A EUROPEAN JOURNAL
CHEMPHYSCHEM
OF CHEMICAL PHYSICS AND PHYSICAL CHEMISTRY

10/2014

CHEMICAL PHYSICS & CHEMISTRY

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DOI: 10.1002/cphc.201400099

Electrochemical Energy Conversion: Past, Present, and Future

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Dating back at least to the late 18th century, electrochemistry and energy conversion have had an inextricably intertwined history. Galvani’s experiments with a frog’s leg showed that living systems are not only affected by electricity, but can also generate it. Volta’s pile, comprising alternate plates of zinc and silver separated by a cloth or paper, may be regarded as the birth of the modern battery device for energy storage. Soon after, Nicholson and Carlisle used a similar “pile” to electrolyze water, triggering a flurry of electrolysis experiments by distinguished scientists including Berzelius, Davy, Faraday, Kohlrausch, and others. In addition to batteries and electrolyzers, other electrochemical energy-conversion devices also have a long history, notably the fuel cell pioneered by Grove in 1839.

Electrochemical energy conversion has continued to play a pivotal role in our everyday life to this day—a role that is easily overlooked by the lay person! For example, it is not often that we pause to reflect how batteries have transformed the way we live. We press a button or turn the switch to start our automobiles on the coldest (or the hottest) day; however, our forefathers had to exert themselves in the early 1900s to

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turn a mechanical crank to start the car engine! The incremental and invisible advances that have occurred in lead acid battery technology make it virtually maintenance-free as we know it today. Similarly all our notebooks and hand-held communication/entertainment devices are powered by increasingly efficient, miniaturized, and portable batteries. Further improvements, not only in current battery technologies but also new battery chemistries, would be required to sustain the pace of quality-of-life enhancement. An appreciation of what is demanded may be quickly gained by looking at where the internal combustion engine is located on a Ragone plot relative to current state-of-the-art electrochemical energy-conversion devices.

Today, with the energy crisis and the greenhouse gas effect (CO_2 accumulation being one culprit), electrochemistry faces another challenge: As a science located at the interface between chemistry and electrical engineering, electrochemistry has a fundamental role in energy conversion and storage, as well as in the clean and energy-saving production of chemicals. The key to a sustainable energy future thus lies in the development of materials and technologies that rely on earth-abundant and environmentally friendly resources. In this regard, one can hardly overestimate what is ultimately possible with solar-energy utilization.

Electrochemical energy conversion received a huge impetus in the late 1960s and early 1970s when it was shown that water could be split by using a semiconductor electrode that responded to solar photoexcitation in contact with an electrolyte. Now hydrogen could be generated from water and sunlight paving the way to storing the energy available from the sun. We can take a further leaf out of Nature's playbook and artificially construct assemblies that can split CO_2 (like plants do) or even nitrogen (like certain enzymes do) to fuels such as methanol and ammonia, respectively. The key to economics lies in adding value to the overall process by combining energy generation (or storage) with an abatement scenario like in CO_2 remediation.

Another possibility for the conversion of solar energy is via biofuels (ethanol, methane) using fuel cells. A further important aspect of (and driving force for) fuel-cell development is their possible use for automobile propulsion, which supposedly leads to a more efficient and less pollutant conversion of chemical energy into electric and mechanical energy than in combustion engines. Various kinds of fuel cells are fairly well developed; the most important challenge for fundamental electrochemistry here is the search for better catalysts for both the oxidation of organic fuels and the reduction of dioxygen.

As already pointed out above, the classical way to store electric energy in the form of chemical energy is using batteries. Battery research has been immensely popular in recent years, first because of the need for lightweight, long-life rechargeable batteries for consumer electronics (such as notebooks and smart phones) on the one hand and also because Li-ion batteries are capable of meeting such needs to a large extent. Today's challenge is to find new types of batteries, in particular in respect to higher energy density (e.g., Li-air batteries), such that they can be used not only in hybrid cars, but also in plug-in electric cars. Another important prospective use of improved batteries (improved with respect to stability and energy efficiency, but less so for energy density), is in energy storage for smart power grids.

While the ideas espoused in the preceding paragraphs point to a way toward a sustainable energy future for our succeeding generations, many challenges remain in the R&D realm. The practical process efficiencies must be boosted (almost by an order of magnitude) before many of the aforementioned technologies become viable for large-scale use. More stable and economically viable active materials must be developed for solar-conversion devices, and similar challenges also exist for energy-storage devices; for example, both the performance and stability of Li-ion batteries must be substantially improved. In this regard, it is encouraging to note the exceedingly active efforts by the R&D communities that have resulted in the discovery of new electrode materials (e.g., nanocarbons, organic perovskites), ion-selective membrane separators, and battery chemistries.

A representative sampling of what has been accomplished may be found in the pages that follow in this special issue, and in the papers from many distinguished research groups scattered across the globe. The topics covered run the gamut of energy-conversion devices ranging from batteries, fuel cells (including biofuel cells), supercapacitors, to solar cells. Also addressed in these papers are issues related to materials preparation, hydrogen storage, nanotechnology, and so on. We thank the authors for their contributions, and hope that you, the readership, will derive benefit (even inspiration!) in your own efforts to enrich this important R&D discipline of electrochemical energy conversion.


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