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Article

Smart materials for sustainable energy

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Abstract: In the new era of technologies, different smart or responsive materials are used which can respond to external stimuli, such as a specific amount of mechanical stress, pressure, temperature, pH, or sunlight radiations, by modifying their shape or dimensions or mechanical properties. As global temperatures rise and weather patterns become more erratic and severe. The risk to communities with energy-passive structures is growing, smart materials such as smart rooftops, thermoelectrics, photovoltaics, pyroelectrics, chromoactive, photoluminescent, as well as other innovations, help to conserve renewable energy smartly and sustainably. This review paper reflects on the applications of different smart materials as renewable smart resources. Intelligent quantum dot solar cells, Schottky solar cells, organic thin-film photovoltaic cells, dye-sensitized solar cells (DSSCs), and organic-inorganic heterojunction solar cells have high conversion efficiency, low cost, and possess wide absorption spectra that reach the near-infrared range. Biomechanical energy can be transformed into green energy using triboelectric and piezoelectric-based smart nanogenerators such as zinc oxide nanowires. Shape memory materials such as Nitinol (NiTi) have been embedded in the wind turbine blades to enhance aerodynamic efficiency. Piezoelectric nanogenerators can convert mechanical energy directly into electrical energy by using wireless sensors to harvest energy from moving water in hydroelectric power plants. Thermoelectric materials such as silver antimony telluride (AgSbTe2) offer a sustainable energy option, which employs industrial waste heat to produce power. Smart materials like graphene are more reliable and effective than carbon nanotubes for storing green hydrogen. Smart non-enzymatic biofuel cells are used in biomedical gadgets such as anesthesia machines and pacemakers, which are self-powered and have great sensitivity. Shape memory materials (SMM) are introduced in natural gas and oil reservoirs because they offer exceptional qualities such as the shape memory effect (SME), lightweight, corrosion resistance, and superelasticity, which enhance the performance and robustness of offshore industries. These new advancements, challenges, and applications of smart materials for renewable energy are covered in this review paper.

Keywords: biofuel; dye-sensitized solar cells; green hydrogen; photovoltaics; piezoelectric; smart materials; stimuli; triboelectric

1. Introduction

Various materials and techniques used have a significant impact on the environment and the economy [1–3]. Therefore, the ability to choose from numerous environmentally friendly and cost-effective options without compromising on material efficiency, structural integrity, longevity, cost, and industrial integrity is crucial. Advanced technologies and high-performance materials are continuously being developed to meet these requirements, offering innovative solutions to long-standing issues. These solutions provide benefits across various aspects, including structural strength, environmental impact, maintenance, and repair. Smart materials and smart structures are two categories worth exploring [3–5]. Several researchers have pioneered the study and application of smart materials in smart structures. Smart materials, such as shape memory alloys, magnetostrictive materials, piezoelectric materials, and Titanium Dioxide-coated nanomaterials, and their architectural applications in smart structures, have been extensively detailed.

The future of smart materials needs to focus on sustainability, surpassing current standards. We must prioritize the development of smart materials derived from natural sources, putting sustainability at the forefront rather than solely emphasizing their smart properties. Fortunately, nature provides abundant resources for renewable materials such as cellulose, lignin, chitosan, gelatine, starch, polylactic acid (PLA), and polyglycolic acid [5–7]. These materials can be processed into various forms, including nanocrystals, nanofibers, nanopowders, emulsions, gels, and composites [6–9]. Additionally, inorganic materials like carbon-based materials can be derived from nature through various treatment processes. By combining inorganic materials with sustainable alternatives, we can enhance sustainable materials' mechanical, electrical, and chemical properties without compromising their sustainability goals. **Figure 1** portrays the evolution of smart materials for the energy storage market over a few years. Chemosphere is the largest and most productive publication that publishes documents on this topic, followed by Science of the Total Environment, ACS Applied Materials and Interfaces, Environmental Research, and Nanoimpacts as shown below.

