



Research Highlight

E-fuel system: a conceptual breakthrough for energy storage

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The demand for renewables such as solar and wind power has become stronger than ever in the past few decades and their numerous advantages have nearly risen to the status of common knowledge. However, as solar and wind power are intermittent in nature, the electricity generated from these renewable sources only comprise a low fraction of global electricity production. Enabling the widespread use of renewables requires energy storage technology that is site-independent, efficient, scalable, stable, cost-effective, safe, energy dense and continuous in operation. To date, none of the existing technologies have adequately met the attributes necessary for storing intermittent and scattered solar, wind and other sources of renewable energy. Pumped hydro and compressed air are scalable and cost-effective, but are limited by geography and geology [1]. Supercapacitors exhibit short response time and high power density, but have the disadvantages of low storage capacity and severe self-discharge [2]. Lithium-ion batteries are efficient and site-independent, but safety becomes an issue when scaled-up [3]. Redox flow batteries are scalable, site-independent and stable, but have low energy density and high capital cost [4]. Next-generation solar or wind power systems must be able to store enough energy for several days to approximately one week, with or without connection to the electric grid. Converting electricity to chemical energy using chemical fuels as storage will fulfill this requirement. The hydrogen storage system is the most developed system based on this concept to date, which utilizes locally-generated hydrogen via electrolysis from solar or wind power as the energy carrier. Being combined with air or oxygen in engines or fuel cells, hydrogen can regenerate electricity on demand. However, the system is expensive, low in energy efficiency, and has a short lifetime [5,6].

A research team led by Professor T.S. Zhao at the Hong Kong University of Science and Technology, has for the first time proposed a novel energy storage concept that incorporates electrically rechargeable liquid fuels containing electroactive species, abbreviated as e-fuels [7]. The system comprises an e-fuel charger and an e-fuel cell, and adopts liquid e-fuels as the medium of energy storage. The e-fuel charger is an electrochemical energy-conversion device that is able to charge e-fuels with electricity harvested from the environment using solar cells and wind turbines. Adding the charged e-fuels to the e-fuel cell, electricity can be re-generated

whenever and wherever on demand. Similar to a conventional hydrogen-storage system, e-fuels can be stored long-term, but unlike gaseous hydrogen, liquid e-fuels are safe to store, and can be transported with ease much like gasoline. Moreover, the design of the e-fuel charger and the e-fuel cell retains the unique advantages of conventional flow battery architecture, but adds the flexibility of e-fuel selection, component design and system optimization, creating abundant room for performance enhancement and system cost reduction.

The Zhao group [7] demonstrated an example e-fuel energy storage system using inorganic e-fuels composed of V^{2+}/V^{3+} and VO^{2+}/VO_2^+ redox couples. Their results showed that the e-fuel charger performed at a charge efficiency of 94%, which is 30% higher than that of water electrolysis for hydrogen production. Maintaining a discharge efficiency higher than 80%, the e-fuel cell was able to discharge at an ultra-high current density of $1,000 \text{ mA cm}^{-2}$, and delivered a peak power density of 3.4 W cm^{-2} , 2.7 times of that by conventional hydrogen fuel cells. The vanadium ion e-fuel storage system may represent the most efficient energy storage system reported in the open literature.

It is worth mentioning that e-fuels are not limited to the V^{2+}/V^{3+} and VO^{2+}/VO_2^+ redox couples demonstrated in Ref. [7]. The range of redox couples suitable for conventional flow batteries is typically limited by the tradeoff between reversibility and other important properties such as energy density, cell potential, cost and stability. Therefore, redox couples that meet all other requirements but exhibit poor reversibility for a fixed electrode surface cannot be used in flow batteries. However, in the e-fuel system, the decoupling of the charge and discharge processes allows the e-fuel charger and e-fuel cell to have an electrode for the reduction of e-fuels only, and an electrode for the oxidation of e-fuels only, eliminating the stringent requirement for reversible electrodes in conventional flow batteries. The oxidation-only and reduction-only electrodes for the e-fuel storage system provide much higher flexibility in selection and creation of electro-active materials for e-fuels. Future exploration of a number of other e-fuels, including inorganic electroactive materials, organic electroactive materials, and suspension of solid electroactive materials, will expand the spectrum of desired e-fuels, which are energy dense, efficient, stable, flowable and cost-effective, and are catered for different applications. The e-fuel cell can provide an off-grid power supply for powering locations not connected to the grid and can be readily integrated with the grid or a micro-grid. The standalone e-fuel cell with energy

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dense e-fuels even holds the potential to propel next-generation electric vehicles with not only a safe driving experience, but also a refueling time akin to that of gasoline, at a fraction of that of today's electric vehicles [8].

In closing, the e-fuel energy storage system proposed by Zhao represents a conceptual breakthrough for energy storage, has the potential to revolutionize energy storage technology, and removes the long-standing barrier in storage of intermittent and scattered renewable energy sources at high efficiency and low cost.

Conflict of interest

The authors declare that they have no conflict of interest.

Acknowledgments

Argonne National Laboratory's work was supported by the U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy, Office of Vehicle Technology, Mater Materials Research Program under contract DE-AC02-06CH11357.

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