Potential Possibilities of Raw Materials Recovery from Waste Batteries and Accumulators on the Example of Poland

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Abstract

The paper assesses the possibilities of metallic raw materials recovery from batteries and accumulators in Poland. On the basis of available data on the amount of waste generated (CIEP, Statistics Poland), production volume as well as literature review in the field of technological recovery and verification with recyclers, an estimation of the amount of recoverable metals was calculated, at the present time and over a dozen or so years. Assumptions were adopted that in line with the concept of a circular economy, activities in the field of recycling and obtaining metals from waste will be supported in Poland. It is realistic because in January 2019 a new National Intelligent Specialization – The Circular Economy - water, fossil raw materials, waste was created. Moreover, for a few years there has been a broad discussion on the implementation of the State's Raw Materials Policy, in which obtaining raw materials from waste is also planned. In addition, within EU policy there has been already implemented a strong policy support in both batteries production and recovery, therefore the EU activities and policy have also presented.

Keywords: batteries, accumulators, recycling, metal recovery, circular economy

1. Introduction

The management of waste batteries is particularly difficult due to the dispersion of this type of waste. Batteries and accumulators are found in many devices, used in virtually every area of life and in every branch of industry. While the society is increasingly aware of the selective collection of batteries such as AA or AAA, it is problematic to selectively collect larger batteries. Batteries and accumulators have a significant raw material value, as they can replace fossil-fuel mining undergoing recovery processes. They also have a significant market value: the value of recovered products from one Mg of waste is over 800 USD (Moorthi, 2006).

The battery consists of materials from which electrons are obtained as a result of chemical reactions, for example in the reaction of lead and lead oxide (IV) with sulfuric acid (VI) in the lead-acid battery. To ensure ionic conductivity, the battery contains an electrolyte, i.e. a solution containing salts consisting of ions (electric charge carriers) and the solvent in which they are dissolved. In zinc-carbon cells, the electrolyte is an aqueous solution of zinc chloride, and in alkaline zinc-manganese cells it is 30% potassium hydroxide. These reagents must be immobilized. Dies that serve as collectors of electric charge serve for this purpose. An example here can be lead-acid batteries, in which the active compounds of reagents are placed on grates made of lead alloys. These grates serve as a matrix (carrier) of the active mass and the electric charge collector. To prevent a short circuit between the electrodes with an opposite electric sign, the anode reagents are separated from the cathode by a separator. It is made of special cellulose or plastic derivatives (e.g. polyethylene). All mentioned elements together with the sealing system and the outlet of electrical contacts are embedded in the housing. For example, alkaline cells are placed in steel cups, zinc-carbon in zinc cups and a steel casing. Zinc-carbon batteries after discharge contain zinc ions, unreacted metal zinc, manganese (III) and (IV) compounds and zinc chloride. The most easily recovered waste from these batteries is a steel casing that can be recycled (Rogulski et al., 2014).

2. EU policy for waste batteries and accumulators and its implementation

Special rules for waste management apply to batteries and accumulators. They include both the collecting of these products and the management after use. A company introducing car batteries and accumulators to the market, after their consumption must provide collection from the consumer, retailer and wholesaler, as well as transferring them for processing and recycling; it must also ensure an adequate level of collection and recycling ('extended producer responsibility'). It is in line with the European Union is Directive 2006/66/EC of the European Parliament and of the Council of 6 September 2006, on batteries and accumulators and waste batteries and accumulators, and repealing Directive 91/157/EEC with later amendments, introducing mechanisms for more effective and fuller protection of the environment against the negative impact of waste batteries and accumulators – a directive on batteries and accumulators and their waste. The Directive also introduced the obligation for Member States to maximise the separate collection and to monitor the collection levels of portable batteries and accumulators and to report annually on the collection rate achieved within six months of the end of the calendar year. Member States were required to achieve a minimum level of collection of 25% by 26 September 2012 and 45% by 26 September 2016. In Art. 13 above the directive states that "Member States shall encourage the development of new recycling and treatment technologies and support research into environmentally friendly and cost-effective recycling methods for all types of batteries and accumulators”. All batteries collected must be recycled through processes that at least reach the minimum efficiencies established by the directive, in order to attain a high level of material recovery. Targets are defined for three groups of batteries: lead-acid, nickel-cadmium and all other batteries ('general').

