

Технологія спільного спалення відходів у цементних печах зарекомендувала себе надійним, ефективним та зручним методом утилізації відходів (побутових та промислових). Проте країни по всьому світу зіштовхуються з наступними ключовими бар'єрами на шляху до впровадження технології суцільної переробки відходів у цементних печах: нечітке законодавство, відсутність фінансової підтримки, сприйняття громадськістю, тощо. Ці бар'єри можуть бути частково усунуті за допомогою заходів, запропонованих у цьому дослідженні.

Крім того, сортування та переробка відходів часто не проводяться систематично. Національні та міжнародні цементні компанії працюють із сучасними печами, які можуть замінити частину викопного палива та сировини відповідними потоками підготовлених відходів, які підлягають спільному спаленню. Спільне спалення відходів, що не підлягають вторинній переробці, є надійним варіантом закриття існуючих прогалів для впровадження принципів циркуляційної економіки. Ця технологія широко використовується в різних країнах Європи, але з різним екологічним впливом на навколишнє середовище. Отже, важливим є дослідити екологічний потенціал цієї технології, який є змінним для різних умов морфології відходів.

Досліджено потенційні переваги впровадження технології спільного спалення твердих побутових відходів у цементних печах. Застосовано методіку оцінки викидів парникових газів для біогенних викидів при визначенні переваг та екологічного потенціалу при впровадженні технології. На прикладі української цементної промисловості визначено можливість: зменшення споживання антрацитового вугілля у виробництві клінкеру до 262 тис. т/рік; запобігання утворенню до 284 тис. т викидів CO<sub>2</sub>екв/рік від заміщення вугілля. Для сектору поводження з відходами було визначено можливий потенціал від спільного спалення: утилізація побутових відходів до 1 213 тис. тТПВ/рік; запобігання утворенню парникових газів до 111 тис. тCO<sub>2</sub>екв/рік на звалищах. Ці висновки важливі для ряду країн, оскільки ключові бар'єри для здійснення спільного спалення відходів у цементних печах є спорідненими. Результати екологічного аналізу та запропоновані заходи щодо уникнення визначених ключових бар'єрів впровадження технології можуть бути використані для умов багатьох країн.

**Ключові слова:** спільне спалення, ресурсозбереження, цементна промисловість, викиди парникових газів, ключові бар'єри

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# ENVIRONMENTAL POTENTIAL ANALYSIS OF CO-PROCESSING WASTE IN CEMENT KILNS

**A. Kleshchov**

PhD, Lecturer

State Higher Education Institution

"Kyiv Electromechanical College"

Povitroflotskyi ave., 35, Kyiv, Ukraine, 03037

E-mail: anton.kleshchov@gmail.com

**D. Hengevoss**

Research Associate in Sustainable Resource Management\*

**O. Terentiev**

Doctor of Technical Sciences, Professor\*\*

**C. Hugi**

Doctor of Technical Sciences, Professor,  
Lecturer in Sustainability and Development\*

**A. Safiants**

PhD

Department of Nuclear Power Stations  
and Engineering Thermal Physics\*\*\*

Department of Heat-Physical Problems  
of Heat Supply Systems

Institute of Engineering Thermophysics  
of National academy of sciences of Ukraine  
Zhelyabova str., 2a, Kyiv, Ukraine, 03057

**A. Vorfolomeiev**

PhD, Senior Lecturer\*\*

\*School of Life Sciences FHNW

Institute for Ecopreneurship

University of Applied Sciences  
and Arts Northwestern Switzerland

Hofackerstrasse, 30, Muttenz, Switzerland, 4132

\*\*Department of Electromechanical Equipment

of Energy Intensive Industries

Institute of Energy Saving and Energy Management\*\*\*

\*\*\*National Technical University of Ukraine "Igor

Sikorsky Kyiv Polytechnic Institute"

Peremohy ave., 37, Kyiv, Ukraine, 03056

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C. Hugi, A. Safiants, A. Vorfolomeiev.

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## 1. Introduction

Waste management has become a serious issue for today. Total waste generation, e.g. in Ukraine, is more than 69,000 kt/a (MSW (9%) and industrial waste (91%)),

mining and agricultural waste excluded [1]. Current waste management challenges in Ukraine and other countries can be described as follows [2]:

– accumulation of waste both from the industrial and domestic sectors in controlled and uncontrolled landfills

having an adverse effect on the environment, human health and land space;

- improper treatment and disposal of hazardous waste from industries;
- disposal of MSW without separation of hazardous fractions (e. g. batteries, oil paints);
- open burning of recyclable waste (e.g. paper, garden waste).

