Small-Batteries Utilization Analysis Based on Mathematical Statistics Methods in Challenges of Circular Economy

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Abstract

The paper contains an analysis of the possibilities of mathematical statistics as a section of mathematics for solving the applied ecological and economic problem: utilization of small electrochemical power source (batteries). The statistical samples of the investigated phenomena are analyzed. Trend lines have been constructed, resulting in projected needs of the population of Ukraine and the world in the volume of battery disposal. A statistical test of the null hypothesis that the content of nickel in the batteries has a Poisson distribution is carried out. The implementation of this project is proposed at State Enterprise "Argentum" - the only Ukrainian battery recycling company located in Lviv.

Keywords 1

Mathematical Statistics Methods, a Poisson Distribution, Zero Hypothesis, Electrochemical Power Source, Small Batteries, Recycling, Utilization, Circular Economy Development, Trendline.

1. Introduction

The problem of evaluating certain values in mathematics, as well as predicting their values in the future, is related to the scientific substantiation of the prediction of probabilistic ways of developing the phenomenon or process for a more or less distant future. Tasks of forecasting are most often used in economics and management.

For today there was a big problem of humanity in connection with pollution of the environment, namely: pollution of the environment by emissions into the atmosphere, poisoning of rivers and lakes with chemicals and the growth of volumes of garbage that needs to be processed or buried. The easiest way to get reliable forecasts is to study the purchase of batteries in Ukraine and the world and create the best conditions for replacing small electrochemical power source (SEPS). The indicated mathematical regularities should be used in the analysis of acute ecological problem of SEPS utilization.

The paper is devoted to the study of the capabilities of mathematical statistics to analyze the problem of battery disposal, as well as the use of these capabilities to calculate the content of valuable metals in waste, to justify the economic benefits of recycling these wastes.

2. Related Works

The beginning of the detection and resolution of the problem of the laws of mass phenomena and their prediction based on data obtained from real experiments conducted in real time and with less data was carried out by scientists from the mathematical statistics [4, 8, 12, 13].

Modern problems of human interaction with nature are solved in the works [1 - 3, 5, 6, 9 - 11] by scientists from ecology, economics and nature protection both in Ukraine and in the whole world.

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Significant general problem of deterioration of life in large cities, including pollution by automobile exhaust gases from air, toxic waste from the territories of landfills, underground water of cities and villages of Ukraine, emission of harmful substances from factories and factories, is the accumulation of such dangerous small batteries, accumulators to mobile phones or laptops, and also energy-saving bulbs, to which we are all accustomed and do not even notice the dangers. The problem of economic evaluation of the volume of utilization of small batteries by means of mathematical statistics is devoted to this article.

3. Mathematical Statistics Methods in Challenges of Circular Economy

The main tasks of mathematical statistics are statistical verification of hypotheses, estimation of the distribution of statistical probabilities and its parameters, studying statistical dependence, determining the basic numerical characteristics of random samples. The term "statistics" means practical activities in collecting, processing, analyzing quantitative information that characterizes a certain aspect of public life (trade, production, population, education, etc.) [14]. In general, mathematical statistics is a section of mathematics in which the probabilistic laws of mass phenomena are studied on the basis of experimental data, statistical verification of hypotheses is carried out, and the distribution of statistical probabilities is evaluated, that is, the systematization of data for scientific and practical conclusions is carried out [12].

Mathematical statistics solves two categories of problems [13]: 1) statistical estimation (point, interval) of parameters of the general population; 2) checking the truthfulness of statistical hypotheses about the meaning of the parameters of the general population or the law of distribution of the feature of the general population on the basis of processing the results of the sample.

The range of statistical methods is extremely wide. The most important area of application of statistics is the economy. As an example of an actual task, it may be a prediction of subsequent economic development based on economic data obtained in the presence of random perturbations.

