Rocznik Ochrona Środowiska

Volume 23 Year 2021 ISSN 1506-218X pp. 715-730

https://doi.org/10.54740/ros.2021.050 open access

Received: 26 July 2021 Accepted: 15 October 2021 Published: 06 December 2021

The Recycling of Secondary Waste in Polish Recycling Companies

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Abstract: This article analyses the recycling of secondary waste in Polish recycling companies. An innovative method of processing PCBs is presented and trends that should be followed by plants processing non-ferrous metal waste are indicated. In conclusion, it is emphasised that the Polish WEEE recycling market is still at the early development and growth stage and the most important goals that enterprises should set themselves include cost optimisation, improvement of waste management logistics and increases in the level of recycling.

Keywords: recycling industry, circuit boards, precious metals recovery

1. Introduction

Recycling secondary waste in Polish enterprises begins with the extraction of metallic waste of various types, after which, it is then separated. No company in Poland has yet developed a complete waste stream processing technology, i.e., a waste stream with more specific dimensions, density and chemical composition, etc; it is mainly copper scrap together with PCB scrap – printed circuit board scrap- as well as alkaline batteries. It is assumed that from one tonne of printed circuit boards – with one piece weighing approximately 150 g – it is possible to recover approximately 27 g of metals, such as, gold, copper and palladium (Woynarowska & Żukowski 2009). One tonne of processed alkaline batteries contains from 26% to 65% of steel in the form of a shield, from 4% to 10% of electrolyte in the form of potassium hydroxide, from 20% to 35% of manganese powder, from 20% to 35% of zinc oxide and trace amounts of carbon. The average recovery of these metals by Polish companies is 70-75%. The problem with today's processing of waste scrap, in terms of environmental protection, is the processing capacity of installations in Poland, which theoretically amounts to 12 million tonnes, of which 20% of enterprises do not have an address, which raises doubts as to their actual storage and operation.

The recycling industry is one of the most innovative branches of the economy. In less than 10 years, the extraction of raw materials from landfills will become an important business field, as the content of elements such as copper and gold, in waste, is higher than that for extracted ore (Burzyńska 2018).

2. The importance of recycling in waste management

In managing materials, raw materials and recycled materials are becoming ever more important. A clear upward trend can be observed in the recovery of materials. Due to ever increasing improvement in waste sorting systems and to a consistent policy favouring its use, the "return rate" of materials can, in some cases, be as high as 75%. The use of waste, that is, the recovery of secondary raw materials, both from production processes and from purchasing, is becoming increasingly important for ecological and economic reasons, related to the protection of the natural environment in the limiting of greenhouse gas emissions (Jacyna et al. 2018) and water pollution, as well as limiting the energy consumption of production (Woźniak et al. 2017a, Woźniak et al. 2017b); this entails an increase in the use of waste being a source of cheap and environmentally-friendly raw materials.

This applies, inter alia, to scrap steel and waste, along with non-ferrous metals, such as copper, aluminium, lead, zinc and tin. Extracting metals from waste materials is less energy intensive than from primary sources. End-of-life vehicles (Chamier-Gliszczyński 2010, Kosacka-Olejnik 2019, Merkisz-Guranowska 2018), waste batteries (Dobrzycki et al. 2019), waste electrical and electronic equipment and municipal waste enable the recovery of metals to a large extent (GUS 2016).

Table 1. Trade in recyclable waste in commercial units in 2016-2017 (Institute for Research on Market Economy 2017)

Waste	Year	Revenue			
		Total	From own activities	Purchase	Import
		in tonnes			
Steel and cast iron	2016	4373166	223083	4103038	47046
	2017	4564604	288082	4167234	109288
Copper	2016	238519	43957	141003	53559
	2017	218449	7258	167151	44040
Lead, zinc and tin	2016	32224	1353	27417	3454
	2017	27741	1220	23164	3357
Alumin-ium	2016	273130	3184	241881	28065
	2017	272121	3394	229216	39511

Customer expectations towards green-technology (Kanalikova et al. 2019, Marczewska et al. 2020), recycling companies are constantly growing, especially in the context of supporting the implementation of sustainable development goals (Zajac at al. 2020), including the implementation of the principles of the circular economy. The primary goal of companies is to maximise the recycling of production waste, which can be achieved through sorting-at-source, efficient internal logistics (Straka et al. 2020, Zajac et al. 2017) and transportation and above all, increasing the number of fractions that can be recycled. Effective recycling is also an important element of an increasingly important model of an innovative approach to business, which is the circular economy (Chamier-Gliszczynski & Krzyzynski 2005, Czwajda et al. 2019). The European Union is also working towards a circular economy. It is an idea that will significantly support enterprises in reducing the over-exploitation of raw materials and reduce environmental pollution (Gabryelewicz et al. 2020). Recycling materials from used products and reusing them is one way to save natural resources and, at the same time, meet the growing demand for these raw materials (Chamier-Gliszczyński 2011a, Chamier-Gliszczyński 2011b). In order to improve the recovery of materials from used cars, Directive 2000/53/EC (Chamier-Gliszczyński 2011) and Directive 2002/96/EC introduced minimum levels of recovery and minimum levels of re-use and recycling (Table 2).

