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Estimation of the Potential Recoverable Amount of Critical Metals from Waste Electric and Electronic Equipment in Lithuania

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The criticality of some materials, defined it the European Union Raw Materials Initiative is relevant for the industry of electrical and electronic equipment (EEE) from 2 perspectives: on the one hand the identified metals are necessary for the development of new technologies; on the onther hand – a potential risk exist to face the supply shortage of these materials, what could negatively impact EEE industry. The waste of EEE (WEEE) is one of the best sources for critical metals (CMs), as secondary raw materials, extraction. Therefore, this paper analyses the availability of CMs in the WEEE collected in Lithuania. The total amount of CMs contained in WEEE is estimated based on 2 methodologies and the amounts in 2020 are forecasted. It was evaluated how much CMs recovered from WEEE generated in Lithuania could cover the demand of European decarbonisation technologies in 2020. The estimated modest amounts of CMs, which is determined by a relatively small country in which WEEE management sytem is still in the development phase, shows the need for future research in order to analyse the best availabale technologies or other waste management alternatives in order to retrieve CMs.

Keywords: *critical metals, WEEE, recovery.*

Introduction

In order to tackle climate change, increase energy supply security and foster sustainability and competitiveness of the European economy, the European Union (EU) has made the transition to a low-carbon economy a central policy priority. The EU has created the Strategic Energy Technology Plan (SET Plan) to help Europe meet its ambitious 2020 targets for reducing greenhouse gas emissions and increasing the European energy supply from renewable resources (IET, 2011). Moreover, the EU is committed to reducing greenhouse gas emissions to 80-95% below 1990 levels by 2050 (IET, 2013).

The development and manufacturing of most environmental (green) technologies and applications needed for this transition (e.g. wind turbines, photovoltaic cells, electric and hybrid vehicles) is underpinned by the usage of advanced (high-tech) materials, such as rare earth elements (REE), platinium group metals (PGM), niobium, lithium, cobalt, indium, etc. In fact, the impact of advanced materials on the energy sector has been steadily growing from 10% in 1970 to an expected 70% in 2030. (EC, 2015). Population growth and economic development will continue to drive mineral resource use on an upward trajectory.

As the first step towards helping the EU form a common approach in the international discussion on raw materials, the European Commission (EC) published the Raw Materials Initiative (RMI) [COM(2008) 699 final]. In 2011, a list of 14 materials crucial to the EU's economy (critical raw materials – CRMs) was published. In 2014, the EC revised the list and expanded it up to 20 CRMs, namely: antimony, beryllium, cobalt, fluorspar, gallium, germanium, indium, magnesium, natural graphite, niobium, platinum group metals, heavy rare earths, light rare earths, tungsten, borates, chromium, coking coal, magnesite, phosphate rock, and silicon metal (COM, 2014). The supply of CRMs is limited since less than 3% of CRMs supply arising from within the EU. Moreover, the concentrated supply of CRMs in only few countries also causes concern: Brasil (niobium), USA (beryllium), South Africa (platinum) and China (REE, antimony, magnesium, and tungsten) (EC, 2015).

The EC has identified the following strategies to address bottlenecks in the supply of CRMs: (i) higher material efficiency; (ii) increasing primary supply (within the EU); (iii) material substitution; and (iv) reuse, recycling, and waste reduction. According to UNEP (2013), one of the most promising sources of critical metals (CMs), i.e. metals of CRMs, is recycling of waste electronic and electrical equipment (WEEE). WEEE is also one of the fastest-growing pollution problems worldwide given the presence of a variety of toxic substances that can contaminate the environment and threaten human health, if disposal protocols are not meticulously managed (Kiddeea, Naidua, & Wongc, 2013). The recovery of CMs from WEEE through 'urban mining' could reduce Europe's exposure to potential supply bottlenecks for these CMs. Moreover, recycling of metals usually has much lower environmental impacts (lower energy demand, greenhouse gas emissions etc.) than the production of primary metals from natural ores (UNEP, 2009).

About 3.1 million tonnes of WEEE were reportedly collected in the EU in 2008, but it is estimated that around 7 to 8 million tonnes of WEEE were generated, which implies a collection rate about 40% (CRI, 2014). The UNEP (2009) report estimates that the current post-consumer recycling rates for REE, gallium and tellurium globally are at less than 1%, compared with over 50% for many base and precious metals.

According to the Lithuanian Register of waste treatment enterprises, there were 8 WEEE treatment companies in 2014 (with treatment capacity up to 45 thousand tonnes annually). From the recent interview with the largest WEEE treatment enterprise in Lithuania, it can be concluded that enterprises barely know about CMs and focus mostly on the extraction of base and some precious metals. Therefore, it is necessary to provide the information to WEEE treatment companies and consumers of electronic and electrical equipment (EEE) about the possibilities to contribute to securing the supply of CMs. The aim of the study was to estimate the amounts of CMs that could be recovered from WEEE in Lithuania in 2020.

Materials and methods

Scope definition

The generated WEEE in Lithuanian was selected as a research object since it is a potential source for CMs' recovery. The work methodology was built on the basis of the Copenhagen Resources Institute (CRI) report "Present and Potential Future Recycling of Critical Metals in WEEE" (CRI, 2014).

