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Published in:
JOM

DOI:
10.1007/s11837-020-04493-x

Published: 01/01/2021

Document Version
Final published version

JOM, Vol. 73, No. 1, 2021
https://doi.org/10.1007/s11837-020-04493-x

Advances in the Circular Economy of Lanthanides

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Rare earth metals (REMs), classified as critical materials by the high-tech economies, are used in a variety of applications including catalysts, permanent magnets, phosphors, etc. They play a crucial role in the evolving technologies such as clean energy and high-tech military components. Figure 1a depicts the usage of REMs in different parts of electric vehicles (EVs) and smartphones, which are predominantly lanthanides (La, Ce, Pr, Nd, Pm, Sm, Eu, Gd, Tb, Dy, Ho, Er, Tm, Yb, Lu). Manufacturing of an EV consumes > 15 kg of REMs in different parts,[1] and a smartphone can consume up to 0.25 g of REMs. Figure 1b shows plug-in light EV sales worldwide from 2015 to 2020; the projection for 2020 was based on the available sales data up to July 2020.[2] The global fleet of EVs is estimated to reach about ten times more than the current ~ 13 million EVs in use. Consequently, the consumption of lanthanides is also expected to increase drastically.

REMs are found in the Earth's crust in different minerals such as allanite (hydrous silicate mineral), bastnaesite (fluorocarbonate mineral), gadolinite (silicate of yttrium), monazite (phosphate mineral), and xenotime (phosphate of yttrium).[1] Most REMs, except promethium, are even more abundant than Cd, Ag, Au, or Pt in the Earth's crust; however, they are often found in dilute concentrations in ores, making them challenging for the prevailing techno-economic extraction and environmental regulations. Furthermore, the relatively mineable ores of REMs are concentrated only in limited geographic locations of the world. For instance, China, which has led the world production of REMs for decades, accounts for $> 90\%$ of the global production and supply of primary REMs.[1]

The vital role of REMs for high-tech industry and their supply risk to a substantial extent within high-tech economies have pushed REM recoveries from waste streams and industrial side streams, which have been highlighted. Several secondary resources such as Nd-Fe-B permanent magnets (PMs), spent catalysts, super-alloy scrap, spent batteries, sludge, dusts, etc., are rich in REMs. However, until recently most of the REMs in such wastes have been lost into different unrecoverable fractions, and the recovery rate of REMs is generally very low. Therefore, efficient recoveries of REMs from the e-waste and industrial side streams are the key enablers of the move toward circular economy of lanthanides. To facilitate this move, besides designing recyclable products, effective waste management and innovative recycling technologies are essential.

Previously, *JOM* advisors of the Recycling and Environmental Technologies and Process Technology and Modeling technical committees of the TMS (The Minerals, Metals & Materials Society) have organized special issues focusing on improved extractions and recoveries of the strategic metals including REMs, "Cleaner Manufacturing of Critical Metals,"[3] and "Thermodynamic Modeling of Sustainable Non-Ferrous Metals Production".[4] For this special topic, original research and review papers focusing on improved recycling efficiency of lanthanides from both e-waste and industrial side streams were invited, and six articles were approved for publication after rigorous peer review by experts in the field.

The first paper, "Nitrophosphate Solution Purification by Calcium Precipitation as Gypsum" by Banihashemi et al., proposed that in the two-stage leaching method of REM from phosphate ores,

Fiseha Tesfaye, Mingming Zhang, and Hong Peng are Guest Editors for the Recycling and Environmental Technologies Committee; Process Technology and Modeling Committee; Energy Conversion and Storage Committee; and Energy Committee of TMS and coordinated the topic "Advances in the Circular Economy of Lanthanides" in this issue.

(Received November 5, 2020; accepted November 5, 2020; published online December 18, 2020)

