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Potential of Using Selected Industrial Waste Streams in Loop-Closing of Material Flows—The Example of the Silesian Voivodeship in Poland

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Abstract: Every year, the industrial sector produces a significant amount of waste. Bearing in mind the need to improve resource efficiency and reduce the impact of industrial plants on the environment, an attempt was made to identify and determine the processing potential of selected waste streams with respect to the circular economy, along with an indication of sectoral connections. The subject of the study was industrial waste, which is the dominant stream of waste generated in the Silesian Voivodeship—the area of research. The paper presents the results of quantitative and qualitative analysis of the selected industrial waste streams and provides a visual representation of the flow. The study was based on available statistical data covering quantities of industrial waste. The article also includes the characteristics and possibilities of closing their circulation in the economy. The conducted SWOT analysis identified factors that strongly affect the possibility of implementing the circular economy model. The research allowed us to indicate possible waste flows and identify sectors closing their loop according to the assumptions of industrial symbiosis. The research path carried out on the example of Silesia shows the potential of the model and thus the possibility of implementation in other locations. This study showed that the strongest connection exists between mining-related plants, industrial power plants and combined heat and power plants, cement plants, and construction plants, especially road construction.

Keywords: waste management; circular economy; resource efficiency; sustainable supply chain management

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1. Introduction

Despite the development of waste technologies and increasing financial outlays on the implementation of environmentally friendly solutions, industrial waste is still a significant ballast that negatively affects the environment. The implementation of the circular economy (CE) concept means that more and more attention is paid to the use of the raw material and energy potential inherent in the waste generated by the industry, as well as taking actions at the source to reduce its formation [1]. In this context, the industrial waste generated must have an even composition and properties that significantly differentiate it from municipal waste. This largely allows for economically, ecologically, and socially effective planning its treatment methods. Referring to these arguments, the general aim of the study was to indicate possible waste flows and identify sectors closing their loop according to the assumptions of industrial symbiosis.

It is worth noting that globally, the European Union has a particular approach to the implementation of CE due to the mechanisms introduced and the scope of influence involving member countries. In the case of North America under the North American Agreement on Environmental Cooperation, the Commission for Environmental Cooperation was established in 1994. Since that time, the Commission has pursued some green waste management activities under an agreement between the United States, Mexico, and Canada. The Association of Southeast Asian Nations (ASEAN) and East Asia did not have such an agreement or committee to implement CE regulations [2]. In the case of Africa, so far there is little indication of their involvement in implementing pro-environmental initiatives. However, it appears that the level of involvement is very high and is dictated by cultural and livelihood issues. In Africa, there are organizations and projects such as the African Circular Economy Network (ACEN), ICLEI Africa, or Footprints Africa that are active in the field of CE [3]. Also, Australia's transformation into a circular economy demonstrates high potential by creating plans and regulations that provide an approach to changes in the area of waste management [4]. There are many examples from Europe and the world of CE approaches and projects. Increasing awareness must encourage efforts to implement pro-environmental actions. In Poland, the priority sectors for implementing the circular economy include mining, processing (including the steel industry), energy, construction, the agri-food industry (bioeconomy) and plastics. Due to the hitherto low level of reuse of materials, parts, and waste, as well as the constantly growing demand for products and services of the abovementioned industry sectors, they are shown as key to the implementation of the postulates for sustainable development and a circular economy [5].

Poland has all the conditions for the wider implementation of a closed-loop economy. At this moment, the following points related to the current state of the system are relevant [6]:

- In terms of material consumption, Poland is in third place among the Community countries, and material efficiency in Poland is 3.5 times lower than the average in the European Union (EU).
- Poland has the highest share in Europe in terms of the use of fossil fuels, from which comes as much as 90% of the primary energy consumed in Poland.
- According to statistical data, as much as 45% of all waste is generated by coal mining (hard coal and brown coal) and metal ore mining. These are waste, a small part of which is recycled, which confirms the low effectiveness of Polish waste management.
- One of the more perspective groups of industrial waste is the by-products of combustion, of which about 35% is disposed in landfills. This represents a significant resource loss, given that this waste can be an important source of recovery of economically important minerals.
- The mining and quarrying industries are the largest waste-generating industries. Annually, they generate about 67 million tons of waste.
- The Polish construction market is the seventh largest in the EU and one of the fastest growing in Europe. Across the EU, the sector is responsible for using around half of all extracted raw materials. This is an important reference point in closing the waste cycle.

Despite the numerous activities carried out in recent years as well as the noticeable progress made in the management of municipal and industrial waste, there is a need for further development of systems.

The implementation of tasks concerning waste management (in reference, e.g., to the Waste Framework Directive (Directive of the European Parliament, 2008/98/EC) or the Landfill Directive (Council Directive 1999/31/EC)) is a result of the necessity to carry out work in various social and economic areas. In a specific approach, such as in the case of the Silesian Voivodeship, which is the research area of this paper, a key role is played by the process of transformation of mining regions towards a climate-neutral economy. These actions stem directly from the adopted European Green Deal (COM (2019) 640 final), the need to achieve EU climate neutrality by 2050 and thus the establishment of the Fair Transition Mechanism. Polish mining regions, especially Silesia (in addition to Greater Poland, Lower Silesia, Lodzkie, Lublin and Lesser Poland) are facing various challenges in the transformation process. Recent years have shown that ongoing initiatives are contributing to significant progress on the topic of energy diversification. Despite this, ensuring a comprehensive and successful transition to a climate-neutral economy requires revolutionary CE development. In line with the roadmap and the classification based on the work of the Ellen MacArthur Foundation and applied by the European Commission—ReSOLVE, the following actions are highlighted to enable the transformation towards CE [5]:

- Regenerate
- Share
- Optimize
- Loop
- Virtualize
- Exchange.

The source of new solutions for business models based on CE is primarily cooperation, not only between consumers and producers but also among producers themselves and between entrepreneurs, scientists, and the public sector.

Waste management is one of the most problematic areas of environmental protection. In this context, industrial waste, in particular from mining and quarrying activities, industrial processing and energy generation and supply have a special meaning in Poland. Although this waste is not homogeneous, it has the potential to be reused. In many industries, the primary method of waste management for many years has been landfilling, including storage on heaps. Due to advances in technology, it is reasonable to assume that some of this waste may be an alternative source of raw materials for use in other sectors of the economy.

The appearance of industrial waste in the environment causes enormous risks to all its components. This especially applies to waste from the mining, energy, and metallurgical industries. The deposited waste has a negative impact on the environment, causing:

- Pollution of underground and surface waters due to leaching of hazardous substances from the landfill area
- Air pollution as a result of dusting
- Poil pollution connected with leaching and dusting processes
- Harmful and direct and indirect impact on plants, animals, and people.

The degree and extent of negative impacts is depending on the type and chemical composition of the deposited waste and the location of the landfills or heaps. Flotation waste causes relatively the greatest threat to the environment due to its quantity and heavy metal content. In the absence of appropriate safeguards, these metals can migrate into the environment. Also, waste from the zinc and lead industry are a serious threat to the atmospheric air. If landfills are not protected against dust, heavy metals may be emitted into the atmosphere. It should be noted that water is an environmental component with highest vulnerability to the impact of waste. Hazardous components, mainly inorganic salts, including heavy metal ions, can be released into groundwater and surface water through infiltration and rainwater runoff [7].

Disposal of waste through landfilling is treated as a loss of resources and inefficiency of the economy. According to statistics, the amount of waste landfilled in 2019 was about 49 million tons and covered a total area of more than 8000 hectares [8]. The largest disposal areas are located in provinces where the mining and energy industries develop dynamically and where the largest amounts of waste are generated, including the Silesian Voivodeship. Waste from the mining and processing sector, such as waste from the construction sector, has a high potential for reuse. Conducting less and less wasteful production activities and closing the industrial waste stream may significantly contribute to increasing the profitability of production in Poland, even in the long term.

