

GOOD PRACTICES IN IMPLEMENTING THE CIRCULAR ECONOMY IN THE ENERGY SECTOR – CONVERSION OF FLY ASH INTO CONSTRUCTION MATERIALS

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Abstract

The support of actions aimed at reducing levels of pollution emissions into the environment requires popularization of good practices, including those involving solutions in the field of the circular economy. These actions are particularly important in sectors of the economy characterized by a high share of total emissions, as their modernization through economies of scale translates into greater environmental benefits. An example of such a sector is the energy sector. The aim of this paper is to identify and characterize selected processes within the activities of the energy sector, where a circular economy approach can be applied, and to assess the implemented solutions. This analysis was carried out using the largest entity in the Polish power sector as a case study. Process analysis was conducted using the value stream mapping method. The identified circular solutions in the process and product areas constitute an important contribution to promoting the activation of economic entities in actions aimed at improving the state of the environment.

Keywords: circular economy, energy sector, 6R, recycled materials, value stream mapping

1. INTRODUCTION

Implementing a low-emission economy is one of the key tasks set by decision-makers to minimize the negative impact of human activity on the environment. To achieve this, multiple actions must be carried out simultaneously to leverage the synergy effect and achieve the desired outcome. These actions can be implemented by both governmental or local authorities as well as individual businesses [1,2]. The reduction of emission levels can also be implemented differently depending on the sector of the economy. Different actions will be appropriate for the agricultural [3], industrial [4], or service sectors

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[5]. However, regardless of the economic sector, the conceptual principles aimed at reducing emissions are similar and closely interconnected in many aspects. These include concepts such as the 6R approach (reduce, reuse, recovery, recycle, remanufacture, and redesign) [6], the sharing economy [7], and the circular economy [8]. In this study, the perspective of the circular economy was adopted as an approach that is effectively implemented in environmental engineering practice [9] and can help identify good practices in minimizing the negative environmental impact.

Specific solutions in the field of the circular economy vary depending on the sector in which they are implemented. However, the greatest systemic effect can be achieved by changing processes in those sectors of the economy characterized by the highest initial emissions. According to the European Environment Agency, one such sector is energy production, which accounts for 26% of greenhouse gas emissions [10]. One of the actions of European Union countries is efforts to reduce primary energy consumption. In this area, most EU countries achieve the set goals. Unfortunately, not all countries manage to achieve the set targets. Poland is the largest country that does not achieve this level. In addition to quantitative changes in energy consumption, qualitative actions are also being taken to minimize negative impacts. The energy industry in Poland operates based on power plants, heating plants, and combined heat and power plants, which produce primary energy, as well as energy transmission networks as a system enabling energy distribution to consumers [11]. Numerous actions are being taken to minimize negative environmental impacts, including modernization of individual installations, construction of photovoltaic farms, offshore wind farms, or construction of nuclear energy production facilities. However, until the target state is reached, the Polish economy and the entire energy sector (electricity and heat production) are still largely based on hard coal and lignite, with their share in electricity production still exceeding 70% in 2022 [11], despite previous investments in the entire energy sector.

Despite the significant contribution of the energy sector to greenhouse gas emissions, it is worth noting that in recent years, this sector has achieved the largest reduction in emissions levels, confirming the effectiveness of the implemented actions in this area. Considering the achievements in this field, it is valuable to review the processes in the energy sector and leverage the experience to promote good practices helpful in reducing the economy's emissions. Therefore, the aim of this study is to identify and characterize selected processes within the activities of the energy sector, where an approach of the circular economy can be applied, and to assess the implemented solutions. The obtained results may contribute to their popularization and systemic changes in the organization of processes in entities within the energy sector.

2. MATERIALS AND METHODS

2.1. Materials

The identification and evaluation of solutions in the field of the circular economy in the energy sector were conducted using the example of the Polska Grupa Energetyczna (PGE) Capital Group. PGE is the largest enterprise in Poland's power sector in terms of revenue and generated profit. Identifying actions implemented within this entity ensures the representativeness of processes in the conditions of the Polish energy sector. The study utilized statistical data, reports, and documents provided by PGE, including source data regarding the Circular Economy Segment, waste-related documents, and technological documentation. The acquired data include information about by-products of combustion, including fly ashes produced as part of the company's operations, their quantities, parameters, and the processes used for their reuse in production.

2.2. Methods

In the study an analysis of source materials (encompassing both technical specifications and quantitative data compilations) and process analysis within PGE's operations based on the Value Stream Mapping (VSM) method was utilized. VSM is a standard Lean Management tool used for identifying and reducing waste in organizations. It serves to create value and improve efficiency in any industry [12]. VSM is essential among various Lean tools as it presents the current and future scenario of the organization, indicating systemic improvement areas to be implemented. VSM serves as the basic methodology of the evaluation process and can uncover significant opportunities for increasing production speed, reducing costs, saving time, and minimizing environmental degradation [13]. In this study, the presentation of the process in two states refers to the state before the implementation of circular economy actions and after their implementation. Furthermore, as the quality control stage contributes to circularity approach, it was also subjected to process mapping.

