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CONDITION OF CIRCULAR ECONOMY IN POLAND

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The manuscript presents the condition of circular economy in Poland in diversified approach: subjective (waste streams, energy), sectoral (construction, wastewater treatment, coal energy), related to the resources (phosphorous and anthropogenic minerals) and considering proper energy management (almost zero energy buildings). The achievements reached in different sectors as well as the requirements towards implementation

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of CE are presented. The advancement of recycling technologies does not deviate from the global level, in terms of areas specific to Poland. Limiting the exploitation of natural resources and usage of new materials as well as producing more durable products are of CE concern. Also energy and heat recovery in buildings and technological processes (e.g. during wastewater treatment), ways of utilization of combustion by-products and water decarbonization waste are described. The implementation of CE in Poland needs not only research and technical activities, but also the modification of technological processes, the right policy, overcoming cross-sectoral barriers, developing legal regulations and support schemes for CE.

Keywords: circular economy, municipal waste, CE in construction, wastewater management, primary resources, zero-waste coal power, combustion by-products

1. INTRODUCTION

The Circular Economy (CE) concept is finding increasing understanding and better reflection in the policies of states, economy sectors, companies and citizen behaviour.

Essentially, the simple message of this idea involves a transition from linear production processes to circular processes, which would not only include improving the effectiveness of primary resource utilization, but also the application, to the maximum possible extent, of already used products (recycling) and by-products of the main manufacturing processes. The latter could be used within the same main process or, most often, in another, as a substitute for the primary resource or its alternative.

Hence, CE refers to the eternal practice of pre-industrial societies, which involves repeated recovery of materials from used things. Although this resulted from limited access to various goods, yet at the same time it reduced pressure on the natural environment (saving primary resource and minimizing waste) – Fig. 1.

A full implementation of circular economy, including not only mass but also power stream within the entire life cycle, as well as the issue of harmful emissions, places CE as an avant-garde to green economy – Fig. 2.

Subsequent industrial revolutions, through increasing the production efficiency and product availability, changed the consumption model and lead to a significant growth of by-products and waste. Because the grounds for contemporary raw material, product and service circulation and the entailing by-product and waste stream (within the understanding of matter and energy streams) is political economy[14], circular economy has its technical and social aspect and as such should be a part of a complete and integrated approach. In other words, the CE concept and its effective implementation is associated with changing the entire economic system, including business models and approach toward consumption (Fig. 3).

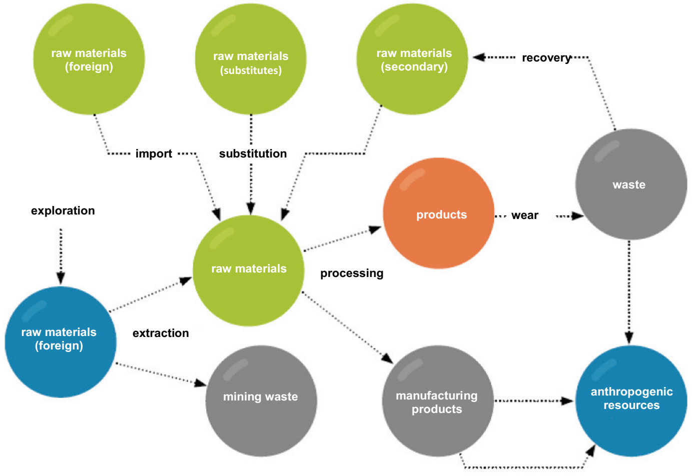

Fig. 1. CE in resource management [115]

[14] **Political economy** – a theoretical sciences of positive nature, aimed at learning and describing reality. […] Political economy studies the laws governing the process of production, distribution and exchange of resources used to satisfy human needs. Production, distribution and exchange have two main sides, technical and social. The technical side is expressed by way of manufacturing capacities, and informs about the application methods of specified production measures and human labour. This side is subject to technical and natural research. Since humans have always gain and still gain goods commonly and collectively, the social side are reflected by production relations. They inform about the manners people organize in within social processes of manufacturing, distribution and exchange of goods, and constitute grounds behind the economic systems of societies [3].

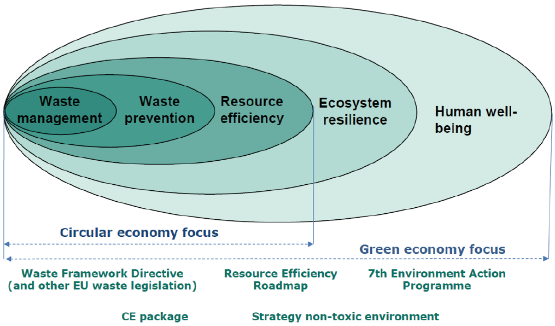

Fig. 2. CE environmental context [115]

This is why the Polish CE Road Map [86] emphasizes four areas, which are consumption and production sustainability, bioeconomy and new business models. This means a need for a multidisciplinary approach and overcoming barriers between national economy sectors. It is necessary to develop relevant legal (e.g. REACH), normative, environmental and economic regulations, scientific support and necessary coordination (integration) at a sufficiently high management tier.

An EEA report [42] indicates that EU Member State policy lacks ambitious CE-related objectives, which is hindered by its political implications and no unambiguous indicators measuring progress in closing circuits. It also points to the growing sense of convergence between resource management policies and circular economy.

This article discusses the condition of circular economy in Poland and, as such, is a review by nature. CE has been shown from various perspectives, namely, subjective (waste streams, energy), sectoral (construction, wastewater treatment plants, coal energy) and resource-related (on the example of phosphorous and anthropogenic minerals). This enabled a reference to the dynamic understanding of CE, which shall not be limited only to mass streams and the entailing energy streams, but also see the relevant energy management in the construction industry (nearly zero-energy buildings). Referring to the changes in the perception of CE in EU states reported in [42], the need to overcome cross-sectoral barriers was also highlighted. The authors also presented the idea of Zero-Waste Coal Power, as an example of mature, integrated and synergistic CE implementation in various branches of economy, such as construction, especially infrastructural and coal-based power, which in Poland will still remain a significant element of the energy mix for a long time, and cross-sectoral CE can contribute to – as demonstrated – limiting harmful emissions and protecting primary resources.

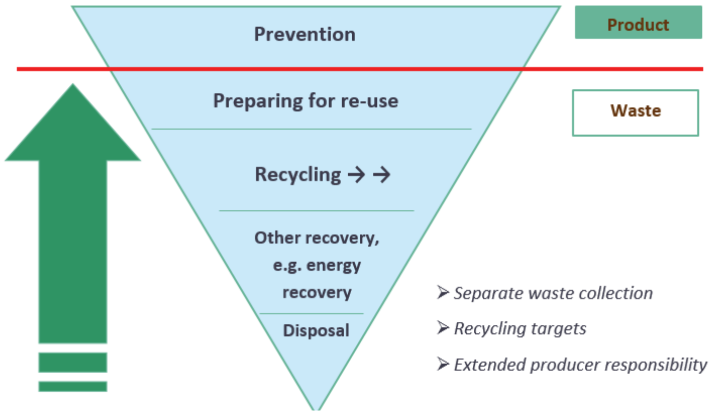

Fig. 3. CE – changes in the value chain [115]

2. CE AND THE MUNICIPAL WASTE STREAM

The aforementioned general relationships are clearly demonstrated by the example of municipal solid waste, where two main ways of perceiving CE can be identified.

One of them is based on the concept of industrial symbiosis and is applied for industrial waste, while the second one perceives CE in the light of the supply chain, and possibilities to close material circuit loops and search for the right business model to suit them. The second approach finds application in terms of municipal solid waste.

In CE, waste must be perceived differently than before, therefore, it is required to give them a resource value. This is one of CE foundations, consistent with the *cradle-to-cradle* approach, which assumes designing durable products that can be repeatedly used in closed cycles. The transformation of waste management systems, which changes the approach towards market and utility value of waste, first of all requires an actual implementation of waste hierarchy [71, 88]. A distinction between two parallel cycles, namely, biological (managing the stream of renewable resources) and technological (managing the finite resources) is introduced in the field of processing waste within a circular approach, as per the primary assumptions adopted by the Ellen McArthur foundation [39]. Therefore, the waste hierarchy shall also be analysed in this context (Fig. 4).

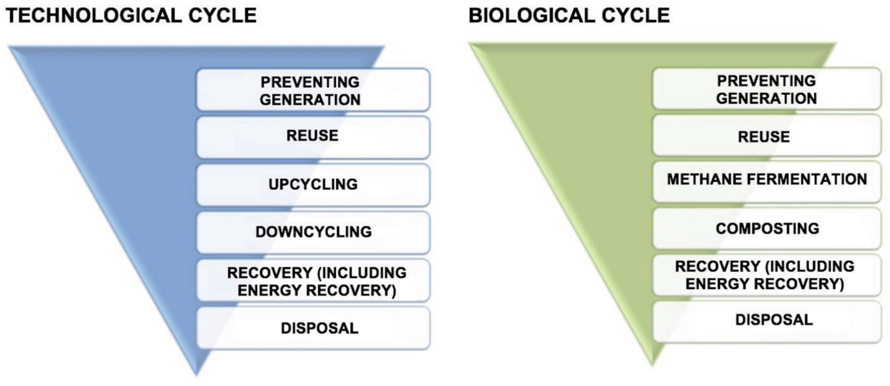

Fig. 4. The waste hierarchy within the circular economy model for a technological and biological cycle

When analysing CE consequences within the municipal solid waste management, one should identify critical elements, necessary for closing a cycle (biological or technical). Given the condition of waste management in Poland [76], requirements arising from the EC announcement Closing the loop – an EU action plan for the Circular Economy, the package of amended waste directive and the road map for the transformation towards CE in Poland, the most important waste stream associated with the municipal sector should be mixed municipal solid waste (residual waste), biowaste and food waste, as well as recyclable waste (mainly plastic waste). That waste is also significant in the European scale and critical from the perspective of the waste management system in Poland [86, 76].

