

Beyond Lithium: A New Era of Sustainable Energy Engineering

Ben Bin Xu¹, Yinzhu Jiang², Terence Xiaoteng Liu¹, Zaiping Guo³, Guihua Yu⁴ and Maria-Magdalena Titirici⁵

Prof. Ben Bin Xu, Dr. Terence Xiaoteng Liu
Mechanical and Construction Engineering,
Faculty of Engineering and Environment,
Northumbria University,
Newcastle upon Tyne, NE1 8ST, UK
E-mail: ben.xu@northumbria.ac.uk

Prof. Yinzhu Jiang,
School of Materials Science and Engineering,
ZJU-Hangzhou Global Scientific and Technological Innovation Centre,
Zhejiang University,
Hangzhou 310027, P. R. China
E-mail: yzjiang@zju.edu.cn

Prof. Zaiping Guo,
School of Chemical Engineering and Advanced Materials,
The University of Adelaide,
Adelaide, SA 5005, Australia
E-mail: zaiping.guo@adelaide.edu.au

Prof. Guihua Yu
Materials Science and Engineering Program and Walker Department of Mechanical
Engineering
Texas Materials Institute, UT Energy Institute
The University of Texas at Austin,
Austin, TX 78712, USA
E-mail: ghyu@austin.utexas.edu

Prof. Maria-Magdalena Titirici
Department of Chemical Engineering,
Imperial College Road, Kensington,
London, SW7 2AZ, UK
E-mail: m.titirici@imperial.ac.uk

Since first commercialized by SONY in 1991, Lithium-ion batteries (LIBs) have played a vital role in the translational development of portable electronics and the electrification of transportation, which has re-shaped our life dramatically. However, there is an increasing concern regarding the resilience of supplying raw ingredients in LIBs production, including the unevenly distribution of lithium in the world (~40% in South America) and naturally insufficient in the Earth's crust (0.0017 wt%), the unethically sourcing of Co in the Democratic Republic of Congo, as well as the eccentric availability of graphite in only a few regions globally, predominantly in China. These concerns are further corroborated by the slow implementation of recycling strategies at a relevant industrial scale. Although the 'conventional' LIBs will likely continue to play a critical role in our sustainability roadmap towards Net Zero emission, it is highly desirable to explore future sustainable battery technologies to diversify the battery market to satisfy a variety of demands in energy storage and mobility as well as to ease the dependency on the critical materials.

Guided by above vision, the Special Issue of '*Beyond Lithium: A New Era of Sustainable Energy Engineering*' scopes the interdisciplinary research towards novel electrochemical energy conversion and storage technologies, with the aim to enable further fundamental understanding of disruptive structure-property relationships in new battery chemistries along with novel and battery recycle strategies for future. Apart from scanning the curriculum development, this editorial particularly highlights technical remits from the realization of frontier electrochemical energy storage system (i.e. metal and metal ion battery technologies (Na, K, Ca-, Al, Zn, etc), solid state batteries, dual/multiple ion batteries, flow batteries, etc) and battery recycling strategies (circular economy).

1. *The frontier electrochemical energy storage system.* Lithium Oxygen/air (Li-O/Li-Air) batteries, Lithium sulphur (Li-S) and Lithium Selenium (Li-Se) batteries are a group of redox batteries sharing the advantages of ultra-high capacity, long cycling life, environmentally friendly and low-cost due to S and/or Se cathode materials are used. But their intrinsic limitations such as low conductivity and S/Se shuttle effect etc, have been the major hurdles in this research field. Earth abundant elements to act as cation as a replacement to lithium has been discovered, including sodium (Na), potassium (K), magnesium (Mg), calcium (Ca), zinc (Zn) and aluminium (Al) etc., where most of these battery systems are under early-stage development at a relatively low Technical Readiness Level (TRL). Every component within those batteries is under discovery for performance improvement to a level with potential to replace LIBs, for instance, Sodium-ion batteries (SIB) and potassium-ion batteries (KIB), have been recently identified as emerging technologies to supplement, or even replace LIBs, especially in the applications of large-scale energy storage, with hugely reduced cost and relatively competitive cycling performance and capacity retention thanks from the Na and K metals' similar properties to Li. The electrolyte and its additives for aqueous zinc ion batteries (ZIBs) have been reviewed in this collection to provide future directions and insights for ZIBs' commercialization. Novel energy conversion and storage approaches are helpful add-on, such as thin film energy harvesting systems, liquid metal based energy systems, etc, to diversify the energy supply/distribution as per the regional needs. The above approaches are all promising in the development of frontier electrochemical energy storage system.