3. RESULTS

3.1. Linear approach

In the classical setup, before the implementation of circular economy actions, the processes within PGE's operations took on a linear arrangement. These processes are depicted in the diagram (Fig. 1).

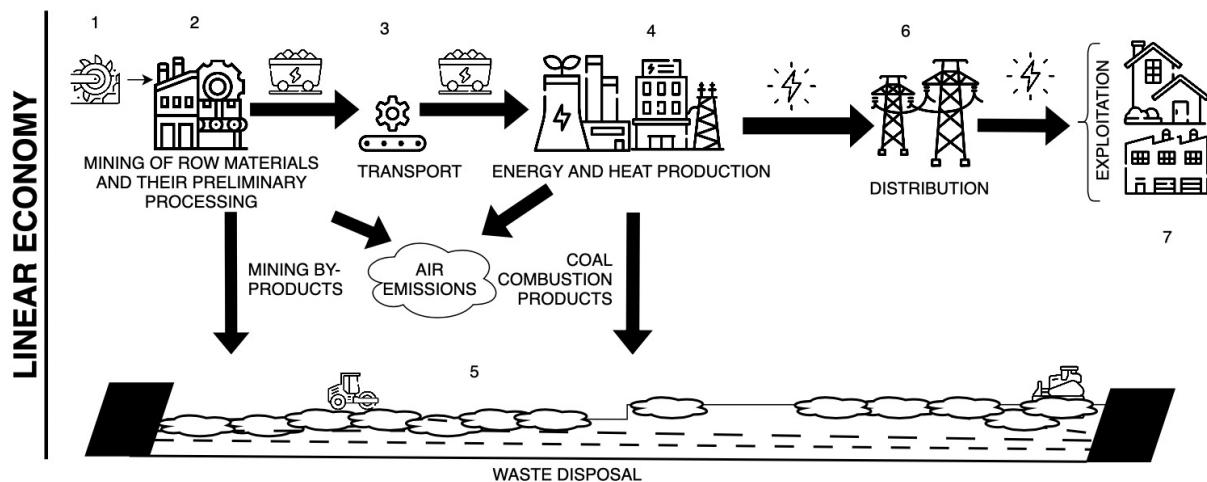


Fig. 1. Main processes in the linear economy system

The energy production process begins with the extraction of energy resources, namely coal (both hard coal and lignite) (1), and their initial processing for energy purposes (2). During this process, by-products of extraction are generated, which ultimately end up in waste disposal sites (5). The next process in the linear economy involves the transportation (3) of processed raw materials to the production unit, where electricity and heat are generated (4). During the combustion of raw materials such as lignite and hard coal, emissions and combustion by-products are produced, which, similar to extraction products, are disposed of in waste disposal sites for proper management (5). The generated energy is distributed (6) to end consumers through transmission networks, where it is utilized for their own purposes (7).

3.2. Output in linear approach

In the linear operation setup of an electricity-generating enterprise, combustion by-products such as fly ash are produced during the energy production process. Fly ash is a pozzolanic material, an inorganic substance of natural or industrial origin that exhibits the ability to react with calcium in water environments under normal temperature conditions, forming insoluble hydrated calcium silicates with hydraulic hardening properties. Pozzolans are divided into two groups: natural and industrial, with the latter sometimes referred to as artificial pozzolans. The primary representatives of natural pozzolans are volcanic pozzolans, which occur as loose volcanic ash sediments or as compact deposits formed from volcanic ash through diagenetic cementation. Considering limitations in accessing natural resources, there is an increasing popularity of industrial pozzolanic materials, with fly ash being a major (if not the only) available pozzolanic resource, the reserves of which are continuously replenished.

Fly ash consists of spherical rounded particles, with varying grain sizes and specific surface areas ranging from 200 to 450 m²/kg. The spherical shape of fly ash particles positively influences the workability of concrete mixtures containing fly ash additives, defining fly ash as a concrete additive according to EN-450:1-2012 standards.

The mineralogical composition of fly ash varies, even within individual particles. The primary components of coal combustion fly ash include quartz, mullite, hematite, and magnetite, with the glassy phase comprising approximately 80% of the composition. The pozzolanic properties of fly ash are closely related to the presence of the glassy phase and the degree of fly ash fineness. Using fly ash as a cement additive improves its fineness through common grinding with cement, leading to micro-cracks on the glassy shell of fly ash particles, enhancing their reactivity.