Table 2. Target values of recovery and recycling rates for individual product categories (Institute for Research on Market Economy 2017)

Item	Product category	Recycling in %	Recovery in %
1	Large household appliances	75	80
2	Vending machines	75	80
3	IT and telecommunications equipment	65	75
4	Consumer devices	65	75
5	Small household appliances	50	70
6	Lighting equipment	50	70
7	Electrical and electronic instruments	50	70
8	Toys, recreation and sports equipment	50	70
9	Instruments for surveillance and control	50	70
10	Gas discharge lamps	80	

The recycling of copper and aluminium reduces the exploitation of these rare and valuable raw materials and also minimises the amount of waste produced during ore extraction. The re-use of plastic reduces the consumption of crude oil and avoids many years of storage in landfills. Thanks to the recovery of materials, water is a valuable resource. Recycling aluminium uses half as much water as when produced from primary raw materials (Duan et al. 2009). In addition, metals that end up in waters and soils pose a significant threat to the natural environment, through inappropriate management (Gabryelewicz et al. 2018). The recovery and re-use of copper and aluminium reduces the possibility of their leakage into the environment. The recycling process uses much less energy than the extraction of natural resources and also reduces carbon dioxide emissions (Reconomy 2017).

3. Recycling enterprises in Poland

In Poland, information on the management of the WEEE is published by the Chief Inspectorate of Environmental Protection in annual reports. It follows, from the reports, that in 2017, in total, more than 518.9 thousand tonnes of WEEE were introduced into the territory of Poland (Główny Inspektorat Ochrony Środowiska, 2018). The collection rate was 34.7%, which amounted to 4.1 kg of waste equipment per capita. The average for one EU citizen is around 15 kg. According to the Chief Inspectorate of Environmental Protection, there are 16,001 enterprises or organisations dealing with electronic waste in Poland; these are divided into collection companies, waste processing companies and companies involved in the recovery process, but there is no single comprehensive company dealing with processing, from start to finish. A very small number of companies – some 180, process about 905 thousand tonnes of waste. Comparing the data on the capacity and quantity of processed or recycled materials, it is clear that there are processing capacities, but these are used to a small extent only. This is due to the existing downturn in the metals market and the growing shadow economy. Analysing the market data, it is possible to confirm the assessment existing in J. Hausner's (Hausner 2017) report that the Polish WEEE recycling market is in the development and early growth phase, but is still very fragmented. None of the legal instruments used in Poland so far, e.g. a ban on depositing certain fractions of waste in landfills, changes in waste management at various levels of administration, introducing additional powers for municipalities and obligations for entrepreneurs, have brought any tangible environmental effect nor have they caused a dynamic development of the market. Pathologies in the WEEE system were also described in the PwC report of 2014, "Irregularities in the WEEE management system in Poland"(Narodowy Fundusz Ochrony Środowiska, 2015), which shows that as much as 40% of officially processed e-waste is only "paper recycling". This is evidenced, inter alia, by the heaps of unprocessed waste equipment lying around, in some processing plants.

The presented analysis of the amount of available scrap and the number of companies dealing with the collection and processing thereof, shows that at least 2.5 thousand potential recipients are registered in Poland. These are companies that are already active in the field of scrap processing and metal recovery. The largest enterprises in the copper scrap processing market in Poland can be mentioned here:

1. KGHM Polska Miedź S.A. – a national enterprise in the extraction and production of copper. In recent years, the Company has been expanding its plant in Legnica to include a scrap ironworks, producing about 65 thousand tonnes of copper from scrap annually and extends further activities in this regard through the combustible construction of a waste treatment centre.
2. KGHM METRACO – the largest company in Poland and central Europe engaged in the purchase, processing, recovery and trade in copper scrap. It is the main supplier of scrap metal to KGHM Polska Miedź S.A. and is one of the largest exporters of copper scrap.
3. OLMET – one of the largest companies in southern Poland dealing with the purchase and processing of scrap metal, including scrap copper.
4. Złomex S.A. – the largest company in Małopolska (Lesser Poland Region) engaged in the purchase and recycling of scrap metal.

