Coordination Chemistry Reviews 353 (2017) 113–141

Contents lists available at ScienceDirect

Coordination Chemistry Reviews

journal homepage: www.elsevier.com/locate/ccr

Review

Nanostructured materials: A progressive assessment and future direction for energy device applications

Pawan Kumar [a], Ki-Hyun Kim [b,*], Vasudha Bansal [c], Parveen Kumar [d]

[a] Department of Nano Science and Materials, Central University of Jammu, Jammu, India
[b] Department of Civil & Environmental Engineering, Hanyang University, 222 Wangsimni-Ro, Seoul 04763, Republic of Korea
[c] Center of Innovative and Applied Bioprocessing (CIAB), Mohali 160071, Punjab, India
[d] Central Scientific Instruments Organisation (CSIR-CSIO), Sector 30 C, Chandigarh 160030, India

ARTICLE INFO

Article history:
Received 29 April 2017
Accepted 6 October 2017

Keywords:
Nanostructured materials
Renewable energy technologies
Energy devices
Li-ion batteries
Supercapacitors
Solar cells

ABSTRACT

Nanostructured materials (NMs) are acknowledged as a viable energy storage alternative to effectively replace conventional materials. With this regard, the development of NMs (nanostructured inorganic materials, metal-based nanomaterials, carbon nanomaterials, coordination polymers, etc.) as energy materials has experienced exceptional progress, especially in the area of high-performance energy storage devices (e.g., supercapacitors, thin film batteries, rechargeable Li/Na batteries, redox flow batteries, and other NM-based batteries). In this review, we critically assess the progress made toward the research and development of NMs for energy device applications. Furthermore, this review is also structured to cover the technical advantages and challenges of NMs in order to outline the future opportunities/direction in this emerging field with the goal of upgrading their feasibility, especially with regard to Li-ion batteries (LIBs), supercapacitors, and solar cell applications.

Contents

* Corresponding author. Fax: +82 2 2220 1945.
E-mail address: kkim61@hanyang.ac.kr (K.-H. Kim).

https://doi.org/10.1016/j.ccr.2017.10.005
0010-8545/

1. Introduction

Recently, a great deal of scientific effort have been put on the establishment of advanced strategies to overcome various challenges associated with energy. Due to a rapid increase in energy consumption, it is important to sustain global economic growth and industrial development with clean energy provisions without the depletion of natural energy resources. To meet these goals, a number of novel technologies have been proposed and developed to resolve various challenges with meaningful solutions to the fields of potential energy applications (e.g., supercapacitors, lithium-ion batteries (LIBs), and solar/fuel cells) necessary for automobiles, phones, and miscellaneous applications (Fig. 1) [1–6]. Worldwide, numerous research groups working within the field of energy storage and conservation have recently placed their focus on novel materials, as reflected by the large number of articles focusing on this topic. With regard to real-world applications, the global production of energy storage was US $31.4 billion in 2015, 60% of which could be attributed to energy storage devices such as commercial LIBs used for electronic devices (e.g., mobile phones). As expected, the demand and growth for energy storage is projected to increase dramatically up to US $53.7 billion in 2020 [7,8].

Currently, common devices for energy storage and conservation (e.g., LIBs, supercapacitors, and fuel/solar cells) cannot fully accommodate the requirements for practical application due to several core challenges including their specific capacity, structural stability, low energy density anode/cathode materials, and low performance rates. As such, the advancement of many common energy storage devices has been significantly hindered, especially by the low performance of charge–discharge rates (e.g., recharge periods of two to five hours) [5–11]. Likewise, supercapacitor capacities are also limited by low energy densities with low restoring capacities. In fact, the energy densities (5–10 Wh kg^{-1}) of supercapacitors are significantly lower than those of other storing devices (e.g., lead-acid batteries (20–35 Wh kg^{-1}), Ni-metal hydride batteries (40–100 Wh kg^{-1}), and LIBs (120–170 Wh kg^{-1})) [7,9]. Fig. 1 depicts the energy/power performance for various energy devises (e.g., conventional gasoline combustion engines, hydrogen fuel cells, and hydrogen combustion engines (HCEs)). Because conventional materials made from organic/inorganic components (e.g., lead acid, Ni–Cd, sodium, carbon, and $LiCoO_2$) have a high specific power output with a poor specific energy, their actual performance can only be compared to that of typical batteries [5–8]. These technologies have been actively accommodated with regard to the development of diverse devices (e.g., power tools, back-up power supply units, and off-peak energy storage (load leveling) from the electric grid [4–8]. For each energy storage and conservation application, technologies must be advanced considerably in order to satisfy the essential criteria for real-world applications, including (a) reduced costs, (b) energy density improvements (e.g., from ~120 to ~250 Wh kg^{-1}), (c) high-power operation of energy storage devices at high-current charge/discharge rates (2–10 °C), and (d) improvements to both low- and high-temperature operation [4–8].