According to the State Statistics Service [1], Ukraine generates more than 6 tons of unsorted waste per capita per year (total amount of municipal and industrial waste). It is higher than the average of the European Union, i. e. 4,931 kg/capita/year in 2014 for EU-28 [3]. Currently, Ukrainian landfills are mostly outdated and overflowing, and therefore pose a quickly growing problem for the country. There are several projects aimed at biogas recovery in landfills in Ukraine (e.g. 26 biogas units in the beginning of 2018, according to the National Agency of Energy Efficiency and Energy Saving of Ukraine, while there are more than 300 landfills). However, it is not enough to improve the waste management situation. Because of an increasing level of collected MSW, the danger of soil and underground water contamination is quickly growing. MSW, even if it is only 9 % of the total waste generation, is in the focus of the Ministry of Environment and Natural Resources of Ukraine and, therefore, of this study as well.

In Ukraine, waste separation and recycling are not done systematically yet. Waste infrastructure is largely outdated with some landfills built more than 40 years ago, overflowing with waste and being unsafe. Waste collection tariffs are too low to cover treatment costs, and the legal framework is complex [4]. This discouraged private investors from entering the waste management market in the past.

For example, it is more expensive for waste collection companies to deliver waste to the only incineration plant in Ukraine (“Enerhiia”), located in Kyiv, than to dump the collected waste nearby, in uncontrolled landfills. Waste collection companies charge on average EUR 8.06 per ton for the collection of waste [5]. The gate fee of the incineration plant and legal landfills is about EUR 2.80 per ton. That means a waste collection company must spend about 30 % of the income on incineration or landfilling. To avoid these treatment costs, the waste has often been dumped in illegal/semi-legal landfills for about EUR 1.6 per ton. Due to weak enforcement of the environmental legislation, this practice, unfortunately, is still widely used today.

National and international cement companies operate modern cement kilns which could substitute a part of their fossil fuel and raw material with suitable waste streams to be co-processed. Using waste as a source for alternative energy and raw material could also reduce the dependency on them being imported.

Of course, prevention, reuse and material recycling are the most preferable options in an integrated waste management system and have higher priority than energy recovery from the point of view of society. Currently, a number of countries start to implement their strategies of sorting and separating waste, a precondition for recycling. However, co-processing non-recyclable waste is often a valid option to close loops towards a more circular economy. According to [6], as far as alternative materials are the case, utilizing waste-derived fuel and industrial by-products instead of conventional fuels and materials result in the significant emission mitigation. Industrial wastes which can be used

as both fuel and raw material simultaneously mitigate emissions in cement plants and landfills.

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## 2. Literature review and problem statement

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According to the investigation [7], GHG mitigation is one of the most attractive benefits of co-processing of biomass. It has been established that co-processing of biomass has less CO<sub>2</sub> emission compared with firing of coal proportionally to the amount of coal offset by biomass, considering biomass as a carbon-neutral source produced sustainably. It shows a possibility of co-processing of municipal solid waste as an alternative fuel for cement kilns.

The authors of [8] have analyzed the harmless disposal rate of sludge in China. It has been increased from 25 % to more than 50 % in the last 5 years due to the expansion of the sludge treatment scale. To avoid this, municipal solid sludge is widely used as an alternative fuel for cement kilns today. The study shows a gap of investigation of the carbon emissions of co-processing projects and the reduction benefits from energy and resource conservation.

As for the hazardous waste, in Gujarat (India) the utilization of it as an alternative fuel and input material in cement kilns increased by 35 times between 2009/2010, from 15,693 tons per annum, to 543,569 tons per annum in 2013/2014 [9]. It has been proved that co-processing is thus a preferred solution in the waste management hierarchy for their current situation. It needs to be mentioned that India has a lot of similarities in the waste management system with Ukraine. The separation system and recycling are not strong, and the government has not enough investments for the higher priority waste management technologies implementation.

The same results have been investigated by the authors of [10]. The economy of Puerto Rico is shrinking in its present recession. It is because the price of electricity has become a stumbling block to attract new investments, and because the supply of electrical energy seems to continue to be dependent on fossil fuels. The poor management and improper disposal of almost five million scrap tires (ST) generated annually on the Island have reached negative environmental, economic and social impacts. The authors demonstrated that the problem can be transformed into an opportunity for ST to become a renewable energy option. It has been shown that ST are an endemic sustainable energy supply, ideal for the cogeneration of electricity or for its inclusion in thermal processes, e. g. in co-processing.

