Key Aspects of Aluminium Value Chain Sustainability in East – Southeast Europe for Red Mud Valorization

Stavroula Giannakopoulou[1], Chrysa Panagiotopoulou[2], Katerina Adam[3], Antonis Peppas[4] and Maria Taxiarchou[5]
1. Junior Researcher
2. Senior Researcher
3. Professor
4. Assistant Professor
5. Associate Professor
School of Mining and Metallurgical Engineering, National Technical University of Athens, Athens, Greece
Corresponding author: gianstav@metal.ntua.gr

Abstract

Nowadays, at the European scale, a fast-growing need for raw materials is observed. At the same time, the industrial processes implementing the whole raw materials value chain, developed several solutions, aiming at the sector's circular economy initiatives and sustainability reinforcement. In the case of the aluminium industry, there is an increasing need for aluminium products globally, indicating the increasing production trend for this material. Taking into account the principles of circular economy and sustainability that are currently adopted by the European industries, and the European low potential, for instance for rare earth elements, it is important to manage the wastes or by-products generated from the Bayer process. Various studies have been conducted for the valorization of red mud / bauxite residue with significant technological breakthroughs. Nevertheless, the successful valorization of this waste / by-product ought to take into consideration, apart from the technological advances, also the current economic / legislative / environmental / social and other frameworks. For this reason, the current study investigates the abovementioned conditions of four countries in East – Southeast Europe: Bosnia and Herzegovina, Greece, Hungary, and Montenegro. Following the review and analysis of countries' status-quo, the major strengths and obstacles to the sustainable utilization of this commodity are presented, using Strengths, Weaknesses, Opportunities, and Threats or else SWOT Analysis. According to the evaluation, all four countries present significant potential for red mud / bauxite residue valorization. For the two countries, Greece, and Bosnia and Herzegovina, which currently have active aluminium production, long-term valorization solutions appear to be more suitable, while for Montenegro and Hungary, short-term solutions focused on environmental relief could be more appropriate to deal with this emerging issue.

Keywords: Red mud, Bauxite residue, SWOT analysis, Sustainability, Environmental management.

1. Introduction

Red Mud or Bauxite Residue (RM / BR) is the major by-product, generated in the aluminium industry through the leaching of bauxite ores at the Bayer process step. RM disposal is considered a techno-economical problem for the aluminium industry, causing environmental harm. On a global scale, RM disposal is calculated at 2.7 billion tonnes, with an increase of 120 million tonnes per year [1]. Those factors influence the need to explore a better solution.

The increasing global aluminium demand indirectly affects RM generation. It is highlighted that to produce 1 tonne of aluminium, almost 2 tonnes of alumina are needed, generating 1 to 2.5 tonnes of RM / tonne of alumina [2-9]. According to World Mining Data, during the last decade, increasing trends were recorded for aluminium production worldwide (approx. 30 % from 2011 to 2015, and 9 % from 2015 to 2019) [2-7]. By the 2030's, RM production increases are expected, given that the growth of aluminium demand is forecasted to 40 % [11]. For the 2040's, RM production is possible to reach 8 billion tonnes, in line with International Aluminium Institute [12]. The aforementioned play an important role in affecting RM generation.

The effects of increasing RM quantities, in combination with the material's environmental impacts, highlight the need to address this issue. The most common practice of RM handling and management by the aluminium industries was lagoons until the 1980's, recently replaced with dry stacking [13]. Material's high pH values ranging from 10.5 – 12.5, the possible alkali seepage into underground water, the large-scale land uses, the dams' instability, and the alkaline airborne dust impact, enhance this view [14]. The Ajka disaster, which occurred at the aluminium refinery in Hungary in 2010, points out the requirement to implement a more suitable solution. As a result of the dam's collapse, the death of 10 people and chemical burns by the flood, etc. were caused, as well environmental impacts, such as land and water contamination in the adjacent areas [15-16]. As stated by Gelencsér et al. [17]:

"This catastrophic industrial accident has been unprecedented in the 120-year-long history of the Bayer process."