The main products of the reaction between the active components of fly ash and the calcium hydroxide formed during cement hydration are primarily hydrated calcium silicates and hydrated calcium aluminates. These compounds are mainly located in the pores of the cementitious matrix, resulting in the sealing of the hardened cementitious-fly ash material.

3.3. Quality control

The quality of the obtained fly ash is closely related to the combustion process in the power plant boilers. Therefore, continuous monitoring of the combustion process parameters in the boiler combustion chamber and the operational parameters of the milling units is conducted in the production units (Fig. 2). The by-products of combustion, including fly ash, are produced in the process of burning coal dust.

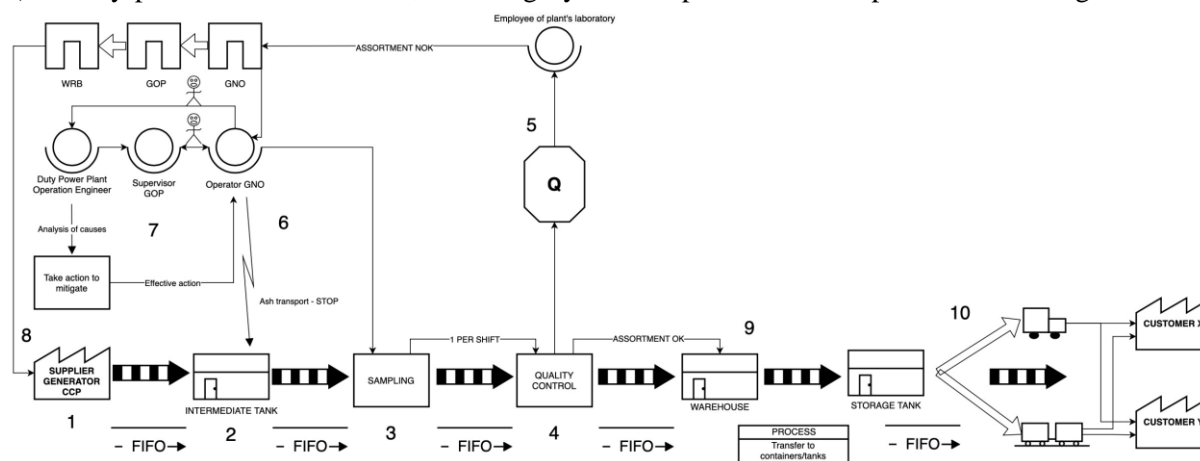


Fig. 2. Combustion by-products quality control process

The production unit (1) generates electric/thermal energy through the combustion of, for example, coal dust, and transports combustion by-products to an intermediate tank (2), from which samples (3) are then taken to determine the loss on ignition and fineness. This action is performed once per shift from the intermediate tank below the electrostatic precipitator for each operating block. The determination of loss on ignition and fineness according to the EN 450-1 standard is carried out in the laboratory of the plant, in accordance with the scope of accreditation held. All measurement values are documented in the laboratory (4), with additional recording of fly ash fineness results from each block at the main ash removal station.

Fly ash is primarily transported from the production unit to storage tanks (9). If the threshold value of the loss on ignition parameter characteristic for the plant is exceeded, or if the fineness exceeds the established limits, the laboratory (5) immediately informs the main ash removal station (GNO). The operator at the main ash removal station, in agreement with the Waste Management Shift Manager, immediately halts the transport of fly ash to the storage tanks (6) and begins transport towards the intermediate tank. At the same time, the ash removal employee informs the block operation department and the Duty Engineer about the situation. The Duty Engineer, in agreement with the subordinate departments, conducts an analysis of the causes of deterioration in the quality of combustion by-products, including fly ash, and takes appropriate actions to eliminate them (7).

After analyzing the effectiveness of corrective actions, the main ash removal station operator orders re-examination of the sampled material by the laboratory. If the loss on ignition and fineness parameters are below the threshold set for the production unit, the main ash removal station, in agreement with the Waste Management Shift Manager, switches the fly ash transport back towards the storage tanks. Information about the resumption of transport is provided to the Duty Engineer and the Block Operation Manager (8).

The laboratory of the production unit exercises internal supervision over the quality of fly ash, thus regularly confirming compliance with the properties of coal combustion products (CCP) according to the EN 450-1 standard. Control determines the chemical and physical properties of the material and compares measurement values with compliance criteria. Sampling is based on a random sample taken from the intermediate tank, the retention warehouse for fly ash destined for shipment, or directly from recipient vehicles (10).