The work [11] shows the results of life cycle assessment for co-processing of construction and demolition waste. As a result, the authors suggest that the purchase of recycled aggregates resulting from waste treatment is cost-effective only if the treatment plant is situated within a 30 km area. The study suggests that the price of recycled aggregates must be kept at least 20 % lower than natural aggregates which at present disregards the aggregates produced from waste.

The authors of [12] investigated that waste co-incineration has a non-significant role on CO<sub>2</sub> emissions from the cement kiln and an important energy efficiency loss can be deduced from the industry performance data, which is rarely considered by life cycle analysis practitioners. If cement kilns are considered as another waste treatment option, the functional unit is usually 1 t of waste to be treated. In this

case, it has been observed that contradictory results may arise depending on the initial assumptions, generating high uncertainty in the results. Air emissions, as heavy metals, are quite relevant when assessing waste co-incineration, as the amount of pollutants in the input is increased. These results show a significant impact of waste morphology on the effectiveness of co-processing of waste in cement kilns.

In the work [13], the authors calculated the costs of setting up and running facilities of thermal co-processing of properly dried and processed MSW with raw materials (limestone, clay materials, silicates and iron oxides). This is needed for the production of clinker which has been proven to be an environmentally friendly process. This study shows the experience of CO<sub>2</sub> reduction possibility using co-processing of municipal solid waste which could be shared with Ukrainian authorities as well.

The result for this paragraph is that co-processing of waste is widely used in different countries, but with different ecological impact. So, it is crucial to investigate the co-processing of waste impact, which is variable for different waste morphology conditions.

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### 3. The aim and objectives of the study

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The aim of the study is to estimate the environmental and resource saving potential of co-processing MSW fractions in cement kilns.

To achieve this aim, the following tasks have been formulated:

- to investigate legal, economic and institutional barriers that hinder its implementation in the context of improving the waste management system in general, and to provide opportunities for overcoming those barriers;
- to estimate potential benefits of implementation of this technology for the cement industry;
- to analyze possible benefits of implementation of co-processing investigated for the waste management sector.

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### 4. Co-processing of waste in cement kilns possibilities

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#### 4.1. Legal, economic and institutional barriers for the implementation of co-processing

According to the investigation [14], the main barriers for co-processing of waste implementation in different countries have been found.

In Belgium, policy makers should recognize the material recovery aspect of co-processing. Market distortions are due to support for power and heat production. To further increase co-processing a more level playing field between the regions on taxation is needed. Regionally different waste legislations lead to fiscal differences in waste pricing [14].

In Bulgaria, RDF quality and low landfill taxes remain amongst the other barriers preventing faster uptake of alternative fuel from waste [14]. Lack of solid waste infrastructure and planning remain major issues slowing the diversion of waste from landfills and its use of alternative waste treatment methods.

The Czech Republic has strong bureaucratic barriers and the lack of suitable waste is the main limiting factor. As the availability of domestic high-quality wastes has peaked, the industry has to look for imports. Lengthy bureaucratic processes slow down the possibility of over-border waste trade [14].

France feels a lack of investment to upgrade processes, which hampers higher use of alternative fuels [14]. A general inability in the cement industry to pursue technology upgrades is the main barrier to increased fuel substitution.

In Greece, there are strong bureaucratic barriers and the lack of suitable waste is the main limiting factor. Very limited availability of suitable waste, lengthy permitting process and lack of recognition in national waste management planning are limiting the co-processing potential in the country [14].

Low landfill taxes and lack of high-quality waste on the domestic market are the main limiting factors for Hungary [14]. As low landfill taxes disincentive production of high-quality pre-processed waste, the cement industry has to look for imports from abroad.

In Ireland, economic uncertainty, lengthy planning and licensing processes and the potential addition of incineration capacity form the main barriers for increasing co-processing. The economic recovery needs to continue to enable investments in co-processing. At two plants, the planning process has caused delays to further co-processing [14].

Mainly political issues are blocking the further uptake of waste in the Italian cement industry [14]. Opposition from regional political authorities supported by public and environmental groups has to be addressed to allow for increased waste uptake in the cement industry.

The cement sector is facing minimum barriers in Poland to further increase its co-processing rate. The waste management industry has to make sure that RDF produced is of high-quality as the cement industry is the main customer [14].

In Portugal, RDF quality and low landfill taxes remain amongst the last barriers preventing faster uptake of alternative fuel from waste. Poor quality of domestically produced RDF along with extremely low landfill taxes are the main barriers. However, the industry managed to gain public acceptance and faces no permitting issues [14].