The transition to a circular economy requires a coherent and comprehensive approach [9]. For this reason, various instruments are created, such as road maps and sets of guidelines, which are aimed to present the main assumptions of the transformation process and implement solutions [10,11]. What is also important is the environmentally friendly attitude of entrepreneurs who increasingly recognize the added value of introducing CE into the existing industrial systems and carry out comprehensive flow analyses in production processes targeted toward reducing resource waste.

An important weak point related to the lack of integration and synchronization of activities can be seen in the activities undertaken in Poland aimed at closing material flows. Limiting the development of industrial symbiosis, the lack of developed cooperation models and readiness to implement innovative technologies causes the need to isolate the most promising sectoral connections and areas of cooperation, enabling closing of flows for various materials. The aim of the work was formulated for such a characterized research area, which was to identify and determine the processing potential of selected waste streams regarding the circular economy together with an indication of sectoral connections.

Due to the postulated implementation of the circular economy, enterprises are required to carry out a comprehensive and systemic change of activity. Therefore, it is justified to undertake works indicating economically and ecologically sectoral connections that will enable closing the waste flow in the economy, following the circular economy paradigm.

2. Materials and Methods

To achieve the main objective of the paper—to indicate possible waste flows and identify sectors closing their loop according to the assumptions of industrial symbiosis, the following steps were carried out:

(I.A) Analysis of other statistical data sources, including those from the European Statistical Office [12] covering data on the amount of waste generated in the country, with particular emphasis on the Silesian Voivodeship. This data was used for quantitative and qualitative analysis of the selected waste streams, taking into account their logistics chain/management system.

(I.B) Analysis of statistical data on waste aggregated at national level. The data from years 2020 and 2017–2016 have been analyzed. Data come from Statistics Poland—the Polish Statistical Office and are related to the thematic area of Environmental Protection for the mentioned date periods [13,14]. The statistics include summary data on industrial and municipal waste prepared under the classification in the Waste Act [15] and the Waste Catalog [16], which divide waste into groups, subgroups, and types, taking into account the source of formation.

It should be noted that the different periods from which the data are analyzed (2016–2020) were due to the limited availability of these data. Some of them have not been updated; however, it is possible to identify important characteristic trends. In addition, these data are mainly used to formulate general frameworks and assumptions, thus the lack of updating the database does not affect the research process of this paper.

(II.A) Analysis of the current state of the waste management system in the Silesian Voivodeship based on the Voivodship Report on Waste Management for 2020 made available by the Marshal Office of the Silesian Voivodeship [17]. The issues of preparing reports are regulated by the Act of 3 October 2008 on sharing information on the environment and its protection, public participation in environmental protection and environmental impact assessments (Journal of Laws 2013.1235) [15].

(II.B.) Critical analysis of reports on the state of the environment in the Silesian Voivodeship, covering 2017 [17], which are the result of cyclical research conducted by the Provincial Inspectorate for Environmental Protection in Katowice as part of the State Environmental Monitoring and are co-financed by the Provincial Fund for Environmental Protection and Water Management in Katowice.

(III) A critical review of source materials within the subject of research characteristics of specified waste and analysis of the existing solutions in the field of effective management of industrial waste in the context of waste logistics and closing its flow. The study was supported by a SWOT analysis for the management system of the identified industrial waste groups. SWOT analysis was derived from critical analysis of source materials and our own observations allowing for the formulation of appropriate conclusions.

The methodology used to analyze the secondary data included defining the scope of data needed to achieve the main goal of the study, locating data, evaluating relevance of the data, assessing credibility of the data, and final analysis of the data. The research framework focuses on indicating possible directions for closing the loop and thus implementing CE. The structure of this work includes a comprehensive approach to the topic based on available statistical and literature data. This is the beginning of further work on the technological and logistical possibilities of transforming waste into a valuable and useful product. The adopted research plan with its framework is shown in Figure 1.

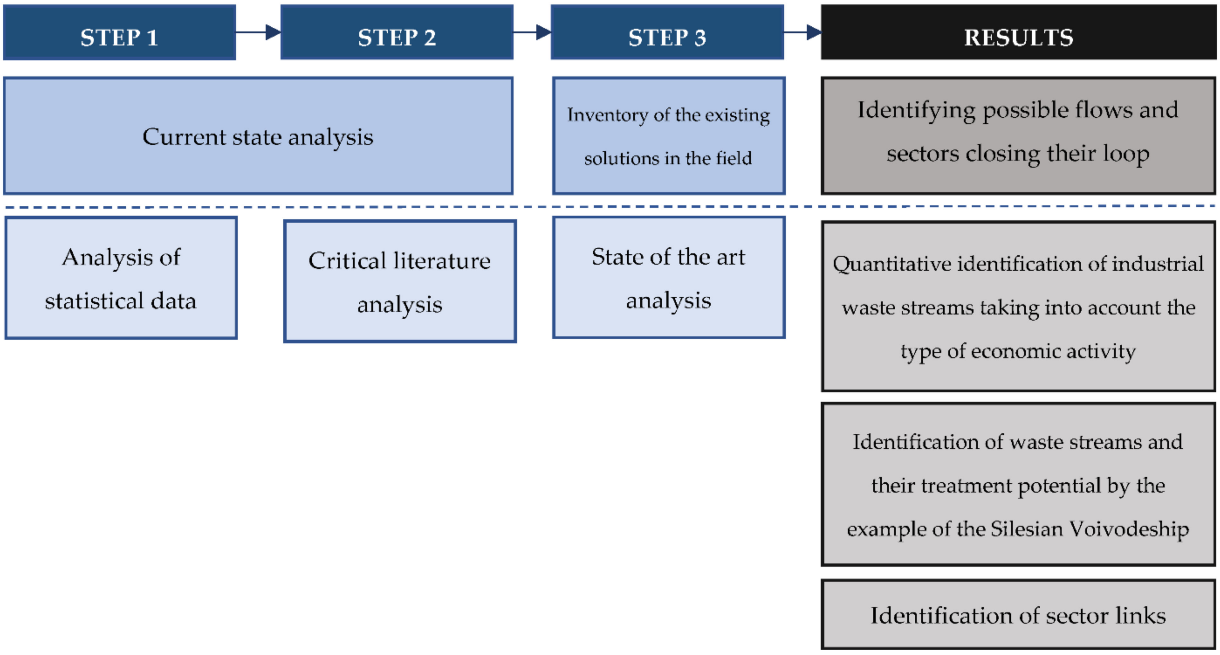

Figure 1. The research plan and conceptual frameworks. Source: own elaboration.

The subject of the study was industrial waste generated in the economic sector, which is the dominant waste stream generated in the Silesian Voivodeship. This results come directly from the high level of industrialization of the region dominated by traditional industries such as hard coal mining, energy, and metallurgy, as well as the automotive industry and other developing industrial sectors, some of which are of strategic importance. The choice of the Silesian Voivodship as the research area resulted from the highest processing potential of industrial waste in the country, which additionally results in utilitarianism in terms of referencing the results to other regions of the country [18].

3. Results

3.1. Quantitative Analysis of Industrial Waste Streams, Taking into Account the Type of Economic Activity

To determine the potential for the use of industrial waste, statistical data covering the amount of waste generated (excluding municipal waste) and directions of its management broken down by Voivodship were analyzed (Table 1).

Table 1. Waste generated and previously stored (accumulated excluding municipal waste) in 2020 by Voivodship (in thous. Mg).