In 2016, 140 million tonnes of waste were generated in Poland, 8% of which was municipal waste (12 million tonnes). The main sources of waste were: mining and quarrying (approximately 52% of the total amount of generated waste), industrial processing (21%) and electricity generation and supply (16%). In the last decade, the largest share in the amount of waste generated was waste generated during the exploration, extraction and the physical and chemical processing of ores and other minerals (56% in 2016) and waste from thermal processes (22%). Of the total amount of waste generated in 2016, 49% of waste was recovered, 42% was disposed of as landfill and 4% was disposed of by other means. The basic method of handling municipal waste in Poland was getting rid of it as landfill.

In 2016, 37% of the total quantity was earmarked for storage, that is, 4.3 million tonnes while 28% - some 3.2 million tonnes of waste – was recycled.

19%, 2.3 million tonnes, was thermally disposed of in incineration plants and 16%, 1.9 million tonnes, of municipal waste was biologically processed (Kulczycka & Karaś, 2016).

In 2016, a total of 233 million tonnes of waste electrical and electronic equipment was collected in Poland, including 224 million tonnes from households.

The largest amount of waste equipment was collected in the group consisting of large-sized household appliances – 50% of the total weight of the equipment collected, ICT and telecommunications equipment (14%) as well as consumer equipment and photovoltaic panels (9%).

In 2016, batteries and accumulators with a total weight of 131 thousand tonnes were placed on the market in Poland, including portable batteries and accumulators, approximately, 13,000 tonnes (10%) of car batteries and accumulators approximately 95,000 tonnes (72%) and industrial batteries and accumulators approximately 24,000 tonnes (18%) (Jajczyk et al. 2020). As was the case the year before, in 2016, it was not possible to reach the level of collection of used batteries and portable batteries specified for Poland. The level obtained was 39% against the required 45% (Raport GUS 2017).

According to the report entitled Countering the Illegal Trade of WEEE, only 35% of the WEEE produced (Huisman et al. 2015) is officially registered in EU countries. The report for individual EU countries shows that:

1. In the EU-28 countries, as well as in Norway and Switzerland, the total amount of WEEE generated was 9.45 million tonnes in 2012;
2. Only 35% (3.3 million tonnes) of WEEE were registered in official reports as having been collected and recycled. The remaining 65% (6.15 million tonnes) were recycled under conditions inconsistent with EU requirements, including 2.2 million tonnes of WEEE which had been mixed with other scrap, 1.5 million tonnes of which were exported, including 1.3 million tonnes which constituted non-documented WEEE exports and used EEE with only 0.2 mln tonnes constituting official exports. 750 thousand tonnes were thrown away with municipal waste with an additional 750 thousand tonnes of WEEE having had their valuable parts removed by collecting companies but not recorded, as such, in the statistics and 950 thousand tonnes having been managed contrary to the regulations, e.g. thrown into forests;

3. In the case of illegal exports, it was indicated that 30% of WEEE was marked as equipment intended for re-use or repair and not for storage;
4. It has been estimated that 4.65 million tonnes of waste is not properly managed or is illegally sold on the European market. This applies in particular to the trade in defective WEEE, from which parts, containing valuable metals are most often removed. In the international waste shipments register, the mass of waste exported and unprocessed in Polish enterprises in 2014/2015 amounted to a total of 778,960 kg; in 2013 this was 115,647 kg. The destination country for the export of used metallic waste was Finland. By 2022, the value of metallic waste in the world is expected to grow from $ 66 billion to $ 400 billion and the amount of waste *per capita* is expected to be about 19 kg.

This exponential increase in waste is mainly due to the fact that the average lifetime of electronic equipment does not exceed 4 years. The environmental management system promoted as being compliant with the requirements of EMAS and ISO 14001, based on the PDCA cycle model, encourages entrepreneurs to identify environmental problems and plan appropriate actions, in order to limit the negative impact on the export of this waste.

4. Innovative approach to recycling in Poland

Since 2019, Polish recycling plants have been applying an innovative approach to the processing of scrap through the innovative use of metallurgical equipment and aggregates, using newly developed metallurgical refiners, as well as using innovative separation methods. An innovative approach to the recovery of Cu and precious metals from low-copper, WEEE and PCB scrap, assumes the production of a metallic phase during processing, the main component of which will be copper, as a solvent for precious metals. This will reduce the loss of precious metals during the "fusion" of scrap, containing Au, Ag, to the metallic phase. The use of this innovative approach at the scrap melting stage, will allow the loss of precious metals, throughout the cycle, to be curtailed, because gold, silver and other precious metals will follow copper, thus avoiding losses in further technological operations.

