Environmental and Sustainable Development indicators for a preliminary strategic assessment of REE recovery from mine tailings

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Abstract. Rare earth elements (REEs) are considered as critical strategic resources. Their significance for the development of modern technologies provided an incentive to search alternative resources which include, among others, industrial tailings. Because of the low REEs concentration in ore from secondary sources and the difficulty in REE separating, there is a need for individual selection of enrichment and recovery methods for individual landfills. At the same time, in line with the EU directives and good planning and development practice, environmental aspects must be taken into account as early as possible in the decision-making process. Presented recommendations are part of the ENVIREE project, which aims to develop environmentally-friendly REEs recovery technologies from selected industrial waste disposal sites. The recommendations complement results of Life Cycle Assessments for ore enrichment and separation technology. Based on a review of the environmental aspects (screening, scoping stage of environmental assessment), a set of environmental, emissions, technology efficiency, sustainable local development indicators are proposed. The set of indicators refers to the stage of acquisition and beneficiation of the material from industrial landfills, and after the determination of the basic emissions levels from the plant in the semi-technical phase, may support the ecological ranking of projects.

1. Introduction
Rare earth elements are becoming an increasingly important resource for the development of modern technologies, including renewable energy sources. The current market monopolisation encourages the search for alternative sources, which include, among others, the recycling of electronic devices and the recovery of REEs from municipal and industrial waste [1-4].
The recovery of rare earth elements from waste involves the development of an efficient, cost-effective and environmentally friendly technology of enrichment and separation of elements and final refining. The possibilities of the recovery REEs from old mining and industrial waste landfills are analysed as part of the ENVIREE project. Its scope includes the development – on a laboratory scale – of the technology for the processing (enrichment) and final separation and refining of rare earth metals from materials deposited on selected landfills. One of the purposes of the project is to assess the environmental nuisance of new technologies through the life-cycle assessment (LCA) and identify the potential impacts on the environment, the sustainable development and the society. More detailed environmental assessments will be possible after the strategic assumptions are defined and the technology is tested on a semi-technical scale. At the current stage, the life-cycle modelling was conducted in the Sima Pro software based on the analogies to other mining and manufacturing sectors and the characteristics of REE enrichment processes. A set of indicators was also proposed for preliminary environmental assessments at subsequent stages of the development of the technology and the formulation of the REE acquisition strategies (the screening and scoping stage).

Due to the key importance of REEs for the development of modern technologies, the strategic assessments should take into account a broader range of economic, social and environmental circumstances.

Alternative REE resources are characterised by a lower concentration of elements and a greater dispersion of resources (landfills, electronic waste collection system nodes) compared to the primary sources. Therefore, it is necessary to take into account the logistical impacts for the entire production chain. This raises the importance of a comprehensive systemic approach in environmental assessments.

The ENVIREE project has initially assessed the possibilities of the recovery of REEs from selected industrial waste landfills in Sweden, Poland, the Czech Republic, Portugal and South Africa. Three landfills with the highest concentrations of REEs – New Kankberg (Sweden), Cumieira (Portugal) and Regtepoort (South Africa) [5] – were selected for the second stage of the works (technology selection). Currently, the development stage for the technology of enrichment of the material from the New Kankberg and Cumieira landfills has been completed.

2. Environmental considerations for the recovery of REEs from industrial and mining landfills

When assessing the environmental and sustainable development aspects for the acquisition of REEs from industrial and mining landfills and their subsequent processing, it is important to point out the significant differences relative to the exploitation of primary deposits. These include:

- A lower concentration of REEs in the material being processed [2-6].
- Smaller resources to be obtained from a single anthropogenic deposit compared to natural deposits [2, 7].
- Possible lengthening of ore and waste transport routes in the case a central system of enrichment of material from dispersed landfills is used.
- The differences in the content of rare earth elements in landfills in the region, resulting from the different properties of the deposits and the processing technologies; the possible variety of share and concentration of REEs in one facility resulting from changes in the processing technology over decades of exploitation[5, 6].
- The nature and granulometric composition of waste can cause problems during re-exploitation (dusting, chemical and radiological contaminants, thixotropy). Mechanical and chemical processing waste (grinding, flotation) have less favourable mechanical properties than natural formations [7].
- The exploitation will be carried out in landfills which are artificial facilities whose stability calculations do not provide for secondary exploitation. Both the new conditions of use and the
potential climatic changes (the change in humidity, heavy precipitation, droughts [dusting], etc.) must be taken into account.

