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Cost-effectiveness analysis and cost-benefit analysis for X-type zeolite production from fly ash

Introduction

Electricity and heat production processes in which hard coal is burned generate large amounts of energy waste. To demonstrate their raw material potential, they are often referred to as anthropogenic minerals or by-products of combustion. The scale of the problem is primarily evidenced by the amount of waste generated and the degree to which it is managed. It is estimated that between 900 and 1,000 million Mg of this type of waste is produced annually worldwide.

In Poland, about twenty million Mg of waste is generated annually in the production of electricity and heat. Energy waste is the third-largest waste in the industry in terms of volume,

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of which only about 60% is recycled. In the European Union, they amount to around 100 million Mg per year, and in the United States, to as much as 130 million Mg. In the USA, the energy waste management rate is around 41%. The rest is stored or deposited in landfills (Ochociński 2016).

Energy wastes present an enormous scientific and technical challenge. These issues also raise serious challenges in terms of the technology used to convert them into useful products in quantity and quality to ensure safe use in various types of engineering work.

As the provided data shows, the management of such a large amount of energy waste remains a problem worldwide, even in highly developed countries with a high rate of technological advancement, large amounts of energy waste remain in landfills. Experts predict that the amount of energy waste generated per year will continue to grow, with a slight increase in the level of reuse in industry.

A significant proportion of energy waste is used and managed primarily for the production of concrete and cement, as well as for stabilizing land in road construction and mines but also as a base material and for the liquidation of boreholes (Pathan et al. 2022; Heba 2021; Renjith et al. 2021; Hefni et al. 2018).

However, significant amounts of ash is stored, thus polluting the environment. Energy waste, both from energy facilities and from landfills, is a valuable source of raw materials and mineral products. In countries where the share of burnt coal in the energy mix is declining and technological progress is increasing significantly, it is the waste accumulated in landfills that is becoming increasingly important. The reuse of energy waste is crucial not only in terms of many national and international strategies (e.g. circular economy, waste hierarchy, and national raw material safety) but also in terms of the strategies of many different degraded regions, through mining and/or power engineering activities (Decisions EU 2017).

It should be noted that the current management system for such a large source of waste has practically exhausted its capacities, or even failed to meet expectations. At the same time, the growth of technological progress enables the increasingly more advanced directions of waste use (Strzałkowska 2021; Mačala et al. 2017; Stępień et al. 2017; Ochociński 2016; Galos and Uliasz-Bocheńczyk 2015; Hycnar et al. 2014; Strzałkowska 2011; Kapuściński and Probierz 2020).

One such promising direction may be the production of synthetic zeolites from fly ash. The literature review indicates that the methods developed for the synthesis of zeolites from fly ash include methods differing primarily in the pre-treatment processes, the addition of alkali, synthesis process parameters, etc. The research presented in other papers clearly illustrates that the synthesis of zeolites depends on the physicochemical properties of the raw material and the reaction mixture (Ahmaruzzaman 2010; Querol et al. 2001, 2002). The current state of the art can easily be used to further advance the zeolite synthesis processes at the commercial level, using fly ash as the primary source of raw material.

It is known that zeolites have many beneficial properties, but their profitable production in Poland using fly ash as a raw material has still not been determined. The X-type zeolites belong to the group of faujasite (FAU code), the structure of which is as follows: β-cages and hexagonal prisms are connected in such a way that large internal super cages (α-cages) are created. Molecules, including CO2, can enter the α-cages through 12 Membered Ring. The windows have a diameter of 7.4 Å (Deams et al. 2006).

The economic analysis of X-type zeolite production according to the hydrothermal method based on fly ash from the combustion of hard coal (Adamczyk et al. 2020) was carried out to identify the main factors determining its efficiency. The analysis uses available market information, including production-cost analysis including capital expenditure and operating costs, as well as zeolite market-price analysis. The processing of CBPs into fully fledged and safe products, which can then be used in other industries, has become an important element of the circular economy implemented at the European level. It is also of key importance in the context of European climate and environmental policy, focused on the maximum reduction of carbon dioxide emissions. The key factor that determines the use of CBPs is the economic evaluation and profitability of implementing new technologies. The article presents a preliminary profitability assessment of zeolite production in Poland with the use of fly ash as a raw material.

1. Methods and materials

1.1. Synthesis of zeolite

Fly ash from hard coal combustion in a pulverized coal boiler taken from an electrostatic precipitator from one Polish power plant in the Silesian Voivodship was selected for synthesis. The synthesis of zeolites was carried out by the hydrothermal method (Adamczyk et al. 2020; Belviso 2018; Franus et al. 2014).

The main chemical component for fly ash was performed by wavelength dispersive X-ray fluorescence spectroscopy (WDXRF) using a ZSX PRIMUS II analyzer (Rigaku, Tokyo, Japan) equipped with a 4 kW X-ray Rh tube; the samples were prepared by borate fusion (1 g sample: 9 g flux), the beads were obtained by melting the resulting mixture at a temperature of 1,050°C.