Voivodships	Total	Recovered	Recovered-Composted	Recovered-Other Way	Disposed	Disposed-Thermally	Disposed-Stored in Own Facilities	Disposed-Other Way	Transferred to Other Recipients	Temporarily Stored
	in Thousand Mg									
Poland	**109,466.0**	**25,986.7**	**58.4**	**21,730.7**	**21,875.6**	**398.4**	**16,752.3**	**4724.9**	**59,083.7**	**2520.0**
Lower Silesia	33,315.1	1158.8	0.0	86.0	645.1	5.5	616.5	23.1	31,301.0	210.2
Silesia	27,616.6	14,072.5	0.0	13,181.2	2271.1	0.0	2264.9	6.2	11,193.7	79.3
Lodzkie	7191.7	309.8	0.0	76.9	6030.5	65.1	5964.9	0.5	645.6	205.8
Masovia	6048.0	863.0	0.0	861.4	2825.3	191.1	164.3	2469.9	2326.8	32.9
Lublin	5757.4	60.3	0.0	46.1	2795.9	0.0	2793.1	2.8	2886.9	14.3
Lesser Poland	5296.7	2738.9	0.0	2274.6	213.8	59.5	153.2	1.1	2266.7	77.3
West Pomerania	4928.0	460.2	20.4	410.8	3794.3	5.4	1945.8	1843.1	644.2	29.3
Holy Cross	4593.2	957.2	0.0	308.9	2797.4	15.9	2508.7	272.8	698.8	139.8
Greater Poland	3299.1	674.2	14.3	659.9	356.1	0.0	297.9	58.2	2231.9	36.9
Warmia-Masuria	2500.4	1945.2	0.0	1945.2	50.5	9.7	0.0	40.8	492.9	11.8
Podlasie Province	2363.1	706.6	0.0	585.8	7.3	6.8	0.0	0.5	229.0	1420.2
Pomerania	1842.6	694.0	18.1	580.2	56.4	25.6	30.8	0.0	926.9	165.3
Kuyavia-Pomerania	1541.7	352.6	2.1	350.5	4.7	3.1	1.5	0.1	1112.4	72.0
Opole	1394.2	682.2	0.0	116.6	9.1	0.1	9.0	0.0	697.7	5.2
Subcarpathia	1088.3	124.0	3.5	120.1	13.8	10.6	0.0	3.2	935.3	15.2
Lubusz	689.9	187.2	0.0	126.5	4.3	0.0	1.7	2.6	493.9	4.5

Source: Statistics Poland, 2021.

In 2017 in the Silesian Voivodeship, 31,648.2 thous. Mg of hazardous and non-hazardous waste (excluding municipal waste) was produced in 284 plants, which accounted for 24.9% of the total waste generated in the country [19]. In 2018, the amount of generated waste decreased by 10% compared to 2017 and amounted to 28,678.6 thousand Mg. Among the industrial waste generated, 43% was recovered by plants on their own, 49% was transferred to other recipients, and 8% was disposed of by plants on their own. Accordingly, in 2019, 30,502.2 thousand Mg were generated, and for 2020, as shown in the table–27,616.6 thousand Mg was generated, which is the second position in Poland by volume. Of these, 51% were recovered, 41% were transferred to another recipient, and 8% were disposed of. In comparison with other provinces and presented shares of waste management, Silesia shows high effectiveness in the waste management system. However, the statistics do not show how the waste is managed quantitatively by other recipients (49% of all waste). This makes it impossible to specify precisely what part of the transferred waste was treated in recovery processes and what part was disposed of.

The Silesian Voivodeship is recognized as the most important industrial region of the country. Many years of industry activity result in significant environmental degradation. These damages provided encouragement to take initiatives related to the currently implemented economic transformation of the region [20]. In the context of the conducted analyses, the Silesian Voivodeship is therefore a reference point for shaping comprehensive solutions related to the creation of circular economy models for the selected industries against the background of the entire country.

The Polish Central Statistical Office data [13,14] included in Table 2 show the implemented industrial waste management directions according to the Polish classification of activities (NACE), which is a conventionally adopted, systematic division of socio-economic types of activities implemented by units operating in Poland (business entities). The majority of industrial waste was generated by mining and quarrying companies—60,837.90 thous. Mg, which represents 56% of the total industrial waste generated in the country. Manufacturing is second (21%), and electricity plants are third (11%), followed by entities dealing with the production and supply of electricity, gas, steam, hot water and air for air conditioning systems, next construction (7%) and water supply, sewage and waste, and remediation activities (5% and 2.5%, respectively). The remaining plants generate a total of 1% of industrial waste. It should be noted that the table does not include the following waste management methods: transferred to other recipients and temporarily stored. Due to the purpose of the research and this analysis, the mentioned data can be excluded without affecting the result of the work.

In 2018, 37% of the generated waste was recovered at mining plants and 62% was disposed of within the plant—40% and 59%, respectively, in 2020. The processing industry shows the opposite trend, where the largest amount of industrial waste has been recovered (75% in 2018 and 71% in 2020). In this case, plants whose activities are related to the production of chemicals and chemical products deserve special attention. In 2020, only 27% of waste was recovered and as much as 72% was disposed of. Also, in the case of plants related to water and sewage management, more than half of the generated waste (52% in 2018 and 56% in 2020) was disposed of, which indicates the existence of a significant potential for conducting research related to the search for potential possibilities of re-utilization.

Table 2. Waste generated during the year and landfilled (accumulated) so far and their landfill sites according to the Polish classification of activities in 2020 (in thous. Mg).

Classification	Grand Total	Recovered	Recovered [%]	Disposed Total	Disposed [%]	Waste Landfilled (Accumulated) so Far
	in Thousand Mg					
SECTION B—Mining and quarrying	**60,837.90**	**24,398.40**	**40%**	**36,141.80**	**59%**	**828,301.70**
Sector 05—Mining of coal and lignite	27,835.30	21,422.20	77%	6315.50	23%	430,149.50
Sector 07—Mining of metal ores	28,008.30	56.60	0%	27,950.80	100%	317,129.10
Sector 08—Other mining and quarrying	4975.70	2910.10	58%	1875.50	38%	48,060.80
Sector 09—Mining support service activities	18.60	9.50	51%	–	–	32,962.30
SECTION C—Manufacturing	**23,123.20**	**16,418.20**	**71%**	**5908.80**	**26%**	**282,500.10**
Sector 10—Manufacture of food products	2056.00	1659.10	81%	291.40	14%	32.40
Sector 16—Manufacture of wood and of products of wood and cork, except furniture; manufacture of articles of straw and plaiting materials	538.10	347.40	65%	25.20	5%	12,903.60
Sector 17—Manufacture of paper and paper products	1234.20	1103.90	89%	59.00	5%	3341.50
Sector 20—Manufacture of chemicals and chemical products	5314.30	1450.70	27%	3822.90	72%	135,875.10
Sector 23—Manufacture of other non-metallic mineral products	2941.20	1755.20	60%	1134.80	39%	43,673.80
Sector 24—Manufacture of basic metals	8238.60	7699.90	93%	285.80	3%	83,269.80
SECTION D—Electricity, gas, steam, and air conditioning supply	**11,590.90**	**4583.40**	**40%**	**6791.20**	**59%**	**307,029.90**
Sector 35—Electricity, gas, steam, and air conditioning supply	11,590.90	4583.40	40%	6791.20	59%	307,029.90
SECTION E—Water supply; sewerage, waste management and remediation activities	**5464.80**	**2288.70**	**42%**	**3052.60**	**56%**	**357,597.60**
Sector 36—Water collection, treatment, and supply	3996.10	1163.30	29%	2799.90	70%	297.50
Sector 37—Sewerage	1053.00	788.90	75%	190.90	18%	9156.00
Sector 38—Waste collection, treatment, and disposal activities; materials recovery	318.90	239.70	75%	61.80	19%	335,342.60
Sector 39—Remediation activities and other waste management services	96.80	96.80	100%	–	–	12,801.50
SECTION F—Construction	**7351.80**	**4685.50**	**64%**	**5.10**	**0%**	**–**
Sector 41—Construction of buildings	524.30	10.80	2%	–	–	–
Sector 42—Civil engineering	6652.80	4520.70	68%	4.90	0%	–
Sector 43—Specialized construction activities	174.70	154.00	88%	0.20	0%	–
OTHER SECTIONS	**1097.30**	**567.90**	**52%**	**523.10**	**48%**	**12,417.80**

Source: Statistics Poland, 2021.