Most scrap recycling companies and plants are limited to a very narrow scope of work which consists in obtaining a commercial product through a minimum amount of work and involvement in the processing of a given type of scrap. The effect of this approach is to extract a just large enough useful fraction of valuable metal from the entire mass of waste that can be easily sold. In such a procedure, the remaining part of the waste, often containing, for example, plastics, is not managed (Yazici & Daveci 2009). This results in the generation of processed waste, which is very difficult to be managed further and which, in many cases, ends up as landfill. However, this procedure does not contribute to the improvement of the recycling rate of scrap metal in Poland, nor to environmental protection. This procedure is mainly brought about by a lack of knowledge regarding the methods of processing polymetallic waste, including PCBs, which in many cases causes scrap processing plants to focus solely on mechanical separation.

Mechanical methods are an alternative technology for the recovery of precious metals. These technologies are various combinations of comminution and separation processes, using differences in shape, colour and the physical properties of the comminuted materials. There is a view (Havlik et al. 2010) that the process of shredding PCB waste causes losses of precious metals, which, due to the form in which they occur (*contacts, wires, ceramic components in multilayer capacitors*), pass into the dust fractions. Mechanical impacts on components rich in precious metals result in the formation of small-sized particles that pass into the dust fractions or, thanks to the adhesion phenomenon, settle on the elements of other fractions. In order to counteract the loss of precious metals, there is the manual removal of elements with a high content of precious metals. The manual disassembly of PCBs, however, requires knowledge of the board structure and incurring the costs of manual work.

Another method for recovering precious metals from PCBs is to convert the precious metals into a char by pyrolysis. The purpose of pyrolysis is to get rid of organic compounds and concentrate the material into copper and accompanying metals. The material, after pyrolysis, is dark and brittle; it is easy to distinguish the metallic components in it by their characteristic metallic gloss. The char, along with lead, is then melted with refining salts ($NaNO_3$, NaOH, NaCl), in order to maintain the appropriate proportions. The char is then crushed in a vibrating mill and the dark matrix, after grinding, is removed by a set of sieves placed on a vibrating machine, thanks to which the remaining metallic part remains on the sieves (Fig. 1).

Many companies, despite a willingness to develop a method for the complete processing and management of scrap metal, are not able to take up such a challenge. The way forward, for such companies to acquire appropriate knowledge and the appropriate tools, is the transfer of ready-made, technological and technical solutions by purchasing a ready, complete technological line. There are many innovative projects in Poland that respond to such market demands. For many plants, it will be easy to access "know how" in the field of processing polymetallic scrap waste, including PCBs, by purchasing a complete solution in the form of a ready technological line.

Fig. 1. Macro-photography of material rich in Cu and precious metals

The Polish recycling industry, which recovers metallic fractions from printed circuit boards, does not specify any so-called "waste stream", which is a stream with more clearly defined dimensions, density and chemical composition. Typically, this is done in such a way that all PCBs, consisting of about 70% plastic, are subjected to the pyrolysis process. The pyrolysis process of PCBs should take place at a temperature of 780°C, while the non-uniform composition of PCBs causes that the process takes place at a much higher temperature, i.e., 1,100°C, so much higher than it should. Therefore, on the one hand, solutions are sought to effectively separate materials from metals while, on the other hand, solutions are sought in order to define a specific waste stream, *from which non-ferrous metals can be selectively recovered* and then standardize it. Therefore, the authors of this article have attempted to solve the research problem by removing elements rich in non-ferrous metals from the surface of the scrap and categorising them by type, shape and size, as detailed in the article.

4.1. Innovative processing methods on the example of PCBs

One of the few methods of metal recovery is the process of stripping elements rich in non-ferrous metals from the scrap surface. This process is most often used in printed circuit boards, the main components of which are shown in Fig. 2. Plastic, which has been recycled using combined methods, i.e. stripping methods in which the electronic working groups are removed from the PCB surface, is then sent to be segregated (Figs. 3, 4) (Lee & Lee 2012).