According to the newest EU Report from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions on the implementation and the impact on the environment and the functioning of the internal market of Directive 2006/66/EC of the European Parliament and of the Council of 6 September 2006 on batteries and accumulators and waste batteries and accumulators and repealing Directive 91/157/EEC most Member States have met or exceeded the 2012 target for the collection of waste portable batteries (set at 25%), but only 14 Member States have met the 2016 target (set at 45%). The evaluation points out that these targets are generally insufficient to ensure a high level of collection of waste portable batteries. Provisions for collecting the different types of batteries are too diverse: a target has only been set for the collection of portable batteries, not for industrial and automotive batteries. An estimated 56.7% of all waste portable batteries are not collected, annually. This has led to around 35 000 tonnes of waste portable batteries entering municipal waste streams, causing negative environmental impacts and a loss of resources. This amount is significant enough to jeopardise the achievement of the directive’s environmental protection objectives.

On the level of recycling, the vast majority of waste batteries collected in the EU are recycled in line with the directive’s requirements. The lack of specialised recycling facilities would explain the few cases where recycling is not ensured. Moreover, battery-recycling processes did meet the efficiency targets set by the directive, particularly for lead-acid batteries and to a lesser extent for nickel-cadmium and ‘other’ batteries.

The directive’s overall objective to achieve a high level of material recovery is not being met, however. The directive only targets two substances – lead and cadmium – and does not consider other valuable components, as cobalt or lithium. Moreover, the definitions of recycling efficiencies is not geared towards increasing material recovery.

Recovery of cobal and lithium from batteries is in central intrest of many companies, nowdays. According to the newest report State-of-the-art in reuse and recycling of lithium-ion batteries – A research review by Circular Energy Storage (Hans Eric Melin, 2019) the valuable raw materials are recycled mainy from batteries in mobile phones and computers were initially exclusively of the type LCO ($LiCoO_2$) – cells of this type contain between 17 and 20% cobalt, which is the most valuable substance in the batteries. Whereas power tools, energy storage, electric bikes, buses and the majority of all cars, especially in China are equiped with the LFP battery ($LiFePo_4$). This type does not contain cobalt at all, and the recovery from recycling from a value standpoint is very low. The same applies to LMO ($LiMn_2O_4$) which is used in electric scooters, power tools and in many of the first large volume electric cars such as Nissan Leaf and Chevrolet Volt, although in a combination with NMC ($Li(NiMnCo)O_2$). NMC, together with NCA ($Li(NiCoAl)O_2$) has subsequently become the dominant battery chemistry for electric cars in the western world. Both chemicals contain cobalt but only between 2 and 6.5 percent in NMC and less than 3 percent in NCA.

3. Recycling of lithium-ion batteries

Today, there are over 50 companies around the world which recycle lithium-ion batteries on some scale, from small laboratory plants to full-scale factories15. Most companies are located in China followed by South Korea, EU, Japan, Canada and the United States. In principle, each market has greater capacity than the currently available supply of batteries to recycle. Europe has about ten companies that treat lithium-ion batteries in different ways. The recovery efficiency is not as good as in China and South Korea, which is mainly due to lower volumes which does not make it profitable to extract all substances. Both pyrometallurgical and hydrometallurgical methods are used as well as combinations thereof

The data base which is called Urban Mine Platform28 is available for anyone and contains very valuable information for forecasting or pure understanding of how the material flows look (http://www.energimyndigheten.se/globalassets/forskning--innovation/overgripande/state-of-the-art-in-reuse-and-recycling-of-lithium-ion-batteries-2019.pdf).