The identification of phases by X-ray diffraction (XRD) for fly ash and products of synthesis was performed on an Aeris 1 diffractometer (Malvern Panalytical, Malvern, UK) with a CuKα lamp. The conditions of measurement were as follows: voltage – 40 kV, current – 8 mA, time – 4.84 s, increment of the 2-theta angle – 0.003°, range of 2-theta angle – 4°–74°. The HighScore Plus software with the database was used to interpret the XRD spectra.

The efficiency of the synthesis process was evaluated on the basis of the amount of X-type zeolite synthesized in the obtained product by XRD. The conditions under which the greatest amount of X-type zeolite was obtained were established as optimal.

CO_2 sorption measurements were made using an analyzer ASAP 2010 Accelerated Surface Area and Porosimetry System (Micrometrics, USA). Before the measurement samples were rinsed with helium and heated at 473.15K for 4 h. The tests were carried out at a temperature of 25°C and a pressure of 0.1 MPa.

1.2. Cost-effectiveness analysis of zeolite production

The cost-effectiveness analysis of zeolite production using the technology developed in GIG was carried out using the dynamic generation cost (DGC). Dynamic generation cost is equal to the price that enables discounted income equal to discounted costs. The DGC indicates the technical cost of obtaining a unit of product (1 Mg zeolites). The DGC is calculated by the formula (Rączka 2002):

$$DGC = \frac{\sum_{t=0}^{n} \frac{KI_t + KE_t}{(1+i)^t}}{\sum_{t=0}^{n} \frac{P_t}{(1+i)^t}} \tag{1}$$

KI_t – investment costs for a given year,
KE_t – operating costs for a given year,
P_t – production volume for a given year,
i – financial discount rate of 6% according to the announcement of the Narodowy Bank Polski on base rates (NBP),
t – year, takes values from 0 to n, where 0 is the year in which the first costs are incurred, and n is the last year of operation of the installation.

The result obtained in the form of the DGC indicator, by reference to its value to the market prices of the product analyzed (zeolites), will make it possible to determine the profitability of production. If the value of the calculated DGC is higher than the market price of the product, it should be expected that the product offered at a price above the market price will not attract buyers. The investment must then be considered to be economically inefficient.

1.3. Cost-benefit analysis of zeolite production

The cost-benefit analysis was completed using the social cost-benefit analysis (SCBA). The CBA is a method of comparing and assessing the full costs and benefits to society and ecosystems associated with a given activity and covering both its tangible and intangible costs and benefits. This term is used for the economic assessment of specific projects or strategies as well as the results of economic activities (Fiedor 2002).

The CBA is used to assess and compare investment projects, where not all elements determining the level of costs and benefits can be priced by the market. The most important areas of the cost-benefit analysis include (Fiedor 2002):

- defining the purpose of the analysis and identifying the costs and benefits,
- quantification, valuation, and discounting of costs and benefits,
- defining a formula for comparing costs and benefits.

The economic net present value (ENPV) and economic internal rate of return (EIRR) indicators (described below) were used to assess the economic efficiency of the analyzed zeolite production technology.

1.3.1. Economic net present value (ENPV)

Where all elements of the economic analysis can be sufficiently quantified and valorized, the CBA is based on the calculation of the economic net present value (ENPV). The updated values of net cash flow from different years of the project life cycle are added to obtain the ENPV for the analyzed period of the project (Fiedor 2002). The general formula for calculating the ENPV can take the following form for hard-coal mining (European Commission 2008, 2014):

$$ENPV = \sum_{t=0}^{n} a_t \cdot S^E{}_t = \frac{S^E{}_0}{(1+r)^0} + \frac{S^E{}_1}{(1+r)^1} + \ldots + \frac{S^E{}_n}{(1+r)^n} \tag{2}$$

↳ S^E – the balance of economic streams of costs and benefits generated by the production, sale, and use of zeolites in each year of the reference period of the analysis,

n – reference period in years (the period covered by the analysis),

a – social discount factor equal to: $a_t + \frac{1}{(1+r)^t}$,

r – social discount rate of 7%, in compliance with the guidelines (MIiR 2019), 1 percentage point higher than the financial discount rate.

1.3.2. Economic internal rate of return (EIRR)

The level of the economic internal rate of return (EIRR) of the investment is calculated based on the calculated values of the ENPV, using linear interpolation n as follows:

$$EIRR = i_1 + \frac{ENPV_1}{ENPV_1 - ENPV_2} \cdot (i_2 - i_1) \tag{3}$$

i_1 – discount rate at which $ENPV > 0$,
i_2 – discount rate at which $ENPV < 0$,
$ENPV_1$ – $ENPV$ based on i_1,
$ENPV_2$ – $ENPV$ based on i_2.