The specification of the industrial waste generated in the appropriate categories of economic activity is in Table 3, which presents the specified types of waste assigned to the relevant scope of economic classification groups. In this list, mineral waste deserves special attention, accounting for 44.9% of all industrial waste generated in the country and directly related to the mining plant. Incinerated waste accounts for 15.5% of the total waste generated directly related to the energy industry (section D) and the steel industry (section C).

The lack of updated reports makes it impossible to present data for later years. Nonetheless, it is possible to show correlations between waste groups and the sectors in which they occur in the greatest quantity. It can be concluded from previous analyses of individual years that this share has not changed significantly in later years. For the study, these data support the modelling of waste flow within the economic system.

The analysis of the data shows that storage is the dominant method of managing those groups of industrial waste, whose total quantity constitutes the largest share of the total amount of generated waste in the country. This applies to both mineral waste in quantity—25,553.3 thous. Mg and waste from combustion—10,090.9 thous. Mg (Table 4). There is a significant waste of value due to the failure to use the raw material and energy potential of the collected waste. The scale of this loss is equal to the total amount of industrial waste subjected to disposal, for which recovery technologies exist and markets are ready for reuse.

The data presented in Table 4 show that the largest share of waste disposal by landfill is accounted for by household and similar wastes (49%—this is municipal waste, not included in the scope of the problem), combustion wastes (40%), mixed and undifferentiated materials (39%), other mineral waste (32%). The potential for closing the waste cycle is in the mentioned waste groups, given the current waste hierarchy and avoiding disposal by landfill. However, this does not mean that the other groups do not show processing potential. The data presented is intended to outline the share of waste groups in the treatment methods and the current management trend. In addition, it is worth noting that another mineral waste has the largest share in the generated waste (49%), followed by combustion wastes at 15% and household and similar wastes with soils at 7% each. In other cases, the share is below 5%. This shows which waste groups are potential sources of alternative resources and have opportunities for reuse in the economy.

Table 3. Waste generation in 2016 based on categories of economic activity according to PKD classification **.

Waste Category		B—Mining and Quarrying	C—Manufacturing **	D—Electricity, Gas, Steam, Hot Water and Air Conditioning Manufacturing and Supply	E—Water Supply; Sewerage, Waste Management and Remediation Activities **	F—Construction
Total		**70,667,483**	**27,208,541**	**20,512,487**	**21,927,572**	**18,890,577**
Chemical wastes	N *	835	154,988	285	133,588	10,797
	I	266	1,731,274	21,045	8915	1099
Wood wastes	N	0	4015	0	487	1
	I	4827	1,588,136	1016	69,863	71,205
Mixed and undifferentiated materials	N	41	6652	345	5227	153
	I	188,831	2,633,085	44,419	2,956,983	5342
Sorting residues	N	0	737	109	82,532	-
	I	11,171	100,761	21,171	12,155,243	68,020
Common sludges	I	4332	93,704	9285	538,171	166
Mineral waste from construction and demolition	N	327	1797	540	4243	36,145
	I	88,839	255,844	57,968	308,141	2,435,829
Oher mineral waste	N	14	43,717	633	86,298	11,901
	I	69,932,505	9,043,836	66,944	1,497,523	388,836
Combustion waste	N	0	217,986	90	13,942	1
	I	43,555	6,573,859	20,093,732	541,030	70,312
Soils	N	12	567	565	173,988	27,072
	I	204,463	72,398	29,258	304,758	14,866,458
Other waste	N/I	187,465	4,685,185	165,082	3,046,640	897,240

* N—hazardous waste, I—non-hazardous waste. ** concerns selected activities in the section according to data availability. Source: data of the Ministry of the Environment and waste from household data of Statistics Poland [21].

Table 4. Waste treatment in 2016 (in Mg).

Waste Category	Total	Energy Recovery	Incineration	Recovery Other than Energy Recovery-Recycling	Recovery Other than Energy Recovery-BACKFILLING	Landfilling	Other Forms of Disposal
Total	**163,002,317**	**5,412,060**	**572,271**	**75,229,503**	**36,154,389**	**45,619,668**	**14,426**
Chemical wastes	191,976	3710	34,753	115,027	-	36,872	1614
Wood wastes	3,607,312	1,426,406	236	2,180,638	-	32	-
Animal and mixed food waste	574,946	22,624	52,755	498,692	-	208	667
Vegetal waste	1,676,665	9877	83	1,664,852	-	1846	7
Household and similar wastes	11,642,542	2,114,409	151,772	4,045,615	-	5,330,746	-
Mixed and undifferentiated materials	4,856,202	113,994	8398	2,832,238	24,306	1,876,142	1124
Sorting residues	5,802,170	1,462,203	172,633	2,171,957	-	1,995,377	-
Common sludges	547,868	13,334	85,414	440,867	-	3806	4447
Mineral waste from construction and demolition	3,730,719	4612	610	2,592,887	796,862	335,748	-
Other mineral waste *	80,492,766	220	199	30,786,287	24,146,249	25,553,306	6505
Combustion wastes	25,027,040	49,409	-	11,113,479	3,773,223	10,090,929	-
Soils	11,937,413	8	501	4,689,327	7,229,753	17,824	-

* excluding construction and demolition waste, combustion wastes, soils, dredging spoils, waste from waste treatment. Source: data of the Ministry of the Environment and waste from household data of Statistics Poland.

3.2. Identification of Waste Streams and Their Treatment Potential by the Example of the Silesian Voivodeship

Identification of waste groups and their quantitative analysis allowed for determining the total raw material potential of waste generated by selected sectors of the economy. Due to the development of industry, the need to protect the environment, an increase in demand for the search for alternative resources, and increasing difficulties in storing large amounts of waste, there is an increasing interest in the reuse of industrial waste in the region. The increase in the amount of waste and by-products, including those deposited in waste dumps, has resulted in the need for waste valorization. Moreover, it necessitated the commencement of research and implementation works aimed at designing innovative technological solutions to protect against the negative impact of waste on the environment and bring it back into economic circulation [22].

Referring to the results of previous papers [19,23,24] on the research subject, waste such as slags, waste aggregates, fly ash, ash mixtures, waste plastics, or sewage sludge arouse interest. Even though several physicochemical properties determine the direction of further use of waste, in practice they are most often used, among others, in (i) the construction industry and the production of building materials, including cement, clinker, thermal insulation materials, lightweight aggregate, (ii) road engineering—for various types of engineering works, land stabilization, (iii) agriculture in the production of fertilizers or the field of degraded land reclamation, (iv) mining—as components of reinforcing materials stabilizing floors or filling excavations; (v) innovative, advanced technologies such as the synthesis of zeolites, recovery of rare earth metals, or the production of geopolymers.