The research design consisted of the following phases: (i) literature analysis to determine the amounts of CMs contained in EEE, and the existing technologies for their recovery, resulting in initial screening of CMs for further investigation; (ii) selection of EEE product groups, containing the biggest amount of the CMs identified in previous phase; (iii) estimation of WEEE amounts of the selected EEE groups; (iv) estimation of total available and real recoverable amounts of CMs from WEEE of the selected EEE groups; (v) estimation of the EU's demand for CMs and its coverage with CMs recovered from WEEE in Lithuania; and (vi) calculation of the economic value of not yet recovered CMs.

Data collection

The amount of EEE put on the market (POM) in Lithuania (according to EEE categories) and the amount of the collected WEEE were taken from the website of the Lithuanian Environmental Protection Agency (EPA) (2015). The amounts of CMs in EEE as well as the efficiency of WEEE recycling technologies were taken from the CRI report (2014).

Selection of CMs for further analysis

The amounts of CMs used in EEE were defined in the CRI (2014) report, which was based on the other researchers' previous works: Chancerel (2010), Oguchi et al. (2011, 2012). In the report, 13 of 60 metals were identified as critical, based on the criteria for supply risk (reserve-to-production ratio, regional concentration of reserves, and lack of suitable recycling technologies) and for demand/economics (rapid growth in demand, price development, and relevance of EEE in metal consumption) (see Table 1). It is worth mentioning that the research was carried out before the EC's list of CRMs (2011) was published.

Table 1

Selection criteria applied for the selection of metals for further investigation (adapted from CRI, 2014)

Critical metals	Supply risks			Economic relevance			Is in the list of CRMs 2014
	Reserve-to-production ratio	Regional concentration of reserves	Availability of suitable recycling technologies	Rapid growth in demand	Price development	Relevance of EEE in metal consumption	
1	2	3	4	5	6	7	8
Silver (Ag)	X	O	X	X	X	X	O
Cobalt (Co)	O	X	X	X	X	X	X
Indium (In)	X	X	O	X	X	X	X
Lithium (Li)	O	X	X	X	X	X	O
Tantalum (Ta)	X	X	O	X	O	X	O
Tellurium (Te)	O	X	O	X	X	X	O
Tungsten (W)	X	X	X	X	X	X	X
Gold (Au)	X	O	X	O	X	X	O
Beryllium (Be)	O	X	O	X	X	X	X
Gallium (Ga)	O	n.d.	O	X	O	X	X
Germanium (Ge)	O	n.d.	O	X	O	X	X
Palladium (Pd)	O	X	X	X	O	X	X
Ruthenium (Ru)	O	n.d.	X	O	X	X	X

X – criterion fulfilled; O – criterion not fulfilled; n.d. – no data available.

Table 2

Use of the selected CMs in preselected EEE product groups (CRI, 2014)

CMs	Mobile phones	Desktop computer	Flat screen TVs and monitors	Solar power converters	Rechargeable batteries	Notebooks/ Laptops
1	2	3	4	5	6	7
Silver (Ag)	+	+	+	+	+	+
Cobalt (Co)	+(a)		+		+	+(a)
Lithium (Li)	+(a)		+		+	+(a)
Tungsten (W)	+	(+)	+			
Gold (Au)	+	+	+			+
Palladium (Pd)	+	+	+			+
Ruthenium (Ru)		+	+			+

(a) = without batteries

Based on the availability of technologies for CMs' recovery (column 4), 7 metals were selected for further analysis, specifically: silver (Ag), cobalt (Co), lithium (Li), tungsten (W), gold (Au), palldarium (Pd), and ruthenium (Ru). Co, W, Pd, and Ru are also considered as critical by the EC.

The selction of EEE product groups

The WEEE Directive of the EC (Directive 2012/19/EU, 2012) lists 10 categories of EEE, which are divided into corresponding product groups. Different product groups were evaluated in the CRI (2014) report with regard to CMs' material significance (share of physical volumes), economic significance (monetary turnover of product groups), and expected data availability. Table 2 presents the EEE product groups containing CMs identified in the previous section.

Based on the EEE composition, those EEE product groups were selected for further analysis which contained more CMs compared with the others (not considering quantity), specifically: mobile phones, laptops/notebooks, and flat screen TVs and monitors.

According to the WEEE Directive, the former 2 fall into the category of IT and telecommunications equipment (III), while the latter into the Consumer equipment (IV) category.

The current and potential future WEEE amounts

To estimate the current and future generation of WEEE of the selected product groups, POM data of the selected products (EEE product groups), their gradual lifetime distribution (Method A), and their anticipated average lifespan (Method B) were used.

Estimation of EEE product group amount

The data obtained from the EPA (2015) contained information only about the EEE categories (without division of EEE into product groups). The amounts of the POM EEE product groups identified in the previous section were evaluated based on the assumption used in the CRI (2014) report that the collected amount of EEE product group divided by the collected amount of a corresponding WEEE category (ratio *k*) in Germany is equal across the EU (as well as in Lithuania). The data for Germany was obtained from Chancerel's research (2010) (see Table 3). The same ratio was used in this research; however, it was assumed that ratio *k* was also valid for the determination of the product groups of POM EEE (in contrast to collected).