3.4. Parameters of materials

Fly ashes of the silica type (V) produced in cement plant technological installations have been used as the main component of cement. Fly ash for concrete is obtained by burning coal in power plants and combined heat and power plants at temperatures of 1250-1400°C, where a significant part of the inorganic material contained in the coal melts, forming spherical, vitrified grains with diameters ranging from 0.5 µm to about 200 µm. Conventional fly ashes are electrostatically or mechanically precipitated from the flue gas stream exiting the boiler installations and are captured in filters. The particle size fraction of 5-20 µm predominates. The requirements for fly ash as an additive to cement are contained in the PN-EN 197-1:2012 standard.

The composition, requirements, and compliance criteria for common use cements are specified. Fly ash used in cement production can be either the primary or secondary ingredient, but according to the standard definition, fly ash appears as the primary component of cement. Fly ash is obtained by electrostatically capturing dusty particles from flue gases emitted from coal-fired furnaces and can be used in cement compliant with the PN-EN 197-1:2012 standard. The standard allows for the production of cement using silica fly ashes (V).

Silica fly ash (V) is a very fine dust, consisting mainly of spherical particles, with pozzolanic properties. It mainly consists of reactive silicon dioxide (SiO_2) and aluminum oxide (Al_2O_3). The residue contains iron oxide (Fe_2O_3) and other compounds.

Fly ashes used in concrete production must meet the following requirements:

- The loss on ignition content should not exceed 5.0% by mass. Fly ashes with a loss on ignition content ranging from 5.0% to 9.0% by mass may be allowed, provided that individual requirements regarding durability, frost resistance, compatibility with admixtures are met according to the relevant standards and/or regulations for concrete or mortar.
- The reactive calcium oxide (CaO) content should be less than 10.0% by mass.
- The reactive silicon dioxide (SiO_2) content should be no less than 25.0% by mass.
- The free calcium oxide (CaO) content should not exceed 1.0% by mass. Fly ash with a free CaO content higher than 1.0%, but lower than 2.5% by mass, may be allowed, provided that it meets the requirements for volume stability ($\leq 10\text{mm}$) when using a mixture of 30% by mass of ground fly ash and 70% by mass of CEM I cement.

Table 1 presents a comparison of requirements for silica fume fly ashes according to PN-EN 197-1:2012 and the results of ash tests conducted at PGE.

Table 1. Parameters of silica fume fly ash (V) [% by mass] as an additive to cement

Properties	Requirements according to PN-EN 197-1:2012	Test results at PGE
Loss on ignition	$\leq 5,0^1$	2,78
Reactive CaO	$\leq 10,0^2$	4,48
Free CaO	$\leq 1,0^3$	0,19
Reactive SiO_2	$\geq 25,0$	39,76

1) Fly ashes with a loss on ignition ranging from 5.0% to 9.0% by mass may be acceptable, provided that individual requirements concerning durability, frost resistance, compatibility with admixtures are met according to the relevant standards and/or regulations for concrete or mortar in the place of application.

2) Total CaO content reduced by CaO bound in CaCO_3 i CaSO_4

3) Fly ash with free CaO content higher than 1.0% but lower than 2.5% by mass is permitted, provided it meets the requirements for volume stability ($\leq 10\text{mm}$).

The amount of fly ash that can be used as the main component of cement is specified in the PN-EN 197-1:2012 standard. Fly ash-blended cements can be produced in all strength classes, i.e., 32.5; 42.5; 52.5 (minimum compressive strength [MPa] after 28 days of setting). Table 2 presents the requirements for the percentage by mass of the mineral component used in the production of cements for different types of cement.

Table 2. Types of cements with addition of silica fume fly ashes (V)

Cement Type	Designation	Mineral Component Content [% by mass]	Range of Application
Fly Ash Portland Cement	CEM II/A-V	6-20	Commonly used in general construction, industrial construction, including road construction.
	CEM II/B-V	21-35	
	CEM II/A-W	6-20	
	CEM II/B-W	21-35	

Multi-component Portland Cement	CEM II/A-M	12-20	General construction, road construction, specialized construction, water engineering.
	CEM II/B-M	21-35	
	CEM V/A	18-30	
	CEM V/B	31-50	
Pozzolanic Cement	CEM IV/A	11-35	General construction, specialized construction, water engineering, concretes exposed to chemical aggression.
	CEM IV/B	36-55	
Sulphate-resistant Pozzolanic Cement	CEM IV/A-SR	21-35	Construction of sewage treatment plants, foundations in aggressive soils, underground and marine construction.
	CEM IV/B-SR	36-55	

Introducing fly ash into the composition of cement modifies several of its properties, imparting many advantageous characteristics that ordinary Portland cements lack. Fly ash Portland cements are characterized by: extended initial setting time, better workability of concrete mix over a longer period, lower heat of hydration, high density of concrete, high resistance to corrosive agents, significant strength gain over an extended period, and achieving very good strength parameters after low-pressure thermal treatment.

