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Horizons Community Board collection: setting new trends in energy storage and harvesting through innovative approaches

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The demand for efficient and sustainable energy solutions is outpacing the development of advanced materials and technologies for energy storage and harvesting. To address this urgent need, innovative strategies are being explored to enhance energy efficiency and sustainability. Guest edited by *Materials Horizons* and *Nanoscale Horizons* Community Board members Edison Huixiang Ang, National Institute of Education, Nanyang Technological University, Singapore, and Satyajit Ratha, Indian Institute of Technology Bhubaneshwar, India, this collection highlights the latest breakthroughs in energy storage and harvesting. It showcases key innovations and future directions, emphasizing the interdisciplinary efforts at the interfaces of chemistry, physics, and nanotechnology to develop cutting-edge solutions.

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Cutting-edge materials for energy storage

Metallenes, a class of two-dimensional materials with atomic thickness and precisely controlled surface atomic arrangements, exhibit unique physicochemical properties due to their under-coordinated metal atoms. These characteristics make metallenes highly competitive candidates for energy-related electrocatalysis and conversion systems. Recent advancements in metallene synthesis and characterization have enabled the fine-tuning

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of their catalytic activity through chemical modifications of their surface and subsurface atoms. This has led to significant progress in their application as electrocatalysts for oxygen reduction, hydrogen evolution, alcohol and acid oxidation, carbon dioxide reduction, and nitrogen reduction reactions (**https://doi.org/10.1039/D2MH01213H**). Simultaneously, the rise of multifunctional wearable electronics has spurred the development of flexible energy storage devices. Novel electrodes with sophisticated designs, such as serpentine, auxetic, and biomimetic structures, are crucial for achieving flexible batteries and supercapacitors that maintain performance under mechanical deformation. Current research focuses on two-dimensional (2D) planar and three-dimensional (3D) interconnected architectures, assessing key tuneable geometrical parameters to enhance performance, and overcome practical application challenges (**https://doi.org/10.1039/D3MH00045A**). Additionally, a novel strategy involving two-dimensional encapsulation has led to the creation of high-performance fluorinated carbon cathodes composed of a fluorinated carbon/graphdiyne heterostructure (CF_x/GDY). This structure strengthens the contact between CF_x particles and additives, improving charge-transport kinetics and lithium-ion diffusion dynamics. As a result, these electrodes exhibit enhanced voltage platforms, battery rate performance, and energy density, showcasing the potential of GDY encapsulation in improving lithium primary batteries (**https://doi.org/10.1039/D2MH00635A**). Furthermore, hybrid energy storage systems, combining capacitor-type cathodes with battery-type anodes, offer the potential for high energy density, fast rechargeability, and long-cycle stability. Researchers have synthesized 3D nitrogen-doped hierarchical porous graphitic carbon (NHPGC) frameworks using Co–Zn mixed metal–organic frameworks (MOFs) as cathode materials and SnO_2@NHPGC as anode materials. This combination achieves ultrahigh energy density, fast rechargeable capability, and impressive cycling stability, marking a significant step forward in hybrid energy storage technology (**https://doi.org/10.1039/D3MH01473H**). Recent research has concentrated on enhancing the energy storage capabilities of dielectric capacitors through increased polarization and improved voltage endurance, resulting in the achievement of ultrahigh ferroelectric polarization in $(1-x)Ba_{0.15}Ca_{0.85}Zr_{0.1}Ti_{0.9}O_3$–$x$$Bi(Zn_{2/3}Ta_{1/3})O_3$ solid-solution ceramics with a record energy storage density of 8.03 J cm^{-3}. These materials demonstrate exceptional performance in polarization fatigue, energy storage stability, thermal stability, and discharge properties (**https://doi.org/10.1039/D4MH00322E**). Concurrently, innovative strategies in dielectric capacitors utilizing polyetherimide (PEI) and boron nitride nanosheets (BNNSs) have been explored to optimize energy storage performance (**https://doi.org/10.1039/D3MH00907F**). The sodium-ion system is the most sought-after battery chemistry after lithium-ion, as it has been known to the scientific community for a long time. However, it was not thoroughly investigated until the genuine bottlenecks associated with lithium-ion systems became more prominent. Nevertheless, sodium-ion chemistry still faces several challenges that hinder its commercialization, with one of the primary obstacles being the identification of a stable cathode material. Although transition metal oxide cathodes show promise, they suffer from stability issues caused by phase transitions and poor storage characteristics due to their sensitivity to humidity. A recent study outlines these challenges, potentially guiding researchers in developing solutions to achieve stable and advanced cathode materials for sodium-ion batteries (**https://doi.org/10.1039/D1NH00585E**). A cumulative approach, through the combination of theoretical analysis and experimental verification can provide a precise and more coherent solution to the wide range of issues arising in the case of Li–S batteries. A recent study introduces a uniquely designed cobalt-doped vanadium nitride, supported by a nitrogen-doped carbon framework (Co-VN/NC), which acts as an excellent sulfur host, with the initial discharge capacity reaching as high as 1521 mA h g^{-1} at 0.1C. The Co-VN/NC shows much improved polysulfide anchoring behaviour and its catalytic nature enhances the kinetics of the polysulfide conversion process. The significant impact of the Co-VN/NC on the Li–S battery, as a host material, has been further corroborated by theoretical analyses (**https://doi.org/10.1039/D1NH00512J**). The anode plays a significant role in a lithium-ion battery, currently dominated by graphitic materials. However, a novel alloy-type anode material, based on germanium, has been reported recently. For the first time, a binder-free CNT-germanium anode has been fabricated through an electrophoretic deposition process, which will reduce fabrication costs and improve the cycle performance of the cell (**https://doi.org/10.1039/D3NH00501A**). Aqueous lithium-ion batteries (ALIBs) have recently drawn significant interest due to their high-rate capability, safety, and cost-effectiveness. However, strategically designing compatible electrodes (anode and cathode) in a hybrid configuration is essential to achieve optimum device performance. A recent study shows that when a $LiMn_2O_4$ cathode is coupled with a V_2O_5/graphene composite anode, the combination outperforms most of the ALIBs reported in the literature. The specific power and specific energy of the configured device can reach values of 650 W kg^{-1} and 81.5 W h kg^{-1}, respectively (**https://doi.org/10.1039/D3NH00579H**). As a disruptive energy storage system, both Zn–air and Zn-ion batteries are being explored. Zn-ion batteries are of great interest since they run on aqueous electrolytes, which offer safety. Recent studies are specifically focused on the synthesis of novel materials for anode (**https://doi.org/10.1039/D2NH00354F**) and cathode fabrication (**https://doi.org/10.1039/D3NH00576C**). A prototype fibre-shaped aqueous zinc-ion battery (FAZIB) has been reported by implementing novel 3D N-doped/defect-rich $V_2O_{5-x}\cdot nH_2O$ nanosheets (DVOH@NC) as fibrous cathodes for aqueous zinc-ion batteries. The DVOH@NC cathode was obtained *via* an *in-situ* anodic oxidation route, yielding excellent capacitive performance, and outperforming previously reported fibrous vanadium-based cathode materials (**https://doi.org/10.1039/D2NH00349J**). Apart from Zn-ion systems, significant progress has also been seen in the case of