The ratio *k* is calculated using the following equation:

$$k = \frac{m_{prod}}{m_{cat}} \times 100\% \quad (1)$$

Here

m_{prod} is the collected amount of a WEEE product group, t;

m_{cat} refers to he collected amount of WEEE category (see Table 3).

It was assumed that EEE included in the 'Flat screen TVs and monitors' product group in CRI report (2014)

Table 3

Collected waste amounts of the selected product groups and categories in Germany in 2007 (Chancerel, 2010)

EEE product group	EEE category	Collected amount of product group m_{prod} in tonnes, 2007	Collected amount of WEEE category m_{cat} in tonnes, 2007	Collected product group/ Collected WEEE category k in %, 2007
1	2	3	4	5
Mobile phones	3	240.0	117,749.0	**0.20 %**
Laptops/ notebooks/ notepads	3	2,026.0	117,749.0	**1.72 %**
LCD TVs + LCD monitors	4	5,111.0	130,620.0	**3.91%**

are of the same type as in the 'LCD TVs + LCD Monitors' product group in Chacerel's research (2010) and will be labelled as 'TVs' onward in this paper. The product group 'Notebooks/Laptops' will be labelled as 'Laptops' onward in this paper.

Method A. Gradual lifetime distribution

This method implies that WEEE of a particular product group accumulates gradually over products' lifetime, i.e. each year some percent of the total POM EEE becomes waste (WEEE) until no products are left in use. All the products purchased in a particular year will neither all become waste at the same time nor at the end of their expiry date; instead, some of these products will become waste in one year, some others in the following year, some others in the year after and so on. The calculated lifetime distributions for the selected products are presented in Table 4. The percentage figures refer to the portion of the products purchased in 'Year 0' that become waste in the same or the following years.

More than 90% of the particular EEE products once POM will become waste in the following years:

- mobile phones in 5 years;
- laptops in 7 years; and
- flat screen TVs in 10 years.

To evaluate the amounts of generated WEEE of the specific product groups for 2020, the year 2004 was selected as a starting date for further calculations, since it is sufficient for the evaluation of the full lifetime of the product (i.e. in 2014, all POM TVs in 2004 will become WEEE). Based on the amount of POM EEE, and the EEE lifetime distribution, the amounts of generated WEEE were calculated (see section *The current and potential future WEEE amounts*).

Method B. An average lifespan

The generation of current and future annual WEEE amounts in Method B is based on the average lifespan of EEE products. The entire particular amount of POM EEE becomes WEEE after its end of lifetime (differently from Method A where EEE becomes WEEE gradually during the period of products' lifespan and varies from year to year). The average lifespans of EEE products

Table 4

Estimated lifetime distribution for the selected products in % of sold items in Year 0 (CRI, 2014)

Year	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	Total
Mobile phones, %	2.9	6.0	22.7	30.9	23.4	10.7	2.9	0.5	0	0	0	0	0	0	0	0	0	100
Laptops, %	0	2.9	10.6	17.4	20.4	18.8	14.1	8.7	4.5	1.9	0.7	0.2	0	0	0	0	0	100
TVs, %	1.0	1.4	5.1	9.1	12.3	14.0	14.1	12.8	10.4	7.8	5.3	3.3	1.8	1	0.4	0.2	0.1	100

obtained from the report of Statistics Lithuania *Energy usage in houshelds* are provided in Table 5.

Table 5

Average lifespans of EEE product groups (Statistics Lithuania, 2012)

EEE product group	Average lifespan, years
1	2
Mobile phones	2
Laptops	4
TVs	7

Extrapolation

Based on the data received from the EPA (2015), Table 6 presents the amounts of EEE categories POM and collected in Lithuania for the period of 2009-2014. In order to determine the amounts of EEE product groups POM before 2009 (until 2004) and the amounts for 2015-2020, 2 scenarios were considered.

Table 6

The amounts of POM and collected EEE categories (IT/telecommunication equipment and consumer equipment) in Lithuania in 2009-2014 (EPA, 2015)

Year	EEE category	Cat. No.	POM EEE, t	Collected WEEE, t
1	2	3	4	5
2009[m]	IT and tele-communication equipment	3	2483,43.0	686,86.0
2010			2865,20.0	1146,86.0
2011			3061,13.0	1537,32.0
2012			3505,76.0	1843,76.0
2013			3320,26.0	3490,80.0
2014[m]			3144,23.0	3884,55.0
2009[m]	Consumer equipment	4	2042,92.0	860,03.0
2010			1716,49.0	791,29.0
2011			2275,77.0	1200,88.0
2012			2535,22.0	1687,14.0
2013			1872,24.0	1461,37.0
2014[m]			2145,49.0	2175,46.0

[m] – marginal year.

Scenario A

The provided data imply about the gradual annual growth of the POM EEE (Figure 1). Therefore, by using simple linear regression, it was calculated that the annual supply of IT and telecommunication equipment category increased on average by 5.2%, while Consumer equipment by 3.3% during the period 2009-2014. These values were used to forecast the amounts prior 2009 (decreasing trend) and the amounts after 2014 (increasing trend).