In Poland, according to the Chief Inspectorate of Environmental Protection (GIOŚ), over 131 thousand tons of batteries and accumulators were introduced to the Polish market in 2016, including portable (12.5 thousand tons), industrial (24 thousand tons) and car (over 94.6 thousand tons) batteries and accumulators.

On October 3, 2014, the Act on batteries and accumulators came into force (Journal of Laws of 2014, item 1322) amended by the Announcement of the Marshal of the Parliament (Journal of Laws 2015, item 687). Those documents are the transposition of the requirements of Directive 2006/66/WE. The Act specified:

- requirements for batteries and accumulators placed on the market,
- rules for their placing on the market,
- rules for the collection, processing, recycling and disposal of waste batteries and accumulators.

The provisions of the Act are applicable to:

- all types of batteries and accumulators produced and placed on the market, irrespective of their shape, capacity, weight, material composition, method of use and regardless of whether they constitute an affiliation or component of the device or an additive to other products;
- used batteries and accumulators.

The Act also introduced requirements for batteries and accumulators placed on the market as well as equipment and contents:

- more than 0.0005% mercury by weight, with button cells not containing more than 2% mercury by weight;
- more than 0.002% by weight of cadmium.

Sets and button cells should be marked with a selective collection symbol.

Three groups of chemical energy sources stand out on the Polish market:

- lead-acid batteries,
- large and small size nickel-cadmium batteries,
- primary batteries and other secondary batteries.

The processing of lead-acid batteries in Poland is carried out by only two companies that are located in the Silesian province. These companies have a collection network for used batteries, therefore they also deal with the intermediation in equipping customers with acid-resistant containers necessary for the transport of batteries. The recycling process of batteries in these enterprises mainly involves the recovery of lead and sulfuric acid. The volume of demand for lead batteries in Poland is estimated at around 80,000 Mg, and the processing capacity of only these two plants significantly exceed it. The problem with this type of recycling is that it has become less profitable due to the low prices of lead, which is the main product of recycling, which in turn is mainly caused by overproduction of cheap lead in China. Despite such unfavourable economic situation, almost 100% of used batteries are currently processed in Poland. The increase in the processing of one of the companies can only take place at the expense of the other. The best solution would be import, which according to Polish regulations is prohibited (batteries qualify for hazardous waste). Disposal of batteries is associated with negative actions related to their collection and inappropriate processing leading to obtaining nickel plates, the sale of which brings significant economic effects. Other demolition products are removed in a way that threatens the environment, i.e. by pouring electrolyte into the sewage system or into the soil. The iron-cadmium boards are transferred to steelworks as scrap metal. France is an example of a country where an organized system of collecting used batteries and accumulators has existed for a decade. Already in 2007 there were over 33,500 collection points in the service facilities of household appliances as well as electrical and electronic devices, in which individual users can return used batteries and accumulators. There is also a distribution system based on their direct acquisition from users or by public utilities (shops, municipal and municipal offices – special containers). In Poland, such a system is just being introduced and in large stores you can see suitable containers prepared for collecting used batteries. The batteries and accumulators collected in this way are subjected to recovery or disposal processes. In Poland, there are several installations for the processing of batteries, NI-Cd batteries and processing of lead-acid batteries (Pietrzyk-Sokulska, 2016; Witkowska-Kita et. Al., 2019). In these plants, recovery or disposal takes place as part of three processes:

- hydrometallurgical – chemical treatment, which results in the recovery of metals after the precipitation of aqueous solutions, but only after disassembly and separation into homogeneous fractions,
- pyrometallurgical – based on the thermal recovery of metals by putting them into a volatile state; it does not require disassembly of chemical power sources, but is energy-intensive and causes emission of dust and gases,
- thermal – involving the pyrolysis and subsequent distillation, which is supplemented if necessary by a hydrometallurgical or pyrometallurgical process.