The results of the innovative processing of printed circuit boards introduced, indicate that it is possible to recycle non-ferrous metals, especially copper, tin and other accompanying metals (Ag, Au, Pb) (Zhang & Xu 2016) from PCBs by removing EGR from the PCB surface, using combined methods, e.g. a grindstone, sandpaper or CNC machine tools. On the one hand, this is an effective recycling method because it separates metals from plastics and thus minimises the emission of harmful substances in the pyrolysis process. On the other hand, it is quite a tedious process lasting from two to even several hours, depending on the method in which the material is processed (Biswajit et al. 2018). The proposed method of innovation is an alternative to recycling using pyrolysis methods and combined methods of separation and pyrolysis. It is postulated that the proposed method can be applied to the recycling process already in use at the time.

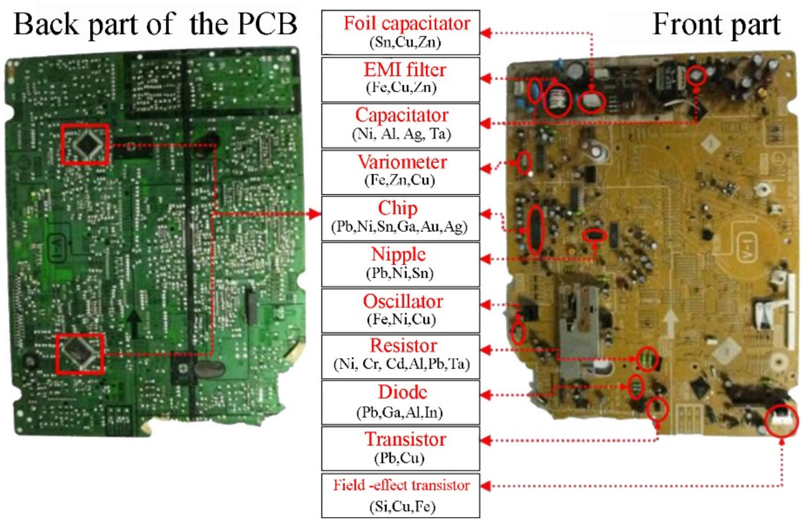

Fig. 2. Identification of the elements present in the isolated PCB

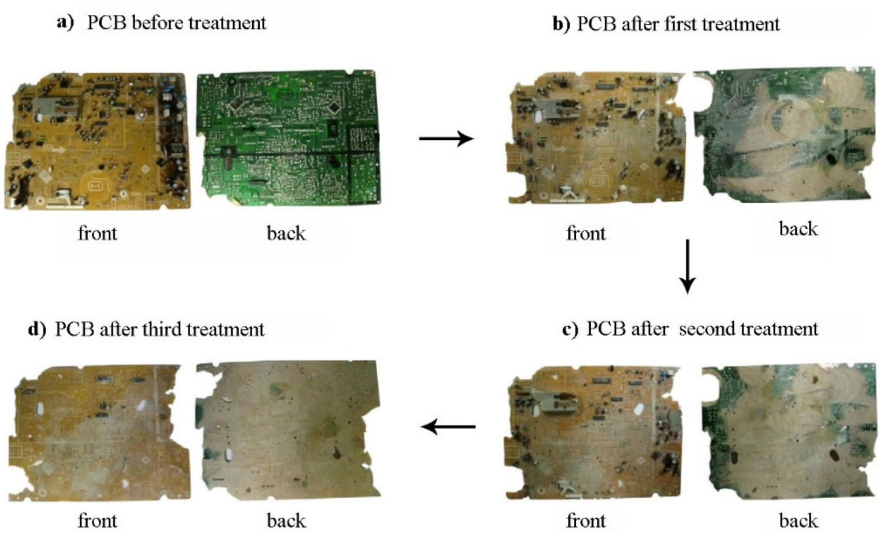

Fig. 3. PCB processing using three combined methods

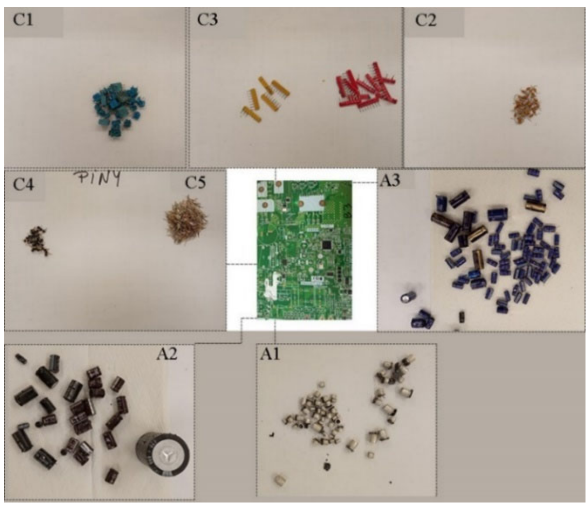

Fig. 4. Disassembled electronic workgroups categorised by type, shape and size

According to a study carried out by PBS, on behalf of Stena Recycling, (Stena Recycling Innovating, 2016) in January 2016, more than 75% of companies are willing to use uncomplicated methods in order to remove metallic materials and thus increase recycling levels. Sustainable waste management is gaining importance in the European Union. Environmental requirements are growing and steps are being taken to introduce a circular economy; environmental awareness is also growing. All this has a direct impact on the activities of companies in Poland and on introducing innovations to enterprises. Entrepreneurs have begun to combine the efficiency of waste management with responsibility and they attach ever more importance to both aspects. According to the above-mentioned study, measurable benefits of this approach are noticed by medium-sized and large companies, both from the industrial and from the manufacturing and service sectors. Therefore, it is important that recycling companies adopt the following scheme for conducting an innovative recycling process (Fig. 5).

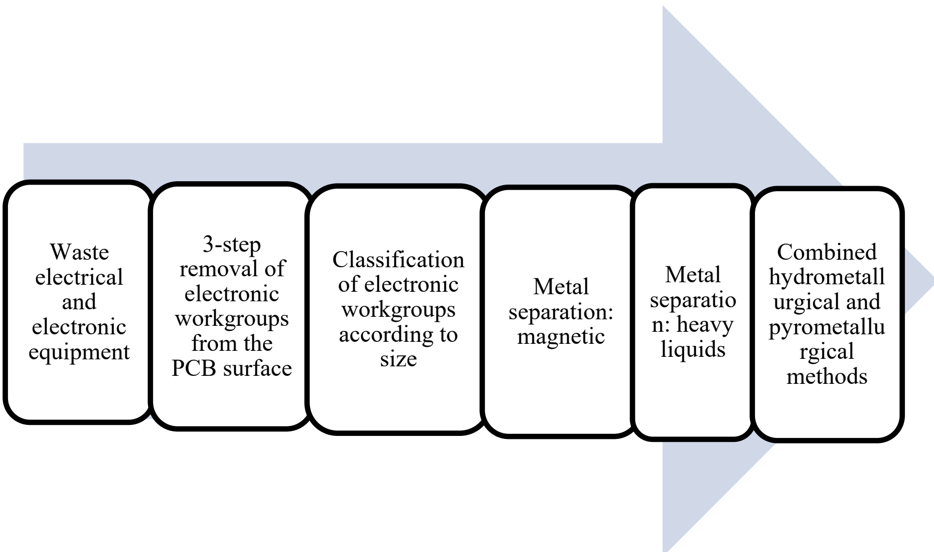

Fig. 5. A sample scheme of waste material flow which enterprises should use in their plants