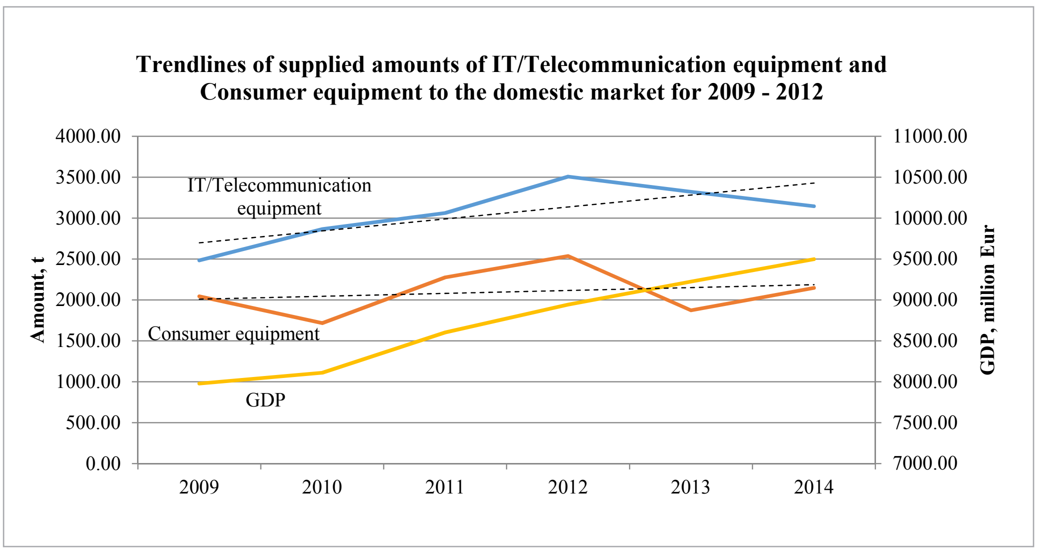

Fig. 1

The actual amounts and trend lines (dotted) for POM IT/telecommunication equipment, consumer equipment, and GDP for 2009-2014 (Statistics Lithuania; EPA, 2015)

Scenario B

Although Figure 1 implies about the growth trend of EEE usage which correlates with the growth of GDP, several significant risks among others exist for making such forecast: (i) a 6 year trend is rather too short for predicting prior/further 4/6 years; (ii) the number of citizens in Lithuania is gradually decreasing (less purchasing power). Consequently, for this scenario it was decided for the periods before 2009 and after 2014 to keep the amounts of POM EEE stable and equal to the marginal year of the existing data (see Table 6).

Potential and recovered amounts of CMs from WEEE

In this section the efficiency of specific WEEE recycling was determined by other authors' works. In this research, the efficiency of the WEEE collection system was not considered. The CMs recovery norm evaluated only technological possibilities, i.e. pre-processing and end-processing. Knowing the amounts of CMs contained in EEE products, and the recovery efficiencies, the amounts of CMs in particular product groups were calculated.

Mobile phones

The amounts of CMs contained in mobile phones were taken from the CRI (2014) report which presented the data of the research carried out by Japanese Ministry of the Environment and Ministry of Economy. In this research the compositions of 15 different types of mobile phones were analysed and the recovery of CMs through different waste management stages was estimated (see Table 7).

Laptops

The material compositions (including CMs) of laptops were disclosed in the research carried out by Central Council on the Environment of Japan (CRI, 2014) (see Table 8).

Flat screen TVs

The research carried out by the Central Council on the Environment of Japan also disclosed the material compositions (including CMs) of desktop monitors. In the CRI (2014) report, an assumption was made that a large proportion of flat screen TVs matched the technology used for flat screen computer monitors. The calculated values are presented in Table 9.

Table 7

The material composition of mobile phones and the estimated efficiency of their recycling chain in 2008, presented in % (CRI, 2014)

CMs	g of CMs / kg of product	Efficiency of recycling chain, %		
		Pre-processing	End-processing	Total
1	2	3	4	5
Ag	0.998	61.0	95.0	58.0
Co	0.177	100.0	90.0	90.0
Li	0.005	100.0	0.0	100.0
W	1.469	49.0	0.0	49.0
Au	0.389	61.0	95.0	58.0
Pd	0.06	61.0	95.0	58.0
Ru	-	49.0	0.0	49.0

Table 8

The material composition of laptops and the estimated efficiency of their recycling chain in 2008, presented in % (CRI, 2014)

CMs	g of CMs / kg of product	Efficiency of recycling chain, %		
		Pre-processing	End-processing	Total
1	2	3	4	5
Ag	0.399	61.0	95.0	58.0
Co	0.019	100.0	90.0	90.0
Li	0.005	100.0	0.0	100.0
W	0.019	49.0	0.0	49.0
Au	0.143	61.0	95.0	58.0
Pd	0.057	61.0	95.0	58.0
Ru	0.003	49.0	0.0	49.0

Table 9

The material composition of flat screen TVs and the estimated efficiency of their recycling chain in 2008, presented in %

