Current Status and Future Perspectives of Clean Energy Technologies at NREL

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1. Introduction

The mission of the National Renewable Energy Laboratory (NREL) is to *advance the science and engineering of energy efficiency, sustainable transportation, and renewable power technologies and provide the knowledge to integrate and optimize energy systems.* NREL is one of the U.S. Department of Energy (DOE) Laboratories. It is stewarded by DOE's Energy Efficiency and Renewable Energy (EERE) office (www.energy.gov/eere). NREL aims to continue to play a vital role in creating a transformed energy system that fully integrates the potential of renewable energy and energy efficiency technology into a robust, reliable, affordable, and sustainable energy ecosystem.

2. R&D Activities related to clean energy technologies

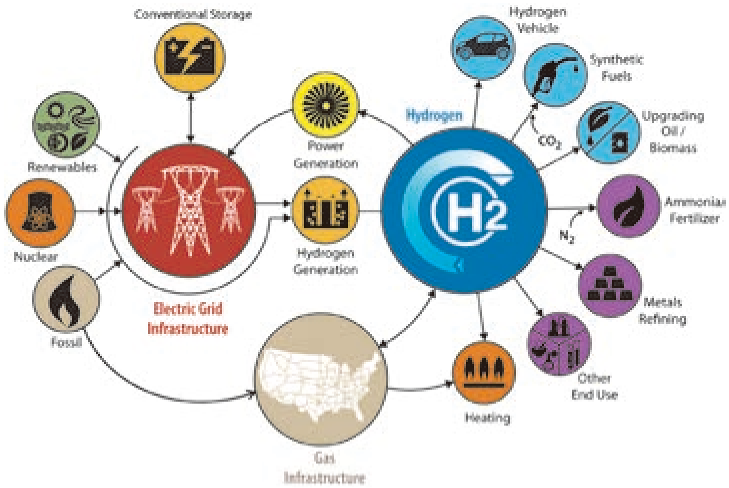
NREL has a broad research and development portfolio that includes: 1) Renewable power: Solar, Wind, Water, Geothermal; 2) Sustainable transportation: Bioenergy, Vehicle technologies, Hydrogen and Fuel Cells; 3) Energy Efficiency: Buildings, Advanced Manufacturing, Government energy management programs; 4) Energy Systems Integration: Grid Modernization; 5) DOE Office of Science Programs: Basic Energy Science, Biological and Environmental Research, Advanced Scientific Computing Research and 6) Industrial Partnerships along with work for other government agencies. Our research spans fundamental chemical, biological and materials science; device fabrication, testing and certification; energy systems; systems engineering; and analysis/assessment.

Overall NREL takes a systems-based, assessment-driven R&D approach to understand the limitations and enhance the performance of current energy systems, accelerate emerging concepts, and develop next generation materials, concepts and systems. As an example of our research in solar energy, we have made advancements in controlling doping in CdTe solar cells to create unprecedented efficiencies in partnership with industry. We have also developed new processing concepts for highly efficient crystalline III-V solar cells and are developing the underpinning science for creating efficient, stable, readily processable perovskite-based solar cells. Other aspects of our solar energy portfolio include fundamental solar photochemistry, theory-driven materials design, durable photovoltaic (PV) module materials to further optimize reliability and capacity of low-cost PV modules, and new concepts for concentrated solar power (CSP) as well as systems integration.

NREL is part of DOE's Grid Modernization Initiative which aims to develop the concepts, tools, and technologies needed to measure, analyze, predict, protect, and control the grid of the future. Our vision for next generation batteries is to create electrical energy storage systems with new concepts, materials, and architectures that leapfrog today's state of the art and are low cost, safe, have a long lifetime, are inherently scalable and manufacturable, and are free of critical or emerging critical materials. We are also working on current battery technologies for multiple scales of energy storage spanning transportation, vehicle fast-charging, behind-the-meter-storage, and grid-scale storage.

3. Specific research activities in hydrogen, CCUS, and related technologies

NREL has a broad R&D portfolio supporting DOE goals in hydrogen production, storage, delivery and utilization. We are an active contributor to the DOE H2@Scale initiative (https://www.energy.gov/eere/fuelcells/h2scale) which aims to advance affordable hydrogen production, transport, storage, and utilization to increase opportunities in multiple energy sectors, including, but also beyond, transportation.



H2@Scale vision with hydrogen as an energy carrier that also serves as a critical feedstock in multiple industries. (https://www.energy.gov/eere/fuelcells/h2scale)

NREL has decades of experience in polymer electrolyte membrane (PEM) fuel cell science and technology including electrocatalysis, membranes, durability and stack testing. We are now applying these capabilities to the electrolytic production of hydrogen from water splitting. NREL integrates its significant capabilities in hydrogen science and technology with its materials science, analysis, and energy systems competencies to drive the foundational science and engineering for interconverting electrical, chemical, and thermal energy. We integrate materials discovery, advanced catalyst and membrane R&D, and durability studies with advanced analysis (systems, techno-economic), systems testing (evaluation, demonstration, and optimization), and energy systems integration (modeling and testing). We are developing systems with lower cost, higher performance, enhanced durability, and intermittent operation associated with renewable energy generation.

NREL leads the DOE HydroGEN energy materials network (https://www.h2awsm.org/) which is a consortium of six DOE national laboratories that address materials challenges in photoelectrochemical, solar thermochemical, and low- and high-temperature electrolysis to accelerate research, development, and deployment of advanced water splitting technologies for clean, sustainable hydrogen production. NREL scientists also carry out fundamental work on solar fuels production examining molecular, nanoscale and semiconductor-based systems, interfacial science, and redox catalysis.

