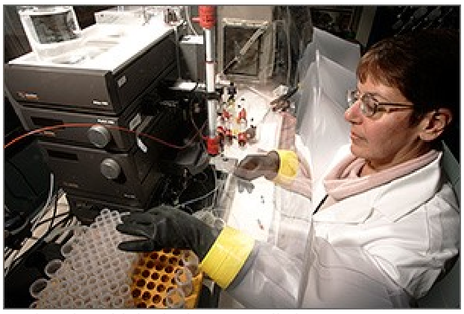
Hydrogen Production and Delivery

Most of the hydrogen in the United States is produced by steam reforming of natural gas. For the near term, this production method will continue to dominate. Researchers at NREL are developing advanced processes to produce hydrogen economically from sustainable resources. NREL's hydrogen production and delivery R&D efforts, which are led by Huyen Dinh, focus on the following topics:

- Biological Water Splitting
- Fermentation
- Conversion of Biomass and Wastes
- Photoelectrochemical Water Splitting
- Solar Thermal Water Splitting
- Renewable Electrolysis
- Hydrogen Dispenser Hose Reliability
- Hydrogen Production and Delivery Pathway Analysis.

Biological Water Splitting

Certain photosynthetic microbes use light energy to produce hydrogen from water as part of their metabolic processes. Because oxygen is produced along with the hydrogen, photobiological hydrogen production technology must overcome the inherent oxygen sensitivity of hydrogen-evolving enzyme systems. NREL researchers are addressing this issue by screening for naturally occurring organisms that are more tolerant of oxygen and by creating new genetic forms of the organisms that can sustain hydrogen production in the presence of oxygen. Researchers are also developing a new system that uses a metabolic switch (sulfur deprivation) to cycle algal cells between the photosynthetic growth phase and the hydrogen production phase.



In the photobiological water splitting process, hydrogen is produced from water using sunlight and specialized microorganisms, such as green algae and cyanobacteria.
Photo by Jack Dempsey, NREL

Publications:

- Biological Systems for Hydrogen Photoproduction. Maria Ghirardi. Annual Merit Review. (2014)
- Biological Systems for Hydrogen Photoproduction. Maria Ghirardi, Paul King, and Seth Noone. Annual Progress Report. (2013)
- Comparing Photosynthetic and Photovoltaic Efficiencies and Recognizing the Potential for Improvement. R. Blankenship, D. Tiede, J. Barber, G. Brudvig, G. Fleming, M. Ghirardi, M. Gunner, W. Junge, D. Kramer, A. Melis, T. Moore, C. Moser, D. Nocera, A. Nozik, D. Ort, W. Parson, R. Prince, and R. Sayre. *Science*. Volume 332. (2011)
- Design of a New Biosensor for Algal Hydrogen Production Based on the Hydrogen-Sensing System of Rhodobacter Capsulatus. Matt Wecker, Jonathan Meuser, Matthew Posewitz, and Maria Ghirardi. *International Journal of Hydrogen Energy*. Volume 36. (2011)
- Truncated Antenna Mutant of Chlamydomonas Reinhardtii Can Produce More Hydrogen than the Parental Strain. Sergey Kosourov, Maria Ghirardi, and Michael Seibert. *International Journal of Hydrogen Energy*. Volume 36. (2011)
- Photosynthetic Electron Partitioning Between [FeFe] Hydrogenase and Ferredoxin: NADP+-Oxidoreductase (FNR) Enzymes in Vitro. Iftach Yacoby, Sergii Pochekailov, Hila Toporik, Maria Ghirardi, Paul King, and Shuguang Zhang. Proceedings of the National Academy of Sciences. Volume 108. (2011)

Contact: Maria Ghirardi

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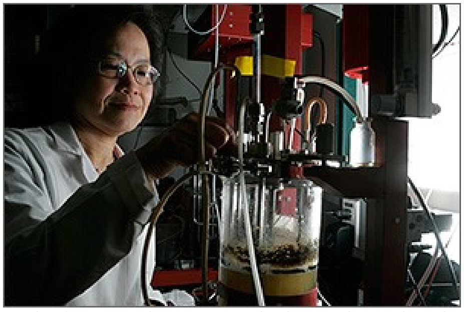
Fermentation

NREL scientists are developing pretreatment technologies to convert lignocellulosic biomass into sugar-rich feedstocks that can be directly fermented to produce hydrogen, ethanol, and high-value chemicals. Researchers are also working to identify a consortium of Clostridium that can directly ferment hemicellulose to hydrogen. Other research areas involve bio-prospecting efficient cellulolytic microbes, such as Clostridium thermocellum, that can ferment crystalline cellulose directly to hydrogen to lower feedstock costs. Once a model cellulolytic bacterium is identified, its potential for genetic manipulations, including sensitivity to antibiotics and ease of genetic transformation, will be determined. NREL's future fermentation projects will focus on developing strategies to generate mutants that are blocked selectively from producing waste acids and solvents to maximize hydrogen yield.