Ongoing work on developing innovative waste recovery technologies means that new industries and branches of industry have the opportunity to use previously unknown properties of waste in their operations. Such examples are, e.g., zeolites, which are used in the chemical industry, microelectronics, environmental protection, medicine, optics, and agriculture [25]. Synthetic zeolites are obtained from fly ash, which is also the subject of research on the development of functionalized materials, i.e., with increased utility. The produced materials can be used in construction (cement and bio cement), agriculture (fertilizers and bio-fertilizers) and environmental engineering—for remediation of contaminated waters or soils [26].

In recent years, there has also been increased interest in the production of alternative (artificial, recycled) aggregates, which complement the natural aggregates market. The resource base for the production of this type of aggregate is wide and includes in particular [27] metallurgical and mining waste from power plants and heating plants, construction, and ceramics.

Since the resource base is mostly made up of waste deposited in various types of landfills, their potential has not yet been comprehensively valorized. It is also possible to produce alternative aggregates from waste from the ongoing operations of the plants. Their size is closely correlated with the volume of production or extraction and therefore depends on the market condition of the plant as well as the entire industry [28].

Every year, many entities are required to submit an annual report on waste generated and waste management. These reports are the source of Voivodship reports on waste, which contain data on the amount of generated waste and methods of its management. The Silesian Voivodeship is a characteristic region of the country and is highly industrial, which is confirmed by aggregate data on industrial waste (Table 5). The table presents a summarized presentation of the amount of industrial waste generated, divided into categories and management methods. In 2017, 284 plants generated 31,648.2 thousand Mg of hazardous and non-hazardous waste, excluding municipal waste, which accounted for 27.8% of the total industrial waste generated in the country. In this case, groups 01 and 10 dominate, due to the largest share of industrial waste generation as well as the amount of waste disposed of so far.

Table 5. Waste (excluding municipal waste) generated during the year and accumulated by type in 2017 (in thous. Mg).

Waste Codes	Waste Generated during the Year (2017)						
	Grand Total	Recovered *On Its Own*	Disposed *On Its Own*			Transferred to Other Recipients	Waste Landfilled (Accumulated) so Far (as of the End of the Year)
			Total	of Which			
				Landfilled in Own Facilities	in Another Way		
	[in Thousand Mg]						
Total	**31,648.2**	**12,163.8**	**2654.4**	**2649.2**	**5.2**	**16,628.3**	**476,284.6**
01	Wastes resulting from exploration, mining, quarrying, and physical and chemical treatment of minerals						
	22,094.9	9522.2	2629.7	2629.7	-	9819.3	432,519.9
02	Wastes from agriculture, horticulture, aquaculture, forestry, hunting and fishing, food preparation and processing						
	93.9	-	1.7	-	1.7	92.2	-
03	Wastes from wood processing and the production of panels and furniture, pulp, paper and cardboard						
	37.0	5.1	-	-	-	31.9	-
04	Wastes from the leather, fur and textile industries						
	7.7	-	-	-	-	7.7	-
05	Wastes from petroleum refining, natural gas purification and pyrolytic treatment of coal						
	2.3	-	-	-	-	2.3	-
06	Wastes from inorganic chemical processes						
	4.5	-	-	-	-	4.5	761.6
07	Wastes from organic chemical processes						
	90.0	31.3	-	-	-	57.5	-
08	Wastes from the manufacture, formulation, supply and use (mfsu) of coatings (paints, varnishes and vitreous enamels), adhesives, sealants and printing inks						
	9.6	-	-	-	-	9.6	-
10	Wastes from thermal processes						
	6957.2	2177.1	13.2	13.1	0.1	4714.0	40,382.2

Table 5. *Cont.*

Waste Codes	Waste Generated during the Year (2017)						
	Grand Total	Recovered *On Its Own*	Disposed *On Its Own*			Transferred to Other Recipients	Waste Landfilled (Accumulated) so Far (as of the End of the Year)
			Total	of Which			
				Landfilled in Own Facilities	in Another Way		
	[in Thousand Mg]						
11	Wastes from chemical surface treatment and coating of metals and other materials; non-ferrous hydro metallurgy						
	21.8	0.7	-	-	-	21.0	3.9
12	Wastes from shaping and physical and mechanical surface treatment of metals and plastics						
	503.7	92.4	-	-	-	411.3	-
13	Oil wastes and wastes of liquid fuels						
	1.8	-	-	-	-	1.8	-
14	Waste organic solvents, refrigerants, and propellants						
	0.1	-	-	-	-	0.1	-
15	Waste packaging, absorbents, wiping cloths, filter materials and protective clothing not otherwise specified						
	65.0	0.1	-	-	-	64.6	-
16	Wastes not otherwise specified in the list						
	116.4	35.4	2.5	-	2.5	78.4	1063.3
18	Wastes from human or animal health care and/or related research						
	1013.8	180.9	-	-	-	829.7	1017.0
19	Wastes from waste management facilities, off-site wastewater treatment plants and the preparation of water intended for human consumption and water for industrial use						
	628.5	118.6	7.3	6.4	0.9	482.4	536.7

Source: IOŚ, 2018.

The presented statistics indicate (Table 5) that the largest need and thus the largest processing potential is waste from the mining and electricity industries. Processing potential, in the context of a circular economy, is understood as the possibility of reusing identified waste streams, whose properties allow for raw material or energy recovery. In the conducted research, the potential for the use of waste was presented as the total amount of waste subjected to disposal processes or deposited so far. This assumption allows measurable determination of the potential for the use of selected industrial waste streams, which are the starting point for taking action for their reuse and loop-closing the material flow.

In addition, the statistics for 2020 provide information regarding the amount of generated and accumulated industrial waste in Silesia from the categories:

- Waste generated at washing and cleaning minerals
- Dust-slag compounds from the wet treatment of furnace waste
- Waste from mineral non-metal ferrous excavation
- Soil and stones
- Coal fly ash
- Wastes from the processing of slag

The presented graph (Figure 2) shows the significant amounts of industrial waste, including mining waste, faced by Silesia every year while trying to find new and more effective ways to manage it.

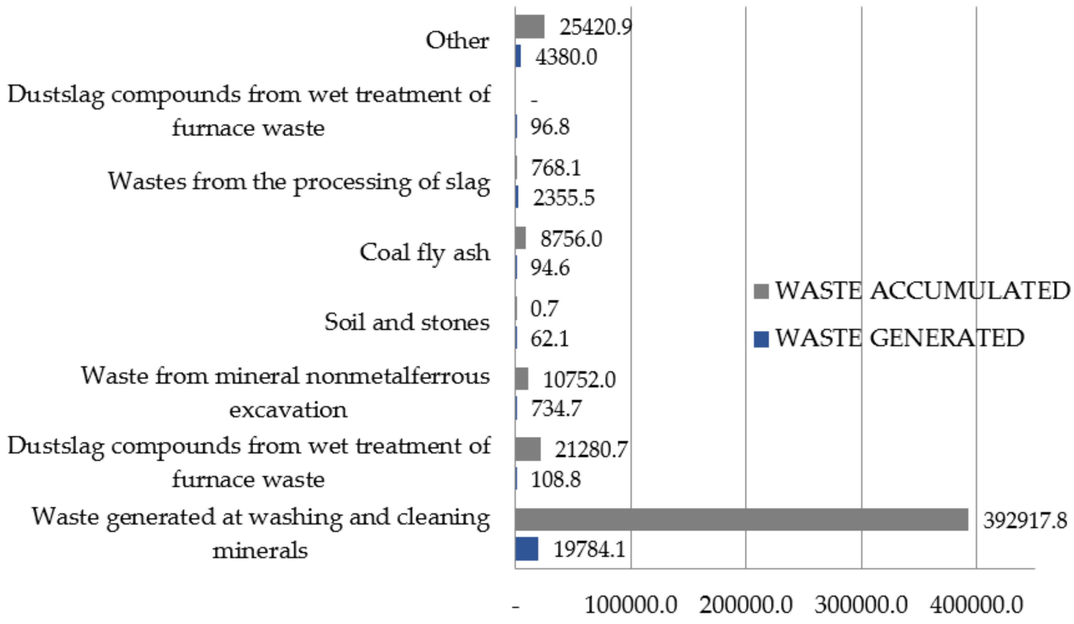

Figure 2. Waste generated and accumulated by types and voivodships in 2020 (excluding municipal waste). Source: Statistics Poland, 2021.

