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EDITORIAL

Harnessing Energy for a Sustainable World

Innovation through scientific discovery is a necessary component of much societal advancement. To truly implement sustainable practices, energy must be harnessed more cleanly and stored for efficient distribution and use. This systems-level change, sometimes referred to as the New Industrial Revolution, will require novel materials as well as savvy analysis and modeling to ensure success.

We have thus chosen a theme of "Harnessing Energy for a Sustainable World" for this issue of *JACS* Select, which for the first time draws content from two ACS journals: *Journal of the American Chemical Society* (*JACS*) and *Environmental Science & Technology* (*ES&T*). The theme was timed in concert with the 2010 ACS Spring National Meeting's similar focus on "Chemistry for a Sustainable World". The publications selected from *JACS* concern materials and methods for energy production and storage; those from *ES&T* speak to how energy could (viz. should) be cleverly harnessed.

The 11 *JACS* articles and communications in this collection consider structural aspects of energy conversion and storage. The hydrogen fuel cell in automobiles is a promising technology for reduction of carbon emissions that result from burning fossil fuels, but its development requires the discovery of more active and less expensive electrocatalysts for the oxygen reduction reaction (ORR) at the fuel cell cathode. Catalytic platinum particles have been the technological mainstay of the field for decades, but scientific breakthroughs in relating catalyst structure to ORR activity, as well as the development of less-expensive non-noble-metal catalysts, are rapidly appearing. **Wang** and **Adzic** reported enhancement of the ORR by depositing monolayer Pt films on Pd_3Co nanoparticles, a consequence of the influence of compressive strains in the Pt shell on the oxygen binding energy.[1] The reverse of the ORR, i.e., the splitting of water, is a viable means to store chemical energy using solar-generated electricity, but this process also requires new and inexpensive catalysts. Two very different approaches to water oxidation catalysts reported in *JACS* show particular promise: **Nocera** developed an inexpensive and self-healing oxygen-evolving catalyst based on the electrodeposition of thin films of Co^{2+} salts,[2] while **Murray** used freely diffusing 1.6 nm catalytic IrO_2 nanoparticles in aqueous solution as the redox mediator to oxidize water to O_2.[3] Both chemistries exhibit 100% Faradaic efficiencies at relatively low electrical driving force.

While lithium-ion batteries remain the leading technology for powering electronics and electric vehicles, recent advances in materials chemistry are providing opportunities for more environmentally friendly and efficient electrical energy storage devices. For example, using the tetralithium salt of tetrahydroxybenzoquinone, **Poizot** demonstrated a Li-ion battery that cycles between $Li_2C_6O_6$ and $Li_6C_6O_6$.[4] These sustainable "organic" electrodes may replace cobalt- and iron-based battery electrodes in the future. In addition to the new electrode materials, advanced membranes for batteries and fuel cells are required, and many have been reported. A *room-temperature* fast-ion conductor was discovered by **Maekawa** by mixing lithium halides with $LiBH_4$, yielding a new electrolyte candidate for all-solid-state room-temperature batteries.[5]

Efficient use of biomass as an energy source is driving research to find new chemical and enzymatic processes for converting biomass into fuels. This past year, **Binder** and **Raines** reported a simple low-temperature, *non-enzymatic* process for the high-yield, single-step transformation of lignocellulosic biomass into 5-hydroxymethylfurfural, which can then be converted into high-energy fuels.[6] Biocatalysts within microbial organisms also convert biomass into useful fuels, but their application for renewable energy requires discovery and screening in order to identify the most useful enzymes and metabolic pathways. Using synthetic

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(1) Wang, J. X.; Inada, H.; Wu, L.; Zhu, Y.; Choi, Y.; Liu, P.; Zhou, W.-P.; Adzic, R. R. *J. Am. Chem. Soc.* **2009**, *131*, 17298–17302.
(2) Surendranath, Y.; Dincǎ, M.; Nocera, D. G. *J. Am. Chem. Soc.* **2009**, *131*, 2615–2620.
(3) Nakagawa, T.; Bjorge, N. S.; Murray, R. W. *J. Am. Chem. Soc.* **2009**, *131*, 15578–15579.
(4) Chen, H.; Armand, M.; Courty, M.; Jiang, M.; Grey, C. P.; Dolhem, F.; Tarascon, J.-M.; Poizot, P. *J. Am. Chem. Soc.* **2009**, *131*, 8984–8988.
(5) Maekawa, H.; Matsuo, M.; Takamura, H.; Ando, M.; Noda, Y.; Karahashi, T.; Orimo, S. *J. Am. Chem. Soc.* **2009**, *131*, 894–895.
(6) Binder, J. B.; Raines, R. T. *J. Am. Chem. Soc.* **2009**, *131*, 1979–1985.