As a result of these processes, 16% of used batteries and accumulators are recovered.

In all types of batteries there are at least two components – metals or their compounds. This necessitates the use of various methods and technologies for the processing of used cells. Depending on the type of batteries, different raw materials may be recovered from them (Bystroń et al., 2013):

- alkaline batteries – its cathode is made of powdered manganese dioxide (MnO_2), and the anode of zinc oxide, and the basic electrolyte is an aqueous solution of potassium hydroxide (KOH);
- zinc-carbon batteries – the cathode is made of a carbon rod surrounded with manganese dioxide, and the anode with zinc, and the electrolyte is an aqueous solution of ammonium chloride or zinc chloride;
- silver batteries – the cathode is made of silver oxide, anode with zinc, and the alkaline electrolyte is a solution of potassium hydroxide (KOH);
- mercury batteries – the cathode is made of mercury, the anode with zinc, and the electrolyte is an aqueous solution of potassium hydroxide (KOH);
- lithium-manganese batteries – the anode is made of lithium, the cathode is powdered with manganese dioxide and the organic electrolyte;
- zinc-air batteries – the cathode is oxygen (O_2), the anode is zinc powder, and the electrolyte is potassium hydroxide (KOH).

Lithium-ion secondary cells (LIBs) contain heavy metals, organic components and plastics in proportions (Maćko et al., 2012): 5–20% cobalt (Co), 5–21% 2 nickel (Ni), 5–7 % Li, 15% organic substances and 7% plastics. This composition may vary slightly depending on the manufacturer. Recycling LIBs encounters two problems: the removal of harmful waste and the prevention of battery explosion during the recycling process, because unlike other types of batteries, LIBs often break out during processing due to the rapid oxidation of metallic lithium recovered during the recycling of batteries.

In the case of accumulators, the following types are distinguished depending on the composition of the electrolyte and electrode construction (Shin et al., 2005; Moćko et al., 2012):

- lead-acid accumulators – the electrolyte is a sulfuric acid solution, the anode is made of lead (with additives), a lead oxide (IV) cathode of PbO_2 immobilized on a lead frame; massively used in cars;
- NiCd accumulators (the so-called secondary alkaline accumulators) – the electrodes are made of nickel hydroxide and cadmium hydroxide, the electrolyte is semi-liquid or solid substances with a chemical composition that differs depending on the manufacturer, but always has a strongly alkaline reaction;
- NiMH accumulators – an improved version of NiCd accumulators in which one of the electrodes is made of nickel, the other of rare-earth sinters in a hydro-

Tab. 1. Typical composition of electrode material for Zn-C and alkaline batteries [%]
Tab. 1. Typowy skład elektrody dla baterii Zn-C i baterii alkalicznych [%]

Battery type/elements	**Zn [%]**	**Pb [%]**	**Ni [%]**	**Mn [%]**	**Fe [%]**	**K [%]**
Zn-C	5	-	0.007	23-30	0.2-1.0	-
Alkaline	12-21	0.005	0.01	26-33	0.17	5.5-7.3

Source: based on Ulewicz M., 2015 - Processes for recovery and recycling of non-ferrous metals and steel. Politechnika. Częstochowska, p.291

Tab. 2. The degree of leaching of some components from used Ni-MH batteries for selected leaching factors
Tab. 2. Stopień wyługowania niektórych składników zużytych akumulatorów Ni-MH dla wybranych odczynników ługujących

The composition of the starting material	**Content [%]**					
	Ni	Co	∑Ln	Fe	Al	Zn
	47.1	9.55	21.62	0.27	1.20	0.60
Leaching factor:	Degree of leaching [%]					
H_2SO_4	98	97	92	93	94	94
HCl	98	94	97	92	99	99
$(NH_4)_2SO_4$	31	27	0.6	0.47	-	-

Source: A. Jarosiński, Selected topics in the technology of obtaining rare earth metals.

gen atmosphere; the electrolyte is a spongy structure impregnated with alkaline substances and a chemically complex catalyst;
- Li-ion accumulators – one of the electrodes is made of porous carbon and the other of metal oxides, the electrolyte is chemically complex lithium salts dissolved in a mixture of organic solvents;
- lithium-polymer accumulators – a variant of Li-ion accumulators in which the liquid electrolyte is replaced with a solid polymeric electrolyte made of, for example, sponges based on polyacrylonitrile.