In NREL's Electrons to Molecules initiative, we are developing the innovative science and technology for using electricity and electrochemical processes to convert low-energy molecules such as water, carbon dioxide (CO_2), and nitrogen (N_2) to higher-value molecules. These molecules can be used as fuels, chemicals, material products, or as chemical energy storage carriers. Using our capabilities in electrochemistry, synthetic biology, nanoscience, catalysis, materials discovery, biological/chemical/materials processing, interfacial science, advanced spectroscopy and imaging, we are exploring a number of electrocatalytic, biological, and hybrid approaches for CO_2 utilization such as:

1. Electrochemical splitting of water to generation hydrogen and subsequent reduction of CO_2
2. Oxidation of water coupled with electrochemical reduction of CO_2 to intermediates such as CO, formate, methanol, methane, and/or higher carbon number compounds
3. Conversion of CO_2-derived reactive intermediates via either catalytic or biological processes to higher carbon number molecules (with or without hydrogen)

4. Generation of molecules that store electrons within easily accessible chemical bonds
5. Microbial electrosynthesis that uses either light or electrons to drive biological systems.

In collaboration with industry, we are demonstrating the direct methanation of CO_2 using bioorganisms and hydrogen from electrolytic water splitting. We are exploring the coupling of semiconductors with nitrogenase enzymes to efficiently reduce nitrogen to ammonia.

4. International collaboration and Joint R&D Activities

NREL has many international collaborations and joint R&D activities. For example, as part of the Global Alliance of Solar Energy Research Institutes (GA-SERI) with AIST in Japan and Germany's Fraunhofer Institute for Solar Energy, we co-led two international workshops on the challenges for terawatt photovoltaics that were published in *Science* (**364,** 836, 2019 and **356,** 141, 2017). GA-SERI and other collaborators ran a workshop in Japan in May 2019 on the Gigaton Hydrogen Challenge. We continue to be actively engaged in a myriad of international conferences and workshops, ministerials, and International Energy Agency activities. We have provided analysis and assessment for renewable energy deployment and many other energy scenarios for a wide number of countries and regions.

5. Future perspectives

The discovery and development of high-performance materials, including functional materials and structural materials, hold one of the keys to innovation across many critical energy technologies. A systems-based approach is also required for the needed innovations in energy science, including hydrogen, CCUS and related activities. There are still major opportunities for cost reductions and performance/reliability enhancements for photovoltaics, CSP, and other renewables in addition to developing scalable, lower capital cost manufacturing processes.

We must improve the efficiency for interconverting thermal, electrical and chemical energy. Carbon utilization will require further advances in selectivity and efficiency—hybrid processes that employ abiotic and biotic concepts appear to be promising along with a number of other approaches. Direct conversion of solar energy to chemical energy (hydrogen or carbon-based fuels) via artificial photosynthesis and other concepts remains a grand challenge.

Innovation in energy systems integration continues to be vital for our energy future. Energy storage (electrical and chemical) is also going to be a critical element of the future energy economy. Vehicles require innovative materials discovery and advanced battery design to enable safe and high specific power storage; and the grid of the future will require massive amounts of storage to support large amounts of variable renewable energy generation, to optimize the competing needs in resource management, and to minimize transmission line build-out.

Dr. William Tumas

2013-	Associate Laboratory Director, Materials and Chemical Science and Technology, National Renewable Energy Laboratory (NREL)
2014-	Director Center for Next Generation of Materials Design Energy Frontier Research Center, NREL
2011-2014	Director, Center for Inverse Design Energy Frontier Research Center, NREL
2009-2013	Chemical and Materials Science Center Director, NREL
2009-	Point of Contact, DOE Office of Science-Basic Energy Science, NREL
2006-2009	Program Director for Applied Energy Programs, Los Alamos National Laboratory (LANL)
2005-2007	Director, DOE Center of Excellence for Chemical Hydrogen Storage, LANL
2004-2006	Program Manager, Hydrogen Programs, LANL
2002-2003	Acting Director, Office of Science Programs, LANL
1994-2005	Group Leader, Inorganic Chemistry, LANL
1993-1994	Research Scientist, LANL
1989-1993	Project Leader, Oxidation/Environmental Catalysis, DuPont Central Research
1987-1989	Research Chemist, DuPont Central Research
1985-1987	NIH and Weizmann Postdoctoral Fellow, California Institute of Technology
1980-1985	NSF and Hertz Foundation Graduate Fellow, Stanford University
1980	Summer Intern, Allied Chemical Company

Research Biography

2011-	Solar Energy Conversion; Materials Design; Materials Science
2009-2011	Green Chemistry, Solar Energy Conversion, Materials Science
2004-2009 –	Catalysis; Chemical Hydrogen Storage; Hydrogen/Fuel Cells; Green Chemistry
1993-2003	Catalysis in Supercritical Fluids; Homogeneous Catalysis; Multiphase Catalysis Green Chemistry
1990-1993	Environmental Catalysis; Waste Treatment Technology Development
1987-1993	Organometallic Chemistry; Homogeneous Catalysis;
1984-1987	Organometallic Chemistry; Photochemistry
1980-1985	Gas Phase Ion Reaction Dynamics; Infra-red Photochemistry
1980	Laser Photocatalysis of Metal Carbonyls; Organometallic Photochemistry
1976-1980	Physical Organic Chemistry; Reaction Mechanisms of Elimination Reactions

Academic Background

1985 Ph.D. in Organic Chemistry, Stanford University

1980 Bachelor of Arts, Chemistry, Ithaca College