg^{-1}.

The data obtained shows that SRF produced from RDF has higher characteristics and better quality and can be used as an alternative fuel in clinker firing. SRF characteristics obtained during experiments correspond to the European standard.

Elemental oxide analysis based on SEM/EDS measurements, which is presented in Table 3, confirms that the oxide composition of SRF corresponds to the oxide composition of the clinker [20].

From the available data, the dominating elements are Si and Ca, which are one of the main in clinker production. Also, Al, Fe, Mg and others are presented, which play an important role in the cement industry.

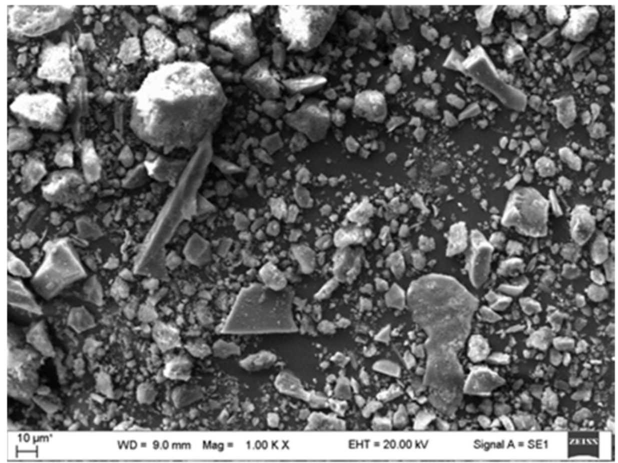
Table 3

Elemental oxide analysis based on SEM/EDS measurements

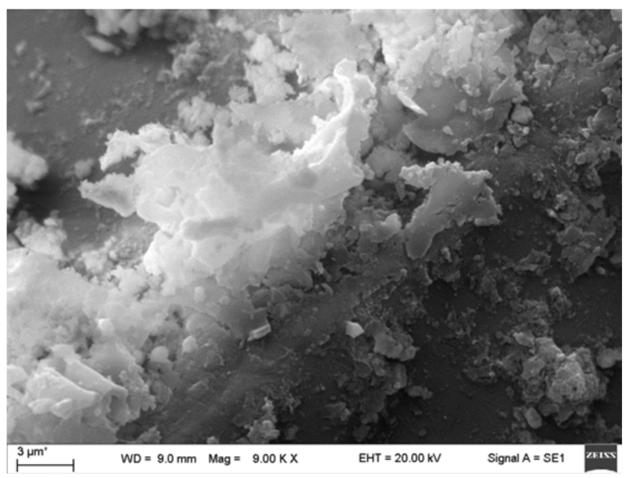
Oxide	SRF, %	Clinker, %	Oxide	SRF, %	Clinker, %
CaO	32.40	66.6	SO_3	1.29	1.0
Fe_2O_3	8.84	2.8	MgO	3.22	1.0
SiO_2	35.66	21.5	Na_2O	4.46	0.2
P_2O_5	1.09	0.2	TiO_2	2.4	0.2
Al_2O_3	9.06	5.2	K_2O	0.56	0.6

However, it should be noted that the percentage amount of SRF and clinker oxides [20] are different. By technological calculations and experimentally, the permissible rate of replacement fuel is determined. There are some oxides, which amount must be strongly controlled. For example, the percentage amount of Al_2O_3 and Fe_2O_3 oxides should not exceed 5–7 %. Increasing the percentage of these oxides creates a fluidity of molten oxides and accelerates the passage of the material in the kiln, which ultimately leads to a deterioration in the quality of the finished clinker. The content of Na_2O and P_2O_5 oxides must also be controlled since they affect the early setting time.

The clinker obtained by sintering is a complex, fine-grained mixture of many crystalline phases and a small amount of a glassy phase in terms of microstructure. SEM-EDS analysis of SRF confirms the presence of crystalline phases (Fig. 3).



a



b

Fig. 3. SEM image of SRF ash: *a* – magnification 1.00 KX; *b* – magnification 9.00 KX

This fact was also confirmed by the performed X-ray diffraction (XRD) analysis (Fig. 4). For the determination of the crystallographic structure of SRF and sewage sludge, XRD analysis was used.