Forecasting is based on keeping the general tendency of the development of phenomena in time, therefore in practice the forecasting process is reduced to the choice based on the data of past periods of analytical dependencies of the investigated parameter on the factors influencing and extrapolation of these dependencies on the future. The forecast of the indicator is obtained by substituting the necessary value of the factor into the obtained regression equation. Thus, the predictive value is a point estimate of the average value of the indicator for these levels of factors [7].

By means of mathematical statistics, the following results were established. Among the 750 pcs. sold for 1 month of batteries with the corresponding content of nickel in the groups of the following quantities of ni were sold during the month (Table 1).

Table 1
Number of batteries with appropriate nickel content in groups

x_i	0	1	2	3	4	5
n_i	424	233	68	20	1	1

To test, we push out and check the hypothesis about the law of distribution of the number of sold batteries with nickel content for a month if the significance level is $\alpha = 0.01$. Let the random variable *X* be the number of batteries sold with the corresponding nickel content. We construct a frequency range (Fig. 1). From the form of the frequency range and the contents of the random variable *X*, we assume that *X* is distributed according to the Poisson law.

Consequently, we propose a null hypothesis H_0: (1):

$$P\,(X = i) = \frac{\lambda^i}{i!} e^{-\lambda}, i \;=\; 0, 1, 2, \ldots, \tag{1}$$

where $\lambda = M\,(X)$ is an unknown parameter.