Considering the industrial accident and in an effort to prevent similar catastrophic consequences, the efficient treatment or even valorization of RM / BR is one of the focal points of aluminium industry research and development (R&D) activities. Nevertheless, the stakeholders' management to adopt technical solutions should also encounter other non-technical aspects such as the economic / legislative / environmental / social framework of each involved country. Within this frame, this paper attempts to map the status-quo of the countries in East-Southeast Europe: Bosnia and Herzegovina, Greece, Hungary, and Montenegro. Simultaneously, to ensure the optimal receptiveness for new technological solutions, SWOT tool was used for managing countries potential [18].

SWOT tools have examined the mining sector's sustainability in the Balkans. The Greek SWOT analysis by Nikolaou and Evangelinos dealt with the strengths and challenges faced by the country's Mining and Metal (M&M) industry when adopting environmental management practices [19]. SWOT/Gap analysis was also conducted to examine the mineral raw materials resource efficiency of six East-Southeastern countries within the Balkans for the growth of regions' economies [20]. Focusing on Bulgarian SWOT, it examined the general frame of the country's mining industry and its potential was addressed for additional valorization [21]. In the current study, RIS-RESTORE, funded by the EIT-Raw materials, is under the priority axis of RM valorization for the four countries. Results included the helpful and harmful factors from the internal and external environment. The total SWOT analysis is the cornerstone for the forthcoming roadmaps' creation in RIS-RESTORE, to develop new plans in the final stage (Figure 4).

2. Status-Quo

As a starting point, the geographic distribution of RM / BR sites for Bosnia and Herzegovina (Birac, and Dobro Selo), Montenegro (Podgorica), Hungary (Ajka, Almasfüzíto-AF I-VII, Neszmely-AF VIII, Mosonmagyarovar), and Greece (St. Athanasios) represented in Figure 1. The produced material's quantities are larger than 65 million tonnes, in alignment with the RIS-RESTORE. Moreover, the countries' current aluminium and alumina production were examined compared to the global players (Figure 2).

In conclusion, the specification of the non-technical features for material valorization has a significance on the required, sustainable management strategies. Roadmaps creation is going to promote decision-making process, taking into consideration the referred non-technical characteristics, as well.

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6. References

1. C. Klauder, M. Gräfe and G. Power, Bauxite residue issues: II. options for residue utilization, *Hydrometallurgy*, Vol. 108, No 1-2, (2011), 11-32.
2. C. Reichl and M. Schatz, M., *World mining data iron and ferro alloy metals, non-ferrous metals, precious metals, industrial minerals, mineral fuels*, 2022, Vol. 37, 1-267, https://www.world-mining-data.info/wmd/downloads/PDF/WMD2022.pdf.
3. C. Reichl and M. Schatz, M., *World mining data iron and ferro alloy metals, non-ferrous metals, precious metals, industrial minerals, mineral fuels*, 2021, Vol. 36, 1-268, https://www.world-mining-data.info/wmd/downloads/PDF/WMD2021.pdf.
4. C. Reichl and M. Schatz, M., *World mining data iron and ferro alloy metals, non-ferrous metals, precious metals, industrial minerals, mineral fuels*, 2020, Vol. 35, 1-265, https://www.world-mining-data.info/wmd/downloads/PDF/WMD2020.pdf.
5. C. Reichl and M. Schatz, *World mining data iron and ferro alloy metals, non-ferrous metals, precious metals, industrial minerals, mineral fuels*, 2019, Vol. 34, 1-264, https://www.world-mining-data.info/wmd/downloads/PDF/WMD2019.pdf.
6. C. Reichl, M. Schatz and Z. Zsak, *World mining data iron and ferro alloy metals, non-ferrous metals, precious metals, industrial minerals, mineral fuels*, 2018, Vol. 33, 1-263, https://www.world-mining-data.info/wmd/downloads/PDF/WMD2018.pdf.
7. C. Reichl and M. Schatz, M., *World mining data iron and ferro alloy metals, non-ferrous metals, precious metals, industrial minerals, mineral fuels*, 2017, Vol. 32, 1-248, https://www.world-mining-data.info/wmd/downloads/PDF/WMD2017.pdf.
8. R. K. Paramguru, P. C. Rath and V. N. Misra, Trends in red mud utilization–a review, *Mineral Processing & Extractive Metall. Rev.*, Vol. 26, No. 1, (2004), 1-29.
9. Valentina Dentoni, Battista Grosso and Giorgio Massacci, Environmental Sustainability of the Alumina Industry in Western Europe, *Sustainability*, Vol. 6, No 12, (2014), 9477-9493.
10. BBC, Eyewitness: Hungary's toxic spill, https://www.bbc.com/news/world-europe-11483414 (accessed on 26 July 2022).
11. International Aluminium, Report Reveals Global Aluminium Demand to Reach New Highs After Covid, https://international-aluminium.org/report-reveals-global-aluminium-demand-to-reach-new-highs-after-covid/, (accessed on 26 July 2022).
12. International Aluminium Institute, International Aluminium Institute launches bauxite residue roadmap, https://international-aluminium.org/news-recycling/ (accessed on 26 July 2022).