2.1. MIXED MUNICIPAL WASTE

Mixed municipal solid waste management still remains a significant challenge in all EU member states. In the case of mixed municipal solid waste, an important aspect in the implementation of CE is a plan aiming at reducing their mass, which is expressed, among others, by the planning reduction of waste storage by 10% until 2030, and ensuring the preparation to reuse and recycle municipal solid waste at a level of 65% by 2035 [117]. Limiting the mass of residual waste should be achieved in two ways – first by increasing the efficiency of source separation of waste that will be then subjected to various forms of recycling, and by general reducing the total mass of waste generated (using techniques for waste prevention). Selective waste collection in Western European countries is much more developed in organizational and social terms than in Central and Eastern European Countries; its average level in Germany, Austria or Switzerland is more than 50%, whereas in countries like Romania or Greece it still does not exceed 20%, and amounted to 34% in Poland in 2017 [42].

Source separation, however, is not the only way to measure the efficiency of resource reuse and the state of waste management. Another important indicator is the generation rate, which provides the mass of waste generated per capita per year. In 2018, this municipal solid waste generation rate was 736 kg in Denmark, 615 kg in Germany, and 739 kg in Norway, which was far beyond the average for 28 EU states (489 kg). In 2018, a single Polish resident generated 329 kg of waste.

The state of waste management is also reflected in the mass of landfilled waste, which amounted to 57 MM tons in 2018 in Europe, equalling 111 kg per citizen per annum [44].

The above data indicate that CE implementation in the field of municipal solid waste management will have to differ depending on the EU member state, due to the various initial state and the social and economic diversity. One of the greatest challenges will be the need to reduce the mass of generated waste, which will require intensive activities in raising consumer awareness [106].

An indispensable element of transformation is the introduction of unified measurement methods, not only for recycling levels, but also to assess waste prevention and reuse activity [106, 10]. There is currently no standardized methodology for measuring CE implementation effects.

Despite the crucial importance of the activities related to waste reduction, safe and efficient processing of stream, the generation of which could not be avoided, is still an important aspect. The least desirable method of municipal solid waste processing is its landfilling, located at the bottom of the waste hierarchy [118].

An intermediate method, between technical or biological recycling and landfilling, is waste-to-energy processing (WtE). A review of the publications indicates that there is still no clear stance, as to the position of this method within the CE concept. Its enthusiasts consider WtE as an indispensable link in the value loop, which enables generating alternative energy from waste, relative to conventional sources, and simultaneously, which solves the issue of waste landfilling [77]. Sceptics are concerned that the massive development of WtE can be a competition for material recycling and hinder the development of selective raw material collection and their recycling. Most specialists see WtE as part of waste management in line with CE principles, though this element must act a supplement, and not an alternative, for a recycling and reuse system. The equilibrium necessary in this regard can be worked out by taking into account all of the conditions, including market, social and process ones.

Using municipal solid waste as a material resource requires ensuring their relevant quality, which results in the need of source separation and requires their further, technologically effective, processing in order to separate the fraction ready for recycling/reuse, which in turn entails organizational and economic consequences. The experience from recent years show that with the poor quality of selective collection and the resulting moderate raw material quality, it is very difficult to create commercially justified conditions for recycling.

To sum up, mixed municipal solid waste shall be treated as non-energy resources, dedicated for reuse and recycling, and such activity should be treated as a priority. However, in a situation where, for economic or technical reasons, the aforementioned activities are not feasible, treating that waste as an energy resource should be allowed. The objective should be activities from the top of the waste hierarchy (prevention, reuse and recycling) and reducing the quantity of the mixed municipal solid waste stream, with a low share in the entire municipal solid waste stream.

In the context of the Polish waste management system, it is also necessary to reflect upon the future of the mechanical and biological treatment (MBT) of mixed municipal solid waste, which is currently a dominant technology in the country [61]. Its primary objective is to prepare waste for landfilling, through processing biodegradable and recyclable fractions, which will not be justified when confronted with CE objectives. After introducing new requirements and with the appropriate development of source separation systems, modern MBT facilities, which meet best-available-technique standards, will allow to have their mechanical part be used for treating selectively collected raw material fractions. The biological part will allow to be used with selectively collected biowaste. MBT systems will enable operation within integrated recycling centres.

2.2. BIOWASTE AND FOOD WASTE

As part of the recent amendment to the directive package, including the waste directive and landfill directive, aimed at implementing CE in the legal systems of the European Union, significant attention was devoted to biowaste – directly or through indirect provisions [117]. The most important changes significant to biowaste management are, among others:

- modifying the definition of biowaste and introducing the term of food waste;
- requirement to halve food waste amount by 2030 (30% by 2025);
- introducing the obligation of selective biowaste collection from 1 January 2023;
- increase in the level of preparation for reuse and recycling all municipal waste.

Biowaste is generated through the entire supply chain, and their significant part is associated with food production, distribution and consumption. For this reason, the biowaste stream shall be analysed in conjunction with bioeconomy and food waste management. Planning a biowaste management system, both at regional and central levels, shall be mutually consistent within the aforementioned fields, in terms of identifying the generation sources, as well as placing facilities for processing acquired material, in particular. The expected outcome of recycling process requires ensuring a constant supply of waste of standardized quality. While the overall biomass stream management strategy (waste biomass in this case) should be determined at a central level, in accordance with the requirements set out in EU legislation (top-down approach), detailed concepts for individual areas shall be planned locally, taking into account the conditions and potential of a given region (bottom-up approach).

Food waste is generated primarily as a result of wasting food, which is a major social and environmental issue in the EU. Approximately 88 MM tons of food waste is generated annually in the Member States, which amounts to around 173 kg ± 27 kg per capita per year [107]. A significant share of that waste is generated at the production, processing and distribution stages. Consumption waste has so far been collected mainly with the mixed municipal solid waste or processed in household composters (to a small extent). Biowaste acquired through the selective collection system traditionally reach industrial composting and methane fermentation plants and are incorporated into the widely understood system of municipal solid waste management.

A more innovative approach can involve the application of more advanced systems, like biorefineries, which process biowaste into a wide range of bioproducts and energy, as per the principles of cascade biomass utilization. In biorefineries, the potential of biowaste, including food waste, can be used for, among others, manufacture organic fertilizers, biopolymers, ethanol, biodiesel or animal feed [104]. This is a bridge between waste management and a perfectly looped system, within the meaning of *cradle-to-cradle* and it seems that this concept has great potential of being used on an industrial scale. Furthermore, this is a significant contribution to limiting GHG emissions, in this case associated with food waste phenomena.

As demonstrated above, a network of systems for processing acquired material is an essential link in closing the loop in a biowaste management system. It enables obtaining a product/products of specific quality and market values. Currently in Poland there are mainly facilities for composting biowaste (this applies to the municipal solid waste stream and food biowaste), although an increasing number of projects adopt the methane fermentation technology [21], which uses food industry waste, especially the ones high in carbohydrates. As for the demand for biowaste processing capacity, this Polish market will be intensively developing over the coming years, due to the development of selective collection and the emergence of the biowaste; it can be concluded that a mass-scale selective household biowaste collection system has been in force in Poland only since 2019. The trends observed in other EU states indicate an increased market share of methane fermentation systems, especially given the fact, that pursuant to EC guidelines, the Member States shall strive for increasing waste biogas production, supplying it into the gas distribution network and using as fuel for means of transport.

In the context of CE requirements, biomass in the future will be used in biorefineries, including cascade management of waste biomass, implemented especially by local biomass management systems (small-scale facilities).

2.3. PLASTIC WASTE

Packaging waste, in particular plastic, are of great importance within the municipal waste in the context of circular economy. Using plastics and the lack of appropriate methods for their management results in many adverse environmental effects, especially the aqueous environment pollution by plastics and the so-called microplastic [46]. For this reason, managing plastic waste, especially packaging waste, became one of CE's priorities. The requirements of the amended waste directive provide for achieving the recycling 70% of all packaging waste by 2030, with 50% for plastics alone in 2025 and 55% in 2030 [117]. In 2019 the directive [119] was adopted, which from 2021 will limit the use of selected single use products made of plastics, among others, plastic cutlery and polystyrene cups. Furthermore, as of 2030, all plastic bottles will have to be made from recycled materials in at least 30%, and their recycling level will have to reach 90%.

Packaging waste currently account for around 15-20% of all municipal waste, and this share is constantly growing [24]. According to the data by Plastic Europe [96], the use of plastics for packaging in the years 2006-2016 increased by 75%, however, the recycling level increased at the same time, reaching an average of 40.8% for plastic packaging in 2016 (38.5% in Poland).

The principle of Extended Producer Responsibility (EPR) is recognized as one of the main tools that can be used in limiting the adverse environmental impact of packaging, including plastic packaging. It imposes legal and economic responsible on the producers, in terms of placing products on the market, throughout their entire life cycle. By assumption, EPR is to stimulate the manufacturers to take actions associated with preventing waste generation (already at the product engineering stage, through the so-called eco-design), and lowering raw material and consumption at every product life cycle stage. It is one of the most economic and legal instruments related to the implementation of CE principles and waste hierarchy.

Plastic packaging waste have a high potential for recycling and being recovered for use as per CE principles. However, the problematic issue remains maintaining the flow of values within a supply chain, where a recycled product is not worse than the one made of primary resources, from the perspective of quality and economic conditions. As indicated by analyses, in the case of packaging waste, especially made of plastics, activities associated with limiting their quantity and introducing innovations decreasing the harmfulness of these products throughout their life cycle are crucial. The actions implemented at the stage of the packaging becoming waste, such as selective collection or developing recycling systems are very important, but are not the main tool to solve the issue of this waste stream [24].

3. CE IN CONSTRUCTION

A showcase example of CE implementation in construction is the "CIRCL" building erected in 2017 in Amsterdam. It is a three-storey pavilion constructed mainly of wood, with its roof and walls covered with vegetation and over 500 solar panels. The most important structural elements within a building come from recycling – demolished office building windows were used, and the wooden floor comes from a bar of one of the football clubs. The acoustic insulation of the ceiling is made from 16 thousand pairs of used jeans owned by the employees of a bank (that owns the building), and their old clothes were processed into acoustic mats [7]. In the course of construction, adhesive and foams were replaced with screws, so as to facilitate disassembly and repairs in the future. The building enables easy fit-out changes, which is why the interior can be easily modified according to various functions.