It is assumed that 1 Mg of used batteries contains the following components on average (Kozłowski et al., 2010):
- manganese dioxide 270 kg (27%),
- iron 210 kg (21%),
- 160 kg zinc (16%),
- graphite 60 kg (6%),
- ammonium chloride 35 kg (3.5%),
- copper 20 kg (2%),
- potassium hydroxide 10 kg (1%),
- mercury (mercury oxide) 3 kg (0.3%),
- several kilos of nickel and lithium (0.4%),
- cadmium 0.5 kg (0.05%),
- silver (silver oxide) 0.3 kg (0.03%),
- small amounts of cobalt.

During the processing of small-size batteries and accumulators, the following fractions are formed (Nowacki et al., 2012; Jaśnikowski et al., 2002):
- ferromagnetic – metal parts containing iron, nickel, chromium constituting approx. 30% of the total mass, then subjected to purification on sieves;
- paramagnetic – in the form of a black powder containing a number of metal elements, constituting approx. 50% of the total mass - subjected to further recovery in metallurgical or hydrometallurgical processes;
- diamagnetic – waste code 19 12 10 (ground PE and PVC plastics, paper, tar gelatin, etc.) constituting approx. 20% of the total waste.

Over 60% of the lead produced and used every year in the world is a product obtained through the recycling of lead-acid batteries. The product of recycling is pure lead, so-called "Soft" or lead alloys intended mainly for the production of new batteries.

4. Recycling of Zn-C and alkaline batteries

Zn-C and alkaline batteries are used, among others in pilots, calculators, watches, radios, portable audio equipment, in toys and flashlights. They contain significant amounts of Zn and are a potential secondary source of its recovery as presented in Table 1.

Batteries of these types can be processed in pyrometallurgical technology, e.g. Citron, Tera, Waelz, Batric, Sumitomo and CJC. They can also be melted in a blast furnace, and the end product is raw iron, slag and Zn oxide accumulated in sub-process dust (can be processed in other technological processes). In many countries, segregated galvanic cells are added to other zinc-coated input materials, e.g. EAF dust and melts in Waelza furnaces (Wójcik et al 2017.) This technology is used in Poland by Bolesław Recykling Ltd., where small amounts of batteries are added to the processing of dust from electric arc furnaces, while Batrec Industry in Wimmis from Switzerland in the process Batrec recovers from 1 Mg of used batteries 360 kg of Fe-Mn alloy, 200 kg of Zn, 1.5 kg of Hg and 20 kg of slag (Ulewicz et al., 2010). Zn-C and alkaline batteries are also processed using hydrometallurgical processes e.g. Batenus (Germany), Cincex MZP (Spain) and TNO (Netherlands, Germany). Ni-MH batteries contain metallic components: nickel and rare earth metals, and

Tab. 3. Chemical composition of the battery electrodes
Tab. 3. Skład chemiczny elektrod akumulatorowych

Electrode	Content [%]								
	Ni	Co	Mn	La	Ce	Pr	Nd	Al	Zn
Positive:	62.4	7.0	-	-	-	-	-	-	0.28
Negative:	61.3	6.9	3.8	11.6	0.9	0.9	3.7	1.4	0.8

Source: A. Jarosiński, Selected topics in the technology of obtaining rare earth metals

Tab. 4. Potential metal recovery from batteries and accumulators with a forecast by 2030
Tab. 4. Potencjał odzysku metali z baterii i akumulatorów z prognozą do 2030 r.

