ACS APPLIED MATERIALS & INTERFACES

Editorial

www.acsami.org

Best Practices for Reporting on Energy Storage

Batteries and supercapacitors have received significant attention for portable electronic devices, electric vehicle propulsion, and bulk electricity storage at power stations. The imperative to implement electrical energy storage in the grid to ensure reliable supply, while enhancing the penetration of renewables, is responsible for a re-evaluation of the energy storage technologies available to these even larger scale applications. These strategic trends have promoted intense research efforts to improve batteries and supercapacitors in terms of energy and power density, safety, cycle life, cost, environmental impact, and other aspects.[1−10] A literature survey has revealed more than 33 000 papers with the words batteries or supercapacitor in the title published from Jan 1, 2015, to May 20, 2015 (Source: Web of Science, May 20, 2015). In alignment with this trend, the American Chemical Society has been receiving a significant number of papers in the area of energy storage for its materials and chemistry journals.

We have written this editorial to provide uniform guidelines to authors, readers, and referees in the characterization and analysis of new and modified materials for batteries and supercapacitors. These best practices for battery and supercapacitor materials characterization and performance testing are not new to the energy storage community, but reflect practices used within the community over many years. Because of the diversity of new or modified materials for batteries or supercapacitors, it is a challenge to provide a comprehensive list of requirements for publication, so a one-size-fits-all template is not realistic. Nevertheless, the goal here is to outline the essentials as a guide for any paper that describes electrochemical performance. The following points should be considered for each paper that discusses the performance of new or modified materials for batteries or supercapacitors.

THOROUGH MATERIALS CHARACTERIZATION

New (nano)materials or modified materials must be appropriately and fully characterized. Techniques including X-ray diffraction, electron microscopy, X-ray photoelectron spectroscopy, Brunauer−Emmett−Teller (BET) effective surface area determination, Raman or infrared spectroscopy, and thermochemical analysis (TGA, DSC), must be included as appropriate, as well as other methods that may be relevant to the material(s) under study.[11] For example, for ultradispersed TiO_2 nanoparticles on graphene, SEM, TEM (HRTEM) and EDX elemental maps are provided to show the distribution of different components; bulk X-ray diffraction (XRD) data and/or Raman spectrum are included to prove the composition and crystal structure (Crystallinity).[12]

BASIC ELECTROCHEMICAL MEASUREMENTS

The conditions under which the electrochemical performance of a material for batteries or supercapacitors is characterized must be thoroughly defined. Appropriate methods include the following: cyclic voltammetry (CV), charge−discharge testing, rate capability characterization, electrochemical impedance spectroscopy (EIS), and other relevant electrochemical measurements.

ELECTROCHEMICAL PERFORMANCE RESULTS IN CONTEXT

Comparison of the electrochemical results with relevant published prior outcomes provides insight into the significance of the findings. Specifics of the electrochemical testing regime (i.e., voltage window, *C*-rate, current density, test temperature) must be provided in the experimental section of the manuscript. It is important, however, to note that the objective of the study may require different types of electrochemical testing and different methods for reporting the data. Gravimetric capacity, volumetric capacity, specific energy, specific power, cycle life, and efficiency are all useful metrics, and should be used as appropriate to describe the system under study. Therefore, the motivation for selection of the particular electrochemical test regime and data reporting style should be described in the body of the text. For example, although the demonstration of an improved synthesis for a previously reported material may be best represented by high-rate long-term cycling, for elucidation of structural changes in an electrochemically active material as a function of reduction/oxidation, lower rate testing with ex situ characterization at different states of discharge/charge may be appropriate.

In addition, material behavior in electrochemical systems can be significantly impacted by factors such as electrode composition, electrode preparation, and electrolyte formulation. Consideration of the mass and volume of the complete electrode or cell may provide additional insight relative to consideration of just the electroactive material, and the electrode or cell characteristics must be provided where appropriate. Furthermore, the differences in these factors relative to prior reports must be considered and highlighted.

