Editorial

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Moving forward with batteries

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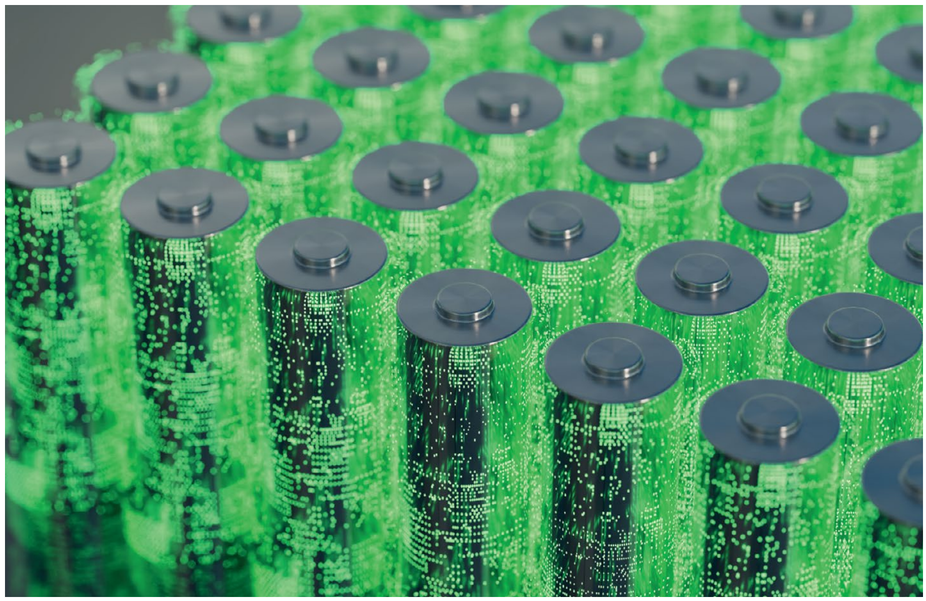
As the research community remembers John Bannister Goodenough for his contributions to the development of batteries, we reflect on his legacy, what it means to sustainability and where we go next in the quest for a more sustainable future.



Batteries have been widely deployed for electric vehicles (EVs) and the storage of the electricity produced from renewable sources such as wind and solar. The invention of rechargeable lithium-ion batteries (LIBs), in response to the oil crisis in the 1970s, has revolutionized not only the consumer electronics but also the broad energy research and practice landscape, making it possible to conceive an energy supply independent of fossil fuels — a major step towards a more sustainable future. Crucial contributions to the development of this technology came from one of the 2019 Nobel Laureates in Chemistry, John B. Goodenough, who recently passed away, leaving a lasting legacy that will take future battery innovations to a level far beyond our reach now.

The remarkable success of LIBs is the result of research and efforts by many. However, Goodenough played an outsized role in terms of the development of the cathode, the component that determines the amount of energy a battery can store. Almost 40 years after his discovery of the lithium cobalt oxide ($LiCoO_2$) cathode that helped usher in the rechargeable era, the chemistry or structure of the cathode sitting inside today's consumer electronics and EVs remains largely the same. For instance, the state-of-the-art cathodes have evolved to $LiNi_{1-x-y}Mn_xCo_yO_2$ (NMC) and $Li_{1+x}Ni_{1-x-y-z}Mn_yCo_zO_2$ (Li-rich NMC) formulations that enable more sustainable LIBs and allow EVs to travel longer distances on a single charge with reduced costs[1].

Goodenough had a grand sustainability vision during his search for cathode materials. He realized that, although favourable in terms of electrochemical activity, cobalt is problematic from a sustainability standpoint — the metal is scarce, mining it pollutes the natural environment and it has serious social impacts along the supply chain. As a result, he looked for alternative elements with less undesirable effects, such as manganese. In fact, he was instrumental in recognizing the utility of lithium manganese spinel ($LiMn_2O_4$) as a category of more affordable materials for cathodes. Although the market share of $LiMn_2O_4$ is relatively small now, novel cathode compositions in the spinel family are still being discovered, and Mn-rich layered oxides are receiving growing interest as a promising class of cathodes for next-generation LIBs[1,2].

Goodenough's work continued to be innovative until late in his career. In his 70s, he identified lithium iron phosphate ($LiFePO_4$, LFP) as another major group of cathode materials that crystallize in a stable ordered olivine structure and show excellent safety, long cycle life and fast charge–discharge performance[3]. Nowadays, LFP is gaining terrain rapidly in the manufacturing of batteries for EVs thanks also to its more sustainable nature.

Nature Sustainability has been actively highlighting the most recent developments in batteries. An earlier *Nature Sustainability* Expert Panel emphasized the need to consider sustainability as an essential dimension to the future of batteries. In this context, the featured paper on the cover of this issue presents the sort of advance much needed by the sustainability community[4,5]. Taking advantage of the abundance and low cost of the zinc anode, the intrinsic safety of the aqueous electrolyte and the high energy density, the authors moved rechargeable zinc metal batteries one important step closer to application by raising the Coulombic efficiency — a metric indicating the battery cycle life — to a new record high under conditions for practical implementation[6]. Even in a scenario in which less sustainable materials such as $LiCoO_2$ have to be used, a way out would be to recycle or even upgrade the materials from the end-of-life devices as reported in another recent *Nature Sustainability* publication[7,8]. These are certainly not the only work worth highlighting here. Instead, the breadth of topics we have published in the battery space suggests that sustainable batteries are an area of great potential.

Goodenough always devoted his broad knowledge in mathematics, physics, materials and chemistry to find engineering solutions. This philosophy is perfectly aligned with what sustainability research is ultimately aiming for — finding holistic solutions that draw from many types of knowledge. We value multidisciplinary research and continue to encourage researchers with different expertise to collaborate to develop fresh ideas and disruptive innovations that could unlock a new revolution in battery technology.

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