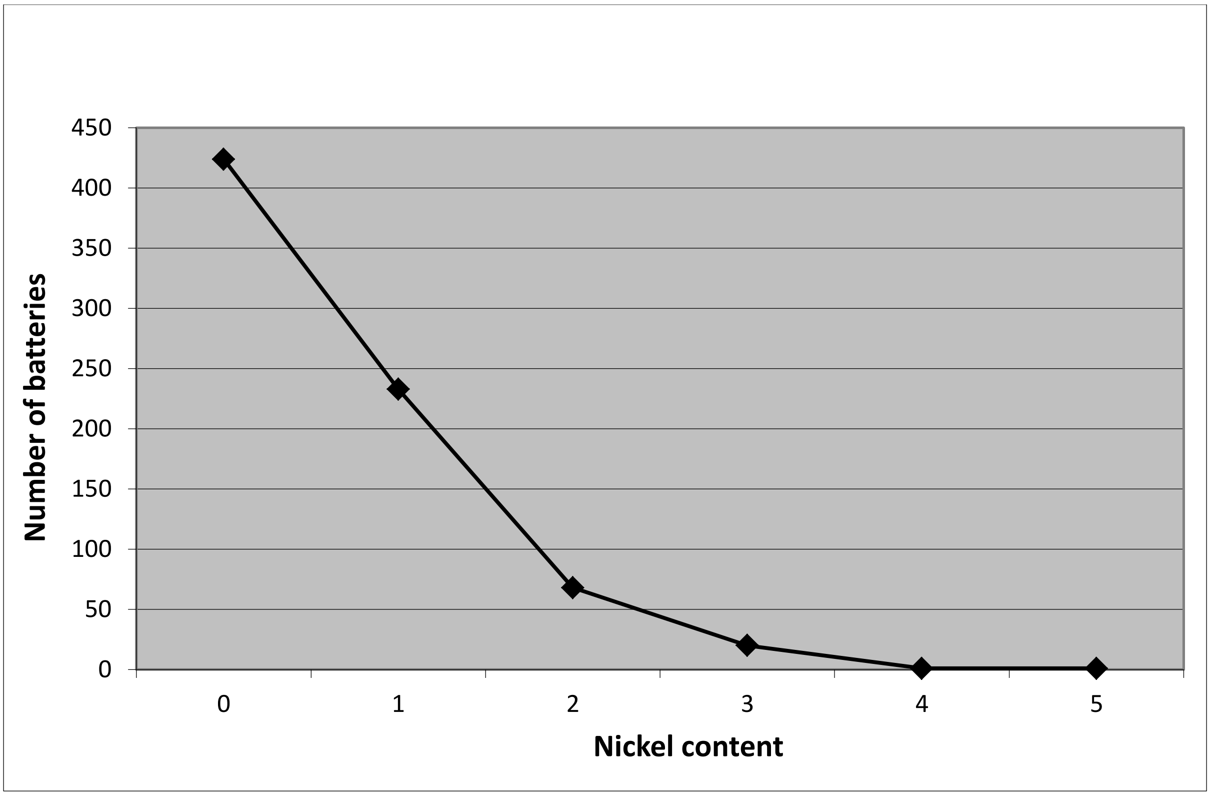

Figure 1: The number of batteries sold with the corresponding nickel content in the specified groups

The point estimate for the Poisson distribution parameter λ is a selective mean $\overline{x}_B$. In this case:

$\lambda^* = \overline{x}_B = (424 \bullet 0 + 233 \bullet 1 + 68 \bullet 2 + 20 \bullet 3 + 1 \bullet 4 + 1 \bullet 5) / 750 = 438 / 750 = 0.584 = 0.6.$

To calculate the theoretical probability p_i by Poisson's formula (2), take into account that $\lambda = 0.6$:

$$. \ p_i = \frac{0.6^i}{i!} e^{-0.6}, \mathrm{i} = 0, 1, 2, 3. \qquad (2)$$

Since the last two variants of the variable X in the statistical distribution of the sample have frequencies less than 5, and the sum of these frequencies is also less than 5, they are combined with the variant $X = 3$. We obtain the value p_0 - p_2 by the formulas (3) - (5):

$$p_0 = P(X = 0) = \frac{0.6^0}{0!} e^{-0.6} = \frac{1}{e^{0.6}} \approx 0{,}549 \qquad (3)$$

$$p_1 = P(X = 1) = \frac{0.6^1}{1!} e^{-0.6} = \frac{0.6}{e^{0.6}} \approx 0{,}329 \qquad (4)$$

$$p_2 = P(X = 2) = \frac{0.6^2}{2!} e^{-0.6} = \frac{0.36}{2e^{0.6}} \approx 0{,}099 \qquad (5)$$

Note also that the last probability p_3 will be determined as an addition to one: $P_3 = P(X > 3) = 1 - 0.549 - 0.329 - 0.099 \approx 0.023.$

To calculate $K_{emp} = \chi^2_{emp}$ we use the formula (6):

$$\chi_{emp}{}^2 = \sum_{i=0}^{3} \frac{(n_i - n_i')^2}{n_i'}, \qquad (6)$$

where $n_0 = 424, n_1 = 233, n_2 = 68, n_3 = 22,$ and the theoretical frequencies n'_i are determined from the equality $n'_i = np_i$. The calculated calculations allowed to determine that $\chi^2_{емп} = 2{,}97$.

Based on the sample data, we estimated the parameter λ *and* $S = 1$, and m = 4 (after combining the last three variants of the sign). Therefore, the number of degrees of freedom $k = 4 - 1 - 1 = 2$. From the table of critical points of distribution χ^2 for $a = 0.01$ *i* $k = 2$ we find the critical value of the criterion $\chi^2_{kp} = 9.2$.

Since $\chi^2_{емп} = 2{,}97 < \chi^2_{kp} = 9.2$, then the hypothesis H_0 is formulated that the number of sold batteries with nickel content within a month has a Poisson distribution at the significance level of $\alpha = 0.01$, is accepted because it does not contradict the statistical data.

4. Results/Discussions

Let's consider the problem of the formation of SEPSs used in Ukraine. Batteries in Ukraine are not manufactured, therefore, they are exported from abroad. To do this, the collection of data on the import of small chemical sources of electricity across the border of Ukraine was carried out. According to the Customs Service of Ukraine in the last years (2008-2020), 304,94 million units were imported into Ukraine in 2020 (Table 2). Since there are no statistical observations in Ukraine regarding the volumes of battery sales, we will assume that all the quantities of imported batteries have been sold and therefore used.

