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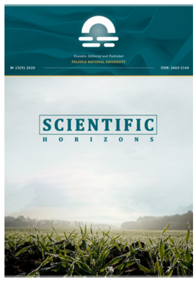

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Development of a System for Recycling Used Batteries and Lead-Containing Batteries: Assessment of the Economic Effect with Minimising Damage to the Environment

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Abstract. The relevance of the subject under study is determined by the issues of practical application of charging batteries and accumulators after the completion of the declared technical lifetime, in connection with the pollution problems due to lack of potential for normal disposal. The purpose of this study is to investigate the prospects of development and practical implementation of a system of recycling used batteries and lead-containing batteries, in the context of assessing the potential economic impact of minimising environmental damage while fully implementing the objective. The methodological framework of this study comprises a combination of quantitative and qualitative methods. The application of methods of analysis, synthesis, induction, and deduction in this paper provides sufficient information about the existing principles of recovery of lead-containing batteries and accumulators. The method of generalisation involves the implementation of a qualitative assessment of the data obtained in this study. The method of modelling provides the display of the results obtained using appropriate schemes and diagrams. The available publications of several researchers engaged in scientific development of the issues of disposal of spent lead batteries and accumulators were analysed. The factors of the economic effect that can be achieved by the high-quality recycling of lead-containing batteries were investigated. An approximate assessment of the economic effect with a given direction to minimise damage to the environment was formed. The results obtained in this paper and the conclusions formulated on their basis have practical significance in terms of the prospects of increasing the volume of production of secondary lead by recycling of used batteries and reducing damage to the environment, when it is uncontrollably contaminated by secondary products of their use

Keywords: recycling of used batteries, industrial recycling, minimisation of environmental damage, economic efficiency of battery recycling, recycling of lead-containing batteries

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INTRODUCTION

Lead is among the metals that are repeatedly included in material production and are relatively little wasted in industrial use (Morachevsky, 2014; Gupta *et al.*, 2022). The environmental pollution by lead and its degradation products poses a considerable risk to all human activities. Low-melting, practical, and convenient to recycle, lead is widely used today. Lead is used to make ammunition; it is used in the finishing of bullets (Akhmadova *et al.*, 2018). It is a component of numerous alloys, in particular, used for heavy loads, such as metal. It is used to produce tetraethyl lead and its different compounds. A large amount of lead dust is emitted into the atmosphere during the production of lead and its alloys. Such dust is involved in the biological cycle, adversely affecting all life (Xu *et al.*, 2021).

Modern disposal systems for lead-containing batteries and accumulators have essentially served to protect the environment by preventing alkali and lead from penetrating into water and soil (Jin *et al.*, 2021). The economic effect of the practical application of such systems is closely related to the prospects of further use of the environment, if there is no need to carry out cleaning of the pollution, caused by violations of regulations for the storage of lead-containing batteries and end-of-life batteries. The practical use of such aggregates is a costly process, which can result in considerable profits (Prasad & Vithanage, 2019). Today, lead-containing batteries account for about 1% of solid domestic waste on the scale of the whole segment (Denisova, 2019). Thus, the development of an efficient disposal system of used batteries and lead-containing batteries is an urgent and relevant task.

The recycling of lead is a critical environmental issue that requires professional solutions (Rovin & Ohremchuk, 2013). Both the state of the environment and the prospects for the development of industrial waste processing, which includes elements that can severely damage the environment and pollute it, depend on the quality of the solutions introduced (Nowroozi *et al*., 2021). The development of a system for recycling used batteries and lead-containing batteries should contribute both to the achievement of a tangible economic benefit from minimising environmental damage and to the development of the entire system for processing harmful industrial waste (Liu *et al*., 2019). The disposal of old, used batteries has an incredibly positive impact on the environmental and economic situation. More recently, however, the need for integrated reuse of battery components has become evident. To date, many countries in Europe have legislated the ban on disposal from used batteries in garbage bins because of the adverse environmental damage.

The purpose of this paper is to investigate the principles of developing a system of recycling used batteries and lead-containing batteries in the context of assessing potential economic effect within a given area to minimise environmental damage.