In Sweden, strong competition for available waste is limiting further development of co-processing in the cement sector. Underdeveloped pre-processing industry, public opposition to incineration and co-processing along with low disposal fees and poor economic situation hamper increased waste uptake in the Spanish cement industry. A very strong competition for waste with one of the most developed incineration industries in the EU, which is the preferred option to co-processing, presents a major barrier to further fuel substitution. There is an opening however, if biomass resources can be mobilized [14].

Alternative fuel from waste availability, logistics and economics prevent faster growth of co-processing in the United Kingdom. Economics dictate the increased use of alternative fuel from waste; a lack of policy-based incentives, logistics challenges and availability of the volume of quality alternative fuel are the main barriers [14].

Germany has a well-developed waste to energy capacity and about 26 % of the waste gets incinerated. However, despite a landfill ban, 22 % of waste is still being disposed of. One of the reasons of this is a difference in GHG accounting between cement plants and incinerators [14].

Ukrainian legislation lacks specification of possible forms of public-private partnership to attract private investments in waste management. It does not define different models of cooperation of territorial communities with private partners (residents and/or non-residents) that have the necessary material and technical base and considerable

experience in conducting entrepreneurial activity in the field of waste management. As most of the waste is created by the industrial sector, agricultural enterprises and municipalities, it is also an important challenge for the economic sector that should be more involved based on the polluter-pays principle. The formation of industrial waste management capacities should be one of the priorities of decentralization and local self-government reform, as well as attracting investments into waste management.

The key message of this paragraph is:

– The need for lower waste management technologies, which should improve the situation immediately is investigated. One of the possible technologies is co-processing of waste in cement kilns, which is widely used in the world. Moreover, according to [15], pre-processed MSW has high net calorific value (NCV) in gigajoules (GJ) per dry tonne (Table 1). Pre-processed MSW also has a much lower CO<sub>2</sub> emissions factor compared to coal when burned in a cement kiln (Table 2).

Implementation of co-processing could help the countries to increase the recovery level in the waste management hierarchy and would be a step towards circular economy by transforming waste into revenue streams [16]. Waste could be used as an energy source (as an alternative fuel for cement rotary kilns) and as raw material (as part of clinker). However, co-processing should complement but not compete with other recycling approaches. The current waste management system in Ukraine is not yet able to cope with the rising generation of waste, which results in increasing landfill areas and environmental pollution. Co-processing could contribute to alter this trend together with the implementation of sorting and recycling infrastructure for the different waste streams.

The key message from this paragraph is: co-processing implementation could significantly contribute to reducing the amount of waste disposed in landfills, as discussed in the following section.

#### 4. 2. Measures to mitigate barriers for co-processing of waste

The key barriers the countries face on their way to implementing co-processing are comparable to the barriers also faced in China [17], plus the issue of increasing waste generation. China is now actively seeking to increase its waste recovery in cement kilns with producers such as Huaxin Wuxue and Sinoma's Liyang having taken up the challenge. They are assisted by the Chinese Research Academy of Environmental Sciences and by the Ministry of Environmental Protection [18]. This helps identify the following seven barriers also encountered in Ukraine:

**Costs:** The costs of RDF generation usually exceed the existing landfill charges.

*Potential solutions:* The current landfill fees do not consider all external costs of future groundwater contamination or emissions of greenhouse gases, such as methane. Therefore, these external costs should be included in landfill fees or in financial incentive. Additional support programmes should be designed to ensure that the technology of co-processing waste is able to compete fairly with other waste management methods.

**Financial support:** Co-processing may not be financially viable if broader public waste management benefits are not taken into account, i. e. external costs.

*Potential solutions:* Municipalities and governments should develop programmes based on full costs and benefits

accounting for local communities and the environment and need to play their part in the financing of waste management and co-processing.

**Infrastructure:** Currently, there is no infrastructure for pre-processing and transporting waste to cement plants.

*Potential solutions:* It is necessary to approve procedures for adequate separation of waste materials and to install specific equipment in order to produce high-quality RDF and treat the remaining waste adequately.

**Lack of qualified workforce:** Co-processing waste in cement plants requires highly skilled specialists and trained personnel to operate the equipment. This capacity is currently limited in most developing countries.

*Potential solutions:* The main cement producers in different countries are linked to such worldwide consortiums as CRH Group, IFCEM, BUZZI, Heidelberg, EuroCement [19]. Most of them have successful experience of implementing the technology of co-processing waste in cement kilns in other countries. Using this experience could help find effective options.

**Permitting:** Cement industry prefers uniform emission standards for co-processing. However, for co-processing certain hazardous types of waste individual permits are needed to ensure safety and compliance with the environmental standards.