Table 2
Sales of batteries

Years	Explored countries of the world, million pcs.				
	USA	Ukraine	Poland	Other	Worldwide
2008	2761,90	274,12	237,86	22868,81	26142,70
2009	2971,55	161,18	233,88	25409,79	28776,41
2010	2784,21	245,00	288,83	23050,77	26368,82
2011	2925,44	258,16	291,16	24202,42	27677,19
2012	3000,00	277,00	290,00	26433,00	30000,00
2013	3011,21	281,86	293,54	27201,75	32415,51
2014	3023,49	284,42	296,13	28652,81	33678,39
2015	3029,51	285,73	298,53	29774,64	35564,73
2016	3033,69	288,81	299,81	31051,45	37459.83
2017	3035,76	291,94	301,72	32756,94	38581,62
2018	3039,67	295,04	306,12	38409,45	42050,28
2019	3045,46	299,99	311,77	40931,89	44589,11
2020	3051,25	304,94	317,42	43854,33	47527,94

Fig. 1 shows the distribution of volumes of sold batteries in Ukraine for 2008-2020, from which it is evident that there is a tendency for growth. A similar tendency to increase are the volumes for all countries of the world (Fig. 2).

MS Excel has a fairly large range of capabilities for predicting events based on existing data. One of the easiest ways of this prediction is to build a trend line. The choice can be made among the following types of functions of available data: linear, logarithmic, exponential, power or polynomial. By comparing R^2 values for different lines, we can choose the type of graph that characterizes the data most accurately, that is, builds the most reliable forecast. Further, indicating the period for which the forecast is made, in our case it is 3 years, we received the results (Figures 4 - 5). We see that forecast values are for Ukraine (Fig. 4) 382 million pcs. and 487 million pcs. in 2019 and 2020, according to the polynomial trend, in which R^2 is closest to the unit ($R^2 = 0.4102$). This method of constructing a trend is rather approximate.