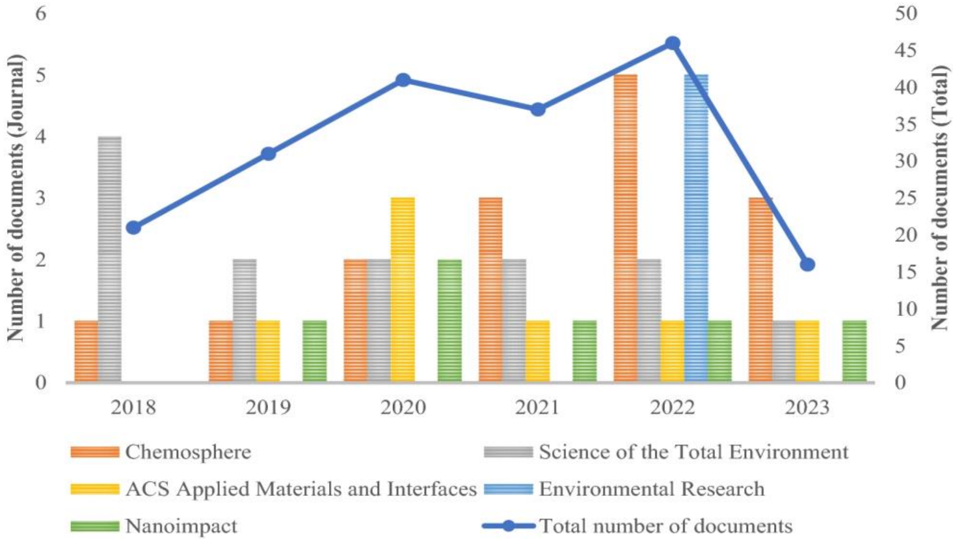

Figure 1. Representation of smart materials market size in 2018 to 2023 [10]. (Reproduced with permission).

2. Smart material

Smart materials can respond to changes in electricity, magnetic waves, or heat. They can sense and adapt to environmental stimuli, integrating functionality into their structures. Smart structures often incorporate these materials, possessing both compositional and structural adaptability. Smart materials demonstrate immediate and innate responsiveness to environmental changes, often exhibiting actions or actions in response to stimuli. These stimuli and responses can vary, encompassing electrical, chemical, radiant, thermal, magnetic, etc. Smart materials can be classified into several categories:

Piezoelectric materials undergo mechanical changes when subjected to electric charge or voltage fluctuations, known as the direct and converse effects [6].

Electrostrictive materials: Similar to piezoelectric materials, they produce displacements in response to electric fields, with the mechanical change proportional to the electric field’s square.

Magnetostrictive materials: When exposed to a magnetic field (and vice versa), these materials undergo induced mechanical strain, finding applications as sensors and/or actuators [7].

Shape memory alloys: These alloys undergo phase changes with thermal variations, facilitating shape changes. They regain their original shape when heated to high temperatures.

Optical fibers: Utilizing polarization, phase, intensity, or frequency, these fibers determine various parameters such as strain, temperature, electrical/magnetic fields, and pressure, making them excellent sensors [8].

Smart materials offer several advantages:

- Cost-effectiveness.
- High strength and toughness.
- Enhanced durability.
- Resistance to chemical corrosion and abrasion.
- Resilience against natural disasters.
- Easy manufacturing and installation procedures.

2.1. Shape memory alloys (SMAs)

These are a notable type of smart material, capable of returning to their original shape after deformation. They find applications in couplings, actuators, and various other fields, owing to their lightweight nature and solid-state operation. SMAs exhibit excellent thermal conductivity, providing rapid responses to heat application. Moreover, they serve as both actuators and sensors, earning them the title of smart or intelligent materials. Commonly available SMAs include Cu-Al-Ni and Ni-Ti alloys, with variations made by alloying zinc, copper, gold, iron, etc. [8]. SMAs exist in different crystal structures, characterized by the recovery of large strains in response to temperature-induced phase transformations between martensite and austenite phases. They are typically fabricated through casting or induction melting methods [9,10].

2.2. High temperature shape memory alloy (HTSMA)

These are advanced materials called Zr-based quasi-binary intermetallics. They are special as they can handle high temperatures, like up to 1100 Kelvin [11–13]. This makes them perfect for “shape memory,” where they remember their original shape even after being bent or deformed. Scientists are particularly interested in alloys like Ni-Ti-Zr, Ni-Ti-Hf, and Zr-Cu since they offer this high-temperature shape memory effect without breaking the bank as shown in **Figure 2**.