*Potential solutions:* Providing standards for different types of alternative fuels could simplify the permitting for co-processing.

**Public acceptance:** A problem of waste incineration is the formation of emissions, especially dioxins, and therefore there is a legitimate concern of the population. Residents and local groups often associate co-processing with incineration and hinder the implementation with protests and legal actions.

*Potential solutions:* Basic knowledge about environmentally responsible co-processing and how it differs from incineration, as well as its potential benefits, needs to be shared with stakeholders at both national and local levels. Cement plants should publicly report emission monitoring data and information regarding the technology of co-processing waste to assure the communities that emissions of pollutants do not exceed permitted levels.

**Regulations and standards:** In some countries, there are no specific rules or standards for co-processing waste in cement kilns. Partial implementation of the waste management system in many developing countries is also one of the main barriers.

*Potential solutions:* Waste legislation should be harmonized with European legislation, and executive policy should be optimized (paragraph 4. 1).

The key message from this paragraph is:

– a number of countries face the following key barriers on the way to implementing the technology of co-processing waste in cement kilns: complicated process of permitting, myriad of regulations and standards, lack of financial support, no full cost accounting, public acceptance, lack of infrastructure and qualified workforce. These barriers could be addressed partly by the measures proposed in this paper.

#### 4. 3. Estimation of potential benefits of implementation of co-processing of waste for the cement industry and for the waste management system

Cement manufacturing is an energy intensive process, and coal is commonly used as the main energy source. The estimation is provided for Ukrainian conditions, but it could be interesting for different countries and the methodology could be replicated. The cement industry consists currently

of five national and international companies, which produce up to 9,000 kt cement/a [20]. The main fraction of cement is clinker, which is produced in rotary kilns at temperatures of about 1,450 °C. The Industrial Emission directive 2010/75/EU defines the conditions for co-incineration (co-processing) waste in cement kilns. The key requirement is that the combustion gases are exposed to temperatures of at least 850 °C for at least two seconds. If hazardous waste with a content of more than 1 % of halogenated organic substances, expressed as chlorine, is incinerated, the temperature must be raised to 1,100 °C for at least two seconds [21]. At this temperature, all organic compounds of the input materials are destroyed. As these conditions are well fulfilled by the technology of co-processing waste in cement kilns, it is a viable option for many high-calorific waste fractions as an alternative fuel and raw materials for clinker production.

Table 1 provides the results of CO<sub>2eq</sub> emissions calculation for anthracite coal burning process and for mixed fuel burning process (i. e. 70/30 ratio of anthracite coal/RDF). Experimental data from Ukrainian cement plants, provided by the representative of the Ukrainian national association of cement producers "Ukr cement" were used. For calculations, it has been estimated that RDF contains plastic, textile, tires, construction and organic waste fractions (which is dried), according to the RDF production technology [22]. The second main estimation is specific calorific value, according to [23]. This is a bulk estimation and, in reality, will depend on the MSW morphology of the individual landfill and the RDF production technology.

Table 1

Results of CO<sub>2eq</sub> specific emissions and specific RDF consumption for clinker production estimation for anthracite coal burning process and for mixed fuel burning process

Parameter, unit	Value
Specific CO <sub>2eq</sub> emission for anthracite coal, kg <sub>CO<sub>2eq</sub></sub> / kg <sub>fuel</sub>	3.37 [24]
Specific thermal heat energy requirements for clinker production, MJ/t of clinker	3.788 [25]
Specific anthracite coal consumption for clinker production, kg/t of clinker (experimental data from Ukrainian cement plants)	116.91
Calorific value of anthracite coal, MJ/kg of coal	32.4 [26]
Specific CO <sub>2eq</sub> emission from anthracite coal in clinker production, kg <sub>CO<sub>2eq</sub></sub> / t <sub>clinker</sub>	394
Estimated substitution rate of anthracite coal with RDF, % of thermal energy	30
Specific calorific value of RDF, MJ/kg	24.1 [23]
Calculated specific RDF consumption in clinker production, kg <sub>RDF</sub> / t <sub>clinker</sub> (by using data from this table)	47.15
Specific fossil CO <sub>2eq</sub> emission from RDF, kg <sub>CO<sub>2eq</sub></sub> / kg <sub>RDF</sub>	1.7 [23]
Calculated specific emission for co-processing, kg <sub>CO<sub>2eq</sub></sub> / t <sub>clinker</sub> (by using data from this table)	356

The specific CO<sub>2eq</sub> emissions could be reduced by about 15 % through co-processing at an energy substitution rate of 30 %, Table 1.