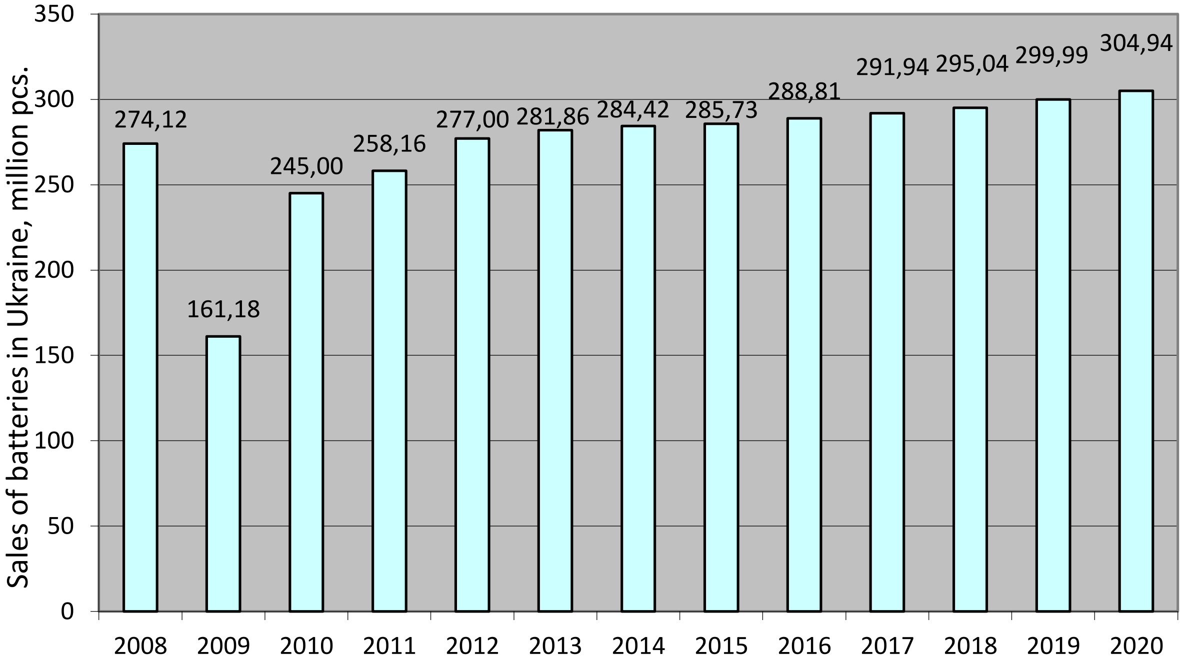

Figure 2: Batteries sales in Ukraine for the 2008-2020 periods

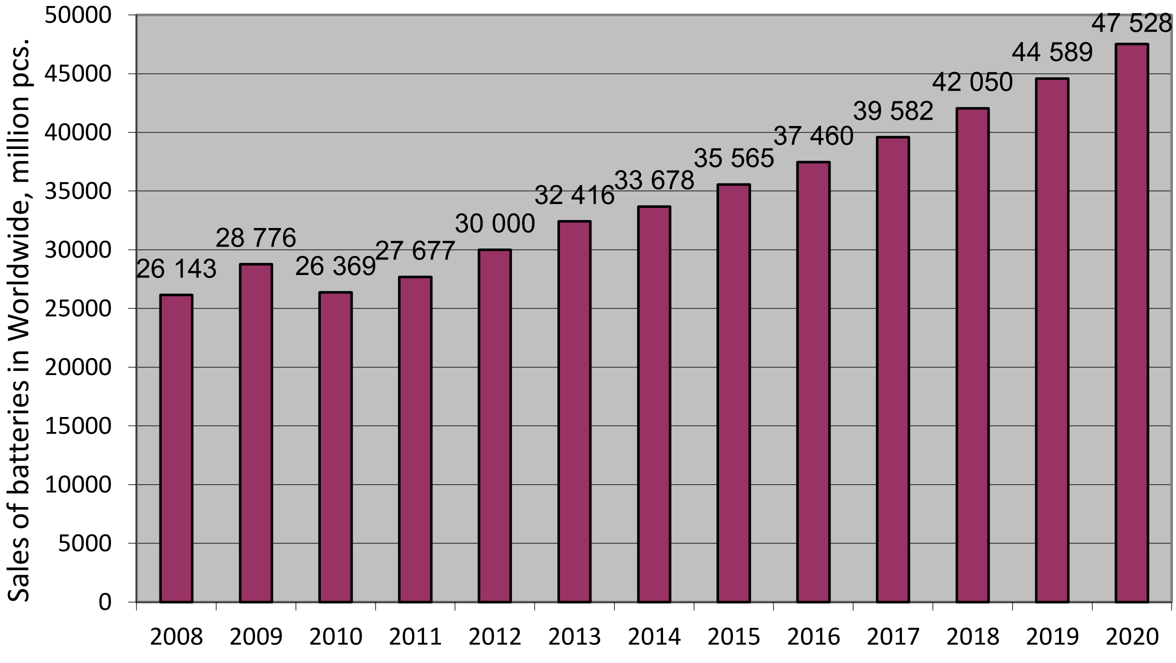

Figure 3: Batteries sales of around the world for the 2008-2020 period