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metagenomics, **Voigt** identified high-activity biocatalysts for converting lignocellulosic biomass into methyl halides, which can be used as chemical precursors for alcohols and synthetic gasoline.[7]

Research on macromolecular architectures for directly converting solar to electrical energy, e.g., polymer-based photovoltaic cells, emphasizes the need to understand and control charge-transfer processes at the molecular level. The efficiencies of capturing sunlight and moving the high-energy photogenerated electrical charge through a macromolecular material without recombination and other energy losses require exquisite design of molecular assemblies. **Bardeen** and **Thayumanavan** investigated dendron−chromophore−polymer triads that emphasize a modular approach in designing molecular scaffolds for separating photo-induced charge.[8] The capability of large-scale production of polymer-based solar cells drives intense research efforts to find new polymeric materials for this application. **Hou** and **Li** reported chemical syntheses of PBDTTT-based polymers with band gaps tuned to the solar energies.[9] Devices based on these new materials exhibit solar power conversion efficiencies as high as 6.5%. Biological macromolecule/solid state hybrid structures are also useful in solar generation of fuels, as demonstrated by **Armstrong** in producing H_2 using visible light by attaching the [NiFeSe]-hydrogenase from *Desulfomicrobium baculatum* to ruthenium-based dye-sensitive TiO_2 nanoparticles.[10]

The many nanotechnologies developed over the past decade offer innovative approaches to energy generation and storage on many different scales. **Wang** used ZnO nanowire array technology to fabricate a hybrid photoelectrochemical/piezoelectric cell that simultaneously converts visible light and environmental mechanical energy directly into electrical energy.[11] These devices may conceivably serve as isolated, round-the-clock, low-power energy sources, deriving energy from multiple environmental resources.

Systems-level thinking plays a large role in the 10 reports from *ES&T*, which were chosen to demonstrate how such an approach can make a difference in developing a sustainable and resilient energy supply and solving the associated gigaton problems. For example, policymakers have proposed and begun to implement standards, bans, and mandates to reduce the use of fossil fuels. Are those policies feasible if the indirect impacts are taken into account? It depends. **Newcomer** and **Apt** examined a national ban on new coal-fired power plants and found that the ban would only achieve a fraction of the policy target but would cause natural gas and electricity prices to increase significantly.[12]

One of the options to achieve energy sustainability is to include more renewable energies in our energy supply portfolio. **Williams** comprehensively reviewed impacts of the implementation of next-generation biofuels, including municipal solid waste, forest residues, dedicated energy crops, and microalgae in the United States.[13] It has been found that next-generation biofuels are generally better than conventional biofuels such as corn grain-based ethanol and soybean-based diesel in a variety of factors including greenhouse gas (GHG) emissions, air pollutant emissions, soil health and quality, water use and water quality, wastewater and solid waste streams, biodiversity, and land-use changes. **Samuelsen** examined the replacement of fossil fuels in the transportation sector with hydrogen energy using a sophisticated simulation tool to quantitatively characterize the potential to reduce GHG emissions and the impact on urban air quality. They considered the use of hydrogen supply infrastructure and hydrogen fuel cell vehicles.[14] The study reported notable reductions in GHG emissions (61−68%) and substantial improvement in urban air quality for a prototypical urban airshed in Southern California.

Although time is required to progress down the cost learning curve, solar photovoltaics (PV) is another promising renewable option to replace fossil fuels. **Kammen** examined large-scale PV deployment on a global scale by examining material extraction costs and supply constraints for 23 promising semiconducting materials.[15] The authors identified 12 highly efficient materials that can be used in PV cells, often at reduced cost as compared to crystalline silicon. In addition, **Denholm** evaluated the potential for reduction of fossil fuels and associated emissions by a

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(7) Bayer, T. S.; Widmaier, D. M.; Temme, K.; Mirsky, E. A.; Santi, D. V.; Voigt, C. A. *J. Am. Chem. Soc.* **2009**, *131*, 6508–6515.

(8) Nantalaksakul, A.; Mueller, A.; Klaikherd, A.; Bardeen, C. J.; Thayumanavan, S. *J. Am. Chem. Soc.* **2009**, *131*, 2727–2738.