In the fermentation process, hydrogen is produced from the fermentation of renewable biomass materials.
Photo by Jack Dempsey, NREL

Publications:

- Fermentation and Electrohydrogenic Approaches to Hydrogen Production. Pin-Ching Maness. Annual Merit Review. (2014)
- Fermentation and Electrohydrogenic Approaches to Hydrogen Production. Pin-Ching Maness, Katherine Chou, and Lauren Magnusson. Annual Progress Report. (2013)
- Hydrogen Production from Cellulose in a Two-Stage Process Combining Fermentation and Electrohydrogenesis. Elodie Lalaurette, Shivegowda Thammannagowda, Ali Mohagheghi, Pin-Ching Maness, and Bruce Logan. *International Journal of Hydrogen Energy*. Volume 24. (2009)

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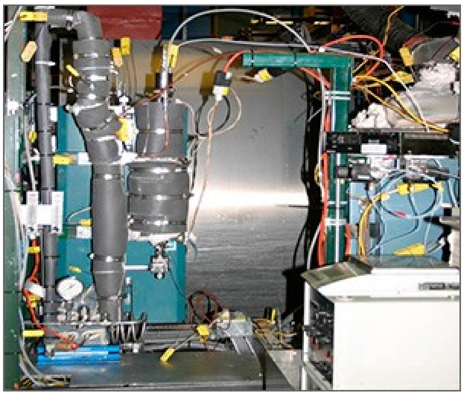
Conversion of Biomass and Wastes

Hydrogen can be produced via pyrolysis or gasification of biomass resources such as agricultural residues like peanut shells; consumer wastes including plastics and waste grease; or biomass specifically grown for energy uses. Biomass pyrolysis produces a liquid product (bio-oil) that contains a wide spectrum of components that can be separated into valuable chemicals and fuels, including hydrogen. NREL researchers are currently focusing on hydrogen production by catalytic reforming of biomass pyrolysis products. Specific research areas include reforming of pyrolysis streams and development and testing of fluidizable catalysts.



The biomass pyrolysis process produces bio-oil, the components of which can be separated into chemicals and fuels, including hydrogen.
Photo by Stefan Czernik, NREL

Publications:

- Distributed Production of Hydrogen by Auto-Thermal Reforming of Fast Pyrolysis Bio-Oil. S. Czernik and R. French. *International Journal of Hydrogen Energy*. Volume 39, Issue 2. (2014)
- Evaluate Impact of Catalyst Type on Oil Yield and Hydrogen Consumption from Mild Hydrotreating. R. French, J. Stunkel, S. Black, M. Myers, M. Yung, and K. Iisa. (2014)
- Distributed Bio-Oil Reforming. Stefan Czernik, Richard French, and Michael Penev. Annual Progress Report. (2013)
- Distributed Bio-Oil Reforming. Stefan Czernik. Annual Merit Review. (2013)
- Production of Synthesis Gas by Partial Oxidation and Steam Reforming of Biomass Pyrolysis Oils. David Rennard, Rick French, Stefan Czernik, Tyler Josephson, and Lanny Schmidt. *International Journal of Hydrogen Energy*. Volume 35, Issue 9. (2010)

Contact: Richard French

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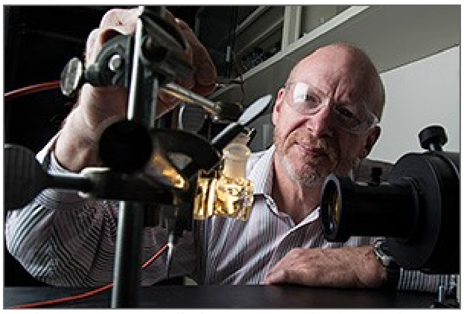
Photoelectrochemical Water Splitting

The cleanest way to produce hydrogen is by using sunlight to directly split water into hydrogen and oxygen. Multijunction cell technology developed by the photovoltaic industry is being used for photoelectrochemical (PEC) light harvesting systems that generate sufficient voltage to split water and are stable in a water/electrolyte environment. The NREL-developed PEC system produces hydrogen from sunlight without the expense and complication of electrolyzers, at a solar-to-hydrogen conversion efficiency of 12.4% lower heating value using captured light. Research is underway to identify more efficient, lower cost materials and systems that are durable and stable against corrosion in an aqueous environment.