- The environmental assessment for the re-exploitation of old industrial and mining waste landfills should take into account e.g. net changes specifying the differences between the environmental impact of old and new landfills (most of the waste exploited from the landfills – potentially 80-90% [8, 9] – returns to their original deposition site or another landfill in the region) [9].
- The recovery of REEs from old landfills creates a positive impact on the environment as a result of the reduction of waste deposited on the surface compared to the exploitation of natural deposits.
- The waste that is a source of REEs is deposited on the surface, which reduces the energy demand (and the associated carbon footprint) and the land area occupied by the landfills compared to the exploitation of natural deposits.
- The assessments of the impact on local communities should include the possibility of partial compensation for the negative impacts at the exploitation stage, the reduction of the negative long-term impacts of the past exploitation (partial demolition of old landfills and higher ecological safety of new facilities).

Three analysis scales will be important in the strategic assessment of the impact of re-exploitation of landfills and REE production in terms of sustainable development: local (surroundings of the exploitation and processing areas), regional (national economy) and global (REE market). The criteria and the final outcome of the assessment may vary depending on the adopted assessment scope, the environmental policy and the definition of sustainability.

The extraction and enrichment of REE ores and their separation and final refining involve significant negative impacts on the environment. Higher-concentration REE deposits are often accompanied by radioactive elements, while the enrichment of ores and refining of individual elements require the use of highly toxic substances. The contamination of the environment and the protests of inhabitants against the storage of radioactive waste are a limiting factor which increases the costs of the exploitation from natural deposits.

The re-exploitation of the industrial waste from the enrichment and production of metals may be a greener alternative. These wastes are subject to legal requirements for waste management in a given country and are currently deposited on the surface and monitored. Rational processing can result in no long-term net changes in the environment (or even positive changes). A problem may be the cost-effectiveness of the recovery of REEs from the resources with a low concentration of elements and the cost of the activities aimed at minimising the negative impacts on the environment.

3. Strategic considerations for the recovery of REEs from industrial waste landfills

Rare earth elements are classified as strategic resources with a high supply risk (especially for the HREE heavy element group). However, they are quite common in the earth’s crust and the risk of supply restriction is mainly due to geopolitical conditions (China’s monopoly [1, 10, 11]) and the limitations resulting from the high environmental nuisance of ore extraction and processing (environmental compliance costs). After the 2011 price peak, works were started to launch the suspended production from well-known deposits (e.g. Mountain Pass, California) and search for new natural deposits and alternative sources of REEs. The price stabilisation after 2013 (and their significant reduction in the case of LREEs [10]) has limited the work on the launch of the exploitation of additional deposits. Due to the high estimates for the risk of REE supply stability, it is necessary to identify crisis scenarios and diversify the sources of supply. The development of efficient, cost-effective and environmentally friendly technologies for the recovery of REEs from waste and the launch of a pilot recovery facilities can make an important contribution to the reduction of the risk of REE shortages in the European market.
Prior to the commencement of strategic assessments for the acquisition of REEs from alternative sources, it will be necessary to adopt assumptions about the development of the situation in the REE market and determine the scope of strategic decision making. Economic, geopolitical, social and environmental factors will influence the decision-making area, both on global and regional scales. One of the key issues that define the scope and detail of strategic environmental assessments is the planning scope (the variants that will be subject to hierarchisation).

One can consider decision optimisations for:

- The maximisation of the recovery of REEs from old landfills and from the waste from the current production in mining and metallurgical plants.
- The preference of the processing of the waste from the current production in mining and metallurgical plants, with an extensive exploitation of landfills (securing the technological opportunities for rapid extraction growth in the case of a reduction in REE supply on the global market).
- The preference of the recovery of REEs from the current stream of mining and industrial waste in the context of optimal use of resources (use of accompanying minerals), ensuring the possibility of recycling of the accumulated waste in the future.
- The improvement of the environmental conditions in the vicinity of old mining and industrial waste landfills (redeposition of the material on landfills with a higher environmental standard).
- The social and economic benefits in the old mining regions affected by unemployment (extending the employment in former mining areas).

With a small market pressure (satisfaction of the demand from current deposits), there is an increase in the importance of environmental and social factors of the decision being made and the implementation of sustainable development principles at a local level.

