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Bio-Inspired Materials for Energy Storage

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ABSTRACT

The advancement of energy storage technologies is crucial for meeting the growing demand for sustainable energy solutions in various applications, from portable electronics to grid-scale storage systems. Traditional energy storage devices, such as batteries and supercapacitors, face challenges like low energy density, high cost, and slow charge-discharge times. This paper explores the potential of bio-inspired materials, which mimic the properties of naturally occurring substances, to overcome these challenges. By leveraging the unique structural and functional properties of biological materials, innovative solutions for energy storage can be developed. The discussion includes the application of bio-inspired materials in supercapacitors, batteries, and rust battery systems, focusing on materials such as aerogels, fibers, hydrogels, sponges, and nanocellulose. This review highlights the promising future of bio-inspired materials in enhancing the performance and sustainability of energy storage technologies.

Keywords: Bio-inspired materials, Energy storage, Supercapacitors, Batteries, Nanocellulose.

INTRODUCTION

Introduction Energy storage refers to the conversion and storage of energy in a form that can be released when it is required. The importance of energy storage has gradually grown over the past few decades due to increasing demand in portable electronics, electric and hybrid vehicles, and even electricity grid-scale storage. Energy storage technologies can range from short-duration, high power density devices such as supercapacitors, to long-duration, high energy density devices such as redox flow batteries (RFBs) or lithium-sulfur (Li-S) batteries [1]. The commercial adoption of these devices is hindered due to their low energy density, high cost, and relatively slow charge-discharge time. Various approaches (new materials, device architecture, etc.) have been undertaken in order to improve device performance in these aspects. This perspective article aims to review materials that are used in energy storage technologies. In particular, bio-inspired energy storage materials that mimic the properties of naturally occurring materials within energy storage applications will be discussed. These naturally occurring materials are used as a template to develop newer advanced materials via biomimicry principles and have been implemented into various energy storage applications. In particular, energy storage applications such as supercapacitors, batteries, and rust battery systems have been identified to have utilized these natural materials. Some of the most common natural materials used have been filtered cellulose materials including aerogels, fibers, hydrogels, sponges, and nanocellulose [1]. Stored energy is used in numerous ways to generate power at the time period or location of its need. This ranges from portable devices such as smartphones and laptops to facilitating long-duration electricity storage and on-demand generation on a large scale by energy sources such as fossil fuel power plants. These various types of devices can be generally classified based on their electrical energy storage density, output power, response time, or usefulness of the stored energy. For instance, "quasi-static" devices feature high energy densities but relatively slower (seconds to minutes) response times and less instantaneous power output, while "static" devices have low to moderate energy densities but rapid power delivery. Technology and services for managing short- and long-duration energy storage within a larger scope already exist and range from batteries and supercapacitors to flywheels, compressed air, and thermal storage. The Energy Storage Association predicts that 9800 MW/ 47000 MWh of energy storage was deployed in the United States in

2010, 160 MW/ 240 MWh of which was subsequently decommissioned or retired that year (i.e. a net gain of 9500 MW/ 46760 MWh). Part of this total was located within the Electricity Reliability Council of Texas (ERCOT), where the installed energy storage capacity was about 68 MW and projected to increase to 230 MW in 2012. Future energy storage must explore various duration options, addressing short-, long-, and seasonal variations in between. Nigeria, in particular, might benefit by employing large-scale energy storage systems to provide benefits for standby power sources, facilitate transactive energy, and store renewable energy. Factors affecting energy storage technologies include research that is streamlining, increasing performance, and enhancing raw materials and components for projected systems. Keep in mind all of the aforementioned important concepts [2].