2. Battery recycling strategies and circular economy approach. While new discoveries and breakthroughs in battery technologies heavily underpin the areas of energy storage

technologies (high energy density and cycling performance), low-cost and sustainability, a circular economy approach enables an effective recycling strategy for Li-ion batteries as well as a promising alternative to extend the life cycle. Research in emerging battery technologies is a multi-faceted subject, therefore, a special issue in this area is timely and will encompass significant advances made in this crucially important research field. It is reported that a very small portion of batteries are currently being recycled worldwide, with some claims as low as 5%, it is imperative that we look at ways to increase this number through a combination of increasing the ease, speed and profitability of the process. There are many areas of battery recycling that are of great importance, now more than ever as the amount of battery increases, currently it is estimated that 80% of a battery can be recycled, but very limited successful cases in Li battery recycling have been proven economically friendly. The road towards a sustainable Li-battery life cycle remains yet to be achieved.

Finally, we anticipate this collection of papers to encompass the research of frontier energy materials to effectively address the challenge toward the Net Zero. We gratefully appreciate the support from the whole editorial team of Small and the reviewers. We would also like to take this opportunity to thank all authors who contributed to this collection.



Ben Bin Xu (FRSC, FIMMM, FRSA) is a Professor of Materials and Mechanics in the Department of Mechanical and Construction Engineering at Northumbria University, UK. Ben obtained his Ph.D in Mechanical Engineering (2011) at Heriot-Watt University in Edinburgh, then moved to the University of Massachusetts, Amherst (US, 2011-2013) to work as postdoc on a NSF project. Since joining Northumbria in 2013, Ben has established a multidisciplinary research group with diverse interests in energy materials and technology, materials chemistry, responsive materials/surface, soft matter, mechanics and micro-engineering.



Yin Zhu Jiang is a professor at School of Materials Science and Engineering in Zhejiang University, China. He received his Ph.D. degree from Department of Materials Science and Engineering from University of Science and Technology of China in 2007. He worked as a post-doctoral researcher in Heriot-Watt University, UK from 2007 to 2008 and an Alexander von Humboldt Fellow in Bielefeld University, Germany from 2008 to 2010. His research interests focus mainly on energy- related materials and electrochemistry, including rechargeable batteries, metal anodes, and solid electrolytes.



Terence Xiaoteng Liu is an Associate Professor and research group lead of Renewable Energy Technology and Materials group in Department of Mechanical and Construction Engineering, Faculty of Engineering and Environment, Northumbria University. He has extensive research experience in novel energy materials and electrocatalysts for advanced batteries, fuel cells, environmental remediation, etc. Terence's current research lies in materials and systems for energy generation and storage applications.



Zaiping Guo received a Ph.D. in Materials Engineering from the University of Wollongong in 2003. She joined The University of Adelaide as a Professor in 2021. Her research focuses on the design and application of electrode and electrolyte materials for energy storage and conversion, including rechargeable batteries, hydrogen storage, and fuel cells. Her research achievements have been recognized through numerous awards, including NSW Premier's Prizes for Science & Engineering (2020), ARC Queen Elizabeth II Fellowship (2010), ARC Future Fellowship (FT3, 2015), ARC Laureate Fellowship (2021), and the Clarivate Analytics Highly Cited Researcher Award (2018-2020).



Guihua Yu (FRSC, FInstP, FIAAM) is William Murray Professor of Materials Science and Mechanical Engineering at The University of Texas at Austin, affiliated with Texas Materials Institute and UT Energy Institute. Yu received B.S. degree with the highest honor from USTC, Ph.D. from Harvard University, followed by postdoc at Stanford. His research has been focused on rational design and synthesis of nanoarchitected polymeric materials and hybrid organic–inorganic nanomaterials, fundamental understanding of their chemical and physical properties, and exploration of their technologically important applications in energy, environment, and sustainability.



Maria Magdalena Titirici received her Ph.D. from the University of Dortmund. She then completed a postdoc and later became a group leader at the Max-Planck Institute of Colloids and Interface. She held positions at Queen Mary University of London between 2013 and 2019, first as a reader and then full professor. She is currently a chair in Sustainable Energy Materials at Imperial College London and RAEng Chair in Emerging Technologies. Her research is in the field of sustainable materials for energy storage and conversion.