Today, clinker firing uses 5 % of sewage sludge as an alternative fuel supplied from Lithuanian sewage treatment plants. According to the data obtained from the Lithuanian cement company, the addition of 25 % alternative fuel will not lead to a deterioration in the quality of the clinker obtained. However, using a replacement ratio of 30 % leads to a deterioration in the quality of the clinker.

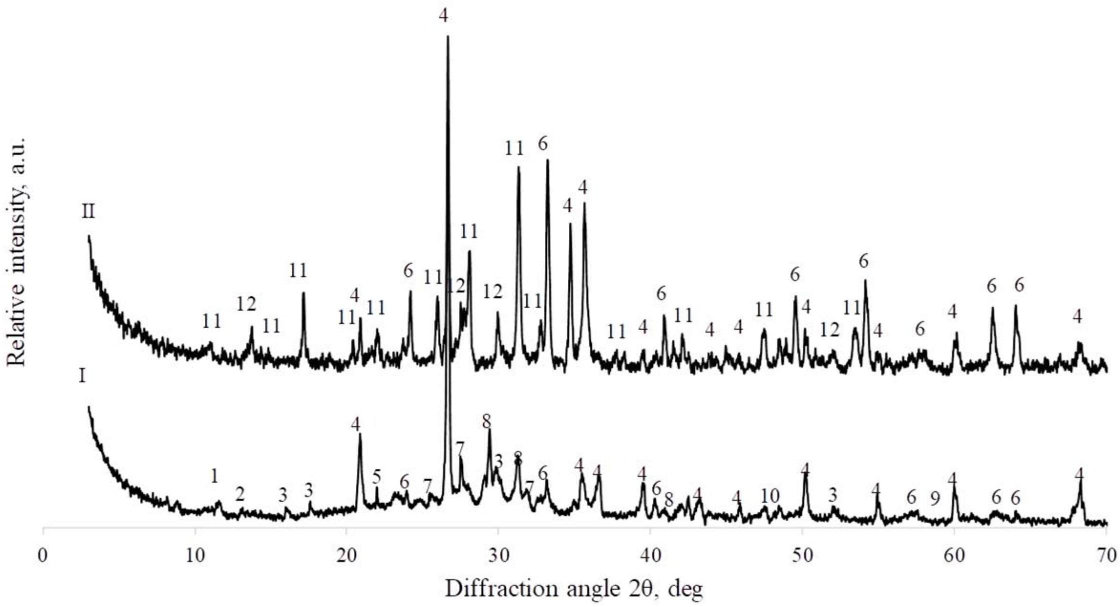


Fig. 4. X-ray diffraction pattern of ash after incineration of SRF (I) and sewage sludge from the wastewater treatment plant (II): 1 – brushite; 2 – albite; 3 – akermanite; 4 – quartz; 5 – cristobalite; 6 – iron oxide; 7 – microcline; 8 – monetite; 9 – perovskite; 10 – calcite; 11 – whitlockite; 12 – monalbite

X-ray patterns presented in Fig. 4 showed that the main minerals are:

– brushite ($CaPO_3(OH)_2H_2O$);
– albite ($Na(AlSi_3O_8)$);
– akermanite ($(Ca_{1.53}Na_{.51})(Mg_{0.39}Al_{0.41}Fe_{0.16})(Si_2O_7)$);
– quartz (SiO_2);
– cristobalite (SiO_2);
– iron oxide (Fe_2O_3);
– microcline ($KAlSi_3O_8$);
– monetite ($CaHPO_4$);
– perovskite ($CaTiO_3$);
– calcite ($Ca(CO_3)$);
– whitlockite ($Ca_{18.53}Fe_4Mg_{1.6}(PO_4)_{14}$);
– monalbite ($NaAlSi_3O_8$).