“The Edge” office buildings, called “A computer with a roof” [6] is recognized as one of the most circular buildings in the world, and as the most eco-friendly building in the world, by the British rating agency BREEAM. It consumes 70% less energy than other office buildings, among others, owing to the installed solar panels and the use of heat accumulators. The building was designed to create a most comfortable workplace for 2.5 thousand employees. It is controlled fully electronically and one can move inside only with a smartphone in hand.

The cited examples show that transformation towards CE in the construction sector is possible and is being effectively implemented. The activity leaders in Poland in this regard are certain organization, i.e., Polish Green Building Council (PLGBC), which is one of the 70 organizations operating around the world, and grouped within the World Green Building Council. Further working groups for CE attempt to indicate preferential support areas aimed at transforming the Polish economy in this direction. There are also some grassroots initiatives among architects who are trying to combine their professional environment into activities aimed at emphasizing the significance of the climatic crisis and highlighting the possibilities the designers have at their disposal [1]. This is particularly important because a circular construction model will be fully possible, when joined by all parties of a building process. The introduced Roadmap for the transformation towards circular economy [86] provides for *developing proposed changes in the public procurement law that would generate demand for products and services created within CE business models*. Raising the awareness among investors at all private, state and local government levels, combined with tangible benefits resulting from promoting sustainable and eco-friendly solutions in tenders, e.g. ones with a lower carbon footprint and LCA (life cycle assessment), which is the environmental assessment of a life cycle through the environmental impact of a product, will somewhat lead to searching for new and to use innovative solutions aimed at “closing the loop”.

Circular economy in construction is a multi-faceted issue, which requires an integrated approach towards the manufacturing of building materials, and managing waste and energy flows, with particular focus on operating building structures.

3.1. CE IN THE BUILDING MATERIAL INDUSTRY

More and more construction companies, including the cement sector, feel an urge for a real reduction of its environmental impact. And it is concrete that can be a material ideally implementing the CE concept. Given the fact that it is the most commonly used artificial material in the world, and is manufactured in quantities of almost three tons per person per year, which is twice as much as all other materials, such as timber, steel, plastics and aluminium combined, the entailing benefits can be significant. Cement is one of the components of concrete. The cement industry in Poland is one of the most modern in Europe; reducing CO_2 emissions by 30% was made possible owing to the huge investments over the last two decades. Carbon dioxide emissions are the sum of emissions resulting from fuel combustion and technological process emissions. For comparison, CO_2 emission reductions in the EU reached 14 percent. Further reductions are possible, among others, thanks to the use of alternative fuels, since a significant share of the emissions is an integral part of the manufacturing process, i.e., calcium carbonate decomposition chemical reaction, which occurs within a cement kiln, and without which clinker cannot be produced. Cement production uses alternative fuels, which replace fossil fuels. Cement plants have implemented co-incineration, invested in own fuel production and storages, and modern alternative fuel dosing systems, e.g. systems feeding liquid fuels, meat and bone meal or dried sewage sludge. Some of the cement plants achieved an 80% substitution of hard coal with alternative fuels. On a national scale, this enables the Polish cement industry to manage 1.7 MM tons of waste, which do not end up in landfills. An additional significant benefit of using alternative fuels in clinker kilns, both for the cement plants, as well as the natural environment, is the reduction of other atmospheric emissions in newly-constructed, aforementioned systems for waste processing. However, cement plants remain a CO_2 emitter, because there is no technology enabling to produce clinker without this type of emissions. At the same time, while conducting actions aimed at meeting the objectives of the European Green Deal and reaching a zero-emission economy in 2050, there are ongoing works on modern CCS and CCU technologies, which involve capturing, storing and further utilization of CO_2. The representatives of the cement sector point out to the need to introduce protective mechanisms against cement-exporting countries, where its production costs are lower, among others, due to the lack of provisions on CO_2 [4, 5] emissions.

Another method applied by cement producers in order to lower CO_2 emissions is using waste, the by-products of other manufacturing processes, such as fly ash and blast furnace slag, as a substitute for production of blended cement. Simultaneously, all mentioned waste materials can be used as additives in concrete (most usually of the II type, pozzolanic additives or with latent hydraulic properties). The most frequently used concrete additives are fly ash [123], granulated blast furnace slag (GBFS) [122] and silica fume. A properly matched quantity of these additives in concrete can favourably modify the properties of a concrete mix and/or cured concrete. Less commonly used concrete additives are natural pozzolans (volcanic ash), metallurgical slag (GSCem), calcareous fly ash [94] and rice husk ash. The research work consider also other ash-type waste from aggregate dedusting in mineral-asphalt mixes [79] plants, titanium white manufacturing waste [45] or ash coming from sewage sludge incineration [80, 74], in order to determine their suitability for cement composites. Designing concrete with mineral additives, which substitute a part of cement in concrete is associated with lowering the carbon footprint, while maintaining the required concrete properties and durability [66].

The construction industry uses approximately 400 MM tons of raw materials per year and is responsible for a third of all generated waste. According to CE, waste shall be recycled to the maximum extent. An example for a material that can be subject to a full recycling cycle would be concrete. It can be crushed and used as aggregate, mainly for road substrates and base courses. It can also be used as secondary aggregate, replacing some natural aggregate. Recycled concrete cement slurry, after separating from its other components, can be reused in the clinker production process. Aggregate recycling is also important for sequestrating carbon dioxide from air. A large area with crushed secondary aggregate is able to absorb significant quantities of CO_2 from the atmosphere [95].

3.2. BUILDING INFORMATION MODELING (BIM)

In the case of the construction industry, certain CE elements are already working, but the great potential for ecological efficiency of this sector should encourage systemic activities aimed at implementing CE at every stage of the construction process, i.e. starting with designing, through workmanship and material manufacturing, operation, demolition until reusing buildings, their sections and remains. Digitization, and above all, the use of BIM (Building Information Modelling), which is the modelling of information on building structures, can be a convenience. A model of a building is developed using software, which reproduces physical and functional properties of its individual components [67]. The created model not only facilitates detecting collisions prior to commencing the work, but is also a “digital repository”, according to the material passport concept, which collects information on the structure and used materials. Such information can be crucial at the building operation stage – among others, in terms of making the decision on effective repairs, easier building disassembly and regaining the greatest economic value out of it [49]. An additional benefit of using BIM is limiting the waste, which results from the possibilities of thorough computations regarding required materials. Other forms of digitization, which are deemed useful in CE implementation in construction, are 3D printing and virtual reality.

3.3. PREFABRICATION

A facility implementation stage, in accordance with CE, shall be based on modern material solutions and innovative technologies ensuring sufficiently high durability. The used materials should have recycling potential or be constructed with durable components that can be easily dismantled and replaced. Technologies of prefabricated elements or entire prefabricated systems are very useful. They are increasingly more often used owing to the additional benefits in terms of construction organization. An example of such implementations would be hotels with prefabricated, fully-equipped rooms installed on-site, e.g. the design of the world's highest, 26-storey modular hotel with 168 rooms in New York, which is to be built in 90 days.

Prefabricated construction can play a large role in the implementation of circular construction. Prefabrication facilitates reuse of buildings or their parts owing to modularity and standardization of solutions. Designing concrete structures made of prefabricates, with the application of bolted or welded joints, provides the possibility of easy dismantling without major damage. Dismantling of old buildings, instead of demolitions, and the reuse of construction elements in new structures is becoming increasingly frequent.

3.4. ENERGY EFFICIENCY

Circular economy in the construction sector is a multi-faceted approach, among others, to waste, material or energy flow management. An example would be, e.g. suspended ceilings, the commissioning of which is offered by some manufacturers in the course of interior rearrangement. For example, intermediary factors, including refrigerants of limited environmental harmfulness, which enable their recovery and reuse are utilized in the case of a HVAC (heating, ventilation, air-conditioning) systems. Closed circuits in buildings, e.g. heat recovery from wastewater or heat recovery in HVAC systems are used in the same field. Currently engineered HVAC systems increasingly utilize devices with growing efficiency, however energy recovery within a single system is often not as effective as in the case of integrating various technical systems. Power loop closing solutions, which include more than one HVAC system are used more often, with an example being energy recovery from exhaust ventilation and using it as the bottom heat pump source for preparing hot utility water, heat recovery from greywater for preliminary preparation of hot utility water (exchangers by the showers) and heat recovery from greywater using heat pumps.

An extremely important element of the construction process is the energy analysis of applied architectonic and system solutions, taking into account the thermal comfort of users. A properly conducted design process enables selecting appropriate systems in terms of energy, thermal comfort, but also materials and solutions, which do not adversely impact the environment and can be reused. Such activities are supported by, e.g. the amended energy performance of buildings directive (EPBD) of 2010. It introduces a requirement to erect buildings with a nearly zero energy consumption.

Energy analyses concerning buildings should be conducted already at an early building design or/and modernization stage, which does not only enable the proper selection of solutions in terms of the heating, ventilation, cooling, hot utility water and lighting systems, but also allow to evaluate the impact of applied solutions on the thermal comfort of the users. The currently applicable regulations in the scope of energy efficiency do not, however, require developing comprehensive analyses using dynamic methods.

Owing to the cooperation between HVAC engineers, architects and constructors, already at the building concept stage, it is possible to discard solutions, which would generate the highest investment expenditure, and often higher operating costs. The building design process more often utilizes integrated engineering, which includes all traditional design phases, supplemented with seeking the best technical and architectonic solutions, in cooperation with the representatives of individual disciplines. Only such a comprehensive approach, with process control at every stage, enables designing buildings with a nearly zero energy consumption. The following aspect should be considered in the context of the least negative impact of the building on the environment and circular economy:

- type of embedded and finishing materials for external surfaces of building partitions,
- selection of heating, ventilation, air-conditioning and hot utility water systems,

– selection of alternative energy sources.