(9) Hou, J.; Chen, H.-Y.; Zhang, S.; Chen, R. I.; Yang, Y.; Wu, Y.; Li, G. *J. Am. Chem. Soc.* **2009**, *131*, 15586–15587.

(10) Reisner, E.; Powell, D. J.; Cavazza, C.; Fontecilla-Camps, J. C.; Armstrong, F. A. *J. Am. Chem. Soc.* **2009**, *131*, 18457–18466.

(11) Xu, C.; Wang, X.; Wang, Z. L. *J. Am. Chem. Soc.* **2009**, *131*, 5866–5872.

(12) Newcomer, A.; Apt, J. *Environ. Sci. Technol.* **2009**, *43*, 3995–4001.

(13) Williams, P. R. D.; Inman, D.; Aden, A.; Heath, G. A. *Environ. Sci. Technol.* **2009**, *43*, 4763–4775.

(14) Stephens-Romero, S.; Carreras-Sospedra, M.; Brouwer, J.; Dabdub, D.; Samuelsen, S. *Environ. Sci. Technol.* **2009**, *43*, 9022–9029.

(15) Wadia, C.; Alivisatos, A. P.; Kammen, D. M. *Environ. Sci. Technol.* **2009**, *43*, 2072–2077.

series of PV penetrations up to 10% of a region's electricity generation.[16] The study showed promising results for replacing fossil fuels by PV in power generation using California and Colorado as case studies.

The global potential of unconventional hydropower from the salinity gradient in mixing river water and seawater has been estimated to be significant. **Hamelers** reported a reverse electrodialysis technique to notably improve the overall energetic efficiency of this system by taking energy recovery into account.[17] The results showed that it is feasible to achieve an energy recovery of >80% using this technique with the current primary technologies.

One main purpose of replacing fossil fuels is to reduce CO_2 emissions. Carbon footprint analyses have been developed as a quantitative tool to appropriately measure how anthropogenic activities are affecting the climate through life-cycle CO_2 emissions. Given the variety of existing carbon footprint quantification protocols and system boundaries, **Matthews**, **Hendrickson**, and **Weber** critically reviewed the literature and addressed the importance of including indirect emissions in carbon footprint estimates.[18] **Hertwich** and **Peters** quantified GHG emissions of 73 nations and 14 aggregate world regions and identified the distinct contributions of eight categories: construction, shelter, food, clothing, mobility, manufactured products, services, and trade.[19] The results suggested over 70% of GHG emissions are related to household consumption activities including food, operation and maintenance of residences, and mobility.

To reduce CO_2 emissions, various technologies for carbon capture and storage from large point sources such as power plants using fossil fuels have been suggested. **Abanades** proposed an innovative $CaCO_3$ calcination method to produce a stream of CO_2 that is suitable for permanent geological storage after purification and compression.[20] The study demonstrated the potential of this technology by showing that the CO_2 emissions of a cement plant can be reduced by around 60% at a relatively low cost. To appropriately store the captured CO_2 in different geologic reservoirs, **Stauffer** reported a computational model to comprehensively assess the engineering and economic performances of geologic sequestration of CO_2.[21] Using this model, the number of wells required to inject a given amount of CO_2 can be calculated and long-term sequestration costs can be estimated, given the different plume sizes.

JACS and *ES&T* continue to welcome submissions addressing chemistry in a sustainable world. Through research and application, sustainability can evolve from a catchphrase to a societal norm.

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Henry S. White, JACS Associate Editor

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(16) Denholm, P.; Margolis, R. M.; Milford, J. M. *Environ. Sci. Technol.* **2009**, *43*, 226–232.
(17) Post, J. W.; Hamelers, H. V. M.; Buisman, C. J. N. *Environ. Sci. Technol.* **2008**, *42*, 5785–5790.
(18) Matthews, H. S.; Hendrickson, C. T.; Weber, C. L. *Environ. Sci. Technol.* **2008**, *42*, 5839–5842.
(19) Hertwich, E. G.; Peters, G. P. *Environ. Sci. Technol.* **2009**, *43*, 6414–6420.
(20) Rodríguez, N.; Alonso, M.; Grasa, G.; Abanades, J. C. *Environ. Sci. Technol.* **2008**, *42*, 6980–6984.
(21) Stauffer, P. H.; Viswanathan, H. S.; Pawar, R. J.; Guthrie, G. D. *Environ. Sci. Technol.* **2009**, *43*, 565–570.