3.5. Circular approach

After implementing procedural changes, it was possible to alter the flow of processes, resulting in the adoption of a closed-loop economy system (Fig. 3). Each stage of the main processes has been numbered for detailed discussion of each step below.



Within the closed-loop economy system, the first stage influencing process modification is the acquisition (extraction) of by-products from combustion and extraction from waste disposal sites, as well as directly from incineration units, e.g., coal dust (4, 7).

Quality control "at the input" (8) of returned materials (substrates) allows naturally formed, so-called "raw" materials to be transported (9) for the production of construction materials. In cases where by-products of combustion/extraction require processing and treatment such as screening, drying, mixing, and grinding, the material is sent for further processing (10). Waste material undergoes recovery

in process R5, in installations and devices by preparing mixtures for industry needs. This process involves recycling or recovery of inorganic materials other than metals or chemical compounds, such as construction materials, mine spoils, or contaminated soil [14]. Loose waste materials are transported to the Production Plant by road transport. Waste destined for unloading in closed storage tanks is discharged hermetically. The remaining waste is delivered by self-unloading trucks and stored in special heaps.

After waste recovery, including by-products of combustion, products are obtained, particularly mixtures and aggregates.

The recovery process is carried out using vehicles and equipment::

- a) Mobile concrete mixing line, i.e., a set of compact, mobile components,
- b) Mobile screening bucket (sieve),
- c) Installation for the production of binders and mortars,
- d) Installation for the production of road substructures and road materials.

The total annual processing capacity of installations and equipment at the waste processing site, including by-products of combustion and extraction, is 1,220,000 Mg tons annually. Data for the year 2023 indicate that nearly 800,000 Mg were produced. This translates to an average utilization rate of installations at 65% for the year. Waste listed in Table 3 is used in the production of mixtures. Selected substrates, which are by-products of combustion (fly ash, gypsum, microspheres), and their processed product (ash-slag mixture) are presented in Figures 4-5.

Table 3. Types of waste that may lose waste status

No.	Waste Code	Type of Waste
1	10 01 01	Slags, boiler ashes, and fly ashes (excluding ashes from boilers listed in 10 01 04)
2	10 01 02	Fly ashes from coal
3	10 01 03	Fly ashes from peat and wood that have not been treated chemically
4	10 01 05	Solid waste from lime-based flue gas desulfurization methods
5	10 01 17	Fly ashes from co-incineration other than those listed in 10 01 16
6	10 01 24	Sand from fluidized bed deposits (excluding 10 01 82)
7	10 01 80	Mixtures of fly ashes and slag from wet discharge of combustion waste
8	10 01 82	Mixtures of fly ashes and solid waste from lime-based flue gas desulfurization methods (dry and semi-dry flue gas desulfurization methods and fluidized bed incineration)
9	19 01 12	Slags and boiler ashes other than those listed in 19 01 11