Both analyses were carried out at fixed prices for a fifteen-year lifetime in compliance with the guidelines (MIiR 2019) for investments under the category “other”. It is assumed that at the end of the fifteen-year operating period, the installation under consideration will be decommissioned and the proceeds from the sale of the assets being decommissioned will finance the costs of this decommissioning.

2. Results

2.1. Process of synthesis of X-type zeolites from fly ash from hard coal combustion – laboratory scale

The first stage of the research was to optimize the process of X-type zeolite synthesis based on fly ash from the combustion of hard coal. The influence of the following parameters on process efficiency was analyzed:

- the type of fly ash,
- the concentration of the reaction solution (NaOH solutions 3–6 M),
- the ratio of ash to reaction solution (a mixture of 10–40 ml of solution per 1 g of ash),
- process temperature (60–90°C),
- process duration (8–36 h).

The ash selected for the synthesis contained 49.50 wt.%. SiO_2 and 28.03 wt.% Al_2O_3. The amount of amorphous phase present in the ash was 78.1 wt.%. (Table 1–2).

Table 1. Chemical composition of ash and LOI

Tabela 1. Skład chemiczny popiołu i LOI

SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	Na_2O	K_2O	SO_3	TiO_2	P_2O_5	Mn_3O_4	LOI	$SiO_2 +$ $+ Al_2O_3$	Molar ratio SiO_2/Al_2O_3
(wt.%)													
49.50	28.03	6.68	3.27	2.70	1.08	3.35	0.48	1.08	0.54	0.09	3.03	77.53	3.0

LOI – Loss on ignition (at 815°C).

Depending on the process conditions, a material containing the following types of phases in various proportion was obtained: Na-LSX, hydrosodalite, ash relict phase (Table 2). It has been established that the optimal process of the synthesis of X-type zeolites based on selected fly ash from hard coal combustion involves the following stages (Figure 1):

- preparation of the mixture of fly ash and 3M NaOH solution at a ratio of 1 g of ash per 25 ml of solution,
- hydrothermal conversion of the mixture at 80°C for 16 hours,
- filtration and washing the product with distilled water to remove residual NaOH solution,
- drying the product at 60°C to a constant mass.

Table 2. The phase composition of ash and zeolite materials

Tabela 2. Skład fazowy popiołu i materiałów zeolitowych

Glass	Quartz	Alumino-silicates	CSPH	OHo
Ash (wt.%)				
78.1	3.4	16.4	0.4	1.7
Zeolite materials (wt.%)				
Na-LSX	Hydrosodalite	Ash relict phase		
0–54.0	0–55.9	34.7–100		

CSPH – carbonates, sulfates, phosphates, halides, OHo – oxides, hydroxide (including spinels), ash relict phase – hematite, mullite, quartz, glass.

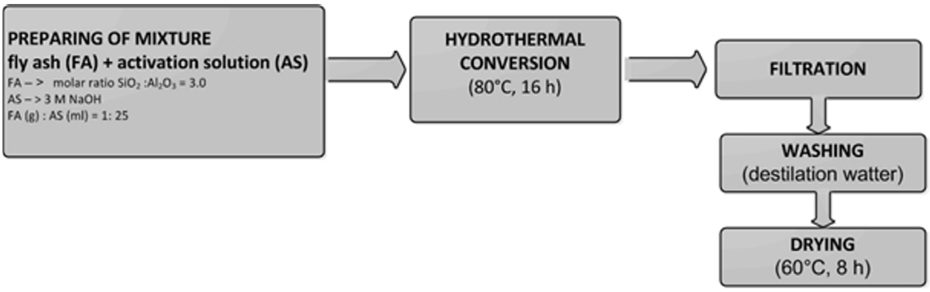

Fig. 1. Scheme of the X-type zeolites synthesis process

Rys. 1. Schemat procesu syntezy zeolitów typu X

The maximum CO_2 volume adsorbed by the zeolite material obtained in the established optimal condition was 34 cm^3/1 g.

2.2. Design of a process line for the synthesis of zeolites from fly ash

The designed industrial installation (Figure 2) consists of five reaction vessels, each with a working capacity of 25 m^3. The synthesis of zeolites is carried out in a periodical system, which takes into account the four-fold turning back of the reaction leachate. The components of the installation (reactor, leachate storage, and intermediate tanks, pipelines, pumps, mixers, etc.) will be made of stainless steel, so-called 18/10 steel (18% Cr, 10% Ni).

The installation consists of four process nodes:

- storage tanks and loading of substrates,
- reactors,
- purification and separation of zeolites,
- drying and storage of zeolites.