CMs	g of CMs / kg of product	Efficiency of recycling chain, %		
		Pre-processing	End-processing	Total
1	2	3	4	5
Ag	0.033	61.0	95.0	58.0
Co	0.001	100.0	90.0	90.0
Li	0.001	100.0	0.0	100.0
W	0.005	49.0	0.0	49.0
Au	0.006	61.0	95.0	58.0
Pd	0.001	61.0	95.0	58.0
Ru	-	49.0	0.0	49.0

The demand for CMs and possibilities to cover this demand from WEEE generated in Lithuania

In this section, the aim was to assess how much of the CMs demand for the decarbonisation of the EU energy sector could be covered through the proper recycling of WEEE in Lithuania. The amount of CMs demand was derived from the report *Critical Metals in the Path towards the Decarbonisation of the EU Energy Sector. Assessing Rare Metals as Supply-Chain Bottlenecks in Low-Carbon Energy Technologies*, developed by the Institute for Energy and Transport (IET, 2013).

The report presents the study that models the implications for materials' demand as a result of the implementation of the scenarios described in the EU Energy Roadmap 2050. The study considers 6 technologies prioritised in the SET-Plan, which aims to accelerate the development of low-carbon energy technologies throughout the EU in support of their subsequent large-scale deployment by 2020, namely: nuclear fission, solar photovoltaics (PV) and concentrated solar power (CSP), wind, bioenergy, carbon capture and storage (CCS), and the electricity grids. The study considers additional 11 technologies, including fuel cells, electricity storage, electric vehicles, lighting, technologies that improve energy efficiency in industry and buildings, and other technologies that may be competing for the same resources. For each technology, the full list of metals and their amounts required in tonnes for the EU in 2020 and 2030 is provided. 60 metals were analysed in the study.

The economic value of not recovered CMs

The economic values of both total available and real recoverable CMs in WEEE were estimated. The metal prices were taken from MetalPrices.com[1]. The obtained numbers represent only the nominal metal price of the specific date, and do not consider the investement/operation costs of CMs recovery infrastructure. As regards the Li price, it was taken from *Shanghai Metals Market*[2] and is represented by lithium metal (≥99%, Industrial Grade, Battery Grade). The date of metal prices were determination was 2015/12.

Results and discussion

The current and potential future WEEE amounts

Scenario A

Based on the data provided in Table 6, the amounts of EEE POM before 2009 until 2004 and forward up to 2020 were predicted by using simple linear regression (Table 10). The amount of mobile phones, laptops, and TVs were determined by the proportion *k* described in the section 2.5 (0.2%, 1.72%, and 3.91%, respectively).

Method A

Based on the POM amounts of the selected EEE products (Table 10) and their lifetime distribution (Table 4), their waste generation 2004 onwards was estimated and is provided in Table 11.

Method B

Based on the POM amounts of the selected EEE products (Table 10) and their average lifespan (Table 5), the waste generation 2004 onwards was estimated and is provided in Table 12.

Scenario B

Table 13 provides the amounts of POM EEE which were determined using Scenario B (POM EEE amounts prior 2009 and after 2014 are equal to marginal years – 2009 and 2014).

Method A

Based on the POM amounts of selected EEE products (Table 13) and their average lifetime distribution (Table 4), their waste generation 2004 onwards was estimated and is provided in Table 14.

Method B

Based on the POM amounts of selected EEE products (Table 13) and their average lifespan (Table 5), their waste generation 2004 onwards was estimated and is provided in Table 15.

Selection of the best option

The results of all the applied options for the estimation

1 https://www.metalprices.com
2 http://www.metal.com

Table 10

The real and predicted amounts of POM EEE in 2004-2020

Year	IT and telecommunication, t			Consumer equipment, t	
	All product groups, t	Mobile phones, t (k = 0.2%)	Laptops, t (k = 1.72%)	All product groups, t	TVs, t (k = 3.91%)
1	2	3	4	5	6
2004*	1,898.61	3.80	32.66	1,728.28	67.58
2005*	2,003.36	4.01	34.46	1,787.07	69.87
2006*	2,113.89	4.23	36.36	1,847.86	72.25
2007*	2,230.51	4.46	38.36	1,910.72	74.71
2008*	2,353.57	4.71	40.48	1,975.71	77.25
2009	2,483.43	4.97	42.71	2,042.92	79.88
2010	2,865.20	5.73	49.28	1,716.49	67.11
2011	3,061.13	6.12	52.65	2,275.77	88.98
2012	3,505.76	7.01	60.30	2,535.22	99.13
2013	3,320.26	6.64	57.11	1,872.24	73.20
2014	3,144.23	6.29	54.08	2,145.49	83.89
2015*	3,308.63	6.62	56.91	2,216.07	86.65
2016*	3,481.63	6.96	59.88	2,288.97	89.50
2017*	3,663.68	7.33	63.02	2,364.27	92.44
2018*	3,855.24	7.71	66.31	2,442.04	95.48
2019*	4,056.81	8.11	69.78	2,522.38	98.63
2020*	4,268.93	8.54	73.43	2,605.36	101.87