13. M. Archambo and S. K. Kawatra, Red mud: fundamentals and new avenues for utilization, *Mineral processing and extractive metallurgy review*, Vol. 42, No. 7, (2021), 427-450.
14. Tatiana Yuzhakova et al., Red mud waste storage problems, solution and utilization alternatives, *Global Journal on Advances Pure and Applied Sciences [Online]*, No. 1, (2013), 1051-1057.
15. Stefan Ruyters et al., The red mud accident in Ajka (Hungary): plant toxicity and trace metal bioavailability in red mud contaminated soil, *Environmental science & technology*, Vol. 45, No. 4, (2011), 1616-1622.
16. M. A. Khairul, Jafar Zanganeh, and Behdad Moghtaderi. The composition, recycling, and utilization of Bayer red mud, *Resources, Conservation, and Recycling*, Vol. 141, (2019), 483–98.
17. András Gelencsér et al., The red mud accident in Ajka (Hungary): characterization and potential health effects of fugitive dust, *Environmental science & technology*, Vol. 45, No. 4, (2011), 1608-1615.
18. Boonyarat Phadermrodab, Richard M. Crowdera and Gary B. Willsa, Importance-performance analysis based SWOT analysis, *International journal of information management*, Vol. 44, (2019), 194-203.
19. E. Nikolaou and K.I. Evangelinos, A SWOT analysis of environmental management practices in Greek mining and mineral industry. *Resources Policy*, Vol. 35, No. 3, (2010), 226-234.
20. Stavroula Giannakopoulou, Fotini Chalkiopoulou and Katerina Adam, Mineral raw materials' resource efficiency in selected ESEE countries: strengths and challenges. *Materials Proceedings*, Vol. *5*, No 1, (2021), 83.
21. Aneta Deneva and Jānis Grasis, (2020, June), Bulgarian Mining Industry between Tradition and Innovation, *Proceedings of 5th International Innovative Mining Symposium IISM*, Kemerovo, Russia, 19-20 October 2020, Vol 174, 01026, https://dspace.rsu.lv/jspui/bitstream/123456789/6109/1/Bulgarian_Mining_Industry_between_Tradition.pdf.
22. Dun&bradstreet, Alumina and aluminium production and processing companies in Bosnia and Herzegovina, https://bit.ly/3Bm99fA (accessed on 26 July 2022).
23. Foundation for Economic and Industrial Research, *The aluminum industry in Greece: Contribution to the economy, challenges and growth prospects*, 2019, http://iobe.gr/docs/research/RES_05_F_27032019_PRE.pdf.
24. European Aluminium, Market Overview, https://www.european-aluminium.eu/activity-report-2019-2020/market-overview/, (accessed on 26 July 2022).
25. Efthymios Balomenos et al., Bauxite residue handling practice and valorisation research in Aluminium of Greece, *Proceedings of 2nd International Bauxite Residue Valorisation and Best Practices Conference BR2019*, Athens, Greece, 7-10 May 2018, 29-38, https://bit.ly/3z67uYN.
26. Panagiotis Davris et al., Viable scandium extraction from bauxite residue at pilot scale, *Materials Proceedings*, Vol. 5, No. 1, (2022), 129.
27. SCALE Scandium Aluminium Europe, SCALE: Production of Sc-Al alloys from European metallurgical by-products, https://scaletechnology.eu/ (accessed on 26 July 2022).
28. RIS-RESTORE, *Deliverable 3.1: Framework for a Roadmap of a regional innovation scheme in the zero waste Al-value chain (SWOT analyses) [Confidential]*, 2021.
29. Government of the Republic of Srpska, Government of the Republic of Srpska holds the 29th special session, https://bit.ly/3zaBouW (accessed on 26 July 2022)
30. Transparency International Bosnia and Herzegovina, *State capture: state capture in extractive industry based on the case study of Birač,* 2018, https://ti-bih.org/wp-content/uploads/2018/05/State-Capture-BH_Ext_Industry_Birach.pdf.
31. Mark Brininstool, *Area Reports-International-Europe and Central Eurasia: U.S. Geological Survey Minerals Yearbook 2008, The mineral industry of Bosnia and*