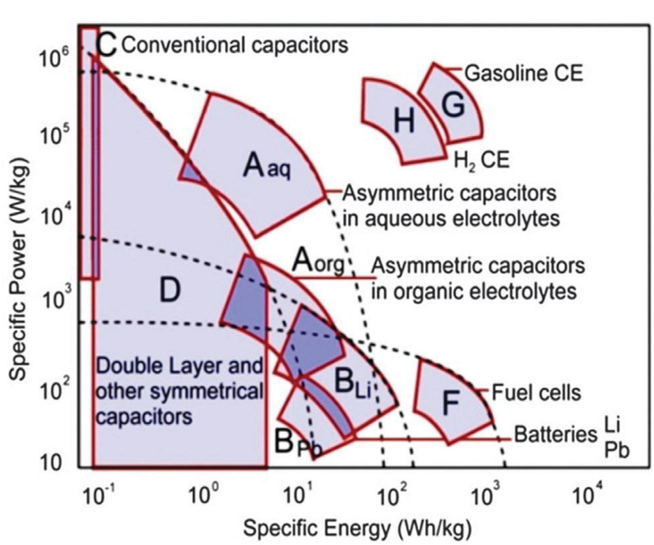

Fig. 1. Ragone plot with specific energy and power for a diverse range of energy storage devices [6].

To achieve rapid progress with regard to energy storage and conservation technologies, various approaches have been proposed for the design of anodes/cathodes/cells through the use of nano-sized particles, surface engineering/modifications, structure optimizations, and the synthesis of nanocomposite materials. These approaches have been utilized to enhance redox reaction rates in battery electrodes as well as to obtain faster kinetic mechanisms for rapid charging and high power [4,5]. Basically, nano-sized particles/materials/composites and their morphologies can easily influence the rates of redox reactions to directly contribute to optimizing the electrode–electrolyte interface. Additionally, nanomaterials can adopt reversible redox reactions, making them a promising tool for clean energy storage and conservation because of their high storage capacities, safety, possible environmental friendliness, sustainability, and potential cost benefits [1–11]. Thus, the use of nano-sized particles is recognized as the most feasible approach toward achieving highly efficient energy storage and conservation technologies [5–11].

Lately, a diverse range of nanostructured materials (NMs), including nanostructured inorganic materials, metal-based nanomaterials, carbon nanomaterials, and coordination polymers have been developed, sharing key properties such as a high conductivity, good electroactivity, and fast kinetics for environmentally–friendly energy storage and conservation applications. As such, NM performance was found to be superior over that of materials made from inorganic compounds (e.g., $LiCoO_2$, $LiFePO_4$, $Li_4Ti_5O_{12}$, sulfides, and Si), organic compounds, and transition metals (e.g., Mn, Fe, Co, and Ni) [6–14].

It is therefore important to enumerate the properties/features/applications of NM-based energy storage and conservation devices. For instance, ideal electrode materials should be made from compounds or elements with a low atomic weight and/or density. They should also be able to accommodate large quantities of metal ions per formula unit. Additionally, such materials should be chemically inert with electrolyte salts or solvents, easily cyclable, high yielding, highly volumetric (mA h cm^{-3}), and reversibly gravimetric (mA h g^{-1}) [14–21]. As a result, the chemical and electrochemical properties of nanomaterials will be enhanced and improved with