Waste storage is the most problematic of issues for both medium and large enterprises. The challenges that medium and large enterprises anticipate in the area of waste management, in their industries, in the coming years include, inter alia, adjusting production to reduce the amount of waste generated (32%) and applying new technologies to improve waste management (28%), as well as materials with controlled biodegradability (Jachowicz at al. 2017). As goals or priorities for the coming years relate to waste management, medium-sized companies most often indicate cost optimisation (50% of responses), improvement of waste management logistics (31%) and an increase in recycling levels (30%). Large companies, in turn, emphasise, first of all, the improvement of waste management logistics and an increase in the level of recycling (42% of responses each) and further cost optimisation (32%) (Stena Recycling 2016).

5. Summary

The most important goals that recycling companies set themselves for the coming years include cost optimisation for medium-sized enterprises and improvement in waste management logistics along with increases in recycling levels for large enterprises. In accordance with applicable regulations, the required level of waste recycling is systematically increasing, thus prompting companies to introduce new processing methods, optimise waste management processes and design products in such a way that recycling them is possible to the highest degree. The elements of the waste management process, which are currently the biggest problem for medium-sized enterprises, are:

a. waste storage,
b. segregation,
c. waste management logistics,
d. contact with many operators,
e. inovative waste processing.

Increasing requirements, vis-à-vis the environment and the steps taken to introduce a circular economy, have a direct impact on the increase in new techniques and in innovation in Polish recycling companies.

The work was supported by the project No. SP2021/71 from the specific university research of Ministry of Education, Youth and Sports of the Czech Republic at VSB – Technical University of Ostrava and the project No. CZ.02.1.01/0.0/0.0/17_049/0008399 from the EU and CR financial funds provided by the Operational Programme Research, Development and Education, Call 02_17_049 Long-Term Intersectoral Cooperation for ITI, Managing Authority: Czech Republic – Ministry of Education, Youth and Sports.