The node of storage and substrate loading tanks are three tanks in which sodium hydroxide solution, water and fly ash are stored. The ash container is equipped with a feeder and vibrator. The ash container is equipped with a feeder and shaker. The belt is equipped with a strain gauge scale, which ensures the dosing of ash at the required amount. The water tank

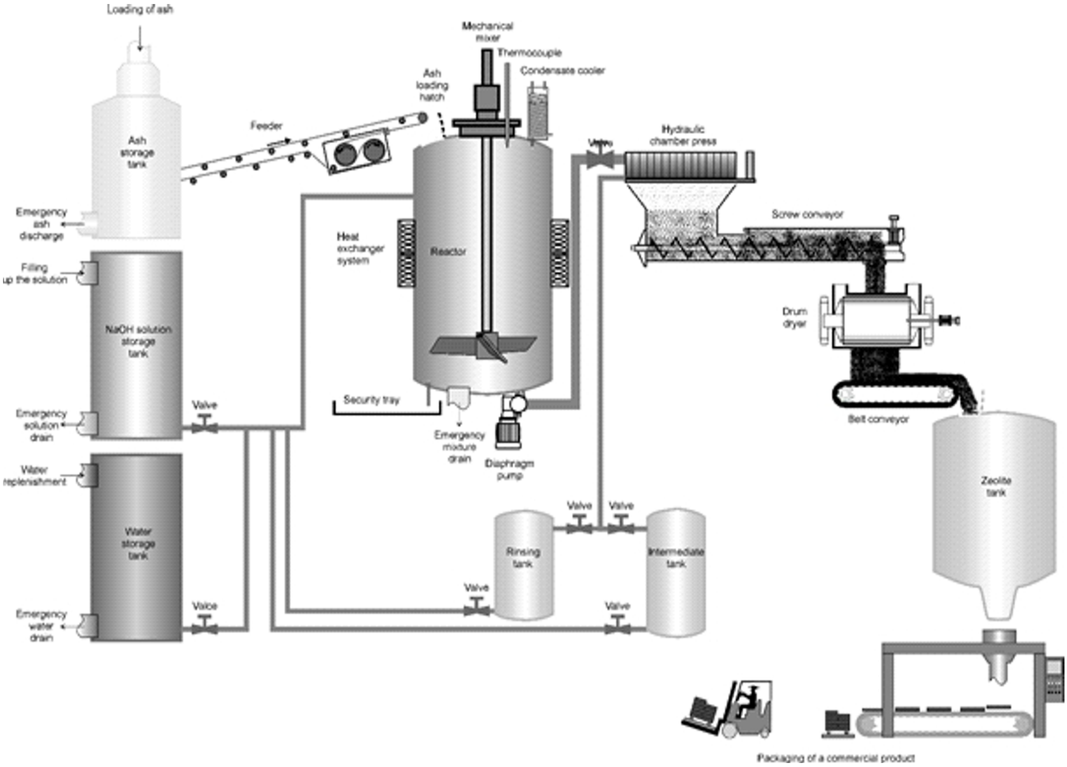

Fig. 2. Diagram of the industrial installation (for 1 reaction vessel)

Rys. 2. Schemat instalacji przemysłowej (dla 1 zbiornika reakcyjnego) has a pump with flow-rate control and a water meter. The NaOH solution tank has a pump and instrumentation to control the quantity and intensity of the pumped reagent.

The reaction tank with a working volume of 25 m^3 (total volume 30 m^3) is equipped with a mechanical mixer with a regulator, a condensate cooler, an ash-loading hatch, connections for water and NaOH solution supply, a thermocouple, a heat-exchanger system, an overflow safety valve, a drain connection for reaction products and control and measurement equipment containing sensors for tank filling, temperature, agitator operation control, and pumps and a conveyor belt dosing substrates to the reactor.

A tray has been built under the reaction tank to limit the consequences of possible failure and to fulfill the need for emergency emptying of the reactor.

In the lower bottom of the reactor, there is a drain connection with a valve and a diaphragm pump. The content of the reactor after the synthesis, suspension, and post-reaction sludge containing zeolites, is pumped to a hydraulic chamber press. The press discharge, in the form of NaOH solution, is pumped to the intermediate tank. After the excess NaOH is removed, the contents of the press are rinsed with water and the resulting leachate, containing the diluted NaOH solution, is directed to the rinsing tank, from which, after being replenished with the NaOH solution to the concentration required in the process, it is pumped, together with the leachate from the chamber press, to another reactor. The sludge of "wet" zeolites obtained after the dehydration of synthesis products on a chamber press is fed by a screw conveyor to a drum dryer for further water drainage and drying. The drum dryer is equipped with a device for measuring the water content in zeolites.

After drying, using a belt conveyor, the zeolites are transported to the finished product storage tank. In the next node of the installation, zeolites are packed into sacks, containers, etc.

All devices and elements of the installation for the synthesis of zeolites are equipped with control and measurement apparatus. This enables ensuring the required process parameters and the quantitative and qualitative optimization of the conducted process.