4. Recovery of REEs from old industrial landfills

In recent years, the literature has been exploring the opportunities of obtaining rare earth elements from the stream of municipal and industrial waste and the waste deposited in landfills [3, 4]. The ENVIREE research project aims to identify an efficient, cost-effective and environmentally-friendly technology of enrichment and final production of REEs from selected landfills used for metal ore processing and mining waste. In terms of their size and nature, the landfills considered in the ENVIREE project can be divided into three groups:

- Large industrial landfills associated with an ongoing, large-scale exploitation of metal deposits (e.g. New Kranberg – 1.500 ha/700 million Mg [Sweden], Żelazny Most Reservoir – 1.570 ha/500 million m³ [Poland] and ZGH Bolesław – 110 ha/60 million Mg [Poland]),
- The average size of a post-exploitation landfill and landfill group (e.g. South Africa –“Source 1, 6, 10”; surface area from 65 to 100 ha (often smaller scattered dumps); “Rudki” – 24 ha/approx. 2 million Mg [Poland]),
- Small, scattered post-exploitation waste landfills (e.g. “Covas A, B, C” – 0.5-2.5 ha/ from 10k to 226k m³ [Portugal]; South Africa: Source 5, 12, 17 – 1-17 ha).

In the first case, the impact on the environment may not be examined without considering it in conjunction with the current exploitation of the deposit and the primary production in the operational mining plants. Both the cumulative impacts, the technological and spatial relationships with operational facilities and the optimal use of the deposits (REE ores as accompanying minerals) will be important. Operational industrial facilities have environmental impact assessments reports, as well as environmental reviews and environmental monitoring data in the areas of production plants and landfills. The environmental problems will result from the scale of the processing associated with both the volume of the
waste stream from the current production (up to a few dozen million tonnes per year) and the amount of the waste deposited in the landfills. A rapid exploitation and processing of waste accumulated in the landfills will make it possible to start their reclamation. On the other hand, REE resources accumulated in landfills so far can serve as a raw material reserve that can be started relatively quickly (based on an already operational processing plant) in the event of a reduction of REE supply in the global market.

In the second and third case, the logistics of ore transport, the location of enrichment and final production plants, as well as the assessment of the net changes in the environment in relation to the redeposition of old industrial waste in new landfills are becoming more and more important. It will also be important to prepare the local communities for the return of the industry to former mining regions (both in terms of the economic benefits to the region and the reappearance of industrial risks and emission of pollutants). The exploitation will include facilities and areas that were reclaimed or underwent natural (often several decades long) succession. A positive aspect may be combining the scattered, poorly documented sources of pollution (small scattered mining waste dumps) and their deposition in accordance with current environmental requirements (landfill monitoring and neutralisation).

There are technologies that minimise environmental impacts to an acceptable level for most stages of the chain of the recovery of REEs from post-mining landfills (mining, transport, enrichment and storage of waste). The main limitations are the cost-effectiveness of their application and the formal and legal aspects of the transport and processing of waste in national and international laws. In the case of Group I deposits, mining and metallurgical plants managing the waste landfills selected for re-exploitation operate under the conditions of the applicable environmental laws, including the regulation in the scope of waste toxicity and radioactivity.

In the case of closed landfills associated with former mining and metallurgical activities, the preliminary impact assessment of individual facilities on the environment and on the development of the region will be possible after the dedicated technology has been tested on a semi-technical scale and the assumptions for the potential location and size of the facility have been adopted (including technical requirements, the coverage of water and energy demand and the scale of cost-effective extraction).

When considering the exploitation of secondary deposits of REEs in the context of sustainable development and indirect environmental impacts, two initial assessment states should be distinguished: a situation of stable supply of rare earth elements in the global market and a situation of a collapse of supply from the current sources, e.g. due to a geopolitical situation or a limitation of production from currently exploited deposits. In the first case, the development of new technologies and the production of equipment that have a significant impact on the reduction of environmental pressures (photovoltaic cell, wind turbines, electric motors, batteries, etc.) will not be jeopardised. In the assessment of the impact of the exploitation of anthropogenic deposits, the dominant position will then be taken by the estimation of the size of emissions and local environmental changes as well as the impact on the local communities and the economy of the region. In the second case, an equivalent place in the assessment should be taken by the estimations of environmental (emission of pollutants) and socio-economic issues on a continent and global scale that result from the hampering of the development of green technologies.