The possibility of using industrial waste identified in the Silesian Voivodeship in other areas of activity along with an indication of current practices in its use is presented below.

3.2.1. Mining Waste

The mining industry is one of the main producers of industrial waste in Silesia. The amount of waste generated from mining plants recorded in 2018 was 22 million Mg [17]. The threat to the natural environment, which is identified with the mining industry, primarily refers to post-mining waste stored in landfills (dumps). At present, approximately 432.5 million Mg of mining waste is stored.

In 2018, the following types of mining waste were reported in the Silesian Voivodeship, in accordance with the ordinance of the Minister of the Environment of 9 December 2014 on the Waste Catalog (Polish Journal of Laws 2014, item 1923): 01 04 08-waste gravel or crushed rocks other than those mentioned in 01 04 07; 01 04 09-waste sands and clays; 01 04 13-waste from rock cutting and processing other than those mentioned in 01 04 07; 01 04 81-waste from flotation preparation of coal other than those mentioned in 01 04 80; 01 05 04-drilling muds and drilling waste from fresh water wells; 01 05 07-drilling mud containing barite and waste other than those mentioned in 01 05 05 and 01 05 06; 01 05 08-drilling muds containing chlorides and waste other than those mentioned in 01 05 05 and 01 05 06; 01 05 99-other waste not mentioned, of which waste with codes [29]: (i) 01 01 02-waste from the extraction of minerals other than metal ores (they are also called mining waste because they come from mining and preparatory works making the main mineral deposit available); (ii) 01 04 12-waste arising from the washing and cleaning of minerals other than those mentioned in 01 04 07 and 01 04 11 accounted for 12% and 87% of all generated waste of group 01, respectively.

Mining waste is divided into three main groups: mining waste, processing waste, and secondary processing waste [30], and depending on where they arise, two groups are distinguished: waste from preparatory works and the exploitation of coal seams, and waste from coal preparation and processing plants.

Considering the significant amount of mining waste generated and deposited so far, it is extremely important to use effective methods of management that do not endanger the environment.

Due to ongoing activities for the recovery of extractive waste, some activities have been undertaken in the industry to develop systematics of industrial by-products according to the economy department and the industries where they arise. In practice, mining waste, which is a valuable alternative material for natural resources and does not pose a direct threat to the environment in connection with its recovery, is [4]: unburnt coal shale, burned coal shale, ground rock from heaps.

Considering the varying degrees of direct or indirect suitability conditioned by many properties and assessment criteria, post-mining waste has potential use in the areas of industrial activity listed below [22,31,32].

(I) Road constructions. Due to the considerable material consumption of works related to road construction, waste from mining and metallurgy is widely used in road construction and used as a material in the construction of appropriate pavement construction layers. An example of such use is the road embankment in Jastrzębie, where 130,000 m^3 of black slate was used, or a fragment of the A4 motorway, where an additional 150,000 Mg of red slate was used [28].

(II) Energy carrier. As practice shows, the industry (especially the cement industry) is increasingly turning to alternative energy carriers and looking for alternative raw materials for clinker production. Considering the desirable properties, cement plants use clinker-burning technology based on coal waste, whose chemical composition is similar to natural resources [33]. Noteworthy is the fact that cement plants are an important element of the circular economy system due to the wide possibilities of using waste raw materials (including fly ash, fluidized ash, shale, blast furnace slag) from various sectors.

(III) Land reclamation. Classified as non-hazardous mining waste that does not show toxic properties is used as part of reclamation works on landfills, e.g., municipal waste. The strategic pursuit of environmental policy to increase levels of waste recovery and reduce their disposal by landfills contributes to the implementation of comprehensive actions aimed at the gradual closure of landfills, which will necessitate their reclamation. The research has shown that selected mining waste does not inhibit plant development, and even supports their growth and improves the possibility of plant development, which confirms the possibility of its use in the reclamation process [9].

3.2.2. Waste from Power Plants

Poland is one of the main producers of combustion by-products (UPS). Despite this, the national legal classification of combustion by-products and their classification as hazardous waste largely limits the possibilities for their wider re-use.

The following products from coal combustion [34] are distinguished: (i) fly ash-mineral parts from coal combustion and mechanically or electrostatically precipitated from exhaust streams (code 10 01 02); (ii) active fly ash from brown coal or a mixture of fly ash and solid waste from calcium flue gas desulphurization methods (10 01 02, 10 01 05 and 10 01 82); (iii) slag-mineral parts with a predominant amount of sand and gravel fraction, originating from coal combustion and precipitated at the bottom of the boiler (10 01 01); (iv) ash-slag mixtures-mineral parts from coal combustion and discharged wet to the landfill (10 01 80).

In 2018, 6957.2 thousand Mg of waste from power plants production was reported in the Silesian Voivodeship, among which the largest share was respectively waste with codes [17]: (i) 10 01 82-mixtures of fly ash and solid waste from calcium flue gas desulphurization methods (dry and semi-dry flue gas desulphurization methods and fluidized bed combustion)-24%; (ii) 10 01 02-fly ash from coal-15%; (iii) 10 01 01-slag, furnace ash and boiler dust (excluding boiler dust listed in 10 01 04)-11%; (iv) 10 01 24-sands from fluidized beds (excluding 10 01 82)-11%.

Experience of using waste from power plants draws special attention to their heterogeneous properties, which vary depending on the fuel burned and the boiler used.

In practice, selected by-products of combustion, due to the formal and legal normalization of their use, are widely used in road engineering. The cement industry is also a significant recipient of fly ash. The economic use of UPS will provide a research area for the development of new technologies in various industrial sectors [35].

(I) Construction. The current state of Polish legislation regarding the use of UPS enables their use as road material. Waste from the energy production process (in particular ashes) is used in earthworks (road embankments), reinforcing layers and foundations. Examples of such applications illustrate the initiatives taken to build national roads, among others, in the regions of Gdańsk, Rybnik, Opole and Poznań [36].

(II) An example of closing the circulation of waste from power plants is technologies for processing ash into granular aggregates suitable for reuse as construction aggregates or for strengthening the surface of dirt roads. Research activities in the field of developing technologies for obtaining aggregates from ashes have in recent years allowed the implementation of many projects and implementation of eco-innovative technologies in economic practice. Among them is the technology of LSA Sp. z o.o., under which the ashes are processed into light sintered aggregate called Certyd [37], or the technology for producing lightweight aggregate FASLA, developed by the Glass and Building Materials Department in Krakow [38]. Innovative technologies also include solutions based on the synthesis of geopolymers based on ash, which create materials that are used in construction, in foundries, as a component of composites, pipes, railway sleepers and many others.

(III) The processing of fluidized ashes, allowing their economic use under environmental protection requirements, is also provided by Energomar-Nord technology. This solution creates a product under the trade name Flubet®, which can be used as a cement component, as a binder component, or an independent binding material. Also, the road binder under the trade name LIPIDUR® is intended for improvement/stabilization and strengthening, primarily with low load capacity soils, and it is produced based on fly ash [28].