FEATURES OF RECYCLING USED BATTERIES AND LEAD-CONTAINING BATTERIES

The development of a system for recycling used batteries and lead-containing batteries implies the need to determine the priority areas of this process, considering the types of recyclable battery devices and the characteristics of the disposal of each particular battery type. In this context, L. Ma *et al.* (2019) classified the batteries according to the type of active substance used in the chemical reaction, where the batteries are grouped as follows:

– alkaline (including zinc anode, manganese dioxide cathode, and a conductive liquid based on a solution of potassium dioxide aqueous);

– lithium-manganese (including lithium anode, manganese dioxide based powdered cathode and organic electrolyte);

– zinc-carbon (including zinc anode, carbon cathode with manganese dioxide, and zinc/ammonium chloride-based electrolytic solution);

– cylindrical (including powder zinc anode, oxygen cathode, and KOH type electrolyte solution);

– mercury (including zinc anode, mercury cathode, and KOH type electrolyte solution);

– silver (including zinc anode, silver oxide-based cathode, and potassium hydroxide-based electrolyte).

All parts of lead-containing batteries and used batteries are to be recycled, and this process necessarily includes the collection of batteries that have used their allotted service life, transportation to the enterprise performing such processing, as well as separation of battery components, followed by melting of lead cells and cleaning. According to A. Manthiram (2020), the main steps of recycling used batteries and lead-containing batteries are electrolyte drain, separation of accumulator batteries into components cell, lead component analysis, incineration or disposal of plastic and ebonite waste, transportation of disassembled batteries to the smelting plant, melting and cleaning, collection and transportation of accumulator batteries

In turn, G. Saldaña *et al.* (2019) believe that upon disposal, lead fragments are dispersed in the air, which causes pollution of the environment and considerably damages the health of workers on whose clothing these fragments settle. Furthermore, toxic smoke causes similar damage during incineration, and, in the case of the burying plastic and ebonite wastes, there is significant soil contamination at such burial sites (Jenkins, 2017; Tran *et al.*, 2018). Without the implementation of a set of measures to ensure technological and engineering control over the recycling of used batteries, it is impossible to fully prevent the release of lead into the environment. Furthermore, it is mandatory to observe occupational health measures to prevent workers from becoming infected and harming their health.

Table 1 presents the main steps in establishing an environmentally safe and effective recycling system for used batteries and lead-containing batteries, as well as the characteristics of each step (Liu *et al.*, 2021; Li *et al.*, 2021).

***Table 1**. Establishment of an efficient system for recycling used batteries and lead-containing batteries*

Centralised monitoring and collection of used batteries and lead batteries	Ensure high quality control and accounting of waste components to prevent loss during collection
Organisation of transportation of waste elements to recycling sites	Control of transport process coherence to avoid loss and pollution
Monitoring the separation of batteries and lead batteries into components	Implementation of measures to prevent harmful substances from entering soil and water at separation sites of batteries and lead batteries
Ensuring the delivery of separated components to the enterprises of their subsequent recycling	Provision of qualitative accounting of volumes of delivery of separated components and measures to prevent their losses during transportation
Monitoring the progress of the recycling of separated components at end points	Ensure that all process and process conditions are met to prevent environmental pollution during process operations
Ensure that recycled components are shipped to their place of use	Tracking accuracy and delivery times of recycled components

Figure 1 presents a graphical display of the global capacity of used batteries and lead-containing batteries from 2016 to 2025 (Smyrnov *et al*., 2020). As can be seen from the data presented in Figure 1, the total global battery capacity has been steadily increasing since 2016 and is expected to reach 170 GW per year by 2025 (Smyrnov *et al*., 2020). Consequently, without the development and implementation of comprehensive measures for the disposal of used batteries, the threat of environmental pollution on a global scale is increasing significantly.