In Table 2, ecological and resource potential, estimated for the Ukrainian cement industry in case of co-processing implementation is shown. The following was assumed for the calculation:

- Traditional fuel used – anthracite coal;
- Alternative fuel – mixed with traditional with the ratio of 70 % anthracite coal per 30 % RDF from MSW.

Co-processing with the above alternative fuel mix is implemented at all Ukrainian cement enterprises.

Table 2

Calculation of the yearly CO<sub>2eq</sub> and anthracite coal reduction potential by co-processing RDF in the Ukrainian cement industry

Parameter, unit	Value
Average annual cement production, kt/a	8,798 [25]
Share of clinker in cement, % (experimental data from Ukrainian cement plants)	85
Calculated average annual clinker production, kt/a (by using data from this table)	7,478
Calculated total annual anthracite coal consumption for clinker production, GJ/a (by using data from Table 1, 2)	28,327.800
Calorific value of anthracite coal, MJ/kg	32.4 [26]
Calculated total annual anthracite coal consumption for clinker production, kt/a (by using data from Table 1, 2)	874.31
Specific anthracite coal consumption for clinker production, kg/t (experimental data from Ukrainian cement plants)	116.91
Calculated potential reduction of anthracite coal consumption for clinker production, kt/a (by using data from this table)	262
Calculated average annual CO <sub>2eq</sub> emission, kt <sub>CO<sub>2eq</sub></sub> / a (by using data from this table)	2,946
Calculated potential reduction for CO <sub>2eq</sub> emissions from substitution of anthracite coal, kt <sub>CO<sub>2eq</sub></sub> / a (by using data from this table)	284

By using the methodology from RTI [27], for landfills without gas collection systems, CO<sub>2</sub> emissions can be calculated from the CH<sub>4</sub> generation as follows:

$$B = A \cdot (((1-F)/F) + OX) \cdot 44/16, \quad (1)$$

where  $B$  is CO<sub>2</sub> emissions, t/a;  $A$  is CH<sub>4</sub> generation, t<sub>CH<sub>4</sub></sub> / a;  $F=0.5$  is fraction by volume of CH<sub>4</sub> in landfill gas, –;  $OX=0.1$  is soil oxidation fraction, –; 44 is molecular weight of CO<sub>2</sub>, kg/kg-mol; 16 is molecular weight of CH<sub>4</sub>, kg/kg-mol.

Model for CH<sub>4</sub> generation is as follows:

$$A = \left[ \sum_{x=S}^{T-1} \left\{ W_x \cdot L_x \cdot \left( e^{-k(T-x-1)} - e^{-k(T-x)} \right) \right\} \right], \quad (2)$$

where  $A$  is CH<sub>4</sub> generation, t/a;  $x$  is year in which waste was disposed, –;  $S$  is start year of inventory calculation, –;  $T$  is inventory year for which emissions are calculated, –;  $W_x$  is the quantity of waste disposed at the solid waste disposal site, t;  $L = L_0 \cdot 16 / 0.02367 \cdot 10^{-6}$  is CH<sub>4</sub> generation potential, t<sub>CH<sub>4</sub></sub> / t<sub>waste</sub>;  $L_0$  is CH<sub>4</sub> generation potential, m<sup>3</sup><sub>CH<sub>4</sub></sub> / t<sub>waste</sub>;  $k$  is decay rate constant, a<sup>-1</sup>.

$L_0$  can be calculated from the degradable organic carbon value:

$$L_0 = 493 \cdot DOC, \quad (3)$$

where  $L_0$  is CH<sub>4</sub> generation potential, m<sup>3</sup><sub>CH<sub>4</sub></sub> / t<sub>waste</sub>;  $DOC$  is degradable organic carbon, t<sub>c</sub> / t<sub>waste</sub>.

Basic data from [28, 29], the specific amount of GHG landfill gas emissions per ton of MSW for Ukraine has been estimated by considering the type of waste and its share in MSW by using (1), (2) and (3). The specific amounts add up to about  $90 \text{ kg}_{\text{CO}_{2\text{eq}}}/\text{t}_{\text{MSW}}$ .

To estimate the total amount of MSW, which is required for producing the needed amount of RDF for co-processing in Ukraine, an analogy based on the ratios of four countries for RDF production from [30] has been used. It shows that 100 kg of RDF production requires on average 344 kg of MSW. The authors of the investigation [31] have estimated close results that 312 kg/h of MSW are required to produce 107 kg/h of RDF, assuming that 50 % of total MSW are recyclables (ceramics, metals, plastics, glasses, etc.), water flow in the separated MSW total flow is about 43 kg/h; according to real (actual) operation of MSW handling, there were considerable material losses in the milling (3 %) and briquetting (2 %) operations [31].