(IV) Mixtures of waste from power plants with the addition of stabilizers are also used as part of engineering works for macro-levelling of degraded areas, e.g., filling excavations after mining coal and other mineral resources. The energy properties of waste generated by power plants are also used for the reclamation of waste dumps, preventing thermal activity, or increasing the content of nutrients in soil [36].

(V) Agriculture. Positive experience from the use of ashes in the reclamation processes also influenced the use of ashes in agriculture as an alternative to calcium-magnesium or mineral fertilizers or potassium (from biomass combustion).

(VI) Mining. The mining industry uses furnace waste primarily in underground mining excavations, for decommissioning, strengthening, sealing, or as a component of filling belts. The use of ashes in mining technologies gains particular importance in the era of economic transformation and levelling of the negative impact of mining on the environment, by use in reclamation, macro-levelling, and filling of post-mining voids.

(VII) Production. Thanks to the use of new recycling technologies, in recent years directions of use of the microsphere found in ashes and slag have been developed. Valuable properties of microspheres such as no harmful effects on the environment (including living organisms), high resistance to chemical agents, and resistance to extreme temperatures make the microspheres have found a lot of applications. In business practice, they are mainly used as fillers for plastics, as additives for sealing compounds, or in the production of prefabricated building materials, thermal insulation materials, and plasters [39].

3.3. Industrial Waste Management System in the Context of the Circular Economy

The ongoing process of transformation of the economy in the direction of a circular economy implies the introduction of changes in structural, organizational, and technological changes in the existing models of enterprise functioning systems. In this context, it is important to identify material flow streams that are a potential source of additional value through the possibility of extending the product's life cycle and closing its circulation in the economy. That is why reverse logistics plays a special role in the circular economy, which focuses on various aspects of securing and implementing the flow of raw material, semi-finished and product streams, and waste from the consumer to the producer to recover value or their effective management [5,6]. Contemporary development trends and the increasing mass of waste determine the effectiveness of both reverse logistics chains and the entire supply chains [1,40], conditioning the extension and coordination of product flows including actions that will increase the service life of returnable components such as resale, repair, reuse, recycling, and regeneration [40].

The basic links in each waste management system are waste producers, waste collection and transport units, and waste management entities [41]. According to the circular economy, waste becomes a valuable resource that comes back into circulation and can be reused [29]. Figure 3 shows a schematic image of the material flow model, taking into account the added value of reusable waste. The key element of the model in this approach is the waste management system, which, from the point of view of a single plant as well as the entire industry, allows the combination of often separate industry sectors that use the specific properties of waste, thus replacing natural resources.

When designing the model of an industrial waste management system in the context of a circular economy, one single stream of waste generated in the plant should be taken into account. Due to the complex nature of the model, which takes into account the needs of various industries, the identification of appropriate waste streams and their properties, as well as the definition of specific criteria that allow evaluation of their reuse, is the starting point for the design of a comprehensive overarching waste management system, e.g., within the industry or sector.

Quantity and environmental impact of waste can be limited by the need to prioritize the production processes and logistics chains issues such as: minimizing resource and energy consumption and the possibility of repairing and reusing or recycling an item already at the design stage [1]. Therefore, the effectiveness of the industrial waste management system in the context of the circular economy is demonstrated by elements such as: minimizing the amount of generated waste, maximum use of generated residues, full reduction of the negative impact on the environment and economic calculation [42]. The above cannot be accomplished without remembering that what is useless within the operation of one plant will be a full-fledged product for another enterprise.

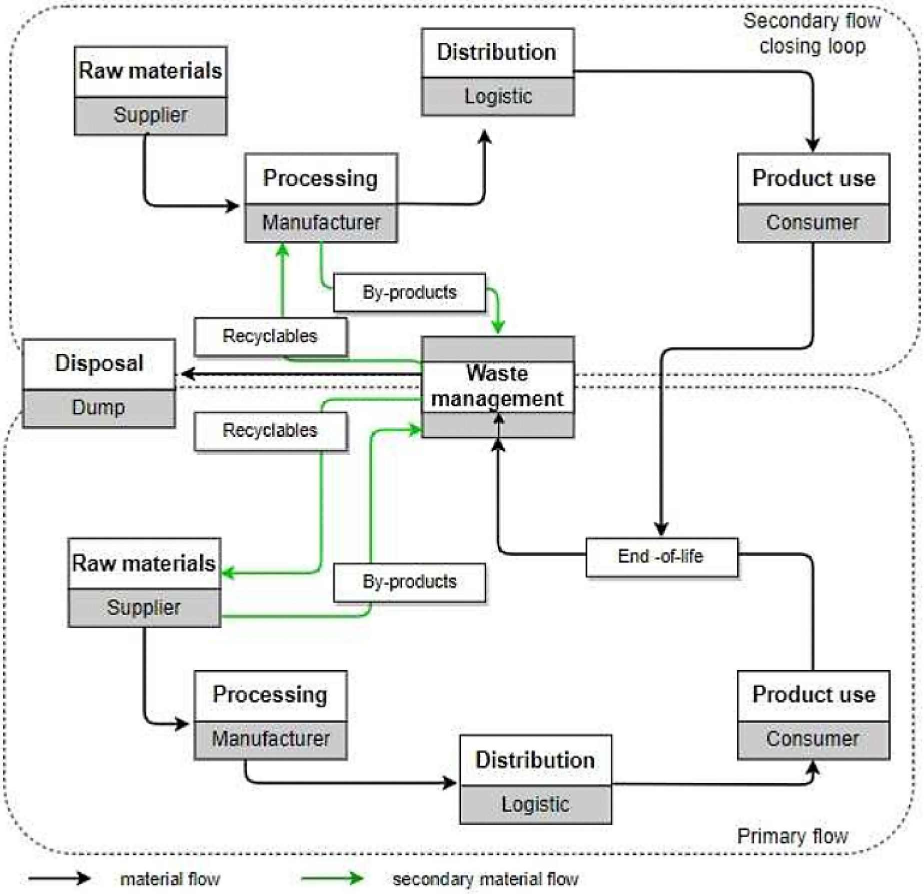

Figure 3. Schematic image of the material flow model. Source: own elaboration.

3.4. Identification of Sector Links

Scientific research and the technical progress in setting new directions for the use of waste from power plants and mines is one of the key areas for creating innovation in the country, especially in the Silesian Voivodeship. Providing waste producers with a catalogue of potential technological solutions that can be implemented in their own business allows them to adopt technologies that respond to individual needs as well as specific market conditions.

The goal of industrial plants attempting to transform towards a circular economy is primarily to take measures to increase resource efficiency and reduce waste. In practice, this means some actions that are presented by CE business models [19,43], such as the ReSOLVE model presented in the scientific literature. This model distinguishes six activities that create a framework for creating value in an enterprise in the context of a circular economy [44], i.e., regeneration, sharing, optimization, loop closing, virtualization and exchange. ReSOLVE gives entrepreneurs and governments tools to build strategies and initiatives consistent with the idea of a circular economy.

A broader view of industry transformation towards a circular economy, however, requires comprehensive and integrated actions throughout the entire industrial system, and therefore the industry deals with the topic of industrial ecosystems or industrial symbiosis (considered as complementary concepts). Their basic assumption is to create conditions that will allow linking and various enterprises concentrated in a certain area (also in a separate industry or sector), whose common goal is to use fewer resources and reduce the plant's negative impact on the environment, including increasing the efficiency of waste management [45–51]. A schematic picture of industrial symbiosis is shown in Figure 4.