Herzegovina, 3rd Edition, Washington, U.S. Government Printing Office, 2010, 67-70 pages.
32. Investinsee, Privatisation of the “Aluminij” D.D. Mostar/Hot, https://investinsee.com/news/bosnia-and-herzegovina/privatisation-of-the-aluminij-dd-mostarhot, (accessed on 26 July 2022).
33. European Aluminium, *Bauxite residue management best practice*, 2015, https://bit.ly/3cPW5oz.
34. Iskra Pavlova, Montenergin Bauxite Mining Co Rudnici Boksita renews exports deal with Hungary’s MAL, https://bit.ly/3PSqQrc (accessed on 26 July 2022).
35. Jelena Žugić, Foreign direct investment and global economic crisis in the Western Balkans, *Journal on European Perspectives of the Western Balkans*, Vol. 3, No.1, (2011), 69-90.
36. The Observatory of Economic Complexity, Montenegro, https://oec.world/en/profile/country/mne (accessed on 26 July 2022).
37. Hungarian Foundry Association, Light metal foundries, https://foundry.hu/category/konnyufem-ontodek/?orderby=title&order=asc (accessed on 26 July 2022).
38. Hungarian Foundry Association, Precision foundries, https://foundry.hu/category/precizios-ontodek/?orderby=title&order=asc (accessed on 26 July 2022).
39. Walter G. Steblez, *Minerals Yearbook Area Reports-International 2001-Europe and Central Eurasia: U.S. Geological Survey, The mineral industries of Czech Republic, Hungary, Poland, and Slovakia*, 3rd Edition, Washington, U.S. Government Printing Office, 2004, 73-84 pages.
40. E. Lee Bray, *U.S. Geological Survey Mineral commodity summaries: bauxite and alumina*, 2021, https://pubs.usgs.gov/periodicals/mcs2021/mcs2021-bauxite-alumina.pdf.
41. Actmedia, Company producing catastrophe nationalized in Hungary, https://www.actmedia.eu/daily/company-producing-catastrophe-nationalized-in-hungary/30037, (accessed on 26 July 2022)
42. Nigel Piercy and William Giles, Making SWOT analysis work, *Marketing Intelligence & Planning*, Vol. 7, No. 5/6, (1989), 5-7
43. Will Kenton, Strength, Weakness, Opportunity, and Threat (SWOT) Analysis, https://bit.ly/3PzPFIB (accessed on 26 July 2022).
44. Christine Namugenyia, Shastri L Nimmagaddab and Torsten Reinersc, Design of a SWOT analysis model and its evaluation in diverse digital business ecosystem contexts, *Procedia Computer Science*, Vol. 159, (2019), 1145-1154.
45. Chenna Rao Borra et al., Leaching of rare earths from bauxite residue (red mud), *Minerals engineering*, Vol. 76, (2015), 20-27.
46. RIS-RESTORE, *Deliverable 4.2: Report on the conditions of red mud tailings [Confidential]*, 2020.
47. Slobodan Radusinović and Argyrios Papadopoulos, The potential for REE and associated critical metals in karstic bauxites and bauxite residue of Montenegro, *Minerals*, Vol. 11, No. 9, (2021), 975.
48. Snežana S. Nenadović et al., Physicochemical, mineralogical and radiological properties of red mud samples as secondary raw materials, *Nuclear technology and radiation protection*, Vol. 32, No. 3, (2017), 261-266.
49. RIS-RESTORE, RIS-RESTORE: Evaluation of red mud tailings in the ESEE region, http://ris-restore.zag.si/ (accessed on 26 July 2022).
50. RemovAL, RemovAL removing waste from alumina production, https://www.removal-project.com/partners/ (accessed on 26 July 2022).
51. RIS ALiCE, Al-rich industrial residues for mineral binders in the ESEE region, http://ris-alice.zag.si/ajax/DownloadHandler.php?file=3294, (accessed on 26 July 2022).