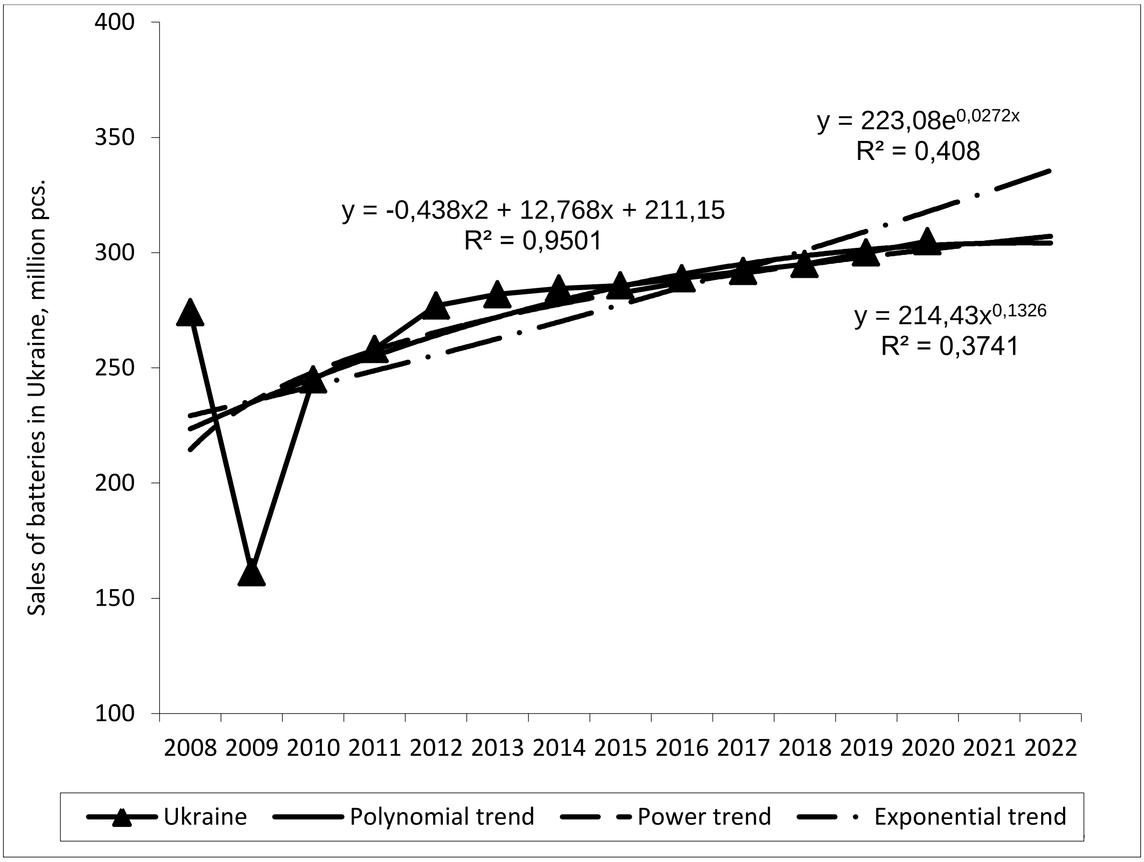

Figure 4: Batteries sales in Ukraine for the 2008-2020 periods, their trendline and forecast values for the next 2 years