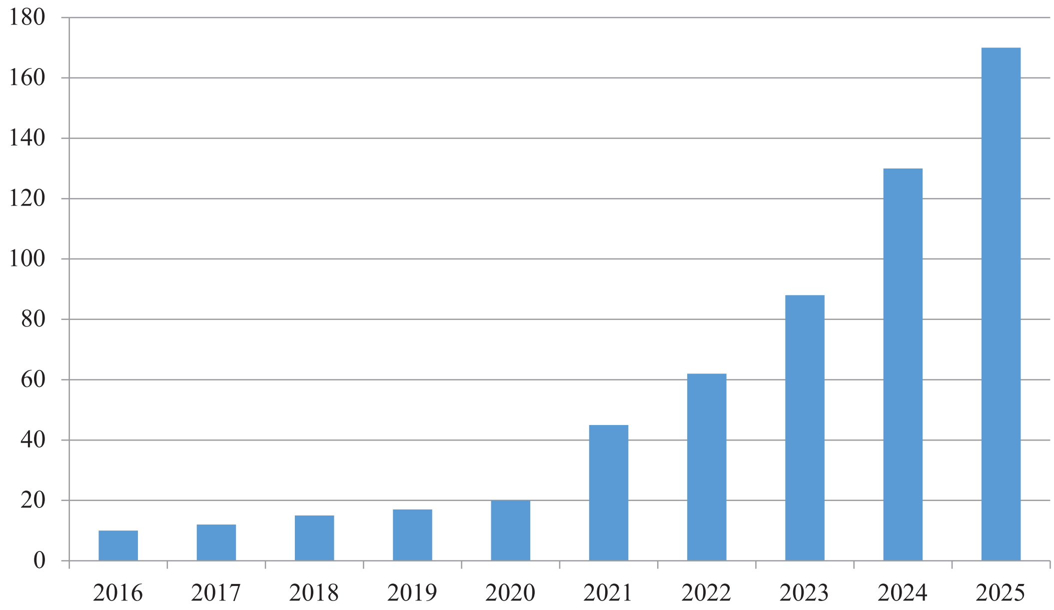

***Figure 1**. Total global capacity of used batteries as of 2016 and in the context of the 2025 forecast*

ASSESSMENT OF THE ECONOMIC EFFECT WITH A GIVEN DIRECTION TO MINIMISE DAMAGE TO THE ENVIRONMENT

J. Shea & C. Luo (2020) are convinced that the economic impact achievable by the high-quality recycling of lead-containing batteries is conditioned upon the following factors: recycled lead can be used to produce a variety of consumer goods; natural reserves of ore are preserved as lead from battery recycling is diverted to industrial use; soil and water are protected against harmful chemical elements and are therefore suitable for further beneficial use; there is no need to use storage facilities to stockpile used batteries. However, V. Kumaravel *et al.* (2021) is convinced that assessment of the economic effect towards minimising the damage to the environment should be formed considering the estimated savings of funds allocated for the restoration of the environment from the effects of its pollution, as well as the cost of recycling used batteries and lead-containing batteries over a specified period of time. In general, the following equation (1) can be used for calculating the economic effect achieved within one calendar year:

$$E_{EF} = E_E - E_{KE} \times Z_Y \tag{1}$$

where EEF is the economic effect that can be achieved during a calendar year in the implementation of a set of measures for the recovery of used allotted life of batteries and lead-containing batteries; EE is the annual savings which can be achieved without the need to spend money on cleaning the environment of lead and its compounds; EKE is the efficiency factor, constant value, depending on the organisation of activities for recycling of batteries and lead-containing batteries; ZY is the costs of disposal of the specified elements.

Thus, the assessment of the economic effect in the chosen area of activity to minimise environmental damage upon recycling used batteries and lead-containing batteries can be made considering the amount of money spent on recycling, as well as making a preliminary estimate of the costs of environmental clean-up if there is actual pollution. In addition, A. Molina *et al.* (2020) believe that the final value of the economic effect achieved per unit of time can serve as a qualitative assessment of the efficiency of measures to recycle a certain number of used batteries and lead-containing batteries in a specified time.