It can also be observed that the intensity of the SRF and sewage sludge peaks are different. Crystalline minerals found in the ash of SRF and sewage sludge using XRD analysis are cement-forming and play an essential role in determining the quality of the finished clinker. For example, brushite for the cement clinker has been recognized for its fast setting but brittleness and low strength. Albite is a framework silicate of the plagioclase feldspar family and plays the role of aggregates. Quartz and cristobalite are minerals, which play the leading role in clinker formation.

The performed SEM-EDS analysis, photo presented in Fig. 3 and X-ray diffraction pattern in Fig. 4 show that the ash of SRF contains crystalline calcium-bearing, sodium-bearing, potassium-bearing, iron-bearing and silicon-bearing phases. The presence of the crystalline phase in materials is favorable in clinker production. The fact that SRF can be used as an alternative fuel by clinker firing is also confirmed by some studies. According to [17], it was found that the use of SRF as a replacement fuel in an amount of 30 % will not lead to a change in the quality of the finished clinker.

For the replacement of the main fuel (coal) with the alternative to be effective, the following conditions must be met: the calorific value of SRF must correspond to the calorific value of coal, the chemical and phase composition must conform to the composition of the finished clinker. Table 4 presents the calorific value of fuels, which can be used for clinker firing.

Table 4

Calorific value of fuels

Fuel	Calorific value, MJ/kg	Fuel	Calorific value, MJ/kg
Coal	31.0	Fuel oil	41.0
Petroleum coke	33.5	Bituminous coal	29.7
Natural gas	34.7	Diesel fuel	40

In turn, such a replacement will reduce the consumption of the main fuel (coal) since the SRF that was produced has a sufficiently high NCV=28.2 MJ/kg to be used as an alternative fuel.

5. 2. Development and calculation of SRF production line

About 35,000 t/year of residual mixed municipal waste are treated at mechanical sorting and biological treatment plants. Fig. 5 presents the SRF production line, which was developed according to the waste stream at the Alytus MBT plant.

The SRF production line has six additional units of equipment. Each piece of equipment has an important role in SRF production. Stages of the SRF production line and their function:

– the first stage – the first drum sieve: extracts residue materials (inert);
– shredding materials: waste is shredded down to 40 mm sized particles to make the material homogeneous;
– the second drum sieve: materials after shredding passed through the second drum sieve;
– metal separation – magnetic separator: ferrous metal separation is used;
– metal separation – eddy current: non-ferrous metal separation is used;
– drying – drum chamber.