Zn–air batteries (**https://doi.org/10.1039/D3NH00108C**; **https://doi.org/10.1039/D2NH00455K**).

Advanced technologies for energy harvesting

Recent advancements in energy storage and harvesting technologies showcase significant strides towards sustainable and efficient energy solutions. A variety of novel approaches are emerging, each contributing to this progress in unique ways. Piezocatalysis has gained attention for green hydrogen production, using innovative UiO-66(Zr)-F_4 metal–organic framework (MOF) nanosheets. These nanosheets achieve high hydrogen evolution rates under ultrasonic vibration, leveraging fluorinated ligands to enhance the piezoelectric response and convert mechanical energy into chemical energy (**https://doi.org/10.1039/D1MH01973B**). Similarly, triboelectric nanogenerators (TENGs) harvest mechanical energy from the environment using oxidation-resistant pure copper nanowires (CuNWs) as electrodes. These devices exhibit exceptional open-circuit voltage and power density, making them suitable for advanced healthcare and electronics applications (**https://doi.org/10.1039/D3MH00404J**). Another innovative approach involves two-dimensional nanofluidic membranes that incorporate cellulose nanofibers and molybdenum oxide (CNF/MoO_3) for osmotic energy harvesting. These membranes leverage surface plasmon resonances (SPR) of MoO_3 to achieve high-performance solar-osmotic energy conversion (**https://doi.org/10.1039/D4MH00286E**). Additionally, dual-mode thermal management materials derived from sustainable cellulose and lignin provide sub-ambient radiative cooling and solar heating capabilities, enhancing building energy efficiency (**https://doi.org/10.1039/D4MH00172A**). Transpiring wood, with enhanced moisture exchange rates, offers effective indoor climate regulation and reduces energy consumption (**https://doi.org/10.1039/D2MH01016J**). Electrochromic energy storage devices integrate energy harvesting and storage functionalities, enabling real-time energy monitoring through colour changes (**https://doi.org/10.1039/D2MH00845A**). The integration of energy-harvesting systems into wearable forms, such as textiles, shoes, and wristbands, has gained momentum with the advent of nanogenerators like piezoelectric nanogenerators (PENGs) and TENGs, which are compact and lightweight. Magnetic nanogenerators, a new class of materials, operate through the application of an external magnetic field. This magnetic field effectively separates ions, creating pools of positive and negative charges that can be utilized for effective energy generation (**https://doi.org/10.1039/D2NH00323F**). These advancements in energy storage and harvesting technologies are paving the way for a sustainable future, demonstrating the potential of cutting-edge materials and innovative approaches in meeting energy demands and promoting environmental sustainability.