IMPORTANCE OF ENERGY STORAGE

The increased utilization of renewable energy proposes high energy storage demand, which allows the matching of energy requirement and its availability to mitigate the fluctuating and uncertain nature of renewable sources and to thereby enhance their penetration. The utilization of energy storage at lower (substation) or higher (transmission) voltage levels improves voltage profile, grid resilience, and stability. Moreover, it helps to shape the load and more effectively manage peak demands, which reduce the requirement of new generators and therefore capital costs in power systems [3]. The most significant challenge of our time is to meet future increasing energy needs and simultaneously preserve the environment. The energy storage market is growing rapidly due to the rising concerns in the global ecosystem to reduce greenhouse gas emissions and optimize the utilization of natural resources. Low capital expenditures and operational costs, on a per cycle and energy basis, have been a main focus in the selection of effective storage technologies. Advanced energy storage systems with high efficiency, energy, and power density are necessary to meet the growing global energy demand in conjunction with the escalating use of renewable energy sources [4]. Incorporating high-efficiency energy storage can potentially lead to large monetary savings by limiting the required generation capacity within a grid system, thereby allowing an elongation of the service life of generating units and minimizing the need to rely on expensive peak electricity, steam, or natural gas peaking turbines. Some of the dynamics related to charging and energy delivery could be easily managed by control, i.e., achieving higher round-trip efficiency, reducing aging, increasing overall system lifespan, adopting fast transient changes, and avoiding thermal, electrochemical, and mechanical stressing of energy storage components [5].

BIOLOGICAL INSPIRATION FOR MATERIALS DESIGN

Introduction In our omnivorous quest for seasoned science papers experiencing flavor-of-the-day, we have a tendency to pass over classics. It is often the case, however, that history is worth repeating, and we deliberately turn back the clock to highlight these beautiful papers. More importantly, in the context of this perspective, papers from times past exploit dynamic trends in science - the interest in climate accountability and 'Materials for a Green Future' - combining classic, pioneering research with knowledge that has accumulated in the interim [6]. We look in particular at the classical problems around electric double layers of colloids, solutions and the recent convergence between soft matter systems and electrochemistry. Another important recent trend in energy materials is to explore photosynthesis - occurring in biomaterials - to optically adapt and encourage visible light charge transfer in photovoltaics (for example p-type/inorganic semiconducting oxides for photoelectrochemical fuel production), here excited valence and/or conduction electron are extracted (as natural solar light conversion). Quantum dots, traditionally believed to require ultraviolet photons, are useful for light harvesting in common nanocrystalline solar cells, but also suffer from too strong an absorption (electron-hole pair-production rate) at energies above the known 'optimum' for indirect semiconductors (1.1-1.3 eV, one low and one high value just below the band gap). Interestingly, this parameter seems also particularly consistent across biological and inorganic accessible space [7].

PHOTOSYNTHESIS AS A MODEL

The key to converting sunlight into chemical energy in plants is an organic molecule, the protein complex photosystem II. The core of photosystem II is like scissors that cut a water molecule into protons, electrons, and oxygen, with the free electrons and protons then being shuttled away and stored in a carboxylation reaction that builds sugars This is the reverse of strategies sometimes adopted by the biologically responsible materials science community, which, in contrast, starts with inspiration from nature as a model, e.g., leaves or plants, and asks whether we might understand which features endue them with efficiency attributes that can be mimicked in a sustainable technology [8]. Indeed, as the world seeks to solve the energy conundrum, it might be the case that looking to strong, lightweight, and durable materials tailored in the evolutionary ebbs-and-flows of living systems could provide the answers for the next generation of energy conversion and storage technologies. If problems were solved before, perhaps our best approach now would be to ask precious material how it was made. This would rationalize bio-inspired design; however, this is a daunting task. Indeed, uptake in the commercial sector is not yet fully apparent; however, an increasing number of reports have shown that taking hints from nature, we can improve the performance of materials for electrical energy storage. Bio-inspired materials and bioelectrodes have been shown to exhibit redox behavior due to their nanostructured and microporous nature. Mimicking nature and working with nature, any opportunities to create advanced materials for electrical energy storage may improve with surprising consequences. Bio-inspired materials are derived from both any part of living systems in nature and bio-abiotic hybrid materials. These materials from nature have unique and desirable properties that can be utilized in a variety of applications, some of which are focused on energy storage [9].

KEY PROPERTIES OF BIO-INSPIRED MATERIALS

Based on the concluded review, bio-inspired materials used in electrochemical energy storage applications should ideally have the following properties to ensure an effective, sustainable energy solution. In a future characterized by environmental awareness, bio-inspired materials are expected to become a major part of the move to renewable energy. The next level of investigation following this review should be directed toward finding new, alternative bio-inspirations to improve the properties of the materials for more effective electrochemical energy storage [6].