5. Assessments of the impact of the exploitation of REEs from old industrial landfills on the natural and social environments

5.1. Sustainable development indicators

The term “sustainable development indicators” is understood as both the sets of indicators covering various sectors that comprise the operational definition of sustainable development (the society, the environment and the economy) and the integrated and complex indicators combining and weighing particular aspects of the development [12, 13]. The volumes of the Sustainable Development Goals
(SDGs) of the 2030 Agenda for Sustainable Development show the preference for simple (non-aggregated) indicators. The following proposal of indicators for the assessment of the recovery of REEs from landfills also includes non-aggregated or simple aggregate indicators which relate to the basic spheres of development and are assessable at the initial stage of the assessment. Once the decision-making options and ecological policy criteria have been established, it will be possible to use them in a multi-criterion assessment (e.g. AHP method).

The definition of an integrated or comprehensive sustainable development indicator always requires the establishment of the context of its definition and application, i.e. at least the basic assumptions of the decision-makers’ environmental policy [14]. The indicators of this kind are useful at the stage of social communication of the results of the assessments as they take into account both the combined impact of the sphere of sustainable development and their importance in the context of the goals of the development. The use of complex indicators at the initial stage of assessment can significantly narrow the perspective from which the problems are perceived. The adoption of simple indicators used subsequently in the multi-criteria analysis process provides greater clarity and flexibility for the assessment.

5.2. A set of indicators for the preliminary comparison of the recovery of REEs from industrial waste for environmental and sustainability purposes

The standard approach to assessing the impact of the planned investments on the natural and social environment is to take into account the value and sensitivity of the environmental components combined with the estimated pressure caused by the planned ventures [14]. For the efficient completion of the preliminary environmental assessment, the indicator set must, on the one hand, include complementary spheres of sustainable development and, on the other hand, it must not be too extensive to avoid distracting the decision-makers.

While constructing the performance indicators, it was assumed that due to the high supply and low price of LREEs, the coverage of the demand for HREE would be the main factor determining the start of the production from alternative sources. In the case of strategic raw materials with a high supply stability risk, a comprehensive impact assessment must take into account the most important environmental, social and economic elements (from the viewpoint of the sustainable development). In the table 1, these include the biodiversity of the environment, the quality of water resources and agriculture, social acceptance and the importance of the deposit for meeting the demand for REEs in crisis situations.

5.2.1. Environmental sensitivity indicators

The environmental sensitivity indicators allow for a preliminary comparison of the quality of the environment and its vulnerability to changes in a location. The calculation of the environmental indicators requires that assumptions are adopted for the spatial layout and scale of the facilities related to the planned venture and the access to the basic environmental layers in spatial information systems. Socio-economic and technological indicators require field inspection.
Table 1. A set of indicators for the preliminary environmental and sustainable development assessment for the recovery of REEs from old industrial and mining waste landfills – sensitivity indicators.

| Name |
| --- |
| **Sensitivity indicators** |
| **Environmental indicators** |
| 1. The share of protected areas within the distance of 10 km from the borders of the exploitation site and the enrichment plant and within the distance of 1 km from ore and waste transport routes [%]. |
| 2. The number of inhabitants within the distance of 10 km from the borders of the exploitation site and the enrichment plant and within the distance of 1 km from ore and waste transport routes [n]. |
| 3. The share of naturally valuable habitats (e.g. from the Appendix to Habitats Directive) within the distance of 10 km from the borders of the exploitation site and the enrichment plant and within the distance of 1 km from ore and waste transport routes [%]. |
| 4. The sum of the degree of risk for all the species included in the red list and identified in the area of the planned exploitation as well as the number of species found (the parameter determined e.g. based on wildlife inventories for neighbouring protected areas or the data available from spatial information systems). |
| 5. The share of agricultural lands in use within the distance of 10 km from the borders of the exploitation site and the enrichment plant and within the distance of 1 km from ore and waste transport routes (or a surface area of agricultural land weighed by the quality of habitats) [%]. |
| 6. The length of the watercourses within the distance of 10 km from the borders of the exploitation site and the enrichment plant and within the distance of 1 km from ore and waste transport routes [km]. |
| 7. The share of surface waters and shallow aquifers within the distance of 10 km from the borders of the exploitation site and the enrichment plant and within the distance of 1 km from ore and waste transport routes [%]. |
| 8. The quality (contamination) of groundwater in the vicinity of the facility (a package of indicators). |
| 9. Landscape exposition of the facility – scoring. |
| 10. An average class of soil quality in the vicinity of the exploitation site, the enrichment and refining plants and the roads used for transport of ore and waste. |
| **Socio-economic indicators** |
| 11. Unemployment level in the region [%] |
| 12. First quartile of the inhabitants’ income in the region [currency] |
| 13. The percentage of higher or equal preference for the industrial development relative to the priority for environment protection among the local community [%] |
| **Technological indicators for the re-exploited landfills** |
| 14. The difficulty scale score for the exploitation of the landfill (geotechnical conditions, landslide hazards, soil liquefaction, leachate intensification, leachate toxicity and chemical reactions in the exposed part of the waste) [point – expert’s scoring] |
| 15. The degree of land reclamation – an estimation of dry biomass per hectare compared to the average dry biomass per hectare in the vicinity of the facility [(t/ha)/(t/ha)] |