*Predicted values

Table 11

Annual generation of WEEE of mobile phones, laptops, and TVs 2004-2020

WEEE, t	‘04	‘05	‘06	‘07	‘08	‘09	’10	‘11	‘12	‘13	‘14	’15	‘16	‘17	‘18	‘19	‘20
Mobile phones	0.11	0.34	1.22	2.47	3.49	4.09	4.44	4.73	5.13	5.59	6.10	6.46	6.57	6.59	6.70	6.96	7.30
Laptops	0.0	0.95	4.46	10.39	17.62	24.74	30.71	35.36	39.25	42.97	46.86	50.39	53.06	56.74	60.19	69.49	80.49
TVs	0.68	1.64	5.15	11.47	20.17	30.32	40.73	50.74	59.05	65.73	71.46	75.63	78.60	82.62	88.74	106.88	129.53

Table 12

Annual generation of WEEE of mobile phones, laptops, and TVs 2004-2020

WEEE, t	‘04	‘05	‘06	‘07	‘08	‘09	’10	‘11	‘12	‘13	‘14	’15	‘16	‘17	‘18	‘19	‘20
Mobile phones	0.0	0.0	3.80	4.01	4.23	4.46	4.71	4.97	5.73	6.12	7.01	6.64	6.29	6.62	6.96	7.33	7.71
Laptops	0.0	0.0	0.0	0.0	32.66	34.46	36.36	38.36	40.48	42.71	49.28	52.65	60.30	57.11	54.08	56.91	59.88
TVs	0.0	0.0	0.0	0.0	0.0	0.0	0.0	67.58	69.87	72.25	74.71	77.25	79.88	67.11	88.98	99.13	73.20

Table 13

The real and predicted amounts of POM EEE in 2004-2016

Year	IT and telecommunication, t			Consumer equipment, t	
	All product groups, t	Mobile phones, t (k = 0.2%)	Laptops, t (k = 1.72%)	All product groups, t	TVs, t
1	2	3	4	5	6
2004*	2,483.43	4.97	42.71	2,042.92	79.88
2005*	2,483.43	4.97	42.71	2,042.92	79.88
2006*	2,483.43	4.97	42.71	2,042.92	79.88
2007*	2,483.43	4.97	42.71	2,042.92	79.88
2008*	2,483.43	4.97	42.71	2,042.92	79.88
2009	2,483.43	4.97	42.71	2,042.92	79.88
2010	2,865.20	5.73	49.28	1,716.49	67.11
2011	3,061.13	6.12	52.65	2,275.77	88.98
2012	3,505.76	7.01	60.30	2,535.22	99.13
2013	3,320.26	6.64	57.11	1,872.24	73.20
2014	3,144.23	6.29	54.08	2,145.49	83.89
2015*	3,144.23	6.29	54.08	2,145.49	83.89
2016*	3,144.23	6.29	54.08	2,145.49	83.89
2017*	3,144.23	6.29	54.08	2,145.49	83.89
2018*	3,144.23	6.29	54.08	2,145.49	83.89
2019*	3,144.23	6.29	54.08	2,145.49	83.89
2020*	3,144.23	6.29	54.08	2,145.49	83.89

*Predicted values

Table 14

Annual generation of WEEE of mobile phones, laptops, and TVs 2004-2020

WEEE, t	'04	'05	'06	'07	'08	'09	'10	'11	'12	'13	'14	'15	'16	'17	'18	'19	'20
Mobile phones	0.14	0.44	1.57	3.10	4.27	4.80	4.96	5.05	5.27	5.64	6.11	6.45	6.53	6.44	6.35	6.30	6.29
Laptops	0.0	1.24	5.77	13.20	21.91	29.94	35.97	39.87	42.59	45.12	48.06	50.98	53.22	54.53	54.98	54.90	54.65
TVs	0.80	1.92	5.99	13.26	23.08	34.27	45.40	55.67	63.73	69.80	74.71	78.00	80.14	81.59	82.50	83.07	83.43

Table 15

Annual generation of WEEE of mobile phones, laptops, and TVs 2004-2020

WEEE, t	'04	'05	'06	'07	'08	'09	'10	'11	'12	'13	'14	'15	'16	'17	'18	'19	'20
Mobile phones	0.0	0.0	4.97	4.97	4.97	4.97	4.97	4.97	5.73	6.12	7.01	6.64	6.29	6.29	6.29	6.29	6.29
Laptops	0.0	0.0	0.0	0.0	42.71	42.71	42.71	42.71	42.71	42.71	49.28	52.65	60.30	57.11	54.08	54.08	54.08
TVs	0.0	0.0	0.0	0.0	0.0	0.0	0.0	79.88	79.88	79.88	79.88	79.88	79.88	67.11	88.98	99.13	73.20

Table 16
Comparison of the results obtained by applying different methods

Method	2020				Average	Δ			
	Scenario A		Scenario B			Scenario A		Scenario B	
	A	B	A	B		A	B	A	B
1	2	3	4	5	6	7	8	9	10
Mobile phones, t	7.30	7.71	6.29	6.29	6.90	0.40	0.81	-0.61	-0.61
Laptops/ Notebooks, t	80.49	59.88	54.65	54.08	62.28	18.22	-2.39	-7.63	-8.20
TVs and monitors, t	129.53	73.20	83.43	73.20	89.84	39.69	-16.64	-6.41	-16.64

Δ = 2020 value – Average value; [dark grey] – max Δ value, [light grey] – min Δ value.

of the unkown data are provided in Table 16. It presents the predicted amounts of generated WEEE in 2020. In addition to both scenarios and methods, an average amount of generated WEEE is provided, as well as delta (Δ) values representing the difference between each value and the average.