A building should be approached comprehensively, since its body, facade glazing degree and selected finishing materials of external partitions impact the possibility of obtaining appropriate parameters in terms of daylight and heat gains, which in turn influence the heating and cooling energy demand. Both the body as well as selected materials will also impact the possibility of utilizing renewable energy sources.

Piping systems must take into account the planned building function and local surrounding parameters. HVAC systems shall be designed in a manner to utilize passive techniques of obtaining energy or supporting the ventilation system to the greatest possible extent. An example would be the use of natural or hybrid ventilation or night-time cooling of rooms. The design of lighting in buildings shall enable compensating for the lack of daylight, hence, such systems should be controlled depending on daylight intensity.

Appropriately chosen renewable energy sources are a good complement for rationally designed HVAC systems. Its design should take into account the actual needs of the building and analyse the periodicity of renewable energy availability.

A showcase example of a concept to modernize existing buildings of the Warsaw University of Technology to a nearly-zero-energy standard was developed within the KODnZEB project. The first of the analysed buildings was the Faculty of Building Services, Hydro and Environmental Engineering, located at the central campus of WUT, while the second building was a student house. Each building had applied different architectural and plumbing solutions, adapted to its function [37, 39]. The results of the project showed that thanks to the application of integrated designing, even in a modernized building, it is possible to achieve significant energy savings.

The energy aspect is only one of the building evaluation elements. Another broader issue is their assessment, along with HVAC systems, in terms of the carbon footprint, which is the total emissions of greenhouse gases (GHG) generated by a given structure. Such an approach is an example of closing a large loop, i.e. emission and energy cycle at the building level, as well as their sources, including also the generation of energy from renewable sources. Norway introduced a building evaluation system based not on the energy demand but on emissions. The ZEB Trondheim Centre applies various definitions of a nearly-zero-energy building, which depend on the number of analysed building life cycles. The first evaluation level is the one where renewable energy production within a building compensates for greenhouse gas emissions over its lifetime (ZEB-O). The second one applies to a case where renewable energy production within a building compensates for greenhouse gas emissions over its lifetime and within the manufacturing process of the materials used therein (ZEB-OM). Whereas ZEB-COM assesses a building in terms of producing renewable energy compensating for greenhouse gas emissions within its construction and operation periods, and the manufacturing process of the materials used therein. The last and broadest approach takes into account the production of renewable energy in a building, which compensates for greenhouse gas emissions over the entire building life cycle, and the construction materials over the following stages, such as construction – operation – demolition/recycling (ZEB – COMPLETE) [8]. Polish building regulations contain no specific provisions regarding CO_2 emissions in buildings. To conduct an analysis as per the aforementioned Norwegian evaluation system is very difficult, due to the need to hold data on the emission of pollutants for each of the products used for the construction at each of the building lifecycle stages. The source literature contains results of lifecycle energy analyses for selected building elements. Most often, these are analyses conducted at a level of the product and operating stage, as the main sources of GHG emissions [18, 25]. The authors indicated that in the analysed case, in Polish conditions, maximum CO_2eq emissions occurred in a building with a glazed facade and decreased with lowering the glazed areas.

Both in the case of the energy approach, as well as when evaluating emissions, the thermal comfort of the users and the quality of the internal environment are extremely important aspects [12]. Costs, energy and emissions cannot remain the only important criteria. All of these issues are interconnected because it is the project assumptions that become the grounds behind selecting system solutions next. Standards describe many criteria for evaluating the thermal comfort of users. The execution of complex and complicated HVAC systems is associated with satisfying most of them without a thorough analysis of the architectural design and without the cooperation of all disciplines within integrated engineering. Certain air treatment processes generate very high energy demand, thus, also emissions in many cases. A good example would be the adjustment of air relative humidity or temperature. Increasing their permissible range while maintaining the user comfort in rooms will lead to decreasing energy demand.

Circular economy in buildings is a complex issue, which requires detailed analysis of the conditions within a given project. This process requires multi-disciplinary cooperation in order to select material and process solutions limiting energy demand and the selection of proper solutions, on the interface between technical systems.

4. CE IN WASTEWATER MANAGEMENT

Implementing circular economy principles in wastewater treatment plants (WWTPs) is associated with changing the current sewage treatment paradigm. Removing impurities from wastewater ceases to be the only objective. According to the new paradigm, technical processes used in WWTPs shall enable the recovery of energy, heat and other valuable resources, including water (Fig. 5), while minimizing the presence of contaminants of emerging concern (CEC). An important element accompanying CE implementation in wastewater treatment plants is using it to evaluate the undertaken activities in terms of life cycle analysis (LCA), including the determination of its carbon footprint.

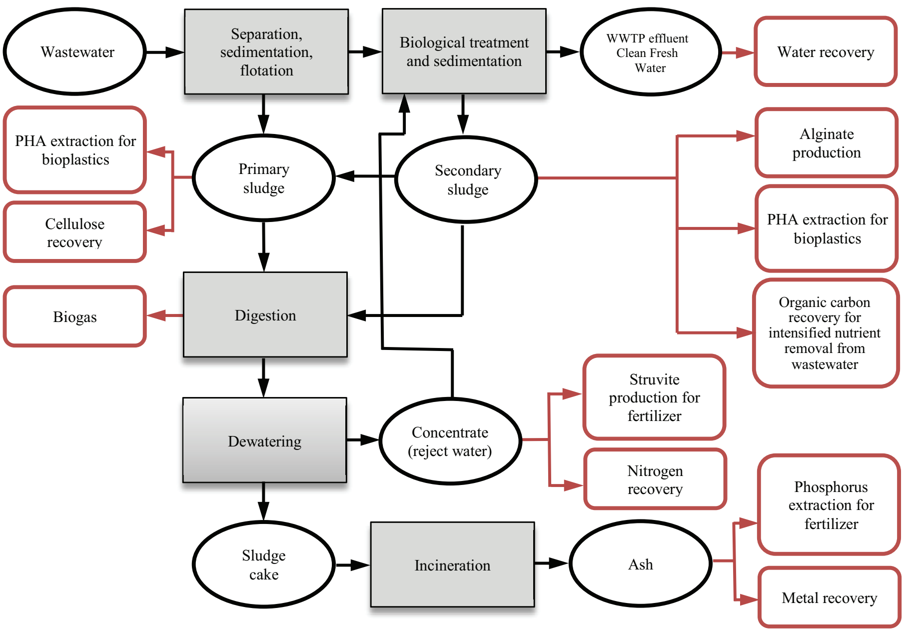

Fig. 5. Concept of energy and resource recovery in a WWTP (after [19] with own supplementation)

Both in Poland and globally, the most advanced solutions suggested for application in wastewater management and falling in line with CE concern energy and heat recovery [93, 84, 20]. This stems from the properties of processes used to stabilize sewage sludge, i.e., decreasing the organic compound content in sludge. Such a process is methane fermentation, which apart from stabilized sludge, generates biogas containing ca. 60-70% of methane. Still in the 1970s', biogas generated as a result of methane fermentation was incinerated in flares, thus irretrievably lost. It was quickly realized that it could have been used as a heat source in the treatment plant, and the development of cogeneration processes resulted in the possibility to use the biogas to also "produce" energy, which was utilized for the house-load of the plant. In the initial period, biogas covered 90 to 100% of a treatment plant's heat demand and ca. 40% of electricity demand. Owing to intensive research focused on increasing biogas production efficiency, it covers over 60% of electricity demand in some treatment plants, and in some facilities, the amount of produced energy is higher than house-load [17, 48, 78, 31]. A good example is one of the Polish WWTPs located in Tychy [17]. In 2017, the average amount of biogas produced therein amounted to 17.4k m^3/d, which allowed to produce ca. 8700 MWh of electricity, with a total treatment plant demand at a level of approx. 7200 MWh.

The aforementioned research aimed at increasing the amount of produced biogas can be divided into two groups:

1) studying the co-fermentation process, which involves methane fermentation of at least two ingredients (substrates, co-substrates) coming from various sources, one of which is the leading one;
2) studying the initial preparation of a batch for the fermentation chamber in order to improve substrate availability for bacteria conducting acetogenesis and methanogenesis.

Compounds characterized by a higher biogas potential than sewage sludge are used as co-substrates in the first study type. Most often these are waste from the agro-food industry, agricultural waste, organic fraction of municipal waste and selectively collected biowaste. An important issue in terms of conducting co-fermentation is the correct selection of co-substrates share in the batch directed to the fermentation chamber. It takes into account both the aforementioned methane potential, as well as the co-substrate chemical composition (dry mass concentration, content of organic substance susceptible to decomposition, carbon to nitrogen ration (C/N), concentration of nutrients necessary for microorganism development) and the potential possibility for toxic substance presence [63, 51, 52].

Another method for intensifying biogas production is the pre-treatment of the batch sent to the fermentation method using disintegration techniques [93, 84]. It involves introducing energy into the sludge, which is aimed at weakening and bursting cell membranes of micro-organisms in the sludge. As a result of disintegration the waste becomes more susceptible to biochemical decomposition [15, 70]. There are numerous sewage sludge disintegration methods, most usually classified as mechanical (i.e. ultrasound, cavitation, microwaves), thermal, chemical, biological or hybrid methods. Table 1 uses source literature examples to show the effectiveness of the methane fermentation process depending on the sludge disintegration method.

Supporting the methane fermentation process through the application of various sludge disintegration methods does not remain solely at the research stage. Such activities are already applied in practice. The first WWTP in Poland to have applied the disintegration process (ultrasound) upstream of the fermentation chambers was the one in Rzeszów. The next ones are, among others, the treatment plants in Kraków-Płaszów, Wrocław, Słupsk, Gdańsk, Gliwice, Lublin and Gorzów Wielkopolski.