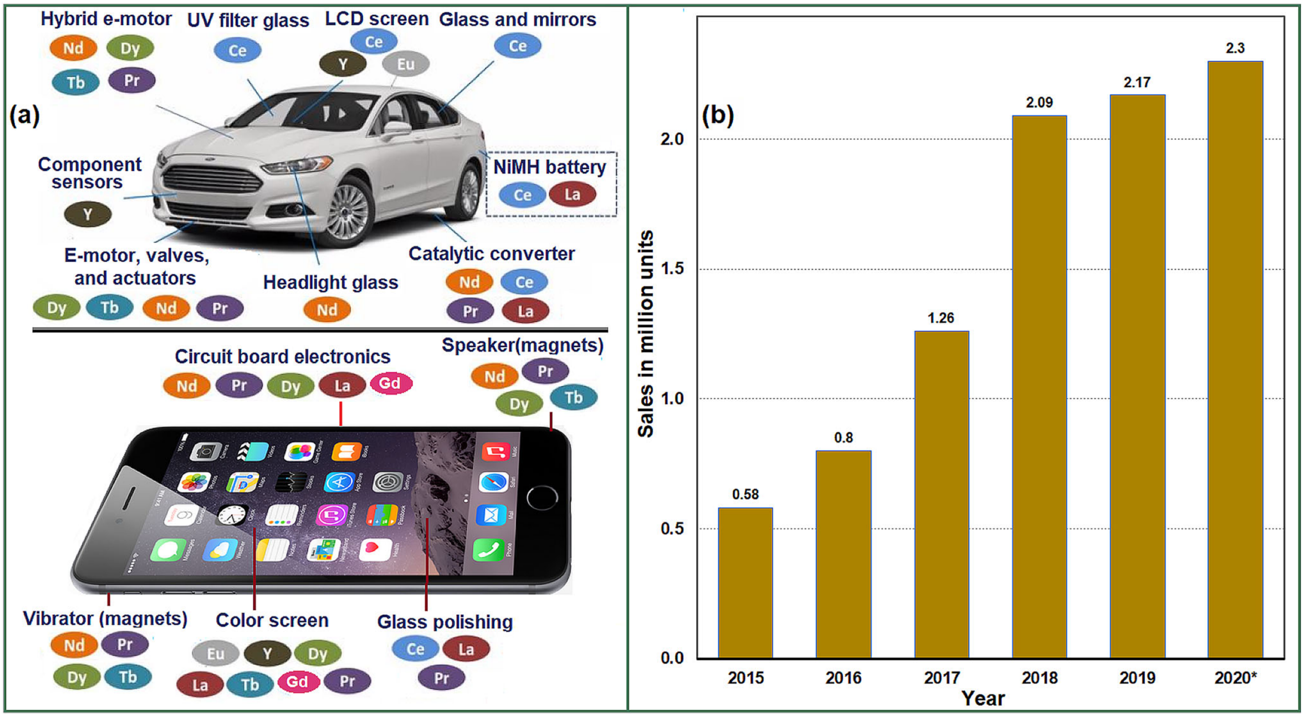

Fig. 1. (a) Typical REMs (mainly lanthanides) in parts of electric vehicles and smartphones and (b) estimated plug-in electric light vehicle sales worldwide from 2015 to 2020; data adapted from Ref. 2.

precipitation of calcium in the form of gypsum is an effective method for purifying the solution from calcium. This method can also be applied for the recovery of REMs from secondary resources. The second paper, "Hydrometallurgical Recycling of Rare Earth Metal–Cerium from Bio-processed Residual Waste of Exhausted Automobile Catalysts" by Ilyasa et al., investigated hydrometallurgical recycling of cerium from a secondary residue of exhausted auto-catalysts. They showed that cerium dissolution improves by up to 96% when HF is introduced into a H_2SO_4 solution. The third paper, "Adsorption–Desorption of La^{3+}, Eu^{3+} and Y^{3+} by $Mg(OH)_2$ Pretreated TP207 Resins" by Niu et al., revealed that the adsorption performance of Tp207 resin for REM ions is highly dependent on the pH value, and the authors proposed optimum desorption conditions.

The paper "Toward Closing a Loophole: Recovering Rare Earth Elements from Uranium Metallurgical Process Tailings" by Vaughan et al., reviewed the conventional and alternative REM processing options from uranium metallurgical process tailings including phytoextraction and other bio-technologies. The last two papers in this issue, "Microwave-Assisted Carbothermic Reduction of Discarded Rare Earth Magnets for Recovery of Neodymium and Iron Values" by Tanvar and Dhawan and "Experimental Determination of Phase Equilibria in the REM_2O_3-SiO_2 (REM = Y/Yb/La) Systems at Elevated Temperatures" by Xia et al., present interesting thermodynamic considerations for efficient recoveries of REMs from the e-waste stream.

As such, the peer-reviewed articles in this special topic should be of interest to a broad readership including those promoting sustainable production of the scarce lanthanides. All titles and authors of the articles published under the topic "Advances in the Circular Economy of Lanthanides" in the first issue of 2021 (vol. 73, no. 1) are listed below. The articles included can be fully accessed via the journal's page at: http://link.springer.com/journal/11837/73/1/page/1.

- "Nitrophosphate Solution Purification by Calcium Precipitation as Gypsum" by S.R. Banihashemi, B. Taheri, S.M. Razavian, and F. Soltani.
- "Hydrometallurgical Recycling of Rare Earth Metal–Cerium from Bio-processed Residual Waste of Exhausted Automobile Catalysts" by S. Ilyasa, H. Kima, and R.R. Srivastava.
- "Adsorption–Desorption of La^{3+}, Eu^{3+} and Y^{3+} by $Mg(OH)_2$ Pretreated TP207 Resins" by F. Niu, Z. Xie, C. Fu, H. Xu, D. Liu, X. Zhang, Y. Yang, and L. Shen.
- "Toward Closing a Loophole: Recovering Rare Earth Elements from Uranium Metallurgical Process Tailings" by J. Vaughan, K. Tungpalan, A. Parbhakar-Fox, W. Fu, E. Gagen, P.N. Nkrumah, G. Southam, A. Van der Ent, P. Erskine, P. Gow, and R. Valenta.
- "Microwave-Assisted Carbothermic Reduction of Discarded Rare Earth Magnets for Recovery of Neodymium and Iron Values" by H. Tanvar, and N. Dhawan.

- "Experimental Determination of Phase Equilibria in the REM_2O_3-SiO_2 (REM = Y/Yb/La) Systems at Elevated Temperatures" by L. Xia, D. Sukhomlinov, F. Ye, Z. Liu, and P. Taskinen.

ACKNOWLEDGEMENTS

Organizers of this topic thank all authors and reviewers that have contributed to the successful publication of this special issue. We are convinced that your expertise has resulted in an excellent issue on this timely topic of *JOM*. The authors are also grateful to the Academy of Finland (Decision Number 311537) and the CircVol 6Aika project for financial support as part of the activities of the Johan Gadolin Process Chemistry Centre at Åbo Akademi University.

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