Metal	**Product**	**Potential metal recovery [kg]**	**Forecast for 2030 [%]**
Copper alloys	Batteries	84 761	> 0,5
Zinc and its compounds	Batteries	54 103	> 1
Nickel	Batteries	54 103	> 1
Silver and its compounds	Batteries	24 464	>1
Cobalt and its compounds	Batteries	72 137	> 1
Cadmium and its compounds	Batteries	8 115	> 1.5
Lithium and its compounds	Batteries	9 130	> 1

The amount of potential recovery was estimated based on CIEP data and literature data. The forecast was estimated based on megatrends

no metallic components such as paper, plastics, resins, etc. The precious components of such batteries are nickel, cobalt and rare-earth metals (Espinosa et al. 2004; Jarosiński et al. 2016).

The basic stage of the hydrometallurgical process for the recovery of rare earth metals from used Ni-MH batteries is leaching (Rećko 2014). The selection of the leaching agent is made in terms of sufficient selectivity, the possibility of regeneration, ensuring sufficient speed and efficiency of the process. The leaching factor should be cheap and easily available. According to these criteria, it is proposed to use solutions of sulfuric acid (VI), hydrochloric acid or ammonium carbonate. The first two leaching factors guarantee a high rate of leaching, whereas ammonium carbonate has a good selectivity towards nickel and cobalt. Unfortunately, this salt does not provide sufficient dissolution rate and the process is more difficult than in the case of the first two leaching factors. Sour acid leaching leads to high degrees of leaching of not only rare earth metals as presented in Table 2 (Espinosa et al., 2004; Jarosiński et al., 2018).

Rare earth concentrate is usually obtained by fractional precipitation of their double salts $Ln_2(SO_4)_3.K_2SO_4.2H_2O$ or $Ln_2(SO_4)_3.Na_2SO_4.2H_2O$. In practice, precipitation of sodium lanthanide sulphates is preferred for economic reasons, despite the fact that the efficiency of precipitation of lanthanide-potassium sulphates is preferable. As already indicated, the method of precipitation of fractionated double salts of rare earth metals can be used to separate them into the ceric and yttrium groups. The most efficient is extraction method (Espinosa et al., 2004, Jarosiński 2016). Another technical possibility for the solutions processing after rare earth elements removal is the extraction of zinc ions into the organic phase and then the reextraction of this phase into the sulfuric acid solution. Other impurities, for example, Cu^{2+} and Cd^{2+} ions from the aqueous solution are removed by precipitation of the sulphides of these metals. The last stage of the technological process is the separation of nickel and cobalt by electrolysis. The obtained precipitate meets the requirements for its reuse for the manufacture of batteries (Jarosiński 2016).

Processing of acidic leaching solutions can be carried out using the D2EHPA solution, di-(2-ethylhexylic acid), and extraction is usually carried out from aqueous hydrochloric acid solutions. The extraction is carried out to convert metals useful from the organic phase to the hydrochloric acid solution. The use of such a technological solution improves the leaching acid balance by repeated use and the obtained metals through a multistage extraction are characterized by a high degree of purity (Kucharski 2010).

5. Potential recovery from batteries and accumulators

Over 60% of the lead produced and used every year in the world is a product obtained through the recycling of lead-acid batteries. The product of recycling is pure lead, so-called "Soft" or lead alloys intended mainly for the production of new batteries. Chemical composition of the battery electrode is shown in Table 3.