Table 1. Impact of sewage sludge disintegration process on the effectiveness of methane fermentation – selected research results

Disintegration method	Increase in biogas/methane*) generation	Source
Ultrasounds	35%	[56]
	30%	[57]
Hydrodynamic	12.7%	[58]
	56%	[45]
	33.9%	[46]
Microwave	56%	[55]
	20%	[59]
Thermal	25%*)	[60]
Chemical	31%	[61]
Hybrid (ultrasounds + alkalization)	24%*)	[62]
Hybrid (alkalization + hydrodynamic)	57%	[63]

Sewage sludge disintegration, besides playing a significant role in the recovery of energy from sewage sludge, is also important for the recovery of organic compounds, which can be used for intensifying the process of nitrogen (N) and phosphorous (P) removal from wastewater (Fig. 6) [65, 85, 99, 35]. For example, Park et al. [65], after introducing supernatant to a bio-reactor separated from the solid phase of disintegrated sludge, recorded increased effectiveness of N and P compound removal, by 30% and 32%, respectively. The cited authors applied ozonisation as the disintegration method. Xu et al. [99] demonstrated increased efficiency of removing N and P compounds owing to the use of an additional carbon source in the form of excess sludge disintegrated using the microwave technique, combined with hydrogen peroxide oxidation, by 10% and 59%, respectively.

Whereas Żubrowska-Sudoł and Walczak [85] have proven the possibility of using hydrodynamic disintegration for intensifying the removal of nutrient from wastewater. After introducing hydrodynamically disintegrated sludge into a bio-reactor, the authors recorded decreased N and P concentrations in treated wastewater, from 42.4±3.89 mg N/l to 21.12±1.59 mg N/l (increased denitrification efficiency by 27%) and from 6.86±1.09 mg P/l to 0.77±0.28 mg P/l (increased biological phosphorus removal efficiency by 68.1%), respectively. The patented CROWN system for the disintegration of a part of recirculated sludge stream (hydrodynamic method) was applied in the central wastewater treatment plant in Wiesbaden (Germany) several years ago [126]. The report on the analysis of wastewater operation prior to and after introducing disintegration of 4% of the recirculated sludge stream (sludge prior to disintegration was concentrated to a 6% dry mass content) indicates that the CROWN system enabled to: 1) fully withdraw from the dosage of additional external organic carbon source, simultaneously ensuring a certain increase in the efficiency of removing nitrogen and phosphorous compounds (by 31% and 41%, respectively) from wastewater, 2) decrease excess sludge production by 20%, 3) and eliminate issues associated with bulking and floating sludge. An attempt at disintegrating a part of the recirculated sludge stream in order to acquire organic carbon compounds to intensify the nutrient removal from wastewater was also made at the Płaszów WWTP in Kraków [28]. Unfortunately, expected results relative to the denitrification and biological phosphorus removal were not recorded. However, a rapid increase in the concentration of sludge in the reactor and higher oxygen consumption were observed. It should be noted that the test described by the cited publication was relatively short (lasted for about a month).

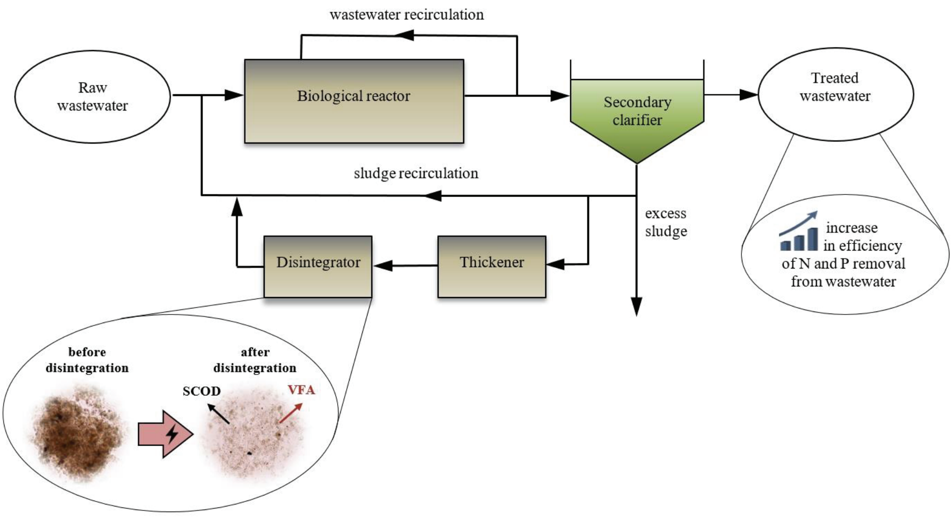

Fig. 6. Obtaining organic compounds from sewage sludge with disintegration methods and using them for supporting the removal of nutrient from wastewater

The most advanced R&D and implementation work in the field of recovering raw materials and materials from wastewater and sewage sludge concern phosphorus recovery. It is estimated that the total amount of phosphorous in municipal wastewater in EU Member States exceeds 2000 t P_2O_5 per day. Until just recently, the aspect of phosphorous presence in wastewater was associated solely with the need to remove this element, since its excessive quantities introduced to waters cause their eutrophication. The novel approach towards the presence of phosphorous in wastewater combines its removal (protecting water reservoirs against eutrophication) with recovery (using it as fertilizer, searching for other applications). One of the methods to close a phosphorous cycle through recovery in wastewater treatment plants is the use of sewage sludge in agriculture and for the environment [16, 97]. Another one involves the precipitation of phosphorous compounds from sludge liquid phase prior to or after the dewatering process [127, 27]. In this case, phosphorous is most frequently recovered in the form of struvite – an ammonium-magnesium phosphate, since it is the most beneficial form of phosphorous in terms of bioavailability for plants (slowly released fertilizer ingredients). Yet another, quite common product is also calcium phosphate, including its most stable crystallized form – hydroxyapatite, which unfortunately exhibits significantly worse fertilizing properties than struvite. The next option is to recover phosphorous from ash generated after the incineration of sewage sludge [19, 110]. The heat treatment process destroys pathogenic organisms and organic pollutants, and the resultant ash contains the most phosphorous compared to other waste streams created in the municipal wastewater treatment process, which means that the recovery of phosphorous from ash has the highest potential (ca. 90%) among the previously mentioned options. A disadvantage of this solution is the presence of heavy metals, which are not decomposed in the course of incineration and can limit the use of recovered phosphorous in agriculture. In order to eliminate this limitation, systems for the recovery of phosphorous from ash include processes enabling the removal of heavy metals. Phosphorous recovery technologies in WWTPs are primarily based on the processes of precipitation and crystallization, wet extraction or oxidation in supercritical water conditions (Supercritical Water Oxidation) [11]. The data presented in the paper by Kabbe [30] indicate that there were 65 phosphorous recovery plants operating worldwide in 2017. The first WWTP in Poland to have undertaken work aimed at introducing phosphorous recovery is the one in Cielcza [23]. Significant efforts targeting phosphorous recovery have been made in Germany [124]. A regulation on the recovery of phosphorous from sewage sludge and ash after thermal treatment of sludge came into force in October 2017. The adopted provisions clearly define: 1) the size of WWTP defined as population equivalent (PE), which this obligation applies to (above 50 000 PE), 2) transition period after which to start the phosphorous recovery process (since 2029 for plants with PE = 100 000 and 2023 for 50 000 PE), 3) date for all treatment plants subject to this obligation to develop a phosphorous recovery concept (by the end of 2023), 4) minimum quantity of phosphorous in sludge (20 g/kg TS), beyond which the sludge must obligatorily be subject to phosphorous recovery, 5) minimum recovery efficiency, both directly from sludge (50%) or ash after their thermal transformation (80%). It is highly probable that these actions will contribute not only to an increase in the number of phosphorous recovery systems in wastewater treatment plants but will also be a driving force behind the development work in this field.

If phosphorous is recovered as struvite, nitrogen is also recovered from sewage sludge. This element can also be recovered through stripping [52, 60], however most researchers believe it to be unprofitable. Despite such an approach, attempts are made at developing a technology, which would ensure high nitrogen recovery efficiency. One that would be justified economically. Such an example is the full-scale demonstrative AECO-NAR (Nijhuis Ammonium Recovery) system in Great Britain [52]. Its efficiency of recovering nitrogen in the form of ammonium sulphate is 85-90%, at a cost (1.0 – 3.0 EUR/kg N) comparable to innovative nitrogen removal technologies classified as economically justified solutions.

Sewage sludge is also a source of poly-β-hydroxyalkanoates (PHA) used for manufacturing plastics [26, 89]. High PHA content is exhibited by dephosphation bacteria. In anaerobic conditions these microorganisms collect volatile fatty acids from the wastewater and store them in their cells in the form of poly-β-hydroxyalkanoates. It has been demonstrated that in order form PHA recovery to be profitable, the content of this compound in biomass should be at least 40 g PHA/g dry organic matter. In the course of the PHARIO project implemented in Scandinavian countries, it was concluded that PHA "production" from sewage sludge enables significant (70%) limitation of their negative impact on the environment and simultaneously obtaining a product characterized by high quality [26].

An important CE element in a WWTP is also water recovery. The most common example of using recycled water is the process system of a WWTP. Treated wastewater are used to, among others, cool power generators, flush grates or to flush equipment in a sludge dewatering station. They can also be used in a biogas treatment station, where they act as a water scrubber where carbon dioxide from purified biogas is adsorbed [17]. However, this is not the only way to use water recovered from treated wastewater. Recycled water also finds application in the industry, for irrigating green areas, supply aquifers, as well as for drinking and for farmstead needs [29]. An example of one of the most effective systems for the recovery of water from treated wastewater are "NEWater" stations in Singapore. They currently satisfy approximately 30% of the water demand in Singapore, and this number is planned to reach as much as 55% of the total demand by 2060. It is worth emphasizing that the quality of produced water exceeds the standards defined by the Environmental Protection Agency (USEPA) and the World Health Organization (WHO) [50].

5. CE AND PRIMARY RESOURCES

5.1. PHOSPHOROUS AS A CRITICAL ELEMENT

Phosphorites in 2014 and phosphorous in 2017 were included in the list of raw materials critical for the European Union owing to their economic significance and high supply risk [32, 33].