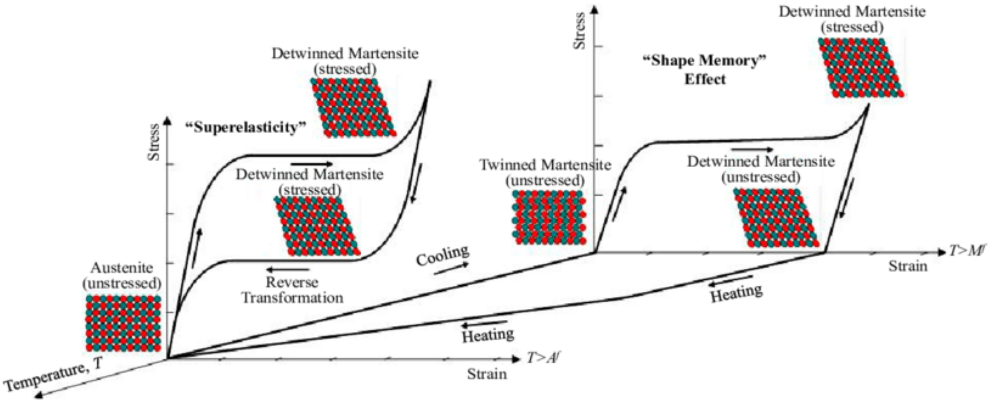

Figure 2. The behavior of superelastic shape memory alloy SMA material, based on phase transformation [14] (Reproduced with permission).

2.3. Magnetostrictive material

Think of materials like iron, nickel, and cobalt. When you expose them to a magnetic field, they change their shape or dimensions a bit. This property, called magnetostriction, is super useful because these materials can convert magnetic energy into movement and vice versa. This makes them perfect for making things like sensors and actuators, which are devices that respond to changes in their environment. Scientists have even found ways to enhance this effect in special alloys like Terfenol-D, which combines rare earth materials with iron. It's like getting the best of both worlds: strong magnetostriction without needing a strong magnetic field [10–15].

2.4. Piezoelectric materials

Imagine if certain materials could get charged up when you apply electricity to them, and then if you squish or stress them, they release that charge. That's what happens with piezoelectric materials like quartz or Rochelle salt. They're like little energy transformers, converting electrical energy into mechanical energy and back again. Scientists measure this transformation using the piezoelectric charge coefficient, which tells us how much charge a material produces when you apply a force to it. Piezoelectric patches are an essential element of smart structures, which ensure stability and performance by suppressing vibrations on small plates. Active Sound Control is utilized to eliminate various types of unwanted noise. Its significance lies in maintaining a healthy workplace environment, and preventing potential hearing loss due to prolonged exposure to loud noises [16].

Active control for shape maintains precise dimensions in structures such as reflectors and antennas, which is particularly crucial in lightweight materials and environments prone to thermal distortion, ensuring optimal performance. Active Health Maintenance involves the integration of actuators and sensors within structural panels to regulate integrity and detect defects early on. This proactive approach provides valuable insights into structural health and longevity [17–19].

3. Innovative techniques in smart structures

Smart windows: Windows incorporating suspended particle device technology act as "light valves," efficiently regulating the amount of light passing through them, as depicted in **Figure 3**. **Figure 3A** shows the visible electromagnetic wave that will be transmitted, and infrared is blocked. It is composed of $(SiO_2/Air)N$ photonic crystal. By filling the cavity layer with water, visible and IR electromagnetic waves will be transmitted, as clear in **Figure 3B**. N clarifies the number of times the photonic crystal periods will be repeated. The proposed smart windows structure will be deposited on a SiO_2 substrate. These windows offer energy savings, cost efficiency, and affordability. The increasing architectural trend toward using more glass, coupled with the demand for energy conservation, presents a unique opportunity for smart windows [20–25].