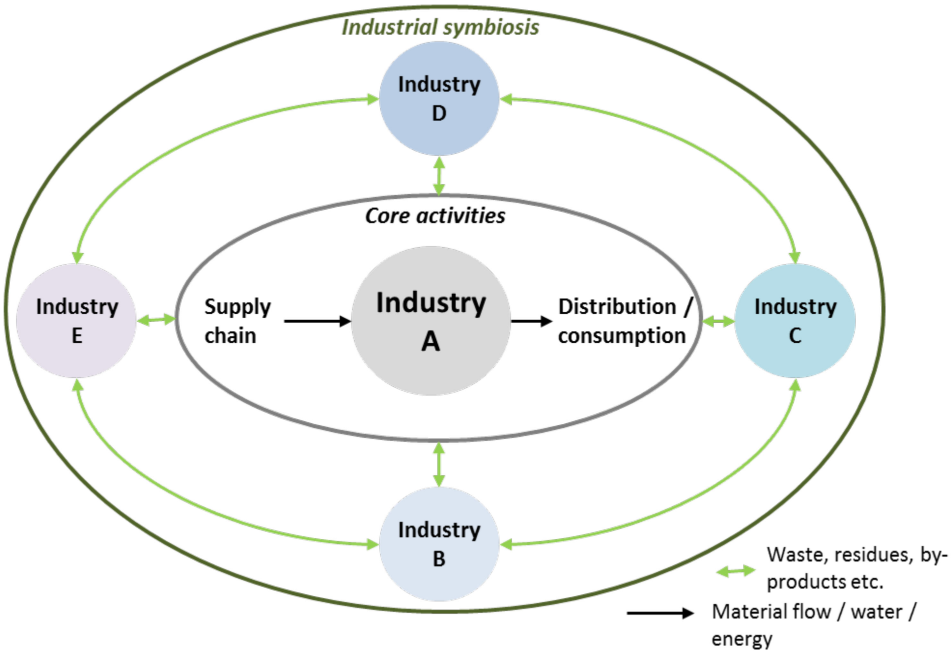

Figure 4. Diagram of industrial symbiosis. Source: own elaboration.

The presented diagram distinguishes the basic activity of the enterprise, where the main flow of materials occurs from industrial symbiosis in which waste is treated as raw materials, which creates new connections and supply chains. Among the benefits of effective connections in an industrial symbiosis network, there are (i) environmental, which includes reducing the amount of waste generated, reducing the plant's environmental impact, and reducing resource consumption; (ii) economical, associated primarily with reducing waste management costs. Some relationships may also provide additional revenues and income related to processing waste into products for sale.

In addition, an effective symbiosis has a positive effect on the social environment and business relations [52,53].

Based on the quantitative and qualitative analyses related to the identified waste streams generated in the Silesian Voivodeship [21,54], as well as the currently used solutions in the field of industrial waste recovery, it was possible to identify the sectors closing the material circulation [23,55]. The strongest connection exists between mining-related plants, industrial power plants and combined heat and power plants, cement plants, and construction plants, especially road construction.

Technological solutions are available to link these plants with various sectors of the economy in line with the assumptions of industrial symbiosis. It is worth noting that examples of industrial symbiosis occur all over the world and take various forms due to existing conditions and needs. This means that the model of industrial symbiosis must be adapted to the specifics of a given area as well as potentially entering enterprises.

To summarize the opportunities for closing the energy and mining waste cycle, a SWOT analysis was conducted to critically evaluate the current waste management system (Table 6).

Table 6. SWOT analysis.

Strengths (S)	Weaknesses (W)
○ Constant supply of the system with waste belonging to the group of mining and energetic waste, ○ Strong concentration of producers in one area–Silesia, ○ industry interaction, ○ Implementation of projects and initiatives from the area of business and science within the framework of innovative methods of mining and waste prom power plants management, ○ Technological development of Silesia, ○ Possibilities of co-financing activities in the pro-ecological area.	○ Lack of effective models for closing the waste cycle, ○ Lack of strong linkages between the mining sector and other industries, ○ Increasing requirements and financial expenses imposed on companies from the waste sector, ○ Low effectiveness of the waste law adopted so far, ○ Lack of comprehensive activities of municipalities focused on the industrial waste management system.
Opportunities (O)	**Threats (T)**
○ High level of reuse of industrial waste, ○ Learning from other countries' experience in effective waste management, ○ Use of facilities and advanced technology for more efficient waste treatment, ○ Wide possibilities of waste reuse.	○ Qualification of selected mining waste as hazardous, ○ Mixing of waste of different groups characterized by different compositions, ○ Lack of data concerning real characteristics of waste, ○ investments with high risk and high financial outlay, ○ pollution caused by waste disposal and the area it covers, ○ The difficulty of implementing new solutions since old and proven methods of waste management have been used for many years.

Source: own elaboration.

Mining operations as well as the energy industry are generating an increasing amount of solid waste and causing more and more negative environmental impacts. Through the use of appropriate tools and technology, strategic management is necessary to reduce the negative effects resulting from the lack of proper management of industrial waste. The SWOT analysis conducted in this paper indicated that the strengths and opportunities facing mining and energy waste management are more important than the weaknesses and threats. The results show that the internal abilities of the industrial waste management system and its support environment allow for creating conditions for further development and opportunities for implementing new solutions.

4. Discussion and Conclusions

Due to the tightening of environmental regulations in recent years and the introduction of several sanctions severe for entrepreneurs, it has become necessary to take measures to reduce the environmental impact of industrial plants. Currently, business entities implement environmentally friendly activities more often than they have done before. Innovative technologies that aim to process the waste generated in plants and convert them into wholesome products are of the greatest interest. Such solutions bring many benefits, ranging from ecological and economic to social and image-related.

Assumptions and guidelines related to the transformation of the current waste management model into a circular economy require coordinated actions from entrepreneurs and local government officials, thus allowing the creation of industrial symbiosis and new synergies between economic sectors, change and extension of the product life cycle model and development of innovative waste treatment technologies.

For this reason, the development of new relationships and connections is recognized as the key challenge facing the economy, as well as the waste management system. At the same time, it identifies the logistics chains of waste management as well as value chains determined by the waste processing potential.

Available statistics, including reporting data on the production and management of waste, allow a preliminary assessment of this potential and indication of the directions of transformations enabling the closing of the waste cycle and the creation of industrial symbiosis. The effectiveness of such connections will occur only when the issue of closing the circuit is comprehensively and systemically taken into account—not only the individual needs of industrial plants but also the real needs to secure permanent and continuous access to critical raw materials.

The research was conducted according to the designed methodological path, taking into account: the current state analysis with the secondary data analyses (national and regional level), inventory of the existing solutions in the field, and identifying possible flows and sectors closing their loop.

Referring to the formulated objective, the research enabled us to: (i) identify the sectors closing material circulation. It was shown that the strongest connection exists between mining-related plants, industrial power plants and combined heat and power plants, cement plants, and construction plants, especially road construction; (ii) conclude that the internal abilities of the industrial waste management system and its support environment allow for creating conditions for further development and opportunities for implementing new solutions; (iii) verification of the methodology developed for this study confirms the feasibility of building initial assumptions for the development of industrial links with the identified waste streams.

For a broader characterization of the problems at the local level, a SWOT analysis was used to assess the current state of the industrial-energy and mining waste management system. This analysis, from the groups analyzed, provided a basic framework of assumptions for building a model for closing the industrial waste cycle. The results can support the further decision-making process, which requires the identification of strategic factors from technological, environmental, social, formal, and legal areas.

Considering that industrial symbiosis is one of the strategies aimed at realizing the objectives of CE models and supporting the transformation of waste management, future research should focus on identifying further connections in the economy that enable the closure of the industrial waste cycle and the generation of added value. It is advisable to conduct research on developing universal tools for analysis of the effectiveness of such symbiosis.

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