References

Biswajit, D., Chowdhury, R. Ghosh, K., (2018). Sustainability of metal recovery from E-waste. *Frontiers of Environmental Science and Engineering*, 1-12.

Burzyńska, K., (2018). Portal Komunalny. In: https://portalkomunalny.pl/gospodarka-odpadami-trendy-2018-r-369823/ (Date of Access: 01.04.2020).

Central Statistical Office (2017), *Material Economy in 2016*, Warsaw 2017

Chamier-Gliszczynski, N., Krzyzynski, T. (2005). On modelling three-stage system of receipt and automotive recycling. *REWAS'04, Global Symposium on Recycling, Waste Treatment and Clean Technology 2005*, 2813-2814, Madrid, Spain, 26-29 September 2004, Conference Paper, ISBN: 8495520060.

Chamier-Gliszczyński, N. (2010). Optimal Design for the Environment of the Means Transportation: a Case Study of Reuse and Recycling Materials. *Sold State Phenomena, 165*, 244-249. DOI: 10.4028/www.scientific.net/SSP.165.244

Chamier-Gliszczyński, N. (2011). Environmental aspects of maintenance of transport means, end-of life stage of transport means. *Eksploatacja i Niezawodnosc – Maintenance and Reliability, 50(2*), 59-71. In: http://ein.org.pl/podstrony/wydania/50/pdf/07.pdf

Chamier-Gliszczyński, N. (2011a). Reuse, Recovery and Recycling System of End-of Life Vehicles. *Key Engineering Materials, 450*, 425-428. DOI: 10.4028/ www.scientific.net/KEM.450.425

Chamier-Gliszczyński, N. (2011b). Recycling Aspect of End-of Life Vehicles. Recovery of Components and Materials from ELVs. *Key Engineering Materials, 450*, 421-424. DOI: 10.4028/www.scientific.net/KEM.450.421

Czwajda, L., Kosacka-Olejnik, M., Kudelska, I., Kostrzewski, M., Sethanan, K., Pitakaso, R. (2019). Application of prediction markets phenomenon as decision support instrument in vehicle recycling sector. *Logforum, 15(2)*, 265-278. DOI: 10.17270/J.LOG.2019.329

Dobrzycki, A., Filipiak, M., Jajczyk, J. (2019). Changes in the range of electric vehicles during operation, *ITM Web of Conferences, 28 (01009)*, DOI: https://doi.org/10.1051/itmconf/20192801009

Duan, C., Wen, X. & Shi, C. (2009). Recovery of metals from waste printed circuit boards by a mechanical method using a water medium. *Journal of Hazardous Materials*, *1*(166), 478-482.

Gabryelewicz, I., Stryjski, R., Wędrychowicz, M., Dąbrowski, T. (2020). The State of the Air Quality in Poland. *Rocznik Ochrona Środowiska, 22*(2), 998-1013.

Gabryelewicz, I., Krupa, P., Sąsiadek, M. (2018). *International Business Information Management Association Conference – IBIMA*: Innovation Management and Education Excellence through Vision 2020, Milan, Włochy, Norristown: International Business Information Management Association (IBIMA), 4720-4727.

Havlik, T. (2010). Leaching of copper and Tin from used printed circuit boards after thermal treatment. *Journal of Hazardous Materials, 183*, 866-873.

Hausner, J. (2017). *The future of the market economy – from opportunistic to relational economic gamej*, Cracow: Open Eyes Book (in Polish).

Huisman, J., Botezatu, I. i Herreras, L. (2015). *Countering WEEE Illegal Trade Summary Report*, Croatia: CWIT consortium.

Institute for Research on Market Economy, (2017). *Functioning and irregularities in the management system of waste electrical and electronic equipment (WEEE) in Poland*, Warszawa (in Polish).

Jachowicz, T., Sikora, J., Dulebova, L. (2017). Investigating effects of prodegradant content on selected properties of polymer composite materials. *Environmental Engineering and Management Journal, 16*(12), 2879-2886.

Jacyna, M., Wasiak, M., Lewczuk, K., Chamier-Gliszczyński, N., Dąbrowski, T. (2018). Decision Problems in Developing Proecological Transport System. *Rocznik Ochrona Środowiska, 20*(2), 1007-1025.

Jajczyk, J. (2016). Use of Personal Computers with Multi-core Processors for Optimisation Using the Genetic Algorithm Method, IEEEXplore Electronic. DOI: https://doi.org/10.1109/CPEE.2016.7738731.