5.2.2. Enterprise pressure indicators
Pressure indicators characterise the intentions in relation to the planned spatial layout, the scale of extraction and processing, and the importance of the exploitation of a secondary deposit for the coverage of the demand for REEs. The performance indicators allow for the comparison of anthropogenic and natural deposits in terms of their richness and basic parameters considered in the context of the sustainable development.

The technological indicators require the adoption of the assumptions concerning the technological system, the scale of the production and the assessment of the toxicity of the material collected from the landfill and the waste generated after the recovery process of an REE concentrate.
The definition of social indicators requires an assessment of local economic conditions and assumptions regarding the number of jobs and the average salary for the job positions related to the planned project, but consideration should be given to the possibility of including jobs indirectly related to mining and industrial activity.

Table 2. A set of indicators for the preliminary environmental and sustainable development assessment for the recovery of REEs from old industrial and mining waste landfills – pressure indicators.

| Name                                                                 |
|---------------------------------------------------------------------|
| **Pressure indicators**                                             |
| **Performance indicators**                                          |
| 16. The estimated amount of HREE in the secondary deposit compared to the global or UE average consumption in last 5 years. |
| 17. The average concentration of REEs in a secondary deposit relative to the concentration in identified primary deposits (worldwide or within the EU, depending on the goals of the assessment) [%]. |
| 18. The efficiency of the enrichment technology for a secondary deposit [%]. |
| 19. The ecological backpack of the REE concentrate – the number of tonnes that need to be moved to obtain 1 tonne of the concentrate (or with the adjustment for the richness of the concentrate) [Mg]. |
| 20. The greenhouse gas emissions per unit of REE concentrate (or per unit of mass of selected elements contained in the concentrate, e.g. HREE). |
| **Technological indicators**                                        |
| 21. The indicative surface area (other than the current industrial areas) required for the implementation of the project in a given location [ha]. |
| 22. The amount of individual chemical reagents per unit of REE concentrate mass – directly or after taking into account the quality of the concentrate (indicator package). |
| 23. The toxicity of chemical reagents per unit of REE concentrate mass – directly or after taking into account the quality of the concentrate [e.g. LD50·mass]. |
| 24. The toxicity of chemical reagents per unit of mass of key elements (e.g. HREE) [e.g. LD50·mass]. |
| 25. The comparison of the nuisance of the waste collected from the landfill (or a manufacturing process) to the waste deposited in the landfill after the REE recovery (indicator package – a set of key indicators for a given plant). |
| 26. An estimated number of tonne-kilometres of ore and waste transports to obtain 1 tonne of concentrate (directly or after taking into account the quality of the concentrate) [Mg·km] |
| 27. An estimated water, energy and heat demand of the REE extraction and processing process in relation to the supply of utilities in the area of the planned exploitation (package of indicators). |
| **Socio-economic indicators**                                       |
| 28. The ratio of annual fixed income of the inhabitants of the region obtained as a result of the implementation of the project relative to the annual income of the inhabitants of the region. |
| 29. The ratio of the average salary paid to permanent inhabitants of the region as a result of the completion of the project compared to the average salary in the region. |
| 30. Probable migration of people in the region related to the implementation of the project (share of the foreign population in the municipality) [%]. |
6. Summary

Both the comparison of environmental effects and the effects on the sustainable development of the recovery of REEs from landfills and their initial estimates for individual facilities will be possible once the assumptions regarding the location of the individual facilities, the scale of the exploitation and the safety principles have been established for each landfill. It is required to provide more detail on the layout and parameters of the installation and the technology of extraction, transportation and deposition of waste as well as the selection of technological and organisational measures to reduce the nuisance to the environment and society. The comparison of the environmental effects of the recovery of REEs from landfills with the impacts related to the exploitation of natural deposits may prove difficult due to the initial stage of the development of the technology for the former and the limitation of access to information for the latter.

The proposed set of indicators may be an element within a preliminary assessment of the environmental and social problems and benefits of the exploitation of individual facilities. A multi-criterion indicator-based assessment will facilitate the optimisation of the investment order, taking into account aspects of sustainable development.

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