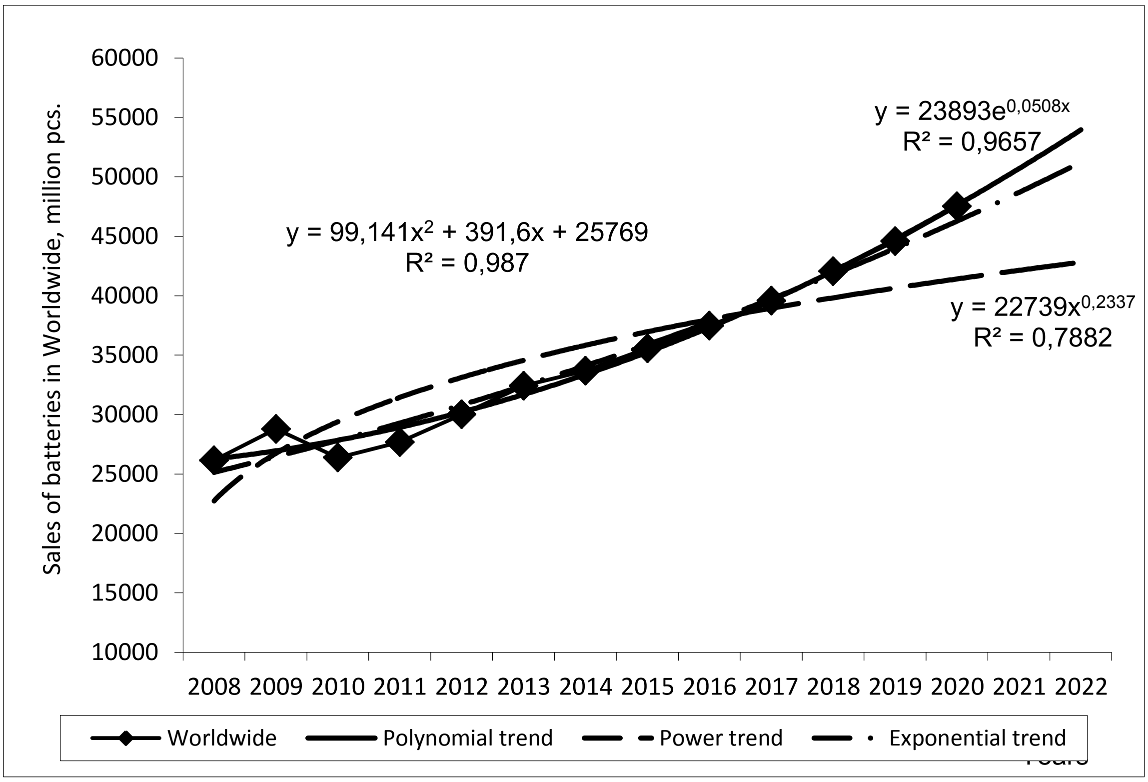

Figure 5: Batteries sales of around the world for the 2008-2020 period, their trend lines and forecast values for the next 2 years

Recycling of storage batteries and batteries is carried out in order to reduce the amount of toxic substances in solid household waste. Used batteries include mercury, cadmium, lead, tin, nickel, zinc, magnesium and other chemical elements and compounds. On landfills, under the influence of atmospheric factors, the batteries rapidly collapse, the substances that are in their composition are evaporated and washed away. Due to water, air and soil, toxic metals fall into living organisms that cause damage to living organisms, impair reproductive capacity and cause genetic changes and cancer.

The share of batteries in household rubbish is 0.05% of the total weight of rubbish. The share of toxic substances from batteries in the same household rubbish is already 50%. In a year is formed, as scientists have investigated in the work [1]: 40 kg mercury, 160 kg of cadmium, 260 t of manganese compounds, 250 t of sodium chloride. Toxic substances from the landfill penetrate the soil, into water, into the air, and heavy metals from biological organisms are practically not derived and settle in bones and tissues, which leads to poisoning of the organism and genetic changes.

In the scientific literature [3] it is estimated that one spent battery can pollute about 20 m^2 of land and 400 liters of surface water. The calculation of the total volume of possible pollution of the environment by the SEPS waste is given in Table 4.

Table 3

Total volume of environmental pollution of the SEPS in Ukraine for the period of 2013-2017

Contamination	Total amount of waste from batteries				
	2013	2014	2015	2016	2017
The area is polluted land, million km^2	5482,45	3223,68	4900,0	5163,28	5540,0
The volume is polluted water, million km^3	109649,12	64473,68	98000,0	116465,86	110800,0