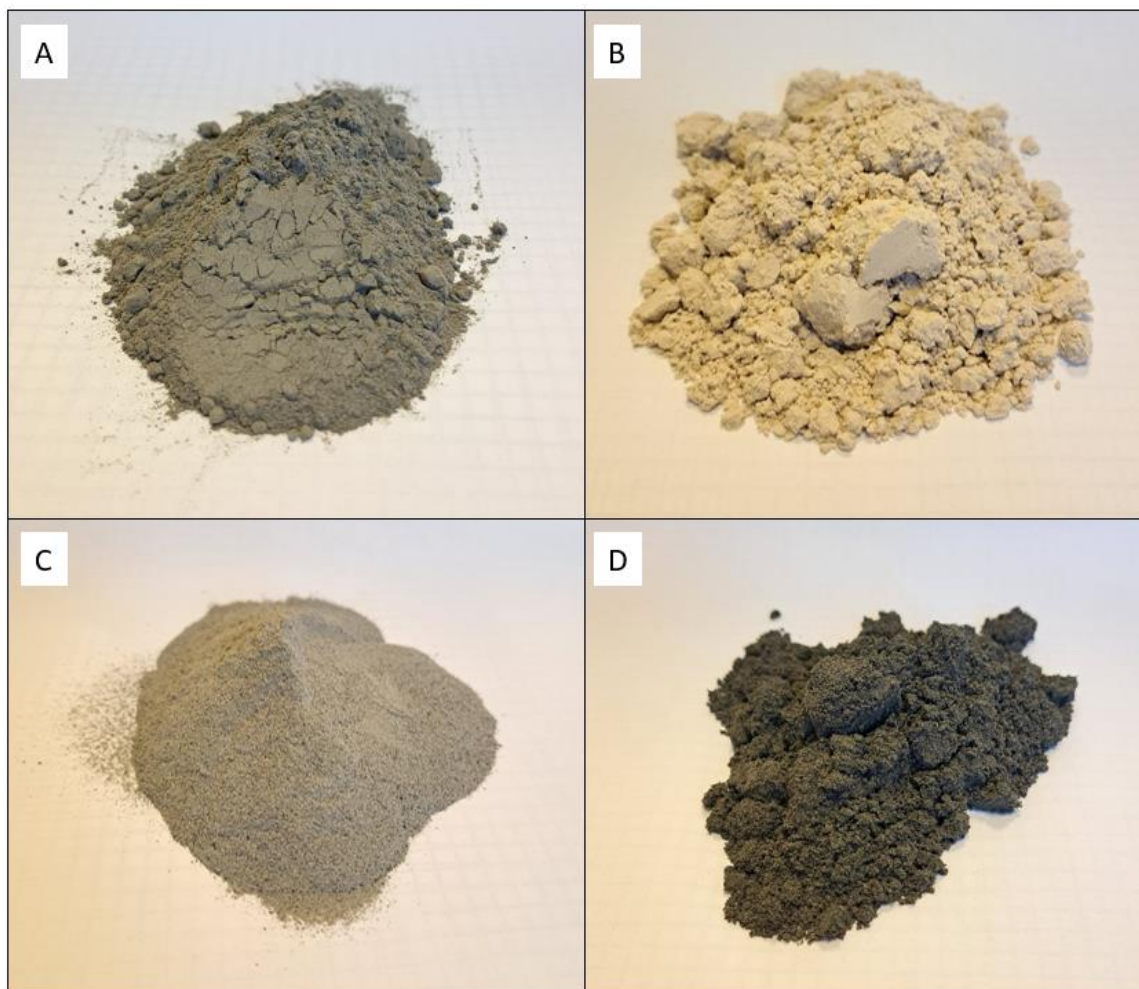


Fig. 4. a) Fly ash, b) Gypsum, c) Microspheres, d) Ash-slag mixture. Photo by P. Całka

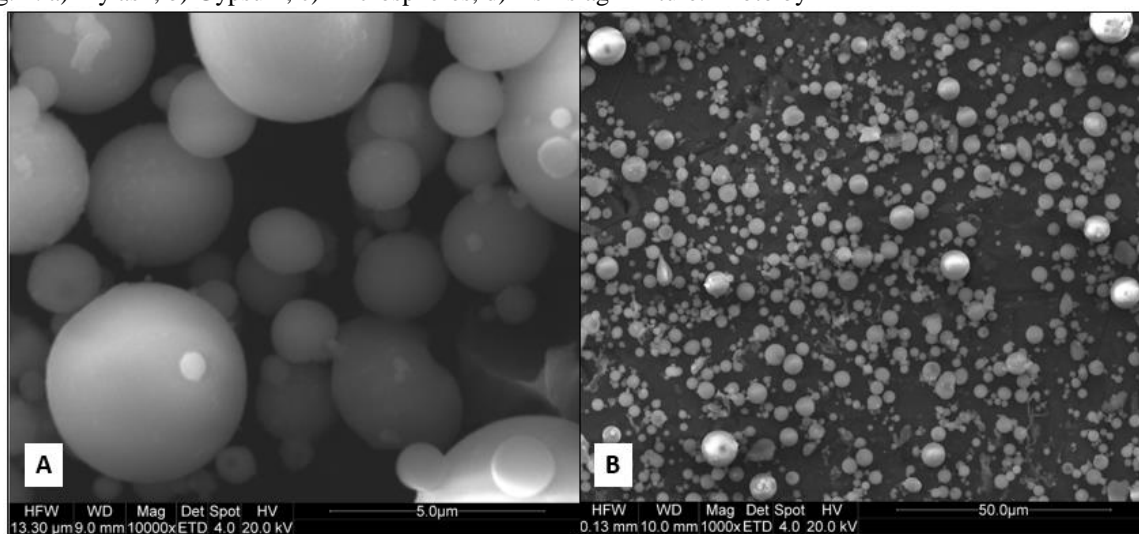


Fig. 5. a) Microscopic image of fly ash, b) Microscopic image of fly ash with microspheres. Photo by P. Całka

Bulk waste is delivered by tanker trucks. Unloading of waste from tankers is carried out pneumatically, through pipelines to closed storage silos. The silos are equipped with dust removal devices built into the top of the silos, ensuring effective filtration. Additionally, the silos are equipped with devices for monitoring the level of raw materials and aeration of the hopper outlets. The remaining waste is delivered by self-unloading trucks and stored in the designated waste storage area located at the installation for the production of road products and building materials, and then transported to containers by a wheel loader. From the appropriate tanks and containers of the installation, waste and non-waste materials are fed through dosing-weighing devices to the mixer.