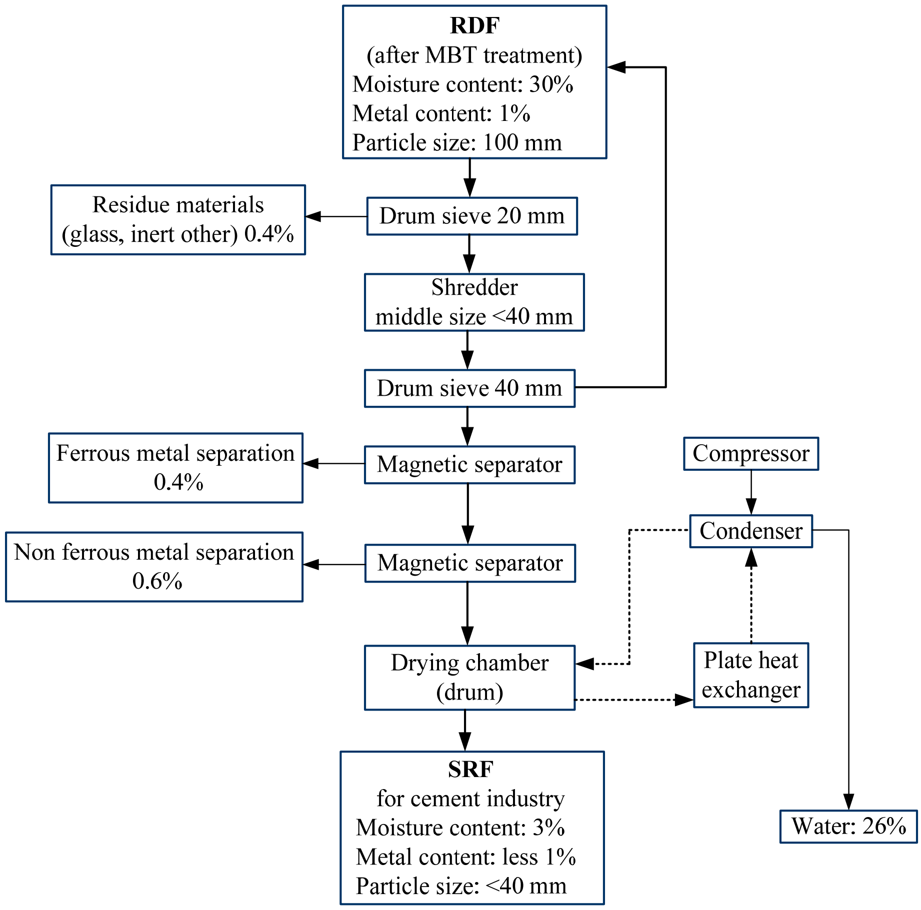


Fig. 5. SRF production line

Drum drying is provided at the end of the production line, and this is because part of the moisture is already lost during the production processes described before. Drying in the drum is the optimal way because it has a low capital cost, is simple to operate, and can proceed with large amounts of production. During the drying process at a drying agent temperature of 200 °C, the volume of the finished SRF decreased by 19 %.

Considering the present situation in the Alytus region, all not recyclable waste that consists of high calorific fractions is sent to the Kaunas CPP for incineration to produce energy. It is impossible to completely convert all of the incinerated waste into SRF not to disrupt the work of the CPP. The amount of RDF for incineration in the CPP and the amount of SRF produced from RDF have to be balanced. Some parts of the waste, it is about half of the incinerated waste, maximum (2.7 t/h) can be converted into SRF production.

Based on this data and eq. (1)–(5), the flow rate of the SRF production line was calculated, and it is 1.89 t/hour. However, if the amount of RDF, which is planned to send for incineration, will increase from 10,000 to 20,000 t/year, in this situation, the amount of SRF production can be obtained at 3.78 t/hour, which, in turn, ensures uninterrupted production of SRF for the cement industry.

During the production of SRF, most of the metals and prohibited materials are extracted. Most of the waste that contains prohibited materials (Cl, Hg) that are not acceptable for use in the production of SRF must be extracted during solid waste treatment.

5. 3. Development of scenarios of MSW generation

According to Eurostat [9], the amount of waste generated in Alytus municipality, Lithuania tended to decrease between 2010 and 2013 but during the period between 2014 and 2020 had an upward growth curve (Fig. 6).

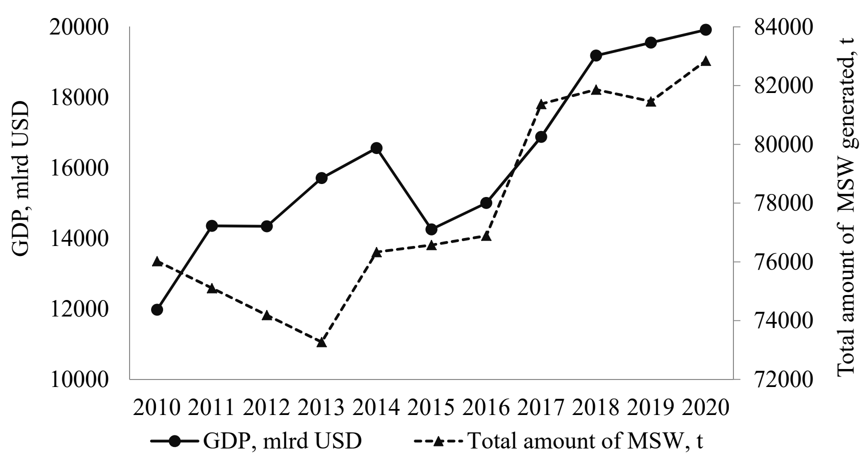


Fig. 6. The total amount of MSW generation in Alytus city and GDP (Lithuania), 2010–2020

The gross domestic product (GDP) indicator per inhabitant has also increased in the last decade, except for the period from the same years as for waste [9, 21]. The decrease in GDP and reduction of MSW generation can be explained by the global economic crisis [22]. Most of the waste generated in Lithuania until 2015 was disposed of at sanitary solid waste landfills. However, since 2015, MBT plants have started to work in Lithuania, and the amount of waste sent to the landfill has significantly reduced.