The most cost-effective is the recycling of nickel-metal hydride batteries. The nickel Mg is worth between 15,435 and 16,555 USD (Kończyk et al., 2016). The highest costs are incurred for the recycling of nickel-cadmium and lithium-ion batteries, due to the low demand for cadmium and its small amount in batteries. The most valuable element used in the production of batteries is cobalt, also used for the production of magnets and high-strength alloys. The price of

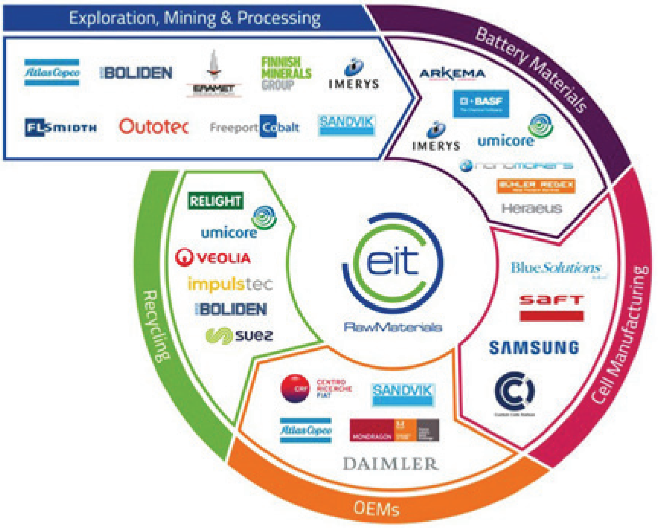

Fig. 1. EIT RawMaterials is one of the key actors in the European Battery Alliance (EBA). Together with some of partners, it is actively involved in the industry stakeholder consultation process coordinated by EIT InnoEnergy as well as in consulting the European Commission in its Strategic Action Plan for Batteries (https://eitrawmaterials.eu/eit-rawmaterials-contribution-to-the-european-battery-alliance-sustainable-materials-as-key-enablers-for-future-mobility/)

Rys. 1. EIT RawMaterials jest jednym z kluczowych podmiotów w European Battery Alliance (EBA). Wraz z niektórymi partnerami jest aktywnie zaangażowany w proces konsultacji z zainteresowanymi stronami z branży, koordynowany przez jest EIT InnoEnergy, a także prowadzi konsultacje z Komisją Europejską w jej strategicznym planie działania dotyczącym baterii (https://eitrawmaterials.eu/eit-rawmaterials-contribution-to-the-european-battery-alliance-sustainable-materials-as-key-enablers-for-future-mobility/)

one Mg of cobalt is 27,300 USD. The average cost of recycling one Mg of batteries in Europe varies around 300 USD (Korkozowicz 2010). It is estimated that from 1 Mg of used Ni-MH batteries, 37.5 kg of rare earth metals with an 80% purity can be obtained (Hycnar et al., 2015). The table 4 indicates the potential recovery of metals from batteries and accumulators.

The recovery forecast for individual metals has been estimated based on megatrends in the world:

- The increase in the population will increase the demand for batteries and accumulators, which will increase the potential for recovery of metals from batteries and accumulators,
- GDP growth will increase the potential for metals recovery from batteries and accumulators, as this will be related to the increase in demand,
- Introduction of the circular economy assumptions will increase the potential for recovery from batteries and accumulators,
- The EC Regulation and Polish legal regulations will have an impact on the increase in the potential for recovery of metals from batteries and accumulators,
- The development of new technologies will increase the potential for recovery of metals from batteries and accumulators,
- The increase of ecological awareness will generate an increase in the potential for recovery of metals from batteries and accumulators,
- Circular economy assumptions about the re-use of products may reduce the potential for recovery of metals from batteries and accumulators,
- New technologies for the recovery of raw materials from batteries and accumulators due to low profitability may reduce the potential quantities.

6. Conclusions

The use of secondary raw materials is a fundamental and key element of waste management, which reduces the total amount of waste generated. Recycling is a process that not only uses secondary raw materials, but is a system of full organization of the circulation of such materials.