Phosphorous (P) is one of the most important elements, which determines the development of agricultural production, regulated by food demand of the growing human population. Phosphorites are the only natural source of phosphorous. The reserves of these materials are non-renewable and are decreasing due to intensive exploitation [109, 82]. The supply risk and scarcity effects for the economy can be greater than in the case of other raw materials. In recent years, EU has been underlining the need to look for alternative phosphorous sources in order to decrease the dependence on external markets. One of the possible methods is the recovery of this valuable raw material from waste, which is in line with CE assumptions defining the economic and environmental benefits for Member States, including Poland [32, 33].

Phosphorous is a critical element, of biochemical importance and necessary for agricultural production [34, 92]. Phosphorites are raw materials critical for the European economy, with particular significance in terms of the environment and are a basic raw material in the production of phosphate (superphosphate) and mineral (phosphate rock flour) fertilizers. Their availability may change due to modifications in the trade policy and commercial flows. This confirms the need to increase the recycling level [82].

According to the information included in the EC Announcement [32], phosphorous resources in the world are large, but European reserves are small (Finland, Russia). The demand of European countries, including Poland, fully covers import from Middle East and North African countries.

There are no alternatives for phosphate rocks in the market, which could replace global production of 20 MM tons (Mt) of P used for food production [92]. The current system of food production and consumption is highly ineffective relative to the use of phosphorous. Only a fifth of the 20 Mt of phosphorous comes in the form of food consumed by humans [34]. Phosphorous is lost (permanently or temporarily) at individual food production stages, which means that there are possibilities to improve effective and repeated use of this element.

The main objective of phosphorous recovery processes is the protection of human health and the environment. Other important goals are limiting water consumption in sanitary and farm systems, and decreasing the demand for mineral fertilizers in agriculture. This can be achieved through recycling and closed circulation of nutrients originating from various sources, with a separation of nutrients, and, as a result, phosphorous [102].

The methods for decreasing dependence on P import include high potential of recycling P from wastewater in manure-rich and densely populated areas, integrating livestock breeding systems and recycling P from food waste. It is also important to properly adjust the amount of used fertilizers to crop needs, biotechnologically decrease the requirements in terms of plant and animal production, reduce waste (wastewater, food waste) and agricultural run-off containing P, as well as managing crops using phosphorous resources in the soil [68, 47].

Phosphorous can be potentially recovered from any stream of organic waste. Phosphorous recovery from waste arouses the greatest interest owing to its huge content in these media [51, 62]. Long-term satisfaction of the growing demand for phosphorous requires a high level of its recovery from human excrements, manure, food waste and mining waste. Waste streams containing phosphorous can include both mixed wastewater, as well as separate organic waste fractions, such as urine and faeces, greywater, animal manure, animal carcasses, detergents, other industrial waste, food waste and vegetable waste. Animal manure (and other animal parts, such as blood and bones) is widely used as a source of phosphate fertilizer in many regions of the world. Urine contains all necessary nutrients for plants (nitrogen, phosphorous, potassium), is essentially sterile and can be reused in agriculture [121]. Approximately 200 million, mainly poor, farmers around the world discharge wastewater directly onto fields, and two-thirds of the global aqueous areas are fertilized with wastewater, since it is a cheap and stable source of nutrients [72].

Currently around 25% of phosphorous in the EU is recovered from municipal waste and reused, mainly as sludge [43]. Selected methods for the recovery of phosphorous from wastewater are shown in Chapter 4. In the course of wastewater treatment, phosphorous can be recovered in the form of struvite (magnesium-ammonium phosphate – $NH_4MgPO_4x6H_2O$). Removing this compound will prevent the formation of crystals, which could clog and damage the systems used for transporting industrial waste and wastewater [87, 69]. Phosphorous-rich water and sewage sludge, as well as sewage leaving the treatment plants can be a source of calcium phosphate precipitation [$Ca_3(PO_4)_2$]. Recovered phosphorous substances can also be processed into elemental phosphorous, which is to be used in industrial production of, e.g. detergents, food additives and livestock feed additives [125, 48].

Phosphorous should be recovered from wastewater and various waste also for such reasons, as issues associated with the eutrophication of water, which leads to, among other, accumulation of phosphorous in benthic deposits in channels, rivers, lakes, and even seas and oceans [83, 53]. Recovery of phosphorous from wastewater and sewage sludge should be mainly due to the need to prevent the penetration of nutrients to aqueous areas [83, 56]. The EU Water Framework Directive requires removing potential pollutants from wastewater prior to discharging them to surface waters [36], hence limiting phosphorous in wastewater through lowering its concentration or complete removal, in order to inhibit eutrophication and algal blooming [58]. Excess nitrogen and phosphorous in surface waters is an issue within the entire EU. This applies primarily to areas with intensive animal production.

Hindered management of P recycling processes can cause the presence of pathogens, plastics and pharmaceuticals. Using sewage sludge in agriculture is limited due to the risk associated with heavy metals and organic pollutants (e.g. pesticides, PAHs) [55].

The recovery and reuse of phosphorous can be defined not only as a technology, but also as a socio-technical system covering the gathering and storage, processing and recovery, transport, refining and reuse [54]. The value of fertilizer produced from recovered phosphorous can be the most important and indispensable factor for the satisfaction of long-term global food demand in the future. This is why phosphorous recovery should be optimized in terms of food production quality. An important problem in terms of the recovery process is the knowledge of the total phosphorous concentration in different raw materials, which is a necessity to estimate recoverable phosphorous. Phosphorous concentration has also a strong impact on the profitability of phosphorous recovery, storage and transport. The lower the phosphorous concentration, the more energy is needed to concentrate P (e.g. through dehydration or other physical and chemical processes).

Phosphorous recovery processes, taking into account the type of source and application, include composting, physical and chemical separation, biological and biochemical phosphorous removal, precipitation and combustion (or a combination of the above). The practical technologies applied all over the world must meet ecological sanitary conditions [22]. Large-scale phosphorous recovery systems cover aqueous environments supplied with wastewater used to acquire food (aquaculture). In these cases, the phosphorus source is the household sewage mixed with industrial wastewater. In countries with intensive animal husbandry (Denmark, the Netherlands), phosphorous is recovered from ground bones and meat meal from animal carcasses. In Nigeria, gas is generated from anaerobic fermentation of slaughterhouse waste for supplying 5400 households, and the produced sludge is sold as organic fertilizer for 5% of the standard fertilizer price, to municipal low-income farmers [37]. Solid organic waste is usually discharged to the ground in rural areas, whereas wastewater with phosphorous compounds from municipal treatment plants almost always go to rivers and oceans. Small, locally applied technologies, which concentrate on recovering nutrients are also known. They include the processes of struvite precipitation from urine, used in Sweden and Nepal [40, 41]. Other small-scale phosphorous recovery systems include composting food and sanitary waste, home sewage treatment plants and local irrigation, reuse of biogas sludge, plant processing and reuse of industrial waste, as well as the common practice of reusing natural fertilizer in farms [40].

Over the past few decades, sustainable use of phosphorous was caused by concerns regarding environmental pollution. The current challenge associated with phosphorous deficiency regards food safety. It is becoming obvious that the population growth entails increased phosphorous consumption and environmental pollution with its compounds. This leads to fluctuations in fertilizer prices, increased environmental costs and energy consumption. Phosphorous will have to be recovered from generated waste and reused within the entire global food production and consumption system. It is necessary to conduct research aimed at indicating the most sustainable method for the recovery of phosphorous from wastewater and waste, and transforming the end product into efficient fertilizer, taking into account the resource consumption, life cycle costs of phosphorous, energy consumption, availability for the agriculture and environmental pollution.

5.2. CE AND MINERAL WASTE

The mineral waste generated within the EU amount to almost 1.8 Bn tons per year, which constitutes 72% of all solid waste. In Poland, where the power sector is still based on coal and the non-ferrous metal ore (mainly copper) mining industry is well developed, the share of mineral waste in the solid waste stream reaches almost 90%. According to the forecast Energy policy of Poland, although the share of coal will decrease within the next 15-20 years, it will still account for 40-45% of the domestic energy mix. This means that coal beneficiation wastes, as well as ash and slag generated by the thermal power sector will still have a significant share in the domestic waste stream.

This should impel to look at mineral waste not only as an obvious subject of interest for CE, but also as a strategic resource limiting pressure on natural (primary) mineral resources, especially aggregates for construction; currently only 8% of the aggregates originate from recycling of construction and demolition.

5.2.1. CCBs MANAGEMENT

The basic source of electricity and thermal energy in Poland is hard coal and lignite combustion (76%, 2018), while the share of other carriers is insignificant [108]. Combustion By-products (CCBs), apart from gases, are generated as a result of the thermal processing of coal, and more precisely, the organic matter contained within. An average of 23 million tons of CCBs are generated in Poland every year, which amounts to approx. 17% of all domestically produced waste [90]. Combustion By-products include fly ash, bottom ash, ash-slag mixtures, microspheres, flue gas desulphurization products, post-reaction gypsum and mixtures of fly ash and flue gas desulphurization products. Combustion By-products, according to the Waste Catalogue, are classified as group 10 "Thermal process waste", subgroup 10 01 "Waste from power plants and other combustion plants" [100]. The status of a product is assigned to gypsum produced in power plants, which is the outcome of flue gas desulphurization, as well as fly ash used, among others, as concrete additive [130]. The range of products manufactured based on CCBs is growing, and in many cases they have become indispensable. They are used as substitutes for natural resources in civil engineering. They do not have an adverse impact on the environment and health, which has been explicitly confirmed by many years of research conducted for the purposes of the EU REACH legislation. The concept of Anthropogenic Minerals (AM) was suggested in terms of combustion by-products by dr Tomasz Szczygielski in 2013, during the "World of Coal Ash Conference (WOCA)" in Lexington, drawing attention to the fact that these are mineral, not artificial resources. The issue of identifying by-products as anthropogenic minerals has been thoroughly described in the publication titled "Przyczynki do systematyki zasobów antropogenicznych *[Impetus behind the systematics of anthropogenic resources]*" published as part of the "Ashes from Power" international conference, which has been organized in Poland for over 26 years [116].