The main aims of the Alytus' MBT plant are to recover high-quality materials and to separate the biodegradable fraction. Using mechanical processes, MSW is divided into the main recovered fractions such as RDF, recyclable plastics and paper, metals and biodegradable fractions for biological treatment. The recyclable and not recyclable fractions are obtained after mechanical treatments.

The recyclable fractions are sent to the companies that process or use them as raw materials. The not recyclable fraction – RDF is sent to the CPP to produce energy.

According to the proposed Scenario I, with the current waste management system, with the existing situation with the population and the rapid increase in waste generation due to GDP growth, the amount of MSW by 2030 will be ≈$147\cdot10^3$ ton and $35.3\cdot10^3$ ton RDF. It was calculated using Eq. (8) and presented in Fig. 7.

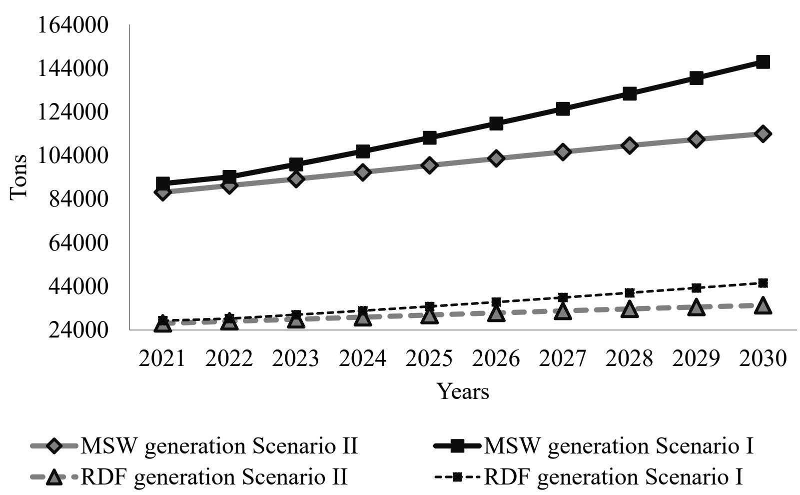


Fig. 7. Forecasted MSW and RDF generated in the Alytus region

The resulting projected amount of waste by 2030 will exceed the amount of waste predicted by the Organization for Economic Co-operation and Development estimates. Under the development of Scenario II, in which the amount of generated MSW remains at the same level and is not going to have rapid growth, the amount of the received MSW will be as follows.

With this scenario development, the amount of MSW will tend to decrease due to a decrease in the birth rate and, accordingly, the population. With this development of the scenario and generation of MSW, by 2030 its amount will consist ≈$114\cdot10^3$ ton and $27.4\cdot10^3$ ton RDF.

As a result of both developed scenarios, the feasibility of construction of the SRF production line was confirmed, which will ensure the uninterrupted production of alternative fuel for the cement plant during the study period.

5. 4. Feasibility of using SRF in the cement industry by clinker firing

Environmental benefits will be achieved by preparing SRF and disposing of it as an alternative fuel in the cement industry during clinker firing. The benefits are: saving consumption of fossil fuels, decrease in imports of hard coal, reduced greenhouse gas emissions, reduced amount of waste sent to CPP to obtain energy.