In the PEC water splitting process, hydrogen is produced from water using sunlight and specialized semiconductors.
Photo by Dennis Schroeder, NREL

Publications:

- Semiconductor Materials for Photoelectrolysis. Todd Deutsch and John Turner. Annual Merit Review. (2014)
- Semiconductor Materials for Photoelectrolysis. Todd Deutsch, John Turner, Heli Wang, and Huyen Dinh. Annual Progress Report. (2013)
- Photoelectrochemical Water Splitting: Standards, Experimental Methods, and Protocols. Zhebo Chen, Huyen Dinh, and Eric Miller. Book published by Springer. (2013)
- Cobalt-Phosphate (Co-Pi) Catalyst Modified Mo-Doped $BiVO_4$ Photoelectrodes for Solar Water Oxidation. Satyananda Kishore Pilli, Thomas Furtak, Logan Brown, Todd Deutsch, John Turner, and Andrew Herring. *Energy and Environmental Science*. Issue 12. (2011)
- Nanoporous Black Silicon Photocathode for Hydrogen Production by Photoelectrochemical Water Splitting. Jihun Oh, Todd Deutsch, Hao-Chih Yuan, and Howard Branz. *Energy and Environmental Science*. Issue 5. (2011)

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Solar Thermal Water Splitting

The High-Flux Solar Furnace concentrates solar energy, generating ultra-high temperatures that enable hydrogen production via thermochemical reaction cycles.
Photo by Warren Gretz, NREL

NREL researchers use the High-Flux Solar Furnace reactor to concentrate solar energy and generate temperatures between 1,000 and 2,000 degrees Celsius. Ultra-high temperatures are required for thermochemical reaction cycles to produce hydrogen. Such high-temperature, high-flux, solar-driven thermochemical processes offer a novel approach for the environmentally benign production of hydrogen. Very high reaction rates at these elevated temperatures give rise to very fast reaction rates, which significantly enhance production rates and more than compensate for the intermittent nature of the solar resource.

Publications:

- Rapid High Temperature Solar Thermal Biomass Gasification in a Prototype Cavity Reactor. Paul Lichty, Chris Perkins, Bryan Woodruff, Carl Bingham, and Al Weimer. *Journal of Solar Energy Engineering*. Volume 132. (2010)
- Development of a Solar-Thermal ZnO/Zn Water-Splitting Thermochemical Cycle. A.W. Weimer, C. Perkins, P. Lichty, H. Funke, J. Zartman, D. Hirsch, C. Bingham, A. Lewandowski, S. Haussener, and A. Steinfeld. (2009)

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Renewable Electrolysis

The renewable electrolysis process uses renewable electricity to produce hydrogen by passing an electrical current through water.
Photo by Pat Corkery, NREL

Renewable energy sources such as photovoltaics, wind, biomass, hydro, and geothermal can provide clean and sustainable electricity for our nation. However, renewable energy sources are naturally variable, requiring energy storage or a hybrid system to accommodate daily and seasonal changes. One solution is to produce hydrogen through the electrolysis—splitting with an electric current—of water and to use that hydrogen in a fuel cell to produce electricity during times of low power production or peak demand, or to use the hydrogen in fuel cell vehicles.

Researchers at NREL's Energy Systems Integration Facility and Distributed Energy Resources Test Facility are examining the issues related to using renewable energy sources for producing hydrogen via the electrolysis of water. NREL tests integrated electrolysis systems and investigates design options to lower capital costs and enhance performance.

Learn more about NREL's hydrogen production cost analysis, renewable electrolysis research, and the wind-to-hydrogen project, which uses electricity from wind turbines and solar panels to produce hydrogen.

Contact: Kevin Harrison

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Hydrogen Dispenser Hose Reliability

Used for hydrogen hose reliability testing, this fueling robot mimics the stress associated with repetitive vehicle fueling.
Photo by Dennis Schroeder, NREL

With a focus on reducing costs and increasing reliability and safety, NREL performs accelerated testing and cycling of 700 bar hydrogen dispensing hoses at the Energy Systems Integration Facility using automated robotics to simulate field conditions. View the video of the robot, which mimics the repetitive stress of a person bending and twisting a hose to dispense hydrogen into a fuel cell vehicle's onboard storage tank. Researchers perform mechanical, thermal, and pressure stress tests on new and used hydrogen dispensing hoses. The hose material is analyzed to identify hydrogen infiltration, embrittlement, and crack initiation/propagation.

Publications:

- Hydrogen Dispenser Hose Reliability Improvement. Kevin Harrison, Huyen Dinh, and Mike Peters. Annual Merit Review. (2014)
- Fueling Robot Automates Hydrogen Hose Reliability Testing. Kevin Harrison. (2014)
- Robot-Powered Reliability Testing. Video produced by NREL. (2013)

Contact: Kevin Harrison

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Hydrogen Production and Delivery Pathway Analysis

NREL performs systems-level analyses on a variety of sustainable hydrogen production and delivery pathways. These efforts focus on determining status improvements resulting from technology advancements, cost as a function of production volume, and the potential for cost reductions. Results help identify barriers to the success of these pathways, primary cost drivers, and remaining R&D challenges. NREL-developed hydrogen analysis case studies provide transparent projections of current and future hydrogen production costs. Learn more about NREL's systems analysis work.

Publications:

- Renewable Hydrogen Potential from Biogas in the United States. Genevieve Saur and Anelia Milbrandt. (2014)
- Hydrogen from Biogas: Resource Assessment. Genevieve Saur and Anelia Milbrandt. Annual Progress Report. (2013)
- Hydrogen from Biogas: Resource Assessment. Genevieve Saur and Anelia Milbrandt. Annual Merit Review. (2013)

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