Given the: 1) growing number of produced anthropogenic minerals originating from the power industry in the future, resulting from the adopted national energy policy, 2) their properties, hence, application opportunities and potential, 3) known method of application within the economy (described in technical standards and approvals) [112], 4) increasing demand of the binder and aggregate market [73, 105], 5) decreasing or scarce natural raw material stock, 6) external conditions associated with the pro-climate policy in force and the need to implement the principles of Zero-Waste Economy *(Zero Waste Europe)*, efficient resource utilization *(Resource Efficient Europe)* and circular economy, we should focus on limiting the harmful effects of the Polish power production process through utilizing the potential of this sector in a way, so that all of its operational outcomes constitute an added value for the economy [113].

Anthropogenic minerals are low-emissions resources. Since ashes from power production are a by-product generated in the course of coal combustion during energy production, their generation does not entail additional CO_2 emissions, which would be created when using traditional binders, such as cement or lime. The application-wise potential of combustion by-products in developing road embankments and base courses is estimated at 100 and 50% of their volume respectively. Whereas the reduction in CO_2 emissions is proportional to the emissions associated with using traditional binders, the production of which entails releasing carbon dioxide to the atmosphere [98]. The *TEFRA JI®* project, using the *Joint Implementation* mechanism provided for in the Kyoto Protocol, concerned one of the branches of this issue, and enabled avoiding the emission of over 350k tons of CO_2 over five years by producing and marketing combustion by-product binders, able to effectively replace cement and lime in selected geotechnical applications – mainly road construction – which has been confirmed by the allocation of an appropriate amount of emission allowances (ERUs) [64]. Modern coal combustion techniques generate new by-products in the form of fly and bottom ash from fluidized-bed combustion, the use of which, in a manner similar to conventional combustion ash is not fully possible. This is due to the specific properties shaped by, among others, the combustion technique, often combined with simultaneous flue gas desulphurization. CCBs from fluidized bed combustion can be successfully used to generate hardening slurries – mixtures of water, binder and a thixotropic components (e.g. bentonite). A hardening slurry can be used for a narrow range of construction work associated with the foundation and prefabricated concrete elements with the ground (walls or piles) and for the execution of independent structural elements, such as vertical or horizontal waterproofing membranes. In an overwhelming majority of cases, a specific hardening slurry composition is determined experimentally, depending on the properties to be exhibited at the place of incorporation. Depending on the dosage of ingredients (water, bentonite, cement, ash), slurries can be non-hardening – used for excavation wall stabilization, hardening – intended for waterproofing screens, semi-liquid; with extreme cases being unstable slurries (due to a too high water loss) and pastes or ashes (with small water share). Laboratory tests involving hardening slurries containing a cement binder with an addition of fly ash from conventional or fluidized-bed combustion of hard coal and lignite [128, 129, 131] confirmed the possibility of applying this types of CCBs for slurries. The slurries not containing cement were also studied. In this case, the binder was a mixture of ground blast furnace slag and fluidized bed lignite combustion fly ash. The obtained binder parameters confirm the possibility of creating hardening slurries with high content of CCBs and without Portland clinker [128]. This not only results in their recycling but also contributes to decreasing CO_2 emissions.

Fluidized bed hard coal combustion ash and slag can be used for stabilizing hard coal extraction spoil – unburnt colliery shale. The material resulting from that combination creates an anthropogenic base with numerous beneficial geotechnical features, which can be incorporated into earth structures. This solution faces certain application-related challenges resulting from the interaction between shale and CCB – in shale and ash mixtures there are complicated, long-term transformations of chemical nature, which lead to usually adverse volumetric changes within the material. Water has a significant share in the course of these processes. Its content in the mixture, in actual conditions, is not only the outcome of producing a shale and CB mixture, but also the operating conditions of this material after embedding into a specific structure, subject to, e.g. atmospheric actions [132].

In pursuit of zero-waste economy, also wastewater sludge or municipal waste are subject to incineration, which results in the formation of ash exhibiting different properties than coal combustion ash. Their management is significantly harder. Nevertheless, attempts are made at using this type of combustion by-products. Their application for producing hardening slurries for waterproofing membranes creates opportunities for using these products instead of gathering them in landfills [91, 75].

5.2.2. OTHER MINERAL WASTE

An example of other waste, which are part of circular economy, are water decarbonization waste (19 09 03) [101].

Water decarbonization waste are generated in the water treatment process for its municipal or industrial use. One of the water treatment methods is decarbonization (softening). The process is aimed at decreasing the carbonate hardness of water caused by water-soluble compounds, i.e. $Ca(HCO_3)_2$, $Ca(OH)_2$, $MgCO_3$, $Mg(HCO_3)_2$, as a result of their transformation into precipitating insoluble compounds, with thermal or chemical methods. The most commonly applied method for removing carbonate hardness is water decarbonization using calcium, i.e. application of $Ca(OH)_2$.

Calcium carbonate $CaCO_3$ precipitates in the form of calcite, sometimes with an admixture of unstable forms of aragonite or vaterite. Magnesium hydroxide $Mg(OH)_2$ precipitates only as gelatinous sludge.

There is approx. 100 000 tons of water decarbonization waste generated in Poland per annum.

Research on the ways to manage water decarbonization waste indicated that the sludge can be used in cement production, within the wet flue gas desulphurization process in coal-fired power plants.

A commonly recommended way to manage water decarbonization sludge is using it for agricultural purposes [81].

There are ongoing studies on the possibility of using water decarbonization sludge in geotechnics, e.g. for road construction, land levelling or sealing layers [13]. Under appropriate incorporation conditions, that sludge can be used to construct sealing layers for landfills with inert and hazardous waste, and other than hazardous and inert waste [14]. Furthermore, this sludge can be successfully used to neutralize wastewater.

In 1989, the Netherlands started producing granulated product from water decarbonization sludge, which was then used as an additive for building materials, chicken feed, in electroplating and for deacidification of groundwater. It was also possible to use the granules for the production of steel and fertilizers, in stabilizing wastewater sludge, wastewater dephosphatation and recalcination of calcium carbonate [81].

6. ZERO-WASTE COAL POWER (ZWCP)

In Polish conditions of CE implementation, the greatest scope of the economy is covered by Zero-Waste Coal Power [59]. This results from, among others, addressing the issues, which are extremely important for Poland, namely, energy-related utilization of fossil fuels, quantities of generated emissions and the amount of waste – starting with the beneficiation of mine working, followed by coal combustion by-products from combined heat and power plants. The project covers several sectors of the economy, such as mining, power, building materials, construction and others. This means that CE in this case covers a significantly large circle and requires overcoming cross-sectoral barriers, with unfortunately growing importance in terms of CE implementation [42]. In many respects, this project is also technologically advanced, since its technical components have been successfully developed for many years (i.a. at the Mineral Engineering Centre of the Institute of Applied Research at the Warsaw University of Technology [2]), and the synergy effect lacks their integration through extra-technical activities, including legal and organization at high management levels (politics) and proper business models.

Conditioning of anthropogenic minerals resulting from coal combustion in the power sector can be executed through proper treatment of fuel, its deliberately controlled combustion and appropriate processing of minerals generated in the course of the combustion process. A power boiler, in addition to converting the chemical energy of fuel into thermal energy, shall also be recognized as a multi-functional chemical reactor for modifying the properties of generated ash and slag, as a function of achieving and maintaining their physical and chemical parameters. ZWCP is an answer to the aforementioned challenge – its block diagram is shown in Fig. 7. ZWCP includes controlling the processes of energy-related coal combustion at the stages of fuel preparation and feeding (ModFuel), combustion of coal in power boilers (ModComb), removing CB from the combustion chamber and transporting it to electrostatic precipitators (ModBreak), as well as CB storage and transport (ModSep). The fifth stage within the presented processing processes is the ModMix module. It involves a further change of already modified anthropogenic minerals (change of the chemical composition or physical properties) in order to obtain new (other) end products. The ModMix module technologies involve mixing ash with additives, also with other ashes or granulating and subjecting it to other processes, as per developed recipes, followed by loading and delivery to the end consumer. Effective implementation of Zero-Waste Coal Power will enable energy producers to avoid the risk of a significant increase in the costs, e.g. generated by misplaced and fragmentary horizontal regulations, failing to take into account the complexity of the aforementioned issues. The suggested approach to anthropogenic minerals shall satisfy the assumptions of the EU package, which will strictly follow the principles of circular economy [114].

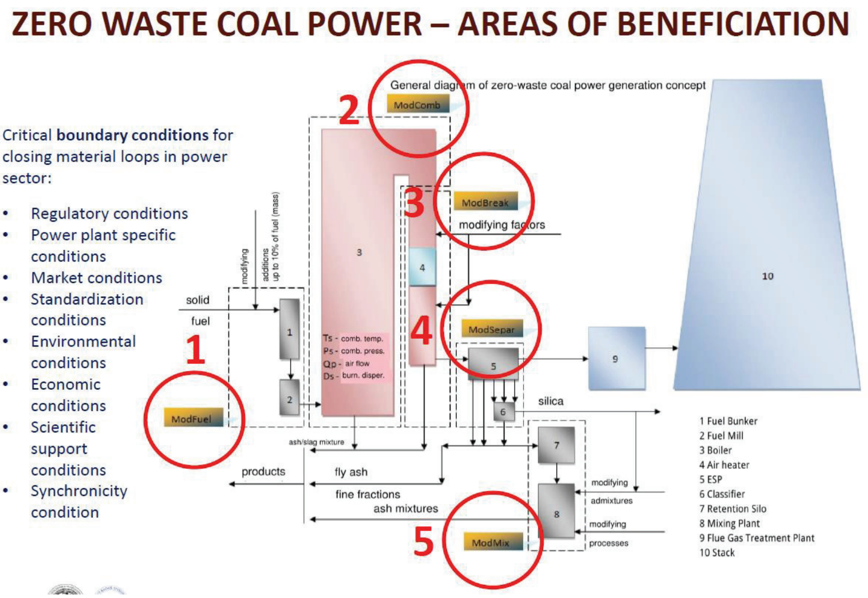

Fig. 7. Zero-waste Coal Power – modifications [59]

To achieve a full implementation, most efficient CE extent, the ZWCP concept requires not only research and technical activities (it seems that they are well developed and have been selectively implemented in this field), but also actions integrating and supporting CE at the current stage. This can be achieved owing to the right policy, overcoming cross-sectoral barriers, developing legal regulations and support schemes for CE, such as e.g. "Zielona geotechnika" *(Green geotechnics)* or "Pierwszeństwo dla wtórnych" *(Priority for secondary)* [111,115], which lead to the inclusion of modified and standardized waste as product in many fields of their potential application, under economically justified principles.