For further calculations, 2 scenarios from Table 16 were distinguished: 1) 'optimistic' (scenario A, method A) which represents higher obtained values compared with the others; and 2) 'pessimistic' which represents lower values compared with others (scenario B, method B).

Predicted available and recoverable CMs in WEEE

Given that the generated WEEE amounts of the specific product groups are known (Table 11-12), it is possible to calculate the amount of CMs in them. Table 17 presents the total available and real recoverable amounts of CMs in the selected WEEE categories in 2020 (pessimistic and optimistic scenarios).

Possibilities to cover the EU demand for CMs from WEEE in Lithuania

Table 18 presents the predicted demand for CMs required by decarbonisation and SET-Plan technologies in 2020 (IET, 2013). Among all the materials considered in the IET report, this research involved only Ag, Co, Li, W, Au, Pd, and Ru, as they were identified as critical in the previous section. The table also presents the possibilities to cover this demand with the amount of CMs recovered from WEEE in Lithuania in 2020 (pessimistic and optimistic scenarios).

From Table 18 it can be seen that only the supply of Au, Pd and Ru has some significance for the satisfaction of the EU's demand for CMs while the recovered amounts of other CMs (Ag, Co, Li, and W) from WEEE are negligible compared with the EU demand (demand coverages are less than 0.01%).

Estimation of CMs' economic value in WEEE

The economic values of CMs contained in WEEE for the year 2020 (pessimistic and optimistic scenarios) are provided in Table 19. 'Total' available value refers to the value of the total amount of CMs in WEEE, while 'Real' recoverable represents the economic value, which can be recovered from WEEE using existing technologies on the market.

The research implies that based on the prices of 2015, in 2020, WEEE might contain CMs of the total value equal to 590.3 thousand EUR (optimistic scenario) or 412.5 thousand EUR (pessimistic scenario). However, with the existing recycling technologies, it would be possible to recover CMs worth 342.1 thousand EUR (optimistic scenario) or 239 thousand EUR (pessimistic scenario).

Considering that WEEE treatment companies already recover Ag and Au in Lithuania, with the recovery of other CMs from WEEE it would be possible to gain additional 62.4 thousand EUR with the existing recycling technologies in the market (or 48.8 thousand EUR according to the pessimistic scenario).

Table 17

Predicted total available and real recoverable amounts of CMs in WEEE of mobile phones, laptops, and TVs generated in Lithuania in 2020

Product group	CMs	CMs in WEEE, g/kg*	CMs recovery norm, %*	CMs in WEEE, kg			
				Pessimistic		Optimistic	
				Total	Real	Total	Real
1	2	3	4	5	6	7	8
Mobile phones	Ag	0.998	58	6.28	3.64	7.29	4.22
	Co	0.177	90	1.11	1.00	1.29	1.16
	Li	0.005	100	0.03	0.03	0.04	0.04
	W	1.469	49	9.24	4.53	10.73	5.26
	Au	0.389	58	2.45	1.42	2.84	1.65
	Pd	0.06	58	0.38	0.22	0.44	0.25
	Ru	-	49	-	-	-	-
Laptops	Ag	0.399	58	21.58	12.50	32.12	18.61
	Co	0.019	90	1.03	0.92	1.53	1.38
	Li	0	100	0.27	0.27	0.40	0.40
	W	0.019	49	1.03	0.50	1.53	0.75
	Au	0.143	58	7.73	4.48	11.51	6.67
	Pd	0.057	58	3.08	1.79	4.59	2.66
	Ru	0.003	49	0.16	0.08	0.24	0.12
TVs	Ag	0.033	58	2.42	1.40	4.27	2.48
	Co	0.001	90	0.07	0.07	0.13	0.12
	Li	0.001	100	0.07	0.07	0.13	0.13
	W	0	49	0.37	0.18	0.65	0.32
	Au	0.006	58	0.44	0.25	0.78	0.45
	Pd	0.001	58	0.07	0.04	0.13	0.08
	Ru	0	49	-	-	-	-
Altogether	Ag	-	-	30.27	17.54	43.68	25.31
	Co	-	-	2.21	1.99	2.95	2.66
	Li	-	-	0.38	0.38	0.57	0.57
	W	-	-	10.63	5.21	12.90	6.32
	Au	-	-	10.62	6.15	15.13	8.77
	Pd	-	-	3.53	2.05	5.16	2.99
	Ru	-	-	0.16	0.08	0.24	0.12
Total		-	-	57.80	33.40	80.63	46.73

*CRI (2014). Losses due to inefficient WEEE collection were not considered.