52. Ministry of Sustainable Development and Tourism Environmental Protection Agency, *Environmental and Social Impact Assessment of Remediation of Five Contaminated Sites*, 2012, https://bit.ly/3zzuvFa.
53. The World Bank, Montenegro Policy Notes 2017, https://documents1.worldbank.org/curated/en/400341486444604697/pdf/112642-WP-MontenegroPolicyNotesEng-PUBLIC.pdf, (accessed on 26 July 2022).
54. Padma Charan Mishra and Manoj Kumar Mohanty, A review of factors affecting mining operation. *World Journal of Engineering*, Vol. *17*, No. 3, (2020), 457-472.
55. Global Rankings 2018 / Logistics Performance Index https://lpi.worldbank.org/international/global, (accessed on 26 July 2022).
56. Efthymios Balomenos, Practice, research and barriers in secondary mining of industrial residues at Aluminium of Greece, *3rd Greek Raw Materials Community Dialogue*, Athens, Greece, 4-5 December 2018, https://bit.ly/3pLCGrY.
57. Akin Akinci and Artir Recep, Characterization of trace elements and radionuclides and their risk assessment in red mud, *Materials Characterization*, Vol. 59, No. 4, (2008), 417-421.
58. Yulong Cui et al., pH-dependent leaching characteristics of major and toxic elements from red mud. *International Journal of Environmental Research and Public Health*, Vol. 16, No. 11, (2019), 2046.
59. Suchita Rai et al., Neutralization and utilization of red mud for its better waste management, *World*, Vol. 6, (2012), 5410.
60. Investopedia, Horizontal Integration vs. Vertical Integration: What's the Difference?, https://www.investopedia.com/ask/answers/051315/what-difference-between-horizontal-integration-and-vertical-integration.asp (accessed on 26 July 2022).
61. Britannica, Bosnia and Herzegovina government and society, https://www.britannica.com/place/Bosnia-and-Herzegovina/Government-and-society(accessed on 26 July 2022).
62. Fotini Kehagia, A successful pilot project demonstrating the re-use potential of bauxite residue in embankment construction. *Resources, Conservation and Recycling*, Vol. 54, No. 7, (201), 417-421.
63. BBC, Hungary toxic spill plant reopens as villagers return, https://www.bbc.com/news/world-europe-11550419 (accessed on 26 July 2022).
64. Doris Schüler et al., Study on rare earths and their recycling. *Öko-Institut eV Darmstadt*, Vol. *49*, (2011), 30-40.
65. Europages, Steel Foundry Jelsingrad Livar, https://bit.ly/3zyRD6I (accessed on 26 July 2022).
66. European Commission, *Critical Raw Materials Resilience: Charting a Path towards greater Security and Sustainability*, 40 COM, 2020, 474 final, Brussels.
67. Basak Anameric and Komar Kawatra, Properties and features of direct reduced iron. *Mineral processing and extractive metallurgy review*, Vol. 28, No. 1, (2007), 59-116.
68. S. Agatzini-Leonardou, et al., Titanium leaching from red mud by diluted sulfuric acid at atmospheric pressure. *Journal of hazardous materials*, Vol. 157, No. 2-3, (2008), 579-586.
69. Satish Chandra, *Waste materials used in concrete manufacturing*, Westwood, New Jersey, Noyes Publications, 1996, 651 pages.
70. Rita Khanna et al., Red Mud as a Secondary Resource of Low-Grade Iron: A Global Perspective, Sustainability, Vol. 14, No 3, (2022), 1258.
71. Centre for European Policy Studies, *Assessment of cumulative cost impact for the steel and the aluminium industry final report aluminium*, 2013, https://op.europa.eu/el/publication-detail/-/publication/a2f56fcb-8d8d-4307-9a17-fcd1dea1fdec.
72. European Commission, Waste and recycling, https://environment.ec.europa.eu/topics/waste-and-recycling_en (accessed on 26 July 2022).
73. Halvor Dalaker, SINTERblog, https://blog.sintef.com/industry-en/red-mud-unnecessary-problem/ (accessed on 26 July 2022).