2.3. Assumptions

The cost-effectiveness analyses (in this case: the dynamic generation cost DGC) and the cost-benefit analysis (CBA) were carried out for a plant with five 25 m^3 process reactors each with the production of zeolites continuously (24 hours a day) for 300 days a year. Capital expenditure, operating costs, and production volumes were estimated for the installation.

In addition to the investment costs, the following items of operating costs were included in the cost analysis:

- purchase of raw materials for zeolite production,
- electricity to supply the associated equipment,
- remuneration of service staff,

- installation repair and maintenance costs,
- installation insurance costs,
- property tax.

The external costs of producing electricity for the production of zeolite are also treated as a cost. The following factors were included as benefits:

- avoided costs of purchasing zeolite from external companies,
- revenue from the sale of zeolite after the process of capturing CO_2 as a building aggregate – it is assumed that zeolites after being used as a CO_2 capture substance will be used as an aggregate in the building industry, which will be an additional source of revenue for its user,
- avoided external costs – the capture of CO_2 and other gaseous pollutants using zeolite,
- avoided external costs associated with the extraction of aggregates as an alternative to zeolite,
- avoided costs of purchasing the right to emit CO_2 into the atmosphere.

Calculation assumptions including estimates of capital expenditure and operating costs are presented in Tables 3 and 4.

It was assumed that it would be an installation operating within the technological structure of a utility power plant, using the waste heat generated in this power plant in the process

Table 3. Capital expenditure for the analyzed installation with a working capacity of 5×25 m^3

Tabela 3. Nakłady inwestycyjne dla analizowanej instalacji o pojemności roboczej 5×25 m^3

Item	Unit cost (EUR)	Qty. (pcs.)	Total cost (EUR)
Waste heat recovery installation	221,000	1	221,000
Process reactor and its equipment	35,000	5	175,000
Installations, fittings, controls	26,000	1	26,000
Hydraulic press	6,000	2	12,000
Intermediate tank for “wet” zeolites	3,000	2	6,000
Drum dryer	4,000	2	8,000
Zeolite storage tank	3,000	2	6,000
Zeolite packaging line	9,000	1	9,000
Substrate tanks with pumps and feeders	4,000	4	16,000
Construction of a hall with an area of 100 m^2 for the production, packaging, and storage of zeolite production parts	177,000	1	177,000
Total			656,000

Own calculations based on producers’ market prices.

Table 4. Operating data of the analyzed installation with a working capacity of 5×25 m^3

Tabela 4. Dane eksploatacyjne analizowanej instalacji o pojemności roboczej 5×25 m^3

Item	Unit	Qty.
Capacity of 1 reactor	m^3	25.00
Ash	Mg/cycle/reactor	2.50
	EUR/Mg	3.73
10% NaOH solution	Mg/cycle/reactor	2.25
	EUR/Mg	108.00
Water	Mg/cycle/reactor	16.25
	EUR/Mg	1.47
Electricity-associated equipment	kW	10.00
	h of work/day	10.00
	kWh/day	500.00
	EUR/kWh	0.18
	EUR/day	90.00
Labor	full-time/shift	2.00
	shift/day	3.00
	full-time/day	6.00
	EUR/months/full-time	1,450.00
Production volume of zeolite	Mg/cycle/reactor	2.50
	Mg/year	3,750.00
The market price of zeolite including transport costs	EUR/Mg	390.00
Number of reactors	pcs.	5.00
Repair and maintenance costs	EUR/year	12,700
Insurance costs	EUR/year	6,200
Duration of 1 charge	h	24.00
Number of production cycles per single reactor per year	cycle/reactor/year	300.00
Number of production cycles for all reactors per year	cycle/year	1,500.00

Own calculations based on market prices and technological assumptions.

of producing electricity. Therefore, the operating costs did not assume the costs of purchase or the production of heat for the installation. In addition, the efficiency of CO_2 capture by zeolites was assumed to be 7% of its mass.

The results of the calculation of external costs for an installation producing 3,750 Mg/year of zeolites was calculated using unit external costs of electricity generation in the commercial power industry in Poland (Radovic 2009) and emissivity indices for electricity in Poland (KOBIZE 2021). The calculation results are presented in Tables 5–8.

Table 5. External costs related to electricity generation for the production of zeolites

Tabela 5. Koszty zewnętrzne związane z wytwarzaniem energii elektrycznej do produkcji zeolitów

Item	Unit	Value
External cost of electricity generation (Radovic 2009) – unit costs:		
SO_2	EUR/MWh	25.10
NOx	EUR/MWh	9.43
$PM_{2.5–10}$	EUR/MWh	0.08
$PM_{2.5}$	EUR/MWh	0.75
NMVOC	EUR/MWh	0.05
CO_2	EUR/MWh	22.07
Total:	EUR/MWh	57.48
Electricity consumption of associated equipment	MWh/year	150
External cost of electricity generation for the production of zeolites	EUR/year	8,622

Source: own calculations based on literature data (Radovic 2009) and technological assumptions.