Table 18

The demand for CMs required by decarbonisation technologies in the EU for 2020 and its satisfaction possibilities from WEEE in Lithuania in 2020 (IET, 2013)

Decarbonisation/ SET-Plan technologies	CMs, t						
	Ag	Co	Li	W	Au	Pd*	Ru
1	2	3	4	5	6	7	8
Advanced fossil fuel power generation	0	1.8	0	242.0	0	0	0
Nuclear energy (fission)	19.0	0	0	11	0	0	0
Solar energy (PV and CSP)	638.0	0	0	0	0	0	0
Bioenergy (including biofuels)	0	18.0	0	0.1	0	0	0.4
Carbon capture and storage (CCS)	0	6.0	0	0	0	0	0
Lighting	69.1	0	0	0.1	24.7	0	0
(H)EV batteries	0	4,412.0	2,214.0	0	0	0	0
Total	726.1	4,437.8	2,214.0	253.2	24.7	5.9*	0.4
Demand satisfaction (pessimistic)	0.002%	0.000%	0.000%	0.002%	**0.025%**	**0.035%**	**0.020%**
Demand satisfaction (optimistic)	0.003%	0.000%	0.000%	0.002%	**0.035%**	**0.051%**	**0.030%**

*The number taken the same as for Platinium because there was no data available for palladium.

Table 19

Economic values of CMs contained in WEEE, ×1,000 Eur

CMs	Price, Eur/g	Date of price	Value of CMs in WEEE in 2020, Eur			
			Pessimistic		Optimistic	
			Total	Real	Total	Real
1	2	3	4	5	6	7
Ag	0.412	2015/12	12,477.4	7,230.6	18,004.4	10,433.6
Co	0.022	2015/12	49.3	44.3	65.7	59.1
Li	0.058	2015/09	21.7	21.7	33.0	33.0
W	0.038	2015/12	401.5	196.7	487.3	238.8
Au	0.031×10^{-3}	2015/12	326,090.5	188,969.4	464,557.6	269,211.1
Pd	0.021×10^{-3}	2015/12	73,202.6	42,420.9	106,822.0	61,903.4
Ru	1.502	2015/12	243.7	119.4	362.7	177.7
Total	-	-	412,486.7	239,003.2	590,332.7	342,056.6

Conclusions

The following results were obtained in the research:

- The predicted amount of WEEE in Lithuania in 2020 was in the range of 73.2 t (pessimistic scenario) and 129.5 t (optimistic scenario).
- By 2020, the amount of Au, Pd and Ru contained in WEEE could satisfy 0.035%, 0.051%, and 0.030%, respectively, of the demand required by Decarbonisation/SET-Plan technologies in the EU; the recovered amounts of other CMs (Ag, Co, Li, and W) from WEEE is negligible compared with the EU demand (demand coverage rates are less than 0.01%).
- Based on the prices in 2015, the generated WEEE amounts in 2020 might contain CMs of the total value equal to 412.5-590.3 thousand EUR. However, with the

existing conventional recycling technologies, it would be possible to recover CMs of the value equal to 239.0-342.1 thousand EUR. Additional extraction of Co, Li, W, Pd, and Ru from WEEE could gain 62.4 thousand EUR.

This paper presents the first attempt to estimate the potential amount of CMs to be recovered from WEEE generated in Lithuania. Although the findings do not provide economic incentive to consider CMs extraction in WEEE treatment process, it must be highlighted that many assumptions and forecasts have been made in this study which may distort the results. Therefore, further research is needed on CMs recovery from WEEE in Lithuania.

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Iš elektros ir elektroninės įrangos atliekų atgautų kritinių metalų potencialaus kiekio įvertinimas Lietuvoje

Gauta: 2016 m. birželis

Priimta spaudai: 2016 m. rugsėjis

Inga Gurauskienė, Antanas Staškevičius, Karolina Ambrazaitienė

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Europos Sąjungos Žaliavų iniciatyvoje apibrėžtas tam tikrų medžiagų kritiškumas yra itin aktualus elektros ir elektroninės įrangos (EEĮ) pramonei dėl dviejų priežasčių: viena vertus išskirti metalai yra būtini naujausioms technologijoms ir jų paklausa nuolat auga, kita vertus – egzituoja pagrįsta rizika susidurti su šių metalų stygiumi, kas neigiamai paveiktų EEĮ pramonę. EEĮ atliekos (EEĮA) yra vienas geriausių kritinių metalų (KM), kaip antrinių žaliavų, šaltinių. Šiame straipsnyje tiriama galimybė išgauti KM iš Lietuvoje surinktų EEĮA. Remiantis dviem metodikomis buvo nustatyti KM kiekiai, kurie gali susidaryti EEĮA 2020 m. Buvo įvertinta, kokią dalį Europos išmetamo anglies dioksido kiekio mažinimo technologijoms 2020 m. reikalingų KM, galėtų patenkinti iš Lietuvos EEĮA atgauti KM. Nustatyti nedideli KM kiekiai, gauti iš sąlyginiai nedidelės valstybės, kurioje dar tik vystoma EEĮA surinkimo sistema, rodo būtinybę tęsti tyrimus, siekiant nustatyti geriausias prieinamas technologijas bei kitas atliekų vadybos alternatyvas KM atgauti.

Raktažodžiai: *kritiniai metalai, elektros ir elektroninės įrangos atliekos (EEĮA), atgavimas.*