Table 3 shows a potential of about 1,213 kt/a of MSW which could be treated for RDF production. The GHG landfill gas mitigation potential could reach up to  $111 \text{ kt}_{\text{CO}_{2\text{eq}}}/\text{a}$ .

Table 3

Potential MSW treatment for RDF and GHG reduction from landfills

Parameter	Value
Specific RDF consumption for clinker production, kg/t (data from Table 1)	47.15
Average annual clinker production, kt/a (data from Table 2)	7,478
Calculated average annual RDF consumption, kt/a (by using data from this table)	350
Calculated MSW to RDF ratio, $t_{\text{MSW}}/t_{\text{RDF}}$ (by using data from [30])	3.44
Calculated potential MSW treatment for RDF, kt/a (by using data from this table)	1,213
Calculated potential of reducing GHG emissions from landfills, $\text{kt}_{\text{CO}_{2\text{eq}}}/\text{a}$ (by using data from this table)	111

This estimated theoretical potential of co-processing RDF in the Ukrainian cement industry to substitute up to 262 kt/a of anthracite coal could hardly be completely utilized. Nevertheless, a reduction of up to  $1,213 \text{ kt}_{\text{MSW}}/\text{a}$  disposed in landfills seems as an interesting treatment path until better options according to the waste hierarchy, as presented in Fig. 4, are made available. According to the IFC [28], in 2013 the recovery rate in Ukraine was only 3 % to 8 % of generated MSW. By 2025, the Ukrainian recovery rate must increase up to 41 % [28]. The potential of using MSW for RDF production is more than 19 % of the total annual MSW generation in Ukraine ( $6,346.50 \text{ kt}_{\text{MSW}}/\text{a}$ ) [1].

It needs to be mentioned that decreasing of  $\text{CO}_2$  emissions is possible, only if pre-treatment of waste streams has exact quality. If calorific value, humidity, morphology or fracture size of prepared and treated waste has low quality, emissions from its co-processing will be increased.

### 5. Results of the environmental potential analysis of co-processing of waste

The technology of co-processing with RDF rate of 30 % could substitute up to 262 kt/a of anthracite coal consumption in the clinker production in Ukraine.

MSW disposal amount could be reduced to  $1,213 \text{ kt}_{\text{MSW}}/\text{a}$  which is about 20 % of total annual MSW generation in Ukraine.

Anthracite coal consumption for clinker production could be reduced up to 30 %.

Annual  $\text{CO}_{2\text{eq}}$  emissions from MSW at landfills reduction potential is up to 10 %.

Total  $\text{CO}_{2\text{eq}}$  reduction potential is up to  $395 \text{ kt}_{\text{CO}_{2\text{eq}}}/\text{a}$ , which is up to 0.3 % of Ukrainian total annual  $\text{CO}_{2\text{eq}}$  generation.

The scientific novelty of this study is as follows. The method of estimation of greenhouse gas emissions for biogenic emissions from separate categories of sources determined the specific amount of greenhouse gas emissions from landfills for the existing situation and for the conditions of introduction of co-incineration technology in cement kilns. The type of waste and its share in the landfill were considered. Considering the morphology of the waste, the environmental potential was analyzed not only for the waste sector but also for clinker production, which allows to achieve the task – to estimate the environmental potential for co-processing of waste implementation. This is one of the key barriers for the list of countries for co-processing of waste implementation (e. g. for Germany or for Ukraine). So, the proposed methodology of environmental potential could be used for different countries to show benefits of co-processing of waste.

### 6. Discussion of possibilities of co-processing waste in cement kilns

The technology of co-processing waste in cement kilns is a viable option and could contribute substantially to achieve this goal. The total  $\text{CO}_{2\text{eq}}$  reducing potential has been estimated to be up to  $400 \text{ kt}_{\text{CO}_{2\text{eq}}}/\text{a}$  (which is up to 0.3 % of Ukrainian total annual  $\text{CO}_{2\text{eq}}$  generation), which includes up to  $111 \text{ kt}_{\text{CO}_{2\text{eq}}}/\text{a}$  from landfills and up to  $284 \text{ kt}_{\text{CO}_{2\text{eq}}}/\text{a}$  from substitution of fossil fuel in clinker production.

Fig. 1 shows the expected benefits for the environment and resource consumption for a full co-processing implementation in Ukraine.