Table 6. Average external costs of air pollutant emissions for domestic thermal power plants

Tabela 6. Średnie koszty zewnętrzne emisji zanieczyszczeń powietrza dla krajowych elektrociepłowni

Item	Average external costs of air pollutant emissions for domestic thermal power plants (EUR/Mg of pollution)			
	SO_2	NOx	$PM_{2.5}$	CO_2
People's health	6,673	6,751	24,261	0
Biosystem	201	906	0	0
Agricultural crops	–54	435	0	0
Building materials	259	131	0	0
Greenhouse effect	0	0	0	36
Total	7,079	8,223	24,261	36

Source: NEEDS 2009.

Table 7. The external costs that were avoided in the extraction of natural aggregates

Tabela 7. Koszty zewnętrzne, których uniknięto przy wydobyciu kruszyw naturalnych

Item	Unit	Value
Emissions from the extraction of 3,750 Mg of aggregates		
CO_2 emission	Mg/year	11.67
SO_2 emission	Mg/year	0.0060
NO_2 emission	Mg/year	0.0055
PM_{10} emission	Mg/year	0.0057
External cost of extraction 3,750 Mg of aggregate		
CO_2 emission	EUR/year	420.00
SO_2 emission	EUR/year	42.18
NO_2 emission	EUR/year	45.33
PM10 emission	EUR/year	138.79
Total	EUR/year	646.3

Source: own calculations based on literature data (NEEDS 2009) and technological assumptions.

Table 8. External costs that were avoided in relation to the use of zeolites for the capture of CO_2 and other pollutants associated with emissions to the atmosphere from the energy industry

Tabela 8. Koszty zewnętrzne, których uniknięto w związku ze stosowaniem zeolitów do wychwytywania CO_2 i innych zanieczyszczeń związanych z emisją do atmosfery z energetyki

Item	Unit	Value
CO_2 capture efficiency	%	7.00
Amount of CO_2 captured per 1 Mg of zeolites	Mg/Mg	0.07
Production volume of zeolites	Mg/year	3,750.00
Amount of CO_2 captured using the produced amount of zeolites	Mg/year	262.50
Value of external cost avoided as a result of CO_2 capture	EUR/Mg	36.00
	EUR/year	9,450.00
Value of external cost avoided as a result of capturing other contaminants	EUR/Mg	35.41
	EUR/year	12,477.00

Source: own calculations based on literature data (Radovic 2009) and technological assumptions.

The operating costs of the zeolite production installation adopted for the calculation as well as additional and avoided social and environmental costs were corrected in the subsequent years of the analysis with the indicator of real growth of service prices, estimated based on macroeconomic data adopted according to (MFiPR 2020). The projection of prices of CO_2 emission rights for the years 2020–2022 was adopted based on a study by the National Centre for Emissions Management in Poland (KOBiZE 2022). In the following years of the analysis, the fixed price from 2028 was adopted. The macroeconomic assumptions used in the calculation are presented in Table 9.

Table 9. Macroeconomic assumptions

Tabela 9. Założenia makroekonomiczne

Year	Forecast				
	energy price growth (%) [1]	rate of property tax (%) [2]	real renumeration growth (%) [3]	real service price growth index (%) [4]	prices of CO_2 emission rights (EUR/Mg CO_2) [5]
2022	10.0	2.0	1.9	106.0	84.45
2023	10.0	2.0	2.2	106.1	86.82
2024	5.0	2.0	2.7	103.9	89.76
2025	5.0	2.0	2.9	104.0	93.02
2026	5.0	2.0	3.0	104.0	96.52
2027	5.0	2.0	3.0	104.0	100.02
2028	5.0	2.0	3.0	104.0	103.52
2029	5.0	2.0	3.0	104.0	103.52
2030	5.0	2.0	3.0	104.0	103.52
2031	5.0	2.0	3.0	104.0	103.52
2032	5.0	2.0	3.0	104.0	103.52
2033	5.0	2.0	2.9	104.0	103.52
2034	5.0	2.0	2.9	104.0	103.52
2035	2.0	2.0	2.9	102.5	103.52
2036	2.0	2.0	2.9	102.5	103.52
2037	2.0	2.0	2.8	102.4	103.52

[1] own assumptions; [2] Polish tax regulations; [3] MFiPR 2020; [4] own calculation based on energy prices growth and real remuneration growth; [5] KOBIZE 2022.

2.5. Results of the cost-effectiveness analysis and the cost-benefit analysis

Tables 10 and 11 show the cash flows and the results of the cost-effectiveness analysis (here: DGC) and the cost-benefit analysis (ENPV and EIRR) for selected years of the study.