Jajczyk, J., Filipiak, M., Dąbrowski T. (2020). Reducing the Use of Electrochemical Sources of Electricity Through the Use of Wireless Power Supply. *Rocznik Ochrona Środowiska, 22*(1), 444-455.

Kanalikova, A., Behunova, A., Mandicak, T., Mesaros, P. (2019) New technologies for sustaining development in infrastructure, logistics and construction industry. *Acta Logistica, 6*(4), 171-177. DOI: 10.22306/al.v6i4.145

Kosacka-Olejnik, M. (2019). How manage waste from End-of-Life Vehicles? – method proposal. *IFAC Papersonline*, 52, 13, 1733-1737. DOI: 10.1016/j.ifacol. 2019.11.451

Kulczycka, J., Karaś, H. (2016). Legal versus illegal trade in waste electrical and electronic equipment – effects and threats. *CUPRUM – Czasopismo Naukowo-Techniczne Górnictwa Rud, 78*(1), 65-75 (in Polish).

Lee, J., Lee, J. (2012). Disassembly and physical separation of electric/electronic components layered in printed circuit boards (PCB). *Journal of Hazardous Materials*, October, 241-242.

Main Environmental Inspectorate, (2018). *The state of the environment in Poland,* Report 2018. Warszawa: Biblioteka Monitoringu Środowisowego.

Marczewska, M., Jaskanis, A., Kostrzewski, M. (2020). Knowledge, Competences and Competitive Advantage of the Green-Technology Companies in Poland. *Sustainability, 12*(21), 8826. DOI: 10.3390/su12218826

Merkisz-Guranowska, A. (2018). Waste recovery of end-of-life vehicles. International Automotive Conference (KONMOT 2018), 421, 032019. DOI: 10.1088/1757-899X/421/3/032019

National Fund for Environmental Protection, (2015). Standards for the processing of individual types of waste equipment and requirements for waste equipment processing plants, Report Ministry of the Environment (in Polish).

Report of the Main Statistical Office, Environmental Protection 2. (2017). Environmental Protecion, Warszawa: Main Statistical Office.

Reconomy, Koalicja na rzecz Gospodarki Obiegu Zamkniętego. (2017). *Gospodarka obiegu zamkniętego – Biznes i konsument na ścieżce zmiany.* Warszawa: no name of the author.

Stena Recycling Innovating, (2016). In: https://odpady.net.pl/2016/04/20/przedsiebiorcy-stawiaja-na-odpowiedzialne-gospodarowanie-odpadami/ (Date of Access: 2020).

Stena Recycling, (2016). In: https://biznesalert.pl/raport-potrzeby-oczekiwania-i-obawy-przedsiebiorstw-wytwarzajacych-odpady/ (Date of Access: 04.05.2021).

Straka, M., Tausova, M., Rosova, A., Cehlar, M., Kacmary, P., Sisol, M., Ignacz, P., Farkas C. Big Data Analytics of a Waste Recycling Simulation Logistics System. *Polish Journal of Environmental Studies, 29*(3), 2355-2364, DOI: 10.15244/pjoes/108684.

Woynarowska, A., Żukowski, W., (2009). Modern methods of recycling electronic waste. *Chemia – Czasopismo Techniczne, 06*(10), 177-182.

Woźniak, W., Nawrocki, W., Stryjski, R., Jakubowski, J. (2017). *Identification and reduction of product defects in mass production at toyota motor manufacturing, Poland.* W: Proceedings of the 30th International Business Information Management Association Conference – IBIMA 2017 4774-4782, Madrid, Spain, 2017.

Woźniak, W., Nawrocki, W., Stryjski, R., Jakubowski, J. (2017). *Diagnosis of process parameters which reduce the defective parts in mass production.* W: Proceedings of the 29th International Business Information Management Association Conference – IBIMA 2017, 2628-2635, Vienna, Austria 2017.

Yazici, E., Daveci, H. (2009). Recovery of metals from E-wastes. *Journal of the Chamber of Mining Engineers of Turkey*, *3*(43), 3-18.

Zajac, P., Kwasniowski, S. (2017). *Modeling forklift truck movement in the VDI cycle and the possibility of energy recovery*. In 23rd International conference on engineering mechanics, 1094-1097. In: https://engmechx.it.cas.cz/improc/2017/1094.pdf

Zajac, P., Stas, D., Lenort, R. (2020). Noise Charge in Rail Transport-EU Regulations Versus Operation of Logistics Systems. *Rocznik Ochrona Środowiska, 22*.

Zhang, L. Xu, (2016). A review of current progress of recycling technologies for metals from waste electrical and electronic equipment. *Journal of Cleaner Production*.