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Hydrogen Technology as Major Avenue for Decarbonization of Society

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Renewable power generation by solar and wind have begun to transform and decarbonize electricity sectors around the world, but reliable and resilient systems based on such intermittent sources will require a combination of firm electricity generation, flexible demand, and energy storage. Aviation, long-distance freight transport, and high-temperature industrial processes, such as steel, cement and ammonia production are historically difficult to electrify and decarbonize. *Electrochemical hydrogen technologies* offer unique solutions to these challenges by enabling low temperatures and pressures processes and using electricity to drive the reactions and store or convert energy. Hydrogen technologies are intertwined with carbon dioxide capture, conversion and valorization, water desalination, wastewater treatment and reuse, contributing to climate change mitigation, improving air quality, urban sustainability, food production and addressing complex water availability quality for industrial, agricultural, and urban use. We will present here a conceptual path is to enable net-zero emissions energy systems and improve human health and prosperity by transforming the chemical, manufacturing, and energy sectors through electrochemical engineering of the interplay between *Hydrogen, Carbon and Nitrogen Cycles*. Central convergent theme is the urgent need to address the decarbonization of manufacturing and chemical sectors, using the means of basic science and engineering integration with technoeconomic and socio-economic analysis, practiced dynamically over the network of multiple economic nodes, to inform and direct the science and engineering effort to the maximum impact.

Low CO2 emission (Green) hydrogen is generated in electrolyzers and then is utilized (converted to electricity) in fuel cells – both processes being electrocatalytic ones. Moreover, the rate-limiting (and efficiency lowering) processes in those devices are oxygen evolution and oxygen reduction reaction (OER/ORR). These two processes surmount to a great proportion of electrocatalysis effort. The range of catalyst materials to be employed in such effort includes metals, oxides, and carbonaceous materials. We will present here an overview of our work on different catalysts synthesis protocols to engineer highly functional materials at nano/micro/meso scale with well-defined morphology, size, shape, surface and bulk composition and structure. An example of one such model material set based on N-doped carbon nanostructures decorated with atomically dispersed nonprecious metals, demonstrating control over carbon particle size and shape, distribution of nitrogen and metal sites. These materials are being coupled with various aqueous electrolytes with a wide pH range to demonstrate functionality in fuel cells, metal air batteries and microbial electrochemical systems.

Another major area of electrocatalysts technology is in capture and conversion of CO_2 to fuels and value-added chemicals. The next target for the electrocatalyst development is to introduce new strategies for the conversion of CO_2 beyond CO and formate to multi-carbon species such as ethylene or alcohols. Current frontier in the development of electrocatalytic materials is in selective conversion of N_2 from air into fertilizers and ammonia by low-temperature and low-pressure electrochemical methods. Direct electrocatalytic reduction of ammonia would address major societal challenges related and is an area of fierce competition marred with sometimes mysterious achievements and overinterpretations, yet aiming high for the better good of society.