The calculated unit technical manufacturing cost of 1 Mg of zeolite expressed by the DGC is lower than the current market price of this product, including transport costs, i.e. about 389 EUR/Mg (MAG, Made-in-China). This indicates the possible financial viability of the operation of the installation.

The results of the calculations show that when the social and environmental costs are included, the zeolite production technology presented in this paper is very profitable for the community. It generates more social and financial benefits than costs. Furthermore, the economic internal rate of return (EIRR) is clearly higher than the discount rate used in the calculation.

In the case of the price of commercial zeolites, the manufacturer does not provide information on the synthesis conditions, installation size, socio-environmental costs, etc. Zguroeva and Boycheva (Zguroeva and Boycheva 2015) referred only to the laboratory scale, assuming the cost of used reagents and energy in the calculation, which significantly affected the estimated value. Franus and Wdowin (Franus and Wdowin 2011) estimated the price of zeolite production in a semi-technical installation with a production volume of 50 Mg/year.

Table 10. Cash flow and the calculated DGC indicator

Tabela 10. Przepływy pieniężne i wyliczony wskaźnik DGC

Item	Unit	Values in years				
		2022	2023	2025	2030	2037
Investment costs	EUR	656,000	0	0	0	0
Raw materials	EUR	0	414,319	447,266	544,167	683,552
Electrical power	EUR	0	27,000	29,768	37,992	49,006
Employee remuneration	EUR	0	104,400	110,328	127,901	156,387
Repair and maintenance costs	EUR	0	12,700	13,710	16,680	20,953
Insurance costs	EUR	0	6,200	6,693	8,143	10,229
Property tax	EUR	0	13,120	13,120	13,120	13,120
Total	EUR	656,000	577,739	620,884	748,003	933,247
Production volume of zeolite	Mg	0	3,750	3,750	3,750	3,750
DGC	EUR/Mg	211				

Own calculations.

Table 11. Cash flow and the calculated ENPV and EIRR indicators

Tabela 11. Przepływy pieniężne i obliczone wskaźniki ENPV i EIRR

Item	Unit	Values in years				
		2022	2023	2025	2030	2037
Costs						
Investment costs	EUR	656,000	0	0	0	0
Raw materials	EUR	0	400,331	432,166	525,796	660,476
Electrical power	EUR	0	27,000	29,768	37,992	49,006
Employee remuneration	EUR	0	104,400	110,328	127,901	156,387
Repair and maintenance costs	EUR	0	12,700	13,710	16,680	20,953
Insurance costs	EUR	0	6,200	6,693	8,143	10,229
Property tax	EUR	0	13,120	13,120	13,120	13,120
External costs of electricity generation for zeolite production	EUR	0	8,622	8,622	8,622	8,622
Total costs	EUR	656,000	572,373	614,406	738,253	918,792
Benefits						
Avoided costs of purchasing zeolite from external companies	EUR	0	1,551,713	1,520,269	1,521,000	1,497,600
Revenue from the sale of zeolite after the capture of CO_2 as a building aggregate	EUR	0	55,500	55,500	55,500	55,500
Avoided external costs–capture of CO_2 and other gaseous pollutants using zeolite	EUR	0	21,927	21,927	21,927	21,927
Avoided external costs associated with the extraction of aggregates as an alternative to zeolite	EUR	0	646	646	646	646
Avoided costs of purchasing the right to emit CO_2 into the atmosphere	EUR	0	22,790	24,418	27,174	27,174
Total benefits	EUR	0	1,652,576	1,622,759	1,626,247	1,602,847
Net cash flow	EUR	–656,000	1,080,202	1,008,353	887,994	684,055
Discounted cash flows	EUR	–656,000	1,009,535	823,116	516,820	247,933
Economic internal rate of return (EIRR)	%	160.9				
Economic net present value (ENPV)	EUR	7,664,898				

Own calculations.

The unit technical cost of zeolite production presented in this work refers to industrial installation with a production volume of 3,750 Mg/year (Table 12). There is no economic analysis of zeolite production based on fly ash in such a broad and comprehensive approach in the literature as is the case in the presented work.

Table 12. Comparison of zeolite price and cost

Tabela 12. Porównanie ceny i kosztu zeolitu

Price/cost Euro/Mg	Description	Source
871–1,045	Commercial product/price of synthetic zeolite – China	Exportv
965–1,158	Commercial product/price of synthetic zeolite – Germany	
389	Commercial product/price of natural zeolite, including transport costs	estimated on the basis of MAG, Made-in-China
2,998	Calculation/price of product – a semi-technical scale (50 Mg product/year)	Franus and Wdowin 2011
2,776 –6,639	Calculation/cost of product – a laboratory scale	Zguroeva and Boycheva 2015
211	Calculation/unit technical cost of zeolite – an industrial scale (3,750 Mg product/year)	own work

The currencies were converted at the exchange rate of 12/08/2022.