NECESSARY CONDITIONS FOR THE HIGH-QUALITY RECYCLING OF USED BATTERIES AND LEAD-CONTAINING BATTERIES

The qualitative resolution of the problems of recycling used batteries and lead-containing batteries is essential for the prospects of improving environmental safety and increasing the real potential for recycling hazardous industrial waste in general. The risk of environmental contamination by lead and its various compounds is clear when used batteries are not stored properly and if there is no well-designed system for their subsequent disposal. Spent batteries contaminate the soil; lead compounds penetrate the water, causing considerable contamination and their rapid spread (Tabelinet *et al.*, 2021). In turn, E. Lizundia & D. Kundu (2021) are convinced that all this necessitates the development of effective measures to create the necessary conditions for the high-quality recycling of used batteries and lead-containing batteries to prevent lead and its compounds from entering the soil and thus worsening the environmental situation.

The general instability of the current environmental situation causes problems of safe use of battery devices and their subsequent disposal (Danilov, 2014). The situation requires a systematic solution, as the removal of such devices to a landfill without proper control may result in severe damage to the overall state of the environment and have extremely negative consequences for the established human living conditions. Therewith, H. Kim *et al.* (2020) think that the correct operation of lead-containing batteries and batteries has a positive impact on the environmental situation, which makes it necessary to find the best combination of innovative development technologies and modern technical solutions, aimed at improving the quality of disposal of used batteries.

According to N. Mittal *et al.* (2021), the orderly disposal of used batteries should be entrusted to specific organisations that specialise in such activities and are authorised to carry out such activities. The organisation of such activities is very strictly controlled around the world. Because carrying out such work without sufficient experience and licenses can entail serious environmental issues (Torabi & Ahmadi, 2019). However, S. Bai *et al.* (2021) believe that this results in continuous improvements in the recycling of used batteries, which has a positive effect on the environment.

Today, the manual method of recycling batteries is often preferred, even though it is quite dangerous in general. According to D. Cao *et al.* (2020), this is because the equipment for the implementation of a full set of such measures is expensive, especially when this refers to the industrial scale of the operations. Efficient performance of such operations requires high qualifications because ignorance of the elementary rules of operation with batteries may further lead to serious health problems (D'Adamo *et al.*, 2019). As a rule, this method is most often abandoned, even though it allows obtaining high-quality raw materials.

The standard car battery holds an average of about 3.5 kg of acid and approximately 6-7 kg of lead. J. Sun *et al.* (2020) are convinced that such substances, as well as their derivatives, can greatly harm the environment and the human body. For this reason, the used batteries must necessarily be recycled by special organizations and using specially developed technologies to prevent the release of alkali elements, metals, and harmful acids into the environment. In several Western European countries, the management and processing of lead-containing batteries is a matter decided by the state. Legislation governs the disposal of batteries in electric vehicles, motorcycles, and automobiles (Levchenko & Britchenko, 2021).

There is an increased global interest in electric vehicles, with governments of many countries supporting this trend by subsidising the sale of electric vehicles and providing tax breaks to electric vehicle manufacturers. Such policies are primarily aimed at supporting environmental protection trends, as electric traction transport is completely environmentally friendly. However, car batteries, which are the key elements of electric vehicles, hold considerable amounts of toxic substances that can severely damage the environment (Farhad *et al.*, 2022). J. Popovic *et al.* (2021) believe that the problem of recycling battery electric vehicles will become acute in European countries by the second half of the 2020s, when a significant amount of such cells will accumulate. Therewith, the battery life of modern electric vehicles, which are produced today in European countries, is at least eight years, which gives Europeans enough time to systematically prepare for the application of battery recycling technologies for active electric vehicles.

All batteries that are currently used in the automotive industry are divided into two large classes: disposable and rechargeable (Garche & Brandt, 2018). N. Meng *et al.* (2021) noted that the first group comprises conventional batteries of many varieties, while the second group includes batteries of all types and technological varieties. Used batteries pose a considerable risk to the environment because they emit heavy metals (Garche *et al.*, 2017). The burial of used batteries at the proper landfills is coupled with percolation of heavy metals, which affect the soil and water by leachate. In a situation where spent batteries are burned in waste incinerators, heavy metals are concentrated in ash and slag, as well as in released gases. According to statistical studies (Denisova & Pirogova, 2020), on average batteries account for about 1% of the total volume of solid household waste, while the level of responsibility for the formation of heavy metals at solid waste landfills is many times higher and reaches approximately 60-70%.