An economic calculation to add SRF to the main fuel (coal) with the replacement ratio of 10 % was made. The calculation is based on the following reference data:

– cement kiln production capacity (Pr) – 3,397 t/day [23];
– number of operating days of the cement kiln (NOD) – 360 day/year [23];
– emission factor of coal (EF) – 95 % [23];
– energy required to produce 1 kg of clinker (ER) – 840 kcal/kg [24];
– calorific value of coal (CV_{coal}) – 7,400 kcal/kg [25];
– cost of 1 ton of coal (C_{coal}) – 137 USD [26];
– cost of 1 ton of SRF (C_{SRF}) – 25 USD [27];
– NCV of SRF (NCV_{SRF}) – 6,735 kcal/kg;
– cost of emissions of 1 ton of CO_2 (EC) – 58 USD [28];
– replacement ratio of SRF (RR_{SRF}) – 12 %;
– coal consumption ratio (CC_{rat}) – 88 %;
– coal consumption (initial situation) $\left(C_{coal}^{init}\right)$ – 19 t/h [23].

Calculation of the energy consumption of coal for clinker production:

$$En = Pr\cdot ER\cdot 1{,}000 = 3{,}397\cdot 840\cdot 1{,}000 = 2{,}568{,}132{,}000,\ \text{kcal/kg}. \quad (11)$$

Saving energy consumption of coal due to the use of the replacement ratio of SRF:

$$SEn = En\cdot RR_{SRF} = 2{,}568{,}132{,}000\cdot 0.12 = 301{,}327{,}488\ \text{kcal/kg}. \quad (12)$$

The amount of SRF per hour that needs to be replaced to achieve the required energy:

$$Am_{SRF} = (SEn/NCV_{SRF})/1{,}000/24 = (301{,}327{,}488/6{,}735)/1{,}000/24 = 1.86\ \text{t/h}. \quad (13)$$

The amount of coal per hour to achieve the required energy:

$$Am_{coal} = (Ren/CV_{coal})/1{,}000/24 = (2{,}259{,}956{,}160/7{,}400)/1{,}000/24 = 12.72\ \text{t/h}, \quad (14)$$

where Ren – energy required for the production of 1 kg of clinker, taking into account the replacement ratio of SRF (kcal/kg):

$$Ren = Pr\cdot ER_{calc}\cdot CC_{rat}\cdot 1{,}000 = 3{,}397\cdot 739.2\cdot 0.88\cdot 1{,}000 = 2{,}259{,}956{,}160\ \text{kcal/kg}, \quad (15)$$

where ER_{calc} – energy required to produce 1 kg of clinker, taking into account the coal replacement ratio:

$$ER_{calc} = (ER\cdot Coal_{cons})/100 = (840\cdot 0.88)/100 = 739.2\ \text{kcal/kg}. \quad (16)$$

The amount of SRF required for replacing 1 ton of coal:

$$AmR_{SRF}=Am_{SRF}/Coal_{cons}=1.86/6.27=0.3, \quad (17)$$

where $Coal_{cons}$ – coal consumption

$$Coal_{cons}=C_{coal}^{init}-Am_{coal}=19-12.72=6.27 \text{ t/h}. \quad (18)$$

Using SRF as a replacement fuel, the annual coal savings consist:

$$Coal_{sav}=Coal_{cons}\cdot NOD\cdot 24=6.27\cdot 360\cdot 24=54{,}216 \text{ t/year}. \quad (19)$$

Annual income in coal savings:

$$AI_{coal}=Coal_{sav}\cdot C_{coal}=54{,}216\cdot 137=742{,}7617 \text{ USD/year}. \quad (20)$$

Annual consumption of SRF

$$SRF_{cons}=Am_{SRF}\cdot NOD\cdot 24=1.86\cdot 360\cdot 24=16{,}106 \text{ t/year}. \quad (21)$$

Annual costs of SRF:

$$AC_{SRF}=SRF_{cons}\cdot C_{SRF}=16{,}106\cdot 25=402{,}664 \text{ USD/year}. \quad (22)$$

Real financial savings:

$$FS=AI_{coal}-AC_{SRF}=7{,}427{,}617-402{,}664= =7{,}024{,}952 \text{ USD/year}. \quad (23)$$

Annual CO_2 emissions savings for the cement plant using coal:

$$AEm_{CO2}=Coal_{cons}\cdot EF\cdot NOD\cdot 24= =6.27\cdot 0.95\cdot 360\cdot 24=51{,}505 \text{ USD/year}. \quad (24)$$