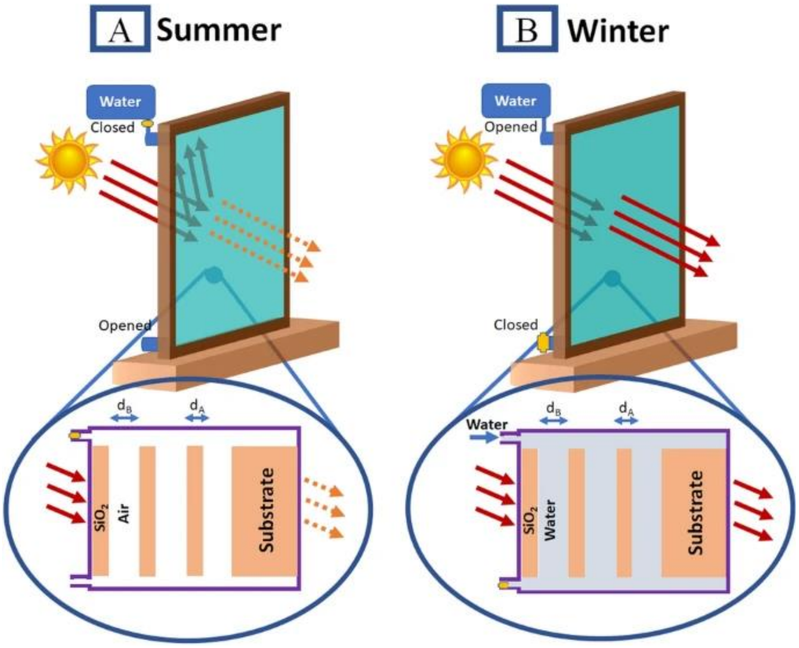

Figure 3. Schematic diagram of proposed smart windows, **(A)** in summer, visible electromagnetic waves will be transmitted and infrared radiation (IR) will be blocked; **(B)** in winter, visible and IR electromagnetic waves will be transmitted [25] (Reproduced with permission).

Smart shades: Smart shades, composed of zinc and steel, utilize shape memory alloy wires to monitor sunlight entering structures and regulate CO_2 levels. They include a "smart window shade," which autonomously adjusts its position. Instructions can be remotely distributed via a computer terminal, storing hand adjustments alongside current room conditions. The shade automatically adapts to lighting and temperature changes within the room [24–28].

Roofing: Photovoltaic modules integrated into roofing materials and mounted on rooftop racks generate electricity from sunlight, powering household needs. While initial installation costs are high, maintenance costs are low. Evaluations consider the energy payback time and CO emissions associated with producing and maintaining photovoltaic roof systems. Photovoltaic energy offers significant potential for sustainable power generation.

Ceilings: Ceilings are equipped with antibacterial coatings that disrupt the cellular membranes of certain microorganisms, preventing their proliferation and survival. These coatings control odor and stain-causing bacteria on ceiling tiles, typically utilizing water-resistant polymeric surface coatings. Incorporating antibacterial agents offers an alternative to systemic antibiotic use, particularly as the emergence of drug-resistant bacterial strains limits antibiotic efficacy.

Smart concrete: Carbon fibers added to concrete enable the detection of stress and small deformations, enhancing structural monitoring. Carbon-fiber reinforced plastic (CFRP) structures utilize a distributed sensor network of conductive carbon fibers, strategically placed on structures to detect stress [29].

Smart bricks: Bricks equipped with sensors, signal processors, and wireless communication links, provide early warnings of hidden stresses or damage caused by natural disasters. These bricks help regulate temperature, vibration, and movement within structures. The widespread adoption and implementation of smart structural mechanisms in design, construction, and infrastructure maintenance are essential for enhancing performance, functionality, safety, and reliability, especially in areas prone to natural disasters.

Zero energy buildings (ZEB): Zero energy buildings (ZEBs) emit zero carbon emissions annually by minimizing energy consumption and utilizing renewable energy sources. Definitions of ZEBs vary based on energy consumption levels and regulatory requirements. Key terms for defining ZEBs include zero site energy, zero source energy, total zero energy discharges, total cost, off-grid capability, and energy surplus. ZEBs represent a highly energy-efficient building type that relies on renewable energy sources to achieve zero net energy consumption from non-renewable sources [26–30].

Smart meters represent a key advancement in modern energy systems, particularly in the context of smart grids. They allow for remote energy consumption monitoring, covering electricity, water, and gas usage, providing more detailed insights than traditional meters. A notable feature of smart meters is their utilization of rapid, reliable, and secure data communication networks to oversee complex power systems effectively. The system architecture consists of three main components: the internal residential network, which includes metering and sub-metering infrastructure, the communication network, and the infrastructure for data collection and management [31–33].

Today’s architectural endeavors often draw inspiration from historical practices, integrating age-old wisdom with modern advancements. A significant shift is seen in adopting these practices within smart structures, where the focus lies on creating autonomous systems.