The entire dosing and mixing process is automated by inputting the appropriate recipe into the computer system. The computer system also provides information on faults and equipment failures. Designated alarm states result in an immediate halt to the product manufacturing process and allow for the diagnosis of the type of failure. After dosing the components, waste is mixed in the mixer until a homogeneous mixture is obtained. The mixing time has been determined experimentally and is executed by the computer system. After mixing is complete, the produced product is loaded onto open trucks or is fed through a loading sleeve located under the mixer, into tankers, and delivered directly to the customer.

Aggregate production: Waste will undergo processing to produce aggregates used in construction. The recovery process will involve the use of a sieve bucket device mounted on a wheel loader. The bucket is equipped with a motor that drives the moving parts. Raw material - by-products of combustion (waste) will be collected by the loader from the heap. After displacement, the bucket drive will be activated, separating the fines. The size of the sieved grains can be adjusted. After sieving, the obtained aggregate will be subject to compliance control with the appropriate reference document for the given product.

As a result of the waste recovery process, the following products are produced:

- a) SOLITEX Hydraulic Road Binder - The product is intended for use in transportation construction for the construction of roads, airports (pavement slabs, parking areas), railways (with limited use to sub-ballast).
- b) Mineral mining binders intended for use in underground methane and non-methane mining operations and extracting hard coal. Binders intended for making isolation belts, plugs, binding casing with rock, eliminating all types of underground workings, shafts and shaftlets, voids, deformations resulting from underground exploitation, and closing of boreholes, for making protective and isolating layers of backfilling, shotcreting of mining workings, construction of isolation dams.
- c) GEOSZYB mixture can be used in methane and non-methane underground coal mining operations. The GEOSZYB mixture is primarily intended for filling (backfilling) drifts or voids formed on the surface as a result of underground exploitation.
- d) Artificial aggregates from boiler slag for unbound and hydraulically bound materials for roads. It can be used depending on needs in road construction either independently or as aggregate for granular materials.
- e) Eco-stabilizations and Eco-subbases, which are intended for use in construction as materials for the construction of structural, auxiliary, and non-structural elements, for stabilizing the subsoil and main and auxiliary sub base layers for the construction and maintenance of roads, airports, and other road surfaces.
- f) Slag-ash can be used for large-scale land improvement, soil exchange, as a building base, and for leveling terrain, for constructing embankments above and below the freezing zone and above the groundwater level (Figure 6).

- g) SOLITEX DSM and SOLITEX ST binders are intended for the construction of anti-filtration screens in flood protection buildings (excluding: flood gates and storm/surge barriers and coastal protection structures), dam buildings, and water management devices.
- h) Fly ash Portland cement is intended for typical applications for this type of cement, i.e., preparing concrete, mortar, grout, and other mixtures for construction and production of building products.



Fig. 6. Slag-ash aggregate used as road subbase. Photo by P. Calka

The finished product based on by-products of combustion (11) undergoes additional quality control (12), then is transported (13) and stored (14). Loading (15) and distribution (16) to the customer/recipient is the final stage of the circular economy, where the substrate is used as a fully valued material in the implementation of investments. From 2020 to 2022, PGE introduced over 3,670,000 metric tons of products to the market. All products described above were obtained from various energy units with nominal parameters of installed power capacities ranging from 0.9 GW to 5.1 GW.

3.6. Characteristics of circular installations

In the example production process of concrete mixtures, a high level of dosing of individual components is maintained. This is possible thanks to the full automation of the technological process. A typical concrete mixing unit consists of silos for cement and fly ash, a closed system of the cement screw and fly ash screw, and a row silo for aggregates, under which there is an electronic belt scale, from which the aggregate, after weighing, is directed to a loading cart. The unit also includes a mixer tower, which houses scales for water, cement, and additives, as well as a concrete mixer. Aggregates for concrete production are delivered by trucks and stored in a row silo. Subsequently, they are weighed on a belt scale located under the silo and delivered to a cart, which moves along a track to fill the mixer.

Cement and fly ash (the substrates for mixture production) are delivered directly from their production by specialized trucks - tanker trucks for bulk material transport. Unloading of raw materials with compressed air takes place into sealed steel silos. The transfer of raw materials is dust-free using a technological installation equipped with the following devices:

- Sealed connection between the truck and the cement/fly ash silo using high-pressure hoses,
- Cement/fly ash silos equipped with self-cleaning venting filters,
- Pneumatic valve cutting off the flow of cement/fly ash from the tanker in case the silo is filled.

Self-regulating electronics for weighing, dosing, optimizing components, handling aggregate bins enable precise implementation of concrete mixture manufacturing technology. The produced concrete mixture should be delivered to the construction site without segregation of concrete components, it should have the appropriate consistency and workability for proper incorporation into concrete structures. Hardened concrete must have the appropriate strength and durability.