To enable these bio-inspired materials to be used for electrochemical energy storage applications, a series of properties are demanded. Firstly, biocompatible and eco-friendly materials are desired to alleviate any hazardous concerns. Bio-inspired materials could address these issues as they are derived from natural sources and, for the most part, are abundant and relatively cost-effective. The extraction-process chemistry and high cost of renewable natural materials are two key factors that render several natural materials economically unfeasible. The ability to store and release electrical energy represents electrochemical energy storage in batteries and supercapacitors; therefore, the bio-inspired materials used within these applications are expected to exhibit high capacity or energy density or, in the case of supercapacitors, high power densities. Several biological systems possess fast shuttling times, which provides the functionality for delivering nutrients and energy quickly to specific active sites. It is just as desirable to be able to take energy from these sites quickly to be used as fuel. Furthermore, when the next source of energy (food) is far away it is beneficial to be able to store some of the present supply for later use. Hence, storage capability is also an important property for investigating bio-inspired materials. Finally, novel stimuli-responsiveness or adaptivity could also be employed within bio-inspired materials, allowing applications within advanced materials systems and even within fields such as biomimicry, integrated control, sensing, and actuation [10].

SUSTAINABILITY AND ENVIRONMENTAL IMPACT

From an ecological standpoint, any viable energy technologies we employ must have as little impact on the planet's ecological footprint as possible. By using natural materials, for example, the carbon quantum dots derived from proteins or amino acids, eco-compatible and even more sustainable electrode materials can be achieved. Such systems exhibit a very low impact on energy systems, where emissions can be reduced by replacing critical materials. This section, like the third criterion, should be taken into consideration in the context of environmental applications, where tissue engineering, artificial organs, and biosensing are developed. Especially with regard to the potential role of green energy conversion and storage for complete energy systems, we must lay the foundation in the valorization of this field of research and continued investigation of the scope of bio-inspired molecules and systems. Finally, from a point of view of human resources and safety, we must try to shield the researchers involved from potential risks at all associated levels. When examining the scope of the production of green batteries, we must recognize the trade-offs between cost and sustainability, as well as both performance and environmental life cycle assessments. In discussions of these larger considerations, matters of safety are linked to the storage of large amounts of power, which should be attended to at least to some degree. We must then cautiously assess the associated broader scientific and societal arguments when developing materials that exemplify a more complete ABS. Therefore, a potential argument in the choice of bio-materials is the severe reduction or even total elimination of crucial resources in the long-term, so that on a very grand timescale we might accidentally acquire a particularly sustainable solution [11].

APPLICATIONS OF BIO-INSPIRED MATERIALS IN ENERGY STORAGE

BATTERY TECHNOLOGIES

Electrochemical energy storage is a revolutionary way to store energy efficiently and sustainably. In recent years, rechargeable battery technologies have experienced tremendous growth and evolution, driving the exploding consumer electronics market. They are now increasingly holding potential for electric vehicles, vehicle-to-grid applications, and grid-integrated energy storage. However, the power and energy density, longevity, and safety remain the main factors that are raising the hurdle for the deployment of such technology [12]. In this context, biomass anabolism offers copious cost-effective raw materials for a palette of hierarchical structures - spanning from macro- to meso- to nanoscale - that are self-organized in nature and possess characteristic properties. These latter could be beneficial for the enhancement of the charge and mass transfer associated with energy storage or a more extensive-scale manufacturing amenability. In the field of energy storage, intriguing parameters include durability and environmental sustainability. This subsection highlights some selected successful advancements in bio-inspired materials engineering due to their synergism on electrochemical energy storage and examines a number of potential applications in bio-hybrid energy storage systems. Bio-inspired cathode materials blend the life-giver with the life-taker to achieve high power and partial-state-of-charge capabilities. Moreover, synthetic nanostructured manganese oxide bio-mimetic architecture and red blood cell-like structural Æit are some personalized examples of stimuli-responsive bio-inspired photocathodes. These applicative outlines highlight some of the practical and conceptual implications derived by the bio-nature-inspired advanced cathode materials reviewed above and represent just a few of the upcoming studies in the area of bio-inspired electrodes for an array of advanced energy storage systems [13].