Concrete-Concrete, which is a fundamental building material, holds immense potential when infused with smart capabilities. Imagine concrete that can autonomously monitor, regulate, adapt, and repair itself without human intervention. Emerging technologies such as nanometers and biomimetic materials offer promising avenues for enhancing concrete’s properties, enabling it to take on skin-like forms and bolstering its resilience. Nano-technology, prevalent in space exploration, pharmaceuticals, and various industries, is gradually finding its place in construction. As we look towards the future of building, incorporating nano-tech materials promises to revolutionize the industry. Transforming existing building stock into energy-producing structures requires innovative approaches, particularly in renewable energy integration. Stricter energy standards demand solutions that optimize efficiency while minimizing environmental impact [30–34].

Smart technology interventions address common challenges faced in building design and construction. Advanced insulation materials, like fiber-reinforced blankets and vacuum-insulated panels, offer superior thermal performance without adding bulk. Additionally, technologies enhancing transparency, self-cleaning, and anti-reflectivity contribute to buildings' aesthetic and functional aspects.

Transparent wood: This emerges as a standout material, offering superior insulation and strength compared to traditional alternatives [35]. Its biodegradability makes it an eco-friendly choice, aligning with the principles of smart building development. Shapeshifting metals proves invaluable in constructing resilient buildings, especially in disaster-prone regions. Incorporating sustainable materials like straw presents a cost-effective and eco-conscious solution, offering enhanced insulation and significant energy savings [36]. Biodegradable materials address concerns about construction waste and environmental impact, paving the way for more sustainable practices. Moving beyond materials, sustainable technology encompasses a holistic approach toward construction, focusing on environmental, social, and economic factors. Green technologies such as solar power, smart appliances, and cool roofs play a pivotal role in reducing carbon footprint and promoting energy efficiency. Sustainable resource sourcing emphasizes the principles of reducing, reusing, and recycling, while innovative solutions like electrochromic smart glass optimize building performance and comfort [36]. Water efficiency technologies tackle the pressing issue of water scarcity, offering solutions for conservation and reuse. By integrating these technologies into building design and construction, we meet our present needs and ensure a sustainable future for generations to come. The 4th International Conference on Low Carbon Asia & Beyond (ICLCA’18) brought together folks from Asia and beyond. Held in Johor Bahru from August 24th to 26th, 2018, it was made possible through a fruitful partnership with Universiti Teknologi Malaysia (UTM) and its Low Carbon Asia Research Centre. This collaboration has fostered strong connections with international research institutions dedicated to reducing CO_2 emissions. Guest editors were tasked with selecting articles that showcased innovative solutions and ideas presented during the conference, focusing on energy-related research. Building upon the groundwork laid at the PRES 2006 conference, efforts to promote energy efficiency and optimize renewable energy use have been a cornerstone of this ongoing endeavor [36–38].

4. Control strategies

SMART materials possess adaptive characteristics that make them suitable for energy conversion and storage applications. Their responsiveness to external stimuli allows for dynamic adjustments, enhancing overall system efficiency. Moreover, SMART materials often exhibit non-linear behavior, which can be exploited to improve energy conversion efficiency from diverse and fluctuating sources. Recent advancements in SMART materials research include developing self-healing materials, nanostructured materials with enhanced properties, and integrating SMART materials into flexible and wearable devices for energy extraction [39,40]. Additionally, ongoing research explores integrating multiple SMART materials in hybrid systems to enhance energy capture efficiency and system adaptability. The potential applications of SMART materials extend to autonomous sensor networks, construction materials for energy-efficient buildings, and biomedical devices powered by energy harvested from the human body [40]. Similarly, thermoelectric materials demonstrate the Seebeck effect, where an electric voltage is generated in response to a temperature gradient across the material. This effect occurs due to the movement of charge carriers in reaction to temperature variations [41]. Thermoelectric materials hold promise for converting waste heat into electrical energy, with applications in industrial processes, automotive emissions, and wearable technology powered by body heat. Innovative control techniques significantly depart from traditional static control methods in the realm of SMART (self-monitoring, analyzing, and reporting technology) materials-based energy conversion and storage systems. These pioneering approaches leverage real-time data analysis, adaptive algorithms, and predictive modeling to optimize energy capture, conversion, storage, and overall system performance [42]. The fusion of SMART materials with intelligent control systems presents a distinct opportunity for heightened flexibility, efficiency, and longevity. Establishing a real-time feedback loop is a foundational element of intelligent control systems. Equipped with sensors, the system continuously gathers data on ambient variables, energy source properties, and material dynamics. This instantaneous data transmission enables constant monitoring of system performance and prompt response to any changes within the control system.