These results are important for the number of countries, because the key barriers for implementation of co-processing are comparable, as it was shown in the literature review before. The provided environmental analysis and proposed measures to mitigate the barriers for co-processing of waste for Ukrainian conditions could be multiplied in different countries.

Some stakeholders are concerned that some constituents contained within some wastes that are recovered for use as either raw materials or fuel could influence the concrete or be released from the cement product or concrete. This concern is heightened as concrete is a major component of residential construction and is often used in pipes. The topic has been the subject of numerous research studies over the last 20 years and more. Aggressive testing carried out by NSF/ANSI Standard 61 [32] (a third party certification process for drinking water pipes in the United States) has shown that metals in the cement become bound in the concrete calcium silicate structure and in this form do not leach from the product. Similar results have been reported in many other reports by the Association Technique de l'Industrie des Liants Hydrauliques [33], Construction Technology Laboratories [34], Forschungsinstitut der Zementindustrie [35],

Cembureau [36], the European Committee for Standardization [37], etc. There is substantial evidence that cement manufactured from the types of waste recommended in these guidelines does not change the performance or characteristics of the cement or concrete; high levels of some minor components can affect cement performance, and the manufacturer needs to take care that specific thresholds are not exceeded [38].

The proposed methodology shows the basis numbers for argumentation of co-processing of waste in cement kilns benefits, which could be found in several specific multipliable steps (it is general for different countries, just the morphology of waste in the region needs to be checked). Such estimation is not provided in [39, 40], which are the basis for the certification of co-processing plants.

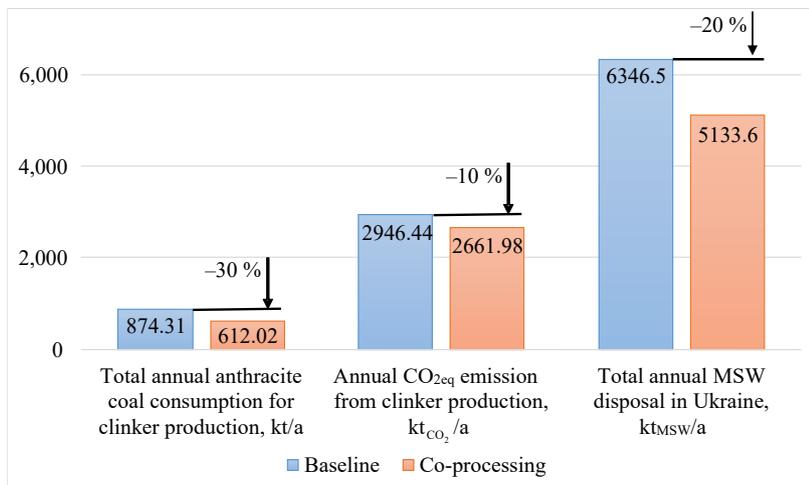


Fig. 1. Estimated benefits for the environment and resource consumption of a comprehensive co-processing implementation in Ukraine

The investigation proposes a short basis step-by-step calculation of environmental potential estimation, which could be used for the preparation of project documents or the argumentation for governments.

The threats of the investigations could be the next:

- not proper estimation of the morphology of waste in the region, which is the basis data for all environmental potential calculations. For some regions, the waste morphology could be not accepted, or it will less high calorific fractures for co-processing in cement kilns;

- not considered season variation of waste (e. g. in touristic regions), which could influence the result of the calculations.

## 7. Conclusions

1. The list of countries are faced with the following key barriers on the way to implementing the technology of co-processing waste in cement kilns: lack of methodologies for investigating the benefits of co-processing of waste implementation, complicated process of permitting, myriad of regulations and standards, lack of financial support, no full cost accounting, public acceptance, lack of infrastructure and qualified workforce. A list of potential solutions and a methodology for the environmental potential of co-processing of waste investigation were proposed.

2. The potential benefits of implementation of the co-processing of waste in cement kilns technology for the Ukrainian cement industry using experimental data on specific fuel consumption and clinker share value:

- decreasing anthracite coal consumption in clinker production by 262 kt/a;
- preventing up to 284 kt<sub>CO<sub>2eq</sub></sub> emissions per year from substitution of coal in clinker production.

3. For the Ukrainian waste management sector, possible benefits of implementation of co-processing were investigated:

- energy recovery up to 1,213 kt<sub>MSW</sub>/a (which is 19 % of total amount of municipal solid waste generated annually in Ukraine);
- prevention of up to 111 kt<sub>CO<sub>2eq</sub></sub>/a of GHG emissions from landfills.

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