CHALLENGES AND FUTURE DIRECTIONS

The trends observed in typical life-cycle assessment (LCA) indicators (i.e., GWP (Global Warming Potential), Main Energy, and Share of Renewable Energy) confirm the higher overall environmental sustainability of bioinspired electrode materials based on carbonized natural PVDF templates with respect to the standard aPVDF precursor. Given the limits of materials scalability imposed by the use of natural polymeric matrices (i.e., PVC-free, PEG-free, and PAN-free BTs), many future research efforts should be directed towards the extrapolation of the present SAR results to other bioinspired electrode materials of industrial interest. According to such reasoning, the moderate aspect of the overall energy consumption characterizing both bioinspired and non-bioinspired FAs should be positively framed as a sugary proof of the scalability potential of this kind of materials at high feeding rates. This review discusses asymmetrical devices, bio-inspired electrode materials with respect to the type of polymeric matrix (PET, PVDF, and bacterial cellulose), spherical and reinforcement materials, capacitive performances, gravimetric and volumetric energy and power, as well as sustainable energy storage derived from these eco-bio-inspired supercapacitors. It provides an overview of the most recent developments in bio-derived electrode materials based on cellulose and its metabolites, chitosan, and polyphenols and plastics based on bio-sourced monomers and bio by-products, and provides insights into the relationship between biodegradation, natural-inspired materials, and sustainable energy storage. Many of the eco-friendly green and bio-polymeric electrode materials used in eco-bio-inspired energy applications represent a combination of biodegradable polymers and conducting bio-sourced nanomaterials. The power, energy density, and capacity of the biological supercapacitors and batteries require further improvements, combined with limitations during electrochemical analysis. Furthermore, for the practical application of bio-inspired electrode materials, it is necessary to scale up the material and processes in a sustainable manner to meet the demand for sustainable energy storage applications [1].

SCALING UP PRODUCTION

There are a few major hurdles that must be negotiated in order to produce bio-inspired materials at scales that are of practical use. After all, the procedures and the associated facilities, which are adapted from our understanding of biology, were not originally intended to be brought beyond the laboratory scale, and physicochemical variations inevitably appear and worsen when scaled up. For example, it may be necessary to splice out or replace component A of a complete process line, as this is one module for large-scale production and so needs to be fed in a different way to obtain equivalent results. In the meantime, most of the processes involved have enjoyed robust development and phasing through pilot stages. This has begun to change only fairly recently, with a few pilot systems dosed far below their rated capacity, promising to come to life and produce some research quantities for one company or another. As this year turns to next year, however, a number of big realizations will have the technological readiness, regulatory approval, objectivity, and support (to lists but four important prerequisites) to begin materials-scale

EMD. The size at which we can produce bio-inspired materials will play a part in how global energy transitions take shape. Many viable industrial processes do exist, in general, and quite a few have even graduated past "paper designs" to the bench- and pilot-scales of testing. These are constantly being tuned and improved as researchers and start-ups drift towards faster synthesis procedures with higher throughput, more environmentally-benign conditions, and better on-time product uniformity and yield. The minute quantities required for the actual demonstration cell can be obtained easily and inexpensively using these bench- and pilot-procedures. The physically-based year of these organisms-scale production units, the greater-planned up the emulations of our - s as we might do make and then will construction rather than youth direct paves the way for a whole number of real-world considerations, including more reliable economic, sustainability, and scalability road maps for new bio-inspired energy storage materials. In this light, bringing bio-inspired materials towards manufacturing scales is an obvious priority for any group looking to integrate out of the lab and into the real physical world.

CONCLUSION

Bio-inspired materials present a promising avenue for improving the performance and sustainability of energy storage technologies. By mimicking the efficient energy conversion and storage mechanisms found in nature, these materials offer innovative solutions to the limitations faced by conventional energy storage devices. The unique properties of bio-inspired materials, such as high energy density, biocompatibility, and environmental friendliness, make them ideal candidates for next-generation energy storage systems. Future research should focus on optimizing the production processes and scalability of these materials to facilitate their commercial adoption. The integration of bio-inspired materials into energy storage technologies holds the potential to significantly enhance the efficiency, cost-effectiveness, and environmental impact of energy storage solutions, contributing to a more sustainable and resilient energy infrastructure.

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