A typical production line for producing concrete mixtures for prefabricated concrete elements made of ordinary and lightweight concrete consists of the following components:

- Silos for storing cement and fly ash, used for concrete production,
- Hoppers - structures for storing sand and aggregates,
- Crane - electrically driven winch. A bucket suspended on steel cables doses the appropriate proportions of the mixture.
- Screw feeder - Cement and fly ash from silos are transported to the mixer using a feeder.
- Planetary mixer - used for wet, dry, and ordinary and lightweight concrete.
- Compressor and compressor unit,
- Water tank for the mixer.

The production process of the line for producing concrete based on by-products of combustion using a planetary mixer starts with the automatic dosing of raw materials such as sand, aggregates, ash, and cement. The described installation can be applied in stationary or mobile variants (Fig. 7).

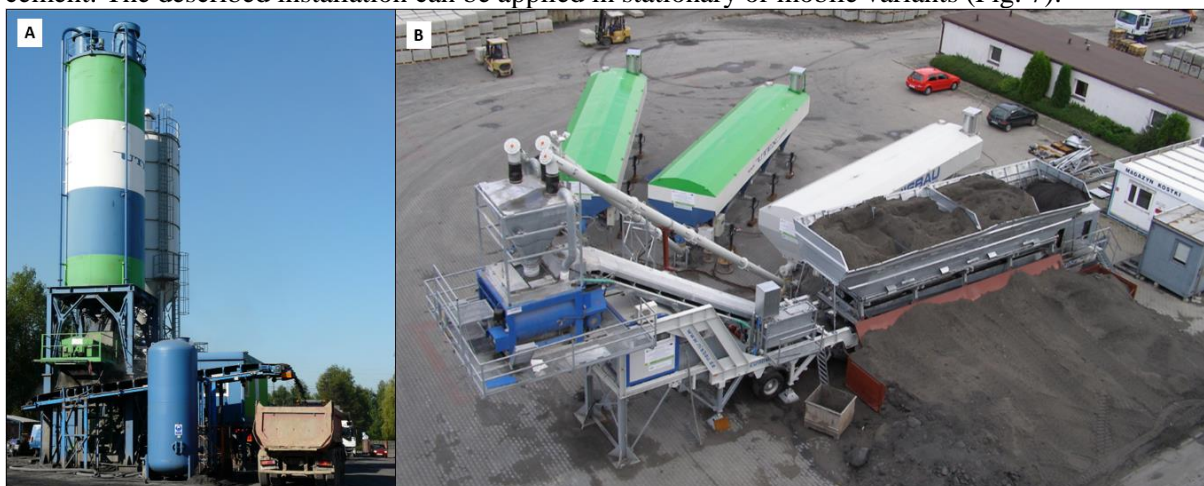


Fig. 7. a) stationary installation, b) mobile installation. Photo by P. Calka

4. DISCUSSION AND CONCLUSIONS

The operation of individual economic entities within a particular sector means that when implementing process modifications, they typically concern that sector. Referring to the materials used in construction presented in this paper, much more research focuses on changes in processes within entities involved in construction. There are numerous publications analyzing the reuse of building materials obtained from the demolition stage of previous structures [15–18]. However, there are certain limitations to reusing certain building materials. This applies, for example, to Portland cement, which, due to irreversible hydration, is not subject to recycling [19]. Another approach is the extraction of raw materials from

landfills, where they have been previously accumulated, known as "landfill mining". This approach is often used for the reuse of solid plastics [20,21], metals [22,23], or soil-like materials [24,25]. Less common than research within one sector are studies that refer to the use of waste from one sector directly in another, bypassing the storage stage. These studies confirm the validity of reusing such raw materials as slag, fly ash, or silica fume [26,27], which have also been used in the circular economy implemented in the analyzed organization. The experiences related to organizing processes in the enterprise and the results of material research contribute to the knowledge about the practical implementation of circular solutions that connect the energy sector with the construction sector.

Despite the significant environmental impact of both the energy and construction sectors, it should be noted that the popularization of the presented solutions can noticeably minimize the negative impact of human activity. The scale of the impact of implemented circular solutions is confirmed by the fact that PGE introduced over 3,670,000 Mg of products to the market over 3 years. This observation indicates that a comparable quantity of natural resources has not been extracted from the environment, and furthermore, the volume of landfill waste has been reduced accordingly. This results in a notable ecological benefit from the process described in this study. Taking into account that the average utilization rate of installations in 2023 was 65%, it can be noticed that there is still potential to increase the production of materials from circular solutions using existing installations.

ADDITIONAL INFORMATION

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