Reducing CO_2 emissions from coal:

$$REm_{CO2}=AEm_{CO2}\cdot EC= =51{,}505\cdot 58=2{,}987{,}311 \text{ USD/year}. \quad (25)$$

Loss of efficiency taking into account the use of SRF:

$$LE=20\ \%\cdot RR_{SRF}\cdot 100=0.2\cdot 0.12\cdot 100=2.4\ \%. \quad (26)$$

The net cost saving:

$$NC_{sav}=((AI_{coal}+REm_{CO2}-FS)\cdot(100-LE))/100, \quad (27)$$

$$NC_{sav}=((7{,}427{,}617+2{,}987{,}311- -402{,}664)\cdot(100-2.4))/100=9{,}771{,}970 \text{ USD/year}.$$

The economic calculation is presented above in which the addition of 12 % SRF as a replacement fuel corresponds to a consumption of 1.86 t/h. The remaining 88 % consist of the consumption of the main fuel – coal with 12.72 t/hour, which ultimately shows energy savings.

6. Discussion of experimental results of production of solid recovered fuel and feasibility of its utilization in the cement industry

Based on the analysis of the existing problem of waste generation, the decrease in the number of natural energy resources and the increase in greenhouse gases, the following was determined. The use of waste as an alternative fuel in the cement industry is a relatively new and quite relevant direction, but it is not fully used. It is known that the cement industry is one of the largest consumers of natural energy resources during clinker firing and, in turn, makes a more significant contribution to air pollution. In this regard, the question arises of the production of viable fuel from waste that meets European standards by developing a technological line for the production of SRF. The use of waste as an additive to the main fuel has been sufficiently studied. It should be noted that in many works, the term RDF is used as an alternative fuel. However, RDF is a non-defined term that refers to waste that has not undergone the proper treatment. RDF is not standardized (composition, impurities, calorific value) and can only be used for combustion in cogeneration plants to produce heat or energy. SRF, in turn, is a fuel produced from non-hazardous waste in accordance with European standards. Its functions are well defined, and it has a classification. It has been found that an alternative fuel that will meet European standards can be obtained by developing a technological line for the production of SRF. The produced SRF will have sufficiently high characteristics, the crystalline phase will correspond to clinker-forming minerals, the oxide composition of the resulting ash will correspond to the oxide composition of the clinker, but in different percentages, and the developed technological line will ensure the uninterrupted production of SRP during the period under consideration.

According to the results of seasonal studies, it was found that after the separation of the biological fraction from the mainstream of MSW, the fraction with a size $d>$ 80 mm, 91 % dominates (Fig. 1). It has been determined that the main materials that make up RDF are plastics, paper and textiles. After several stages of preparation: extraction of prohibited materials, shredding and drying, SRF was produced from RDF (Fig. 2). Based on the results of determining the main characteristics of fuel from waste, it was found that the SRF produced in accordance with the EU standard for SRF, especially EN 15359, belongs to the first class in terms of the main classification characteristics: NCV, chlorine and mercury content. In turn, according to the data obtained, the characteristics of RDF satisfy the use of this type of fuel only to produce heat or energy. This fact is explained by relatively high moisture content, low calorific value and chlorine and mercury content (Table 2). It was experimentally confirmed that SRF has a crystalline structure (Fig. 3), and the oxide composition corresponds to the oxide composition of the clinker (Table 3), but with a different percentage. The SRF crystalline phase consists of calcium-, sodium-, potassium-, iron- and silicon-containing phases (Fig. 4). The presence of phase compounds and high classification characteristics confirm the feasibility of using SRF as a replacement fuel during clinker firing.

Based on the existing MBT line, the SRF production line was developed. The flow rate of the SRF production line was calculated, which is 1.89 t/h, and that will allow the use of 12 % SRF as an alternative fuel by clinker firing.