7. CONCLUSIONS

The review of CE condition in Poland, i.a., against EU documents, indicates that the advancement of recycling technologies does not deviate from the global level, and in terms of areas specific to

Poland, e.g. relating to coal combustion by-products, ensures the possibility of further CE implementation and even to a significant extent.

Issues, just like in numerous other countries, mainly concern overpower the dominating model of mass and intensive consumption, which is based on decreasing the value of primary resources and depreciating waste as a source of renewable resources. The key to overcoming this barrier is changing the mentality of societies and economically conditioned introduction of recycling in the sustainable manufacturing processes.

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Słowa kluczowe*: gospodarka obiegu zamkniętego, odpady komunalne, GOZ w budownictwie, gospodarka ściekowa, zasoby pierwotne, bezodpadowa energetyka węglowa, uboczne produkty spalania*

STRESZCZENIE

W niniejszym artykule przeglądowym przedstawiono stan gospodarki obiegu zamkniętego (GOZ) w Polsce. Pokazano GOZ w zróżnicowanym ujęciu: przedmiotowym (strumienie odpadów, energia), sektorowym (budownictwo, oczyszczalnie ścieków, energetyka węglowa) i zasobowym (minerały antropogeniczne, fosfor), a także pod kątem właściwego gospodarowania energią w budownictwie (budynki niemal-zero-energetyczne).

Wdrażanie GOZ w sektorze komunalnym oznacza projektowanie wyrobów trwałych, które mogą być wielokrotnie wykorzystane w cyklach zamkniętych. Przetwarzanie odpadów wiąże się z rozbiciem na dwa równoległe obiegi: zarządzanie strumieniem zasobów odnawialnych (cykl biologiczny) i wyczerpywalnych (cykl technologiczny). Najważniejsze strumienie odpadów powiązane z sektorem komunalnym to zmieszane odpady komunalne, bioodpady i odpady żywności oraz odpady surowcowe (głównie z tworzyw sztucznych).

GOZ w budownictwie wiąże się z ograniczeniem zużycia nowych materiałów budowlanych i wykorzystaniem tych pochodzących z recyklingu, np. poprzez zainstalowanie elementów pozyskanych z rozbiórki innego budynku. Realizacja idei GOZ to również zastosowanie w czasie budowy materiałów ułatwiających demontaż elementów i remonty. Produkcja betonu również wpisuje się w GOZ dzięki wykorzystaniu paliw alternatywnych (m.in. mączka mięsno-kostna lub wysuszone osady ściekowe) zastępujących paliwa kopalne podczas wypalania klinkieru. Kolejnym sposobem redukcji emisji CO_2 do atmosfery oraz ilości składowanych produktów ubocznych (popioły lotne, żużle wielkopiecowe) jest wykorzystanie ich jako zamiennika części klinkieru w cemencie oraz jako dodatek do betonu (typu II, dodatki pucolanowe lub o utajonych właściwościach hydraulicznych). Coraz powszechniej w branży budowlanej stosowane jest oprogramowanie BIM (Building Information Modeling), które pozwala na stworzenie matematycznego modelu obiektu w przestrzeni wirtualnej , ułatwiającego wykrycie kolizji w fazie projektowej i zawierającego istotne informacje o konstrukcji i wykorzystanych materiałach. Umożliwia to ograniczenie ilości odpadów na etapie wykonania budynku oraz efektywne naprawy na etapie użytkowania i łatwy demontaż. Dużą rolę w implementacji GOZ w budownictwie odgrywa prefabrykacja. Wdrażane są nowe rozwiązania materiałowe i innowacyjne technologie zapewniające odpowiednio wysoką trwałość elementów prefabrykowanych posiadających potencjał do recyklingu.

Niemniej ważnym aspektem GOZ w budownictwie jest przepływ energii podczas eksploatacji obiektów budowlanych. W instalacjach ogrzewania, wentylacji i klimatyzacji (HVAC) stosowane są czynniki pośredniczące, w tym czynniki chłodnicze o ograniczonej szkodliwości dla środowiska, które można odzyskać i ponownie wykorzystać. W budynkach stosuje się obiegi zamknięte umożliwiające odzysk ciepła. Niezwykle ważnym elementem w procesie projektowania jest analiza energetyczna umożliwiająca dobór właściwych systemów pod względem energetycznym, komfortu cieplnego, jakości środowiska wewnętrznego oraz materiałów i rozwiązań nie wpływających negatywnie na środowisko. Kompleksowe podejście z kontrolą procesu na każdym etapie (projektowanie zintegrowane) pozwala na zaprojektowanie budynku o niemal zerowym zużyciu energii. Ma to niebagatelne znaczenie przy ustalaniu całkowitej sumy emisji gazów cieplarnianych generowanych przez obiekt (ślad węglowy).

GOZ w oczyszczalniach ścieków oznacza prowadzenie procesów technologicznych umożliwiających odzysk energii, ciepła i surowców (m.in. wody) jednocześnie minimalizując występowanie w odzyskanych zasobach zanieczyszczeń z grupy tzw. substancji podwyższonego ryzyka. Istotnym elementem jest wykorzystanie analizy cyklu życia (Life Cycle Assessment – LCA), w tym określenie śladu węglowego. Procesy wykorzystywane do stabilizacji osadów ściekowych (fermentacja metanowa) pozwalają na odzysk energii i ciepła z powstającego biogazu, zawierającego ok. 60-70% metanu. Prowadzone są badania ukierunkowane na zwiększenie wydajności produkcji biogazu (proces kofermentacji i wstępnego przygotowania wsadu metodą dezintegracji). Odzyskane podczas procesu dezintegracji związki organiczne mogą zostać wykorzystane do intensyfikacji procesu usuwania związków biogennych ze ścieków. Kolejnym ważnym aspektem GOZ w gospodarce wodno-ściekowej jest odzysk fosforu. Usuwanie fosforu ze ścieków jest konieczne z punktu widzenia ochrony zbiorników wodnych przed eutrofizacją. Zamykanie obiegu fosforu poprzez jego odzysk w oczyszczalniach ścieków umożliwia wykorzystanie osadów ściekowych do celów rolniczych i przyrodniczych. Najwyższy potencjał ma odzysk fosforu z popiołów ze spalania osadów ściekowych. Osady ściekowe są również potencjalnym źródłem PHA stosowanego do produkcji tworzyw sztucznych. Woda recyklingowa odzyskana z osadów ściekowych jest stosowana do celów technologicznych (m.in. płukania krat), a także do nawadniania terenów zielonych, na potrzeby gospodarcze lub jako woda do picia.

Fosfor znalazł się w wykazie surowców krytycznych dla UE ze względu na duże znaczenie gospodarcze i wysokie ryzyko dostaw. Jest to pierwiastek krytyczny o znaczeniu biochemicznym, niezbędny do produkcji rolniczej. Na rynku nie ma alternatywnych źródeł dla skał fosforanowych. Obecny system produkcji i konsumpcji żywności jest wysoce nieefektywny w odniesieniu do wykorzystania fosforu. Główne cele w procesach odzyskiwania fosforu to ochrona zdrowia ludzkiego i środowiska, ograniczenie zużycia wody w systemach sanitarnych i gospodarczych oraz zmniejszenie zapotrzebowania na nawozy mineralne. Można je osiągnąć przez recykling i obieg zamknięty substancji odżywczych pochodzących z różnych źródeł, z rozdzieleniem składników odżywczych, a w efekcie fosforu. Fosfor można potencjalnie odzyskać z dowolnego strumienia odpadów organicznych (odpadów spożywczych, wydobywczych, obornika, odchodów ludzkich itp.). Odzysk fosforu następuje przez kompostowanie, rozdział fizyczny, chemiczny, wytrącanie i spalanie, usuwanie biologiczne i biochemiczne.

GOZ w budownictwie opiera się również na zagospodarowaniu ubocznych produktów spalania, które nie mają zastosowania w produkcji cementu i betonu (popioły fluidalne, popioły ze spalania osadów ściekowych). Są one stosowane do zawiesin twardniejących, z których wykonuje się m.in. bariery przeciwfiltracyjne w podłożu gruntowym. Podobnie jak popioły i żużle, także inne odpady mineralne, np. osady z dekarbonizacji wody, mogą być wykorzystane do budowy dróg, niwelacji terenu, budowy warstw uszczelniających składowiska odpadów.

W prezentowanym przeglądzie głównie technologicznych aspektów GOZ najdojrzalszą jest idea bezodpadowej energetyki węglowej (BEW). Polega ona na ingerencji w procesy spalania węgla w takim stopniu, aby powstające produkty uboczne były (także formalnie) pełnoprawnymi produktami, przydatnymi w innych gałęziach gospodarki. W koncepcji BEW elektrownia staje się wytwórcą energii i pełnowartościowych materiałów o różnym przeznaczeniu. Dzięki temu zmniejszają się: zapotrzebowanie na materiały pierwotne, emisje i ilości składowanych odpadów. Niezależnie od obszaru wdrażania GOZ, w każdym przypadku niezbędna jest właściwa polityka przełamująca bariery międzysektorowe oraz tworząca regulacje prawne i programy wsparcia dla GOZ.

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