PRODUCT ANALYSIS AND REACTION MECHANISM STUDIES

Some papers describe significant synthetic achievements in the synthesis of new materials with unique and novel morphology or structure to enhance electrochemical performance. Examples include core−shell systems, three-dimensional frameworks, hollow structures, meso/microporous structures, crystallite size control, and others. Characterization of the morphology of the electrode materials after electrochemical cycling provides compelling evidence to indicate the effect of morphology on the electrochemical performance and such data should be included. Additionally, the electrochemical reaction mechanisms should be clarified or investigated, especially if mechanisms are used to explain specific aspects of the electrochemical response or performance. Many new analytical techniques are now available that enable analysis of the charging/discharging process through in situ or ex situ characterization techniques, such as XRD, XPS, Raman,

Published: August 5, 2015

DOI: 10.1021/acsami.5b06029
ACS Appl. Mater. Interfaces 2015, 7, 16131−16132

NMR, Mössbauer, SEM, TEM, and synchrotron-based X-ray absorption spectroscopy (XAS). Theoretical calculations can also augment the empirical investigations.

Information regarding reproducibility of the results is an important factor to include. The results of the material characterization described above further increase confidence regarding the performance results reported.

There are no limits on the size of the Supporting Information. Thus, photographs or descriptions of experimental apparatus should be provided as appropriate. The manuscript should include experimental details, such as the composition of reference or counter/reference electrodes, mass of active materials, voltage windows used in testing, and current densities for charge/discharge.

We hope that these guidelines will prove useful to the materials community investigating materials for batteries and supercapacitors. Furthermore, the broader materials community may see benefits from the improved standards for reporting materials and electrochemical data.

Zaiping Guo, Associate Editor, *ACS Applied Materials & Interfaces*

Esther Takeuchi, SUNY Distinguished Professor, Stony Brook University, and Chief Scientist, Brookhaven National Laboratory

AUTHOR INFORMATION

Notes

Views expressed in this editorial are those of the author and not necessarily the views of the ACS.

REFERENCES

(1) Dudney, N. J.; Li, J. Using All Energy in A Battery. *Science* **2015**, *347*, 131−132.

(2) Goodenough, J. B.; Park, K.-S. The Li-Ion Rechargeable Battery: A Perspective. *J. Am. Chem. Soc.* **2013**, *135*, 1167−1176.

(3) Takeuchi, E. S.; Marschilok, A. C.; Takeuchi, K. J. Secondary Battery Science: at the Confluence of Electrochemistry and Materials engineering. *Electrochemistry (Tokyo, Jpn.)* **2012**, *80*, 700−705.

(4) Kim, T.-H.; Park, J.-S.; Chang, S. K.; Choi, S.; Ryu, J. H.; Song, H.-K. The Current Move of Lithium Ion Batteries Towards the Next Phase. *Adv. Energy Mater.* **2012**, *2*, 860−872.

(5) Schaefer, J. L.; Lu, Y.; Moganty, S. S.; Agarwal, P.; Jayaprakash, N.; Archer, L. A. Electrolytes for High-Energy Lithium Batteries. *Appl. Nanosci.* **2012**, *2*, 91−109.

(6) Gogotsi, Y.; Simon, P. True Performance Metrics in Electrochemical Energy Storage. *Science* **2011**, *334*, 917−918.

(7) Etacheri, V.; Marom, R.; Elazari, R.; Salitra, G.; Aurbach, D. Challenges in the Development of Advanced Li-ion Batteries: A Review. *Energy Environ. Sci.* **2011**, *4*, 3243−3262.

(8) Dunn, B.; Kamath, H.; Tarascon, J.-M. Electrical Energy Storage for the Grid: A Battery of Choices. *Science* **2011**, *334*, 928−935.

(9) Scrosati, B.; Garche, J. Lithium Batteries: Status, Prospects and Future. *J. Power Sources* **2010**, *195*, 2419−2430.

(10) Kim, M. G.; Cho, J. Reversible and High-Capacity Nanostructured Electrode Materials for Li-Ion Batteries. *Adv. Funct. Mater.* **2009**, *19*, 1497−1514.

(11) Murphy, C. J.; Buriak, J. M. Best Practices for the Reporting of Colloidal Inorganic Nanomaterials. *Chem. Mater.* DOI:10.1021/acs.chemmater.5b02323.

(12) Li, W.; Wang, F.; Feng, S.; Wang, J.; Sun, Z.; Li, B.; Li, Y.; Yang, J.; Elzatahry, A. A.; Xia, Y.; Zhao, D. Sol-Gel Design Strategy for Ultradispersed TiO_2 Nanoparticles on Graphene for High-Performance Lithium Ion Batteries. *J. Am. Chem. Soc.* **2013**, *135*, 18300−18303.

DOI: 10.1021/acsami.5b06029
ACS Appl. Mater. Interfaces 2015, 7, 16131−16132