74. European Commission, Candidate Countries and Potential Candidates, https://ec.europa.eu/environment/enlarg/candidates.htm (accessed on 26 July 2022).
75. 2000/532/EC: Commission Decision of 3 May 2000 replacing Decision 94/3/EC establishing a list of wastes pursuant to Article 1(a) of Council Directive 75/442/EEC on waste and Council Decision 94/904/EC establishing a list of hazardous waste pursuant to Article 1(4) of Council Directive 91/689/EEC on hazardous waste (notified under document number C (2000) 1147) (Text with EEA relevance), 2000, Official Journal, L 226, 3-24. CELEX: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:32000D0532.
76. Western Balkans Investment Framework, Corridor Vc in Bosnia and Herzegovina, the road for Europe, https://wbif.eu/corridor-vc-bosnia-and-herzegovina-road-europe (accessed on 26 July 2022).
77. European Central Bank, *Financial Stability Review*, 2022, https://www.ecb.europa.eu/pub/pdf/fsr/ecb.fsr202205~f207f46ea0.en.pdf.
78. The Daily Star, Russia-Ukraine war fuels aluminium prices, https://www.thedailystar.net/business/economy/news/russia-ukraine-war-fuels-aluminium-prices-2979566, (accessed on 26 July 2022).
79. Xinlin Chen, Covid-19 impacts aluminium market, *Engineering and Mining Journal*, Vol. *221, No.* 3, (2020), 64-64.
80. World Bank, *World Bank Commodities Price Data (The Pink Sheet)*, 2022, https://bit.ly/3cLAcXH.
81. EU SCIENCE HUB, Policies and definitions, https://rmis.jrc.ec.europa.eu/?page=policies-and-definitions-2d5b5e (accessed on 26 July 2022.
82. CEE Bankwatch Network, Illegal lignite mine expansion in Bosnia and Herzegovina prompts NGO formal complaint, https://bit.ly/3OF9QDM (accessed on 26 July 2022).
83. R. G. Boutilier, L. Black and I. Thomson, From metaphor to management tool: how the social license to operate can stabilise the socio-political environment for business. International mine management 2012 proceedings, 20-21 November 2012, Melbourne, Australia, 227-237.
84. Sophia Lazaretou, The Greek brain drain: the new pattern of Greek emigration during the recent crisis, *Economic Bulletin*, Vol 43, (2016), 31-53