Conclusion

The results of the laboratory tests on the quality of zeolites derived from fly ash initiated the assessment of the costs of the production of minerals on an industrial scale. This analysis covers the investment, raw material and process costs as well as environmental aspects related to avoiding external costs (the purchase of zeolites, emissions, etc.).

The cost-effectiveness-analysis was conducted using the dynamic-generation-cost indicator (DGC) analysis. The analyses showed that the calculated unit technical cost of producing 1 Mg of zeolites using an installation consisting of five reactors with a capacity of 25 m^3 each is 211 EUR and is lower than the market price of this product, including transport costs. This proves the financial viability of the investment.

The cost-benefit analysis (CBA) was completed using the economic net present value (ENPV) and the economic internal rate of return (EIRR) indicators. The results of the calculations prove that when the social and environmental costs are included, the zeolite production technology described by the authors is very profitable from the point of view of the community. It will generate more social and financial benefits than costs. The EIRR is clearly higher than the discount rate used in the calculation.

The results of the cost-effectiveness analysis and the cost-benefit analysis fully confirm the economic viability of such an investment.

The developed concept of zeolite production on the basis of using fly ash on an industrial scale is in line with the assumptions of the circular economy. The presented solution assumes:

- the installation is located on the premises of the power plant,
- waste generated in the energy production process, i.e. fly ash and waste heat, are used for the production of zeolite,
- the obtained product is used to reduce CO_2 emissions from the energy production process.

The obtained material has a wide range of applications. After using it for CO_2 sorption, it can be used as:

- an additive to soil substrates,
- a sorbent to purify water from heavy metals,
- an additive for construction materials, which additionally emphasizes its role in the functioning of the circular economy (COALBYPRO 2020).

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COST-EFFECTIVENESS ANALYSIS AND COST-BENEFIT ANALYSIS FOR X-TYPE ZEOLITE PRODUCTION FROM FLY ASH

Keywords

cost-benefit analysis (CBA), cost-effectiveness analysis,
dynamic generation cost (DGC), zeolite, fly ash

Abstract

This paper presents the results of a cost-effectiveness analysis and a cost-benefit analysis for the production of X-type zeolites from fly ash.

Positive results of the laboratory tests on the quality of zeolites derived from fly ash initiated a cost analysis on the production of this materials on an industrial scale. The cost-effectiveness analysis was conducted using the dynamic generation cost indicator (DGC). The calculated DGC expresses the technical manufacturing cost of 1 Mg of synthetic zeolites. Whereas the cost-benefit analysis (CBA) was completed using the economic net present value (ENPV) and the economic internal rate of return (EIRR) indicators.

The calculated unit technical cost of producing 1 Mg of zeolites using an installation consisting of five reactors with a capacity of 25 m^3 each is 211 EUR and is lower than the current market price of this product, including transportation costs. This proves the financial viability of the investment. The calculations of the economic efficiency of the installation (CBA method) show that it is fully economically viable to operate and use the products from a social point of view.

ANALIZA EFEKTYWNOŚCI KOSZTOWEJ I EKONOMICZNEJ PRODUKCJI ZEOLITÓW TYPU X Z POPIOŁÓW LOTNYCH

Słowa kluczowe

analiza kosztów i korzyści (CBA), ocena efektywności kosztowej,
dynamiczny koszt jednostkowy (DGC), zeolit, popiół lotny

Streszczenie

W artykule zostały przedstawione wyniki oceny efektywności kosztowej i ekonomicznej produkcji zeolitów typu X z popiołów lotnych.

Pozytywne wyniki badań laboratoryjnych dotyczące jakości materiału zeolitowego otrzymanego z popiołów lotnych były podstawą do przeprowadzenia oceny kosztów ich produkcji w skali przemysłowej. Ocenę efektywności kosztowej przeprowadzono przy wykorzystaniu dynamicznego kosztu jednostkowego (DGC). Obliczony wskaźnik DGC wyraża techniczny koszt produkcji 1 Mg zeolitów syntetycznych. Natomiast analiza kosztów i korzyści (CBA) polegała na obliczeniu ekonomicznej bieżącej wartości netto (ENPV) i ekonomicznej wewnętrznej stopy zwrotu (EIRR).

Obliczony jednostkowy techniczny koszt wyprodukowania 1 Mg zeolitów na instalacji składającej się z 5 reaktorów o pojemności 25 m^3 każdy wynosi 211 EUR i jest niższy od ceny rynkowej tego produktu, wliczając koszty transportu. Świadczy to o opłacalności finansowej inwestycji. Przeprowadzone obliczenia efektywności ekonomicznej instalacji (metodą CBA) potwierdzają w pełni opłacalność jej eksploatacji i wykorzystania produktów z punktu widzenia społecznego.