As our society moves towards a New Energy and Mobility Age, strongly driven by digitalization, the resources we depend on fundamentally change. Europe's dependence will expand from global players delivering fossil fuels to those capable of delivering raw materials and advanced materials needed in new energy technologies. Whether we will be able to transform into a truly sustainable global society will depend on the extent to which we can sustainably, swiftly and more efficiently produce these materials as well as keep them in the loop longer and ensure they enter an appropriate recycling process. A good example is the exponentially increasing demand for battery materials: one big battery cell manufacturing facility uses several thousand tons of cobalt, nickel, manganese, and lithium per year. Other raw materials vital for electrification include graphite, silicon, aluminium, and copper. The transition to sustainably designed and sourced new energy technologies comes with challenges but also promising innovation and business opportunities and a pivotal role for actors in the raw materials value chain. The EIT RawMaterials Knowledge and Innovation Community hosts key players from industry, research, and academia who drive the transition – and can make it a success for Europe (see Figure 1). The analysis of metals contained in batteries and accumulators shows that it is a valuable source of recovery important for the development of modern technologies and innovative products of raw materials, among others minerals. However, there is still a lot to do to make the collection and processing system work efficiently using the maximum potential. In recent years, the market for electrical and electronic equipment has been developing very dynamically in comparison with other branches of the economy (Report on WEEE 2013 research). Intensive growth means that every year more and more used equipment and waste batteries are accumulated, and thus the scale of the problem of managing this waste increases. The biggest challenge facing Polish society is the adaptation of good practices related to the management of used batteries.

Currently, it is possible to use a wide range of batteries of different size, shape and type. Over 80% of cells placed on the Polish market are zinc-carbon and alkaline batteries. The accumulator market is associated with such types of rechargeable cells as nickel-cadmium (Ni-Cd), nickel-metal hydride (Ni-MH), lead-acid and lithium-ion batteries. One of the most popular electric energy were nickel-cadmium accumulators. They were widely used in all types of power tools and in various electronic devices, such as flash lamps or radios. Ni-Cd batteries have been partially replaced by nickel-metal hydride batteries. According to Rogulski and Czerwiński's work, there has been a rapid development of lithium cell technology, which after the displacement of nickel-hydride batteries from the segment of portable batteries used to supply electronics begin to compete with them in automotive applications.

In batteries / accumulators there are many different materials that have a specific market value and for the rational management of raw materials, used batteries / accumulators should be recycled. At the same time, virtually all batteries / accumulators contain substances that are toxic and can contaminate the environment. Therefore, some of the batteries and accumulators included in the hazardous waste category should undergo a disposal process and, if possible, be recycled.

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Potencjalne możliwości odzyskiwania surowców z zużytych baterii i akumulatorów na przykładzie Polski

W pracy oceniono możliwości odzyskiwania surowców metalicznych z baterii i akumulatorów w Polsce. Na podstawie dostępnych danych dotyczących ilości wytwarzanych odpadów (GIOŚ, Statistics Poland), wielkości produkcji, a także przeglądu literatury w dziedzinie odzysku i weryfikacji z podmiotami zajmującymi się recyklingiem, obliczono oszacowane ilości metali odzyskiwalnych obecnie i w perspektywie kilkunastu lat. Przyjęto założenia, że zgodnie z koncepcją gospodarki o obiegu zamkniętym w Polsce wspierane będą działania w zakresie recyklingu i pozyskiwania metali z odpadów. Jest to realistyczne, ponieważ w styczniu 2019 r. powstała nowa krajowa inteligentna specjalizacja - gospodarka o obiegu zamkniętym - woda, surowce kopalne, odpady. Ponadto od kilku lat toczy się szeroka dyskusja na temat wdrażania polityki państwa w zakresie surowców, w której planowane jest również pozyskiwanie surowców z odpadów. Ponadto w ramach polityki UE wdrożono już silne wsparcie polityczne zarówno w zakresie produkcji, jak i recyklingu baterii. Przedstawiono działania i politykę UE w tym zakresie.

Słowa kluczowe: baterie, akumulatory, recykling, odzysk metali, gospodarka o obiegu zamkniętym