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Invited review

Artificial photosynthesis: Where are we now? Where can we go?

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ABSTRACT

Widespread implementation of renewable energy technologies, while preventing significant increases in greenhouse gas emissions, appears to be the only viable solution to meeting the world's energy demands for a sustainable energy future. The final energy mix will include conservation and energy efficiency, wind, geothermal, biomass, and others, but none more ubiquitous or abundant than the sun. Over several decades of development, the cost of photovoltaic cells has decreased significantly with lifetimes that exceed 25 years and there is promise for widespread implementation in the future. However, the solar input is intermittent and, to be practical at a truly large scale, will require an equally large capability for energy storage. One approach involves artificial photosynthesis and the use of the sun to drive solar fuel reactions for water splitting into hydrogen and oxygen or to reduce CO_2 to reduced carbon fuels. An early breakthrough in this area came from an initial report by Honda and Fujishima on photoelectrochemical water splitting at TiO_2 with UV excitation. Significant progress has been made since in exploiting semiconductor devices in water splitting with impressive gains in spectral coverage and solar efficiencies. An alternate, hybrid approach, which integrates molecular light absorption and catalysis with the band gap properties of oxide semiconductors, the dye-sensitized photoelectrosynthesis cell (DSPEC), has been pioneered by the University of North Carolina Energy Frontier Research Center (UNC EFRC) on Solar Fuels. By utilizing chromophore-catalyst assemblies, core/shell oxide structures, and surface stabilization, the EFRC recently demonstrated a viable DSPEC for solar water splitting.

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Ralph L. House received his PhD in Physical Chemistry from the University of North Carolina at Chapel Hill (UNC). He is currently Director of Development and Applied Programs at the University of North Carolina at Chapel Hill Solar Energy Research Center where he specializes in identifying fundamental discoveries that are candidates for applied development and commercialization. Projects are based on research in artificial photosynthesis and solar fuels, with a particular focus in CO_2 electrocatalysis.

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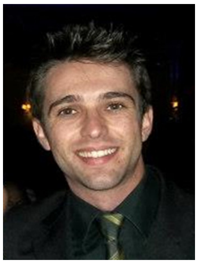

Rodolfo Lopes Coppo received his B.S., 2010, and M.S., 2013, in Chemistry from the Universidade Estadual de Londrina, Brazil. He is a PhD Student at the Universidade de São Paulo since 2014 under the supervision of Professor Neyde Yukie Murakami Iha and will be joining the Meyer group at UNC Chapel Hill in July 2015 for an internship. His research interests include coordination compounds, nanostructured materials and energy conversion devices.

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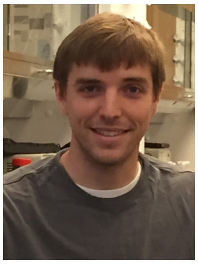

Benjamin Sherman is a postdoctoral researcher in the lab of Professor Thomas J. Meyer. After finishing a B.S. degree at the University of Michigan, he completed a Ph.D. with Professor Tom Moore at Arizona State University in 2013. His research primarily centers on the integration of molecular dyes and catalysts for the development of a photoelectrochemical systems to carry out the conversion of solar energy to a fuel.

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Paul G. Hoertz received his B.S. in Chemistry from Fordham University and received his PhD in Materials Chemistry from Johns Hopkins University. Following postdoctoral research experiences at Pennsylvania State University and UNC Chapel Hill, he served as a Research Chemist at the Research Triangle Institute. He is currently an Applied and Materials Development Scientist at Reynolds American Inc. His research interests include solar energy conversion, energy storage, electron transfer, surface chemistry, nanomaterials, 2D materials, additive manufacturing, and biomaterials.

Thomas J. Meyer designed the first molecular water oxidation catalyst and first described proton coupled electron transfer. He was an early pioneer in the field of artificial photosynthesis and solar fuels. He is a member of the US National Academy of Sciences and the American Academy of Arts and Sciences and has received many awards including the Samson Prize for energy research in 2014. He is currently Arey Professor of Chemistry at UNC Chapel Hill, Director of the UNC Energy Frontier Research Center, and past Vice Chancellor for Graduate Studies and Research at UNC and Associate Laboratory Director at LANL.

1. Introduction

Energy is a unifying theme across the physical and natural sciences, geopolitics, and economics. How we use, distribute and manage our energy resources is at the forefront of the global agenda. There is steadily increasing demand as global affluence increases, and the nagging deleterious effects of climate change if renewable resources aren't used to supply this increasing demand. As a perspective of present and future needs, in September 2000 the United Nations millennium development goals (MDGs) promised to halve the global population living in extreme poverty by 2015. The result has been remarkably successful, decreasing the number of people subsisting on $1 a day from 43% in 1990 to 21% by 2010 [1]. In the summer of 2013, a list of post-2015 MDGs were recommended to the UN, most notably the eradication of extreme poverty by 2030. As shown in many studies, an increase in the global standard of living will result in increasing energy consumption. In Sub-Saharan Africa alone the economy is estimated to quadruple by 2040 with an 80% increase in energy demand [2].

Until now, the global community's energy demands have been largely met by fossil fuels. On the short term, the concept of "Peak Oil" and the predicted decline of oil reserves has been overcome by the advent of modern exploration techniques and the use of horizontal drilling and hydraulic fracturing technologies allowing access to oil and shale gas reserves that were previously out-of-reach. Use of the new technologies comes with an environmental risk, including the impact of methane leakage on global warming [3]