Two scenarios of waste generation in the Alytus region were proposed. It has been found that according to the results of Scenario I, with a very rapid increase in waste generation, by 2030, the amount of SRF will be $35.3\cdot 10^3$ tons, from which $28.2\cdot 10^3$ tons of SRF can be obtained. According to the Scenario II development results, waste generation will continue until 2030 with the same intensity as the current one, and the amount of SRF will be ≈$27.4\cdot10^3$ tons. The calculation confirmed that from this amount, it will be possible to produce $21.9\cdot10^3$ tons of SRF. Based on the development of both scenarios for waste generation until 2030, it is projected to increase waste generation.

A mathematical calculation is proposed, confirming the economic and environmental feasibility of using SRF as an alternative fuel. It has been found that using the replacement ratio of SRF of 12 % and the remaining 88 % in coal (traditional fuel) will bring economic and environmental benefits. With this option, the savings on the purchase of coal will amount to 7,427,617 USD/year using 16,106 t/year of alternative fuel. The net annual savings will be 9,791,970 USD/year, taking into account the cost of SRF, loss of efficiency and the savings in greenhouse gas emissions costs.

Thus, the results of experimental studies have shown that developing a line for the production of SRF from RDF by extracting prohibited materials, shredding and drying will significantly increase the calorific value of the resulting SRF by 22.1 % compared to the calorific value of RDF. The extraction of prohibited materials will improve the quality of SRF in terms of the main characteristics of chlorine content by 35 % and mercury content by 50 %. During the production of SRF from RDF, the moisture content of the finished product will decrease by 90 % and become acceptable for use in cement kilns. The process of drying SRF in a drum chamber will reduce the volume of SRF by 19 %, which will favorably affect transportation and storage. The SRF production line will allow the production of viable alternative fuel, reduce the non-renewable natural resources consumption and decrease greenhouse gas emissions (since SRF is 60 % composed of biogenic materials). The obtained experimental results do not contradict the known theoretical approaches describing the production of fuel from waste and using it in cement kilns. The results showed that the ash obtained after the combustion of SRF has an oxide composition, like the oxide composition of clinker; it has a crystalline structure and consists of clinker-forming minerals.

Difficulty in implementing the most efficient process of SRF production may lie in the recovery of prohibited materials. To date, the extraction of prohibited materials is done manually. Consideration should be given to designing and installing separators to extract prohibited materials.

The disadvantage of this process is the need for constant control of the morphological composition of SRF and, in case of deviation, the need for adjustments concerning the substitution ratio; control for the mercury and chlorine content. In addition, a disadvantage is the installation of additional (six) production units of equipment. However, such economic costs will have a one-time investment.

7. Conclusions

1. In this experimental research, using extraction of prohibited materials, grinding and drying technology, the energy potential and production of SRF from RDF to be used as an alternative fuel in the cement plant in Lithuania were investigated. The characteristics of SRF produced from RDF were determined and compared with the European standard. According to [18], the obtained SRF belongs to the first class by classification characteristics: NCV=28.2 MJ/kg, Cl=0.09 % and Hg=0.02 mg/kg^{-1}. It had been proven experimentally that the ash obtained after incineration of SRF has a crystalline structure; the crystalline phase consists of calcium-bearing, sodium-bearing, potassium-bearing, iron-bearing and silicon-bearing phases. Elemental analysis obtained by SEM-EDS analysis confirmed that the oxide composition of SRF corresponds to the oxide composition of the clinker but with a different percentage.

2. The flow rate of the SRF production line was calculated, which was 1.89 t/hour. The SRF line will provide production of 12 % alternative fuel for clinker firing. Upon completion of the SRF production process, after the drying stage, the volume of the finished product decreased by 19 %.

3. Moreover, the use of 10 % SRF as additional fuel to the coal used in the cement kiln, which is 16,106 t/year, will save 54,216 t/year of coal, 7,427,617 USD/year from the cost of coal imports, 51,505 USD/year from greenhouse gases emissions to the atmosphere, 2,987,311 USD/year only due to the reduction of CO_2 emissions and the net savings will amount to 9,771,970 USD/year.

4. Two scenarios of waste generation were developed. Based on the results of the developed scenarios, it was found that regardless of the outcome of any of the proposed scenarios, the amount of SRF produced from RDF will ensure the operation of the SRF production line and will not disrupt the operation of the CPP.

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