Adaptive algorithms are custom-tailored to extract insights from data, adapt to dynamic conditions, and make informed decisions. Leveraging machine learning algorithms, past data is analyzed to identify patterns, correlations, and nonlinear phenomena. This adaptive learning empowers the control system to forecast optimal energy conversion and storage parameters across various scenarios. Intelligent control techniques dynamically adjust energy harvesting and storage parameters using real-time data and predictive insights [41]. For instance, in a piezoelectric energy harvester, the control system adapts the harvester's resonance frequency to match incoming vibrations, thereby enhancing energy collection efficiency. Real-time intelligent algorithms effectively manage energy distribution by predicting future energy demand patterns. This facilitates efficient energy allocation for current consumption or storage, reducing inefficiencies and enhancing system self-sufficiency.

Predictive maintenance is employed through ongoing sensor data analysis to identify patterns indicative of SMART material wear and tear. This proactive approach helps prevent premature deterioration and prolongs the device's lifespan. The adaptability of intelligent control systems plays a crucial role in handling the unpredictability of energy sources and environmental conditions. The system adjusts settings in response to energy source fluctuations, ensuring optimal energy capture and conversion regardless of changing circumstances. These intelligent control techniques continuously evolve by acquiring knowledge from incoming data, and refining models and algorithms. As a result, the system delivers more accurate predictions, greater efficiency, and improved performance as it adapts to evolving conditions. Some systems may incorporate user-defined parameters and preferences, allowing individual users to influence the control system's decision-making process. The control system can also provide users with valuable insights and recommendations, empowering them to make well-informed decisions. The inherent capability of intelligent control techniques to operate autonomously reduces the need for manual intervention and monitoring. Such systems demonstrate autonomous behavior by dynamically adjusting parameters to optimize energy conversion and storage [39–41]. This adaptability ensures the system's resilience against fluctuations in energy sources or unforeseen environmental conditions. Traditional static control mechanisms have been the cornerstone of energy systems for decades, providing a reliable framework for regulating energy conversion and storage processes. These mechanisms rely on predetermined parameters and preset setpoints, often employing simple feedback loops to maintain system stability. While effective, these controls have limitations when applied within SMART (self-monitoring, analyzing, and reporting technology) systems. Machine learning algorithms play a critical role in implementing adaptive control techniques. These algorithms analyze historical data to identify patterns, correlations, and non-linear behaviors, enabling them to predict optimal energy conversion and storage parameter settings. This predictive capacity allows the control system to adjust in real-time to changing conditions, thereby enhancing efficiency and overall performance. Real-time sensor feedback is essential in intelligent control systems, as sensors continuously monitor ambient conditions, energy source characteristics, and material dynamics. This real-time data is integrated into the control system, enabling dynamic adjustments to settings and ensuring prompt responsiveness to fluctuations [38–43]. Consequently, this enhances the efficiency of energy capture, conversion, and storage processes. Materials-based energy systems utilize various materials for energy generation and storage, undergoing significant physical and chemical changes during energy conversion processes.

5. Conclusive remarks

This review paper discusses how smart structures are built with smart materials, and they have a lot of advantages. It is useful to use smart materials, such as shape memory alloys, because they bend at low temperatures and return to their original shape when heated. Magnetostrictive materials magnetic energy into kinetic energy and vice versa, which can be used as an actuator or sensor for buildings. By harnessing the power of smart materials, we can overcome many of the limitations inherent in traditional energy storage methods. These materials have the potential to store energy more efficiently, respond dynamically to demand fluctuations, and even self-heal when damaged, thus extending their lifespan and reducing maintenance requirements. Moreover, the development of smart materials opens up new avenues for innovation and collaboration across scientific disciplines. The flexibility of smart materials enables the creation of next-generation energy storage devices that are more light, compact, and able to integrate easily with our everyday lives, opening up new applications and possibilities for design.

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to the published version of the manuscript.

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