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Energy materials redesign, reuse and repurpose

Cristina Pozo-Gonzalo,[ab] Bethan L. Charles,[c] Xiaolei Wang[d] and Erlantz Lizundia[ef]

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The transition from a linear economy towards a circular economy is the obvious choice towards more sustainable consumption and production practices and also offers significant environmental and societal benefits. This shift should provide improvements related to climate change and minimise waste and pollution generation, when supported by exhaustive environmental analyses. In the specific case of the transition towards clean energy technologies (*e.g.* solar cells, batteries and wind turbines), the depletion of vital and finite resources has impacted the design of new technologies that rely on low cost, abundant and safe materials and processes. It is known that the manufacturing of batteries and solar cells requires significant energy consumption. In fact, the energy consumption during battery manufacturing (>30–55 kW h per kW h of battery cell) is considerable (Degen *et al.*[1]).

Therefore, current research is devoted to mitigate climate change through different strategies. For instance, some approaches include: (i) redesigning materials and processes to increase device lifetime, (ii) reuse and repurpose of waste as a secondary source, and (iii) recycling of end-of-life devices to reduce waste generation. Such strategies, and many others, are proven to provide a significant decrease in the manufacturing cost, energy consumption and negative environmental impact (Babbitt *et al.*[2]). This themed issued entitled "Energy materials redesign, reuse and repurpose" aims to compile a series of innovative research work on greener materials and their sourcing, solar cells, life cycle assessment (LCA) and end-of-life treatment. This editorial summarizes the key findings of the manuscripts in the series.

Both the design of green materials and/or green processing of energy materials plays a key role towards sustainability. Foster and Bocharova *et al.* developed long-chain polyesters *via* melt copolymerization of cutin-inspired monomers (**https://doi.org/10.1039/D4SU00454J**). Such a bio-inspired polymer with semi-crystalline features shows excellent mechanical properties and represents an ideal platform to create the next generation of commodity thermoplastics that possess advantageous properties, inherent biodegradability, and feedstock stability. Meanwhile, Klaehn *et al.* developed a facile isolation of the valued metals of Ni and Co through co-crystallization forming a sulfate double salt from electrochemical leachates (**https://doi.org/10.1039/D4SU00303A**). This process reduces the total number of steps to isolate the desired metals while also reducing chemical waste generation without employing organic solvents, representing a promising alternative source of critical metals from spent lithium-ion batteries, for a secure and sustainable future supply of Li, Ni, and Co. Pozo-Gonzalo and Mecerreyes *et al.* (**https://doi.org/10.1039/D4SU00098F**) further summarized and extensively compared traditional battery manufacturing methods with the use of emerging waterborne binders, highlighting the benefits in terms of cost-effectiveness, environmental sustainability, and enhanced processing conditions. The integration of aqueous binders promises advancements and also shapes a strategic outlook for future research, contributing significantly to the sustainability of lithium-ion batteries manufacturing and recycling.

[a]*Instituto de Carboquímica (ICB-CSIC), C/Miguel Luesma Castán, 4, 50018 Zaragoza, Spain. E-mail: cpozo@csic.es*

[b]*Institute for Frontier Materials, Deakin University, Melbourne, Victoria, 3125, Australia*

[c]*School of Electrical, Electronic and Mechanical Engineering, Queens Building, University of Bristol, Bristol BS8 1TR, UK. E-mail: b.charles@bristol.ac.uk*

[d]*Department of Chemical and Materials Engineering, University of Alberta, 9211-116 Street NW, Edmonton, Alberta T6G 1H9, Canada. E-mail: xiaolei1@ualberta.ca*

[e]*Life Cycle Thinking Group, Department of Graphic Design and Engineering Projects, Faculty of Engineering in Bilbao, University of the Basque Country (UPV/EHU), Bilbao, 48013, Spain. E-mail: erlantz.liizundia@ehu.eus*

[f]*BCMaterials, Basque Center for Materials, Applications and Nanostructures, UPV/EHU Science Park, Leioa, 48940, Spain. E-mail: erlantz.liizundia@ehu.eus*

Perovskites have drawn huge attention for their promise as solar materials, recently achieving efficiencies of 26.7% and 34.6% for single junction and silicon tandem devices, respectively. However, these devices are notoriously short-lived and the presence of lead fuels raises questions on toxicity. Ouyang and Li *et al.* (**https://doi.org/10.1039/D4SU00431K**) review the current state of the LCA and sustainability analysis of perovskite/Si tandem solar cells. Special attention is drawn to analyse aspects such as the global warming potential, economic costs, and toxicity effects. Valadez-Villalobos and Davies (**https://doi.org/10.1039/D4SU00100A**) focus on remanufacturing processes for perovskite devices, including capture and recycling of lead. Both papers highlight the importance of reducing dependence on toxic solvents in perovskite recovery and remanufacture as vital in improving the environmental impact of these materials. Bai *et al.* (**https://doi.org/10.1039/D3SU00348E**) also focus on lead-containing material recycling. Results show that perovskite composites can be used in piezoelectric ceramic recycling at greatly reduced energy cost during initial manufacturing, offering a potential route for duel recycling of ceramics and halide perovskites.

As a widely recognized methodology to evaluate the environmental impact of materials and products throughout their life cycle (Chen *et al.*[3]), this themed issue also deals with the application of LCA to energy materials. Korre *et al.* (**https://doi.org/10.1039/D4SU00223G**) explored the upstream process for LIBs with particular emphasis on producing lithium carbonate from Chilean Atacama brines. The results highlight a large footprint from NaOH and sodium carbonate use, and the authors emphasize the need for increasing brine evaporation rates to reduce water resource stress in the region where raw battery materials are extracted.

Following the ongoing policy efforts to increase the circularity and reduce the environmental impact of the battery industry Rizos and Urban[4], considered the end-of-life treatment of spent battery materials has received much attention in this themed issue. As one of the largest streams of secondary sources of raw and critical materials in LIBs, Titirici *et al.* (**https://doi.org/10.1039/D4SU00427B**) focused on the recovery of high purity (99.8%) spent graphite from industrially sourced black mass. When compared with graphite production from coal, the recycled graphite offered 75 and 81% savings in energy and water consumption, respectively. As another relevant component in LIBs, the fabrication of cathodes utilizing spent materials is also an area of intense research. In this sense, Younesi *et al.* (**https://doi.org/10.1039/D4SU00131A**) proposed a new method for the upcycling of lithium cobalt oxide (LCO) into $LiNi_{1/3}Mn_{1/3}Co_{1/3}O_2$ (NMC111) materials by firstly leaching LCO with a citric acid followed by acetone antisolvent crystallization precipitation. This method avoids primary and hazardous extraction of cobalt, as the lithium cobalt citrate obtained acts as a precursor for NMC111 sol–gel synthesis.

Although it has not received a great deal of attention to date, the transport distance and cost of shipping electric vehicle batteries between end-use sector facilities and potential second-use locations is a matter that should not be overlooked when establishing a sustainable battery value chain. In this regard, Hatzell *et al.* (**https://doi.org/10.1039/D3SU00319A**) show the potential of machine learning approaches to identify the optimal locations for large LIBs recycling infrastructure using California as a case study.

References

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