Today, a fundamental problem is the disposal of lithium-ion batteries of modern electric vehicles after the end of their service life. About 150,000 of these batteries will be decommissioned by about 2030 (this number equates to their annual production) (Bicer & Dincer, 2018). According to S. Wang *et al.* (2021), unless effective measures are developed for the safe disposal of lithium-ion batteries in modern electric vehicles, the situation could become alarming and gradually become a serious environmental issue.

In the EU, the number of electric vehicles is steadily increasing, and the total number of electric vehicles is expected to increase to 7-8.5 million by 2030. Accordingly, this will aggravate the issue of recycling used batteries from electric vehicles, which requires the adoption of a set of purely legal measures to organise this process and legislatively consolidate it (Mir & Dhawan, 2022). In general, the measures adopted will contribute to the environment preservation and will provide a considerable economic benefit from minimising soil and water contamination in the storage sites of used batteries, provided that they are managed in a timely and high-quality manner.

CONCLUSIONS

The results of this study showed a strong correlation between the sequential implementation of used batteries and lead-containing batteries recycling processes and the economic effect which can be obtained by minimising environmental pollution. A comprehensive assessment of the possibility of causing damage to the environment, in the case of violations of the order of disposal of devices of the batteries and lead-containing batteries was carried out. It was clarified that the problem of recycling used batteries and lead-containing batteries is of considerable practical importance regarding the potential damage to the environment, where lead and its constituents are introduced into soil and water when storage rules are violated.

It was established that in assessing the economic impact, the decision-makers should consider the cost of disposing of these devices and the cost savings, which could be used to clean the environment from lead and its compounds. In general, it was revealed that well-organised and well-executed measures for the recycling of these accumulator devices contribute not only to the preservation of the environment from lead pollution and lead-containing compounds, but also provide considerable money savings, so very profitable in economic terms. This necessitates further research exploring the rational opportunities for optimising the processes of recycling used batteries and lead-containing batteries, as well as exploring additional cost-saving possibilities, provided that the high quality of industrial processing of this type of devices is ensured within the established time frame.

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Розробка системи утилізації відпрацьованих батарейок та свинцевих акумуляторів: оцінка економічного ефекту з мінімізацією шкоди довкіллю

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Анотація. Актуальність тематики визначається численними питаннями практичного застосування зарядних батарей та акумуляторів після завершення заявленого технічного терміну експлуатації, у зв›язку з проблемами забруднення через відсутність потенціалу для нормального утилізації. Основною метою даного дослідження є вивчення перспектив розробки та практичної реалізації системи утилізації відпрацьованих акумуляторів та свинцевих акумуляторів у контексті оцінки потенційного економічного впливу мінімізації шкоди довкіллю при повній реалізації поставленої мети. Основою методології цього наукового дослідження є поєднання кількісних і якісних методів. Застосування методів аналізу, синтезу, індукції та дедукції в даній дослідницькій роботі дає достатню інформацію про існуючі принципи відновлення свинцевих батарей та акумуляторів. Метод узагальнення передбачає здійснення якісної оцінки даних, отриманих у ході наукової роботи. Метод моделювання забезпечує відображення отриманих результатів за допомогою відповідних схем і діаграм. Проаналізовано наявні публікації низки дослідників, які займалися науковою розробкою питань утилізації відпрацьованих свинцевих батарей та акумуляторів. Досліджено фактори економічного ефекту, якого можна досягти при якісній переробці свинцевих акумуляторів. Сформовано приблизну оцінку економічного ефекту із заданим напрямком мінімізації шкоди навколишньому середовищу. Отримані в цій дослідницькій роботі результати та сформульовані на їх основі висновки мають практичне значення з точки зору перспектив збільшення обсягів виробництва вторинної продукції міді шляхом утилізації використаних батарейок та зменшення шкоди, що наноситься навколишньому середовищу, коли воно безконтрольно забруднено вторинними продуктами їх використання

Ключові слова: переробка відпрацьованих акумуляторів, промислова переробка, зменшення шкоди довкіллю, економічна ефективність утилізації акумуляторів, утилізація свинцевих акумуляторів