Table 4

The weight of harmful substances contained in the spent SEPS for 2013-2020

Metal	Share of substance	Total amount of metals contained in spent SEPS, kg					
		2013	2014	2015	2016	2017	2020
Lithium	0,00025	1370,61	805,92	1225,00	1290,82	1385,00	1524,70
Mercury	0,001	5482,46	3223,68	4900,00	5163,28	5540,00	6098,80
Copper	0,16	877192,98	515789,47	784000,00	826124,80	886400,00	975808,00
Cobalt	0,03	164473,68	96710,53	147000,00	154898,40	166200,00	182964,00
Lead	0,02	109649,12	64473,68	98000,00	103265,60	110800,00	121976,00
Nickel	0,01	54824,56	32236,84	49000,00	51632,80	55400,00	60988,00
Cadmium	0,05	274122,81	161184,21	245000,00	258164,00	277000,00	304940,00
Iron	0,05	274122,81	161184,21	245000,00	258164,00	258164,00	304940,00
Zinc	0,01	54824,56	32236,84	49000,00	51632,80	55400,00	60988,00

On the other hand, for the industry, spent batteries are raw materials with a high concentration of valuable elements - non-ferrous metals and minerals. Therefore, it is more advisable to adjust the batteries for recycling than simply throwing them into common landfills. Ukraine has almost no reserves of non-ferrous metal ores, and those that open stocks of colored ores are low-concentrated and polymetallic. Since there are several other metals along with the base metal, such ores need to be enriched several times, and this affects the price of copper. SEPS contain dozens of times more non-ferrous metals. The most used round batteries, depending on their size, contain about 16-20% zinc, 8-13% iron, 17-29% manganese, 23% nickel. Calculate the share in 1 kg of spent batteries of their components and the total volume of toxic substances that can enter the environment through the spent SEPS (Table 4). Consequently, spent SEPS are highly concentrated raw materials for the production of non-ferrous metals. The economic evaluation of the value of valuable substances (metals) that can be obtained during the processing (recycling) of spent SEPS is given in Table 5.

Consequently, spent batteries are a very valuable raw material for the production of non-ferrous metals and minerals for industrial purposes. Only in 2017 the Ukrainian industry could receive from the recycled batteries lithium, whose deposits are not in Ukraine, in the amount of 9 million UAH.

Table 5
The Value of valuable substances contained in spent SEPS for 2013-2017

Metal	Price, UAH/ kg	Total cost of substances (metals) contained in spent SEPS, mln. UAH					
		2013	2014	2015	2016	2017	Total
Lithium	9420	11,356	7,238	8,425	9,536	10,369	46,924
Mercury	820	40,574	37,234	43,146	45,459	48,429	214, 842
Copper	12	7982,455	5749,5623	7659,9642	7798,816	7894,826	37085,625
Cobalt	35	1229,439	773,643	1143,500	1209,453	1304,400	5560,435
Lead	5	855,263	452,091	743,482	780,300	890,600	3721,736
Nickel	60	391,994	201,752	346,495	374,271	402,248	1717,76
Cadmium	9	1781,798	1047,697	1592,500	1678,066	1800,500	7900,561
Iron	1	1781,798	1047,697	1592,500	1678,066	1678,066	7778,127
Zinc	10	427,639	257,573	394,281	401,237	432,000	1912,73
Total		14502,31	13517,194	13524,230	13975,203	14461,438	65938,740

The obtained results indicate that it is expedient to adjust the SEPS processing, since besides non-ferrous metals, we will also receive an advantage in reducing the pollution of groundwater and the total areas of landfill. We recommend that the SEPS be processed in Ukraine at the State Enterprise "Argentum", which has appropriate equipment for this purpose.

5. Conclusion

The work described the composition of the SEPS, and the future prospects for solving this problem through the paths of alternative change. The results of solving the complex ecological and economic problem of utilization of small SEPS prove that it is expedient to adjust the processing of batteries, since in addition to non-ferrous metals; we also get an advantage in reducing the pollution of groundwater and the total areas of landfills. Also, by means of mathematical statistics, the statistical verification of the null hypothesis that the content of nickel in the batteries has a Poisson distribution is carried out. The results obtained confirm the correctness of the research.

The prospect of further development is the economic justification of the corresponding management decision and its adoption at the state level for the purpose of processing all the batteries in Ukraine at the State Enterprise "Argentum", which is located in the city of Lviv.

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