



Hydrogen can be produced using a variety of resources including biomass, hydro, wind, solar, geothermal, nuclear, coal with carbon sequestration, and natural gas. This diversity of sources makes hydrogen a promising energy carrier and enables hydrogen production almost anywhere in the world.

## Fuel Cell Technologies Program: Production

### Hydrogen Production

Hydrogen is an energy carrier, not an energy source—hydrogen stores and delivers energy in a usable form, but it must be produced from hydrogen containing compounds.

Hydrogen can be produced using diverse, domestic resources including fossil fuels,

such as coal (preferentially with carbon sequestration), natural gas, and biomass or using nuclear energy and renewable energy sources, such as wind, solar, geothermal, and hydroelectric power to split water. This great potential for diversity of supply is an important reason why hydrogen is such a promising energy carrier.

Hydrogen can be produced at large central plants, semi-centrally, or in small distributed units located at or very near the point of use, such as at refueling stations or stationary power sites.

### How Is Hydrogen Produced?

Researchers are developing a wide range of technologies to produce hydrogen economically from a variety of resources in environmentally friendly ways.

#### *Natural Gas Reforming*

Hydrogen can be produced from natural gas using high-temperature steam. This process, called steam methane reforming, accounts for about 95% of the hydrogen used today in the U.S. Another method, called partial oxidation, produces

hydrogen by burning methane in air. Both steam reforming and partial oxidation produce a “synthesis gas,” which is then reacted with additional steam to produce a higher hydrogen content gas stream.

#### *Renewable Electrolysis*

Electrolysis uses an electric current to split water into hydrogen and oxygen. The electricity required can be generated using any of a number of resources. However, to minimize greenhouse gas emissions, electricity generation using renewable energy technologies, such as wind, solar, geothermal, and hydroelectric power, nuclear energy, or coal and natural gas with carbon sequestration are preferred.

#### *Gasification*

Gasification is a process in which coal or biomass is converted into gaseous components by applying heat under pressure and in the presence of air/oxygen and steam. A subsequent series of chemical reactions produces a synthesis gas, which is then reacted with steam to produce a gas stream with an increased hydrogen concentration that then can be separated and purified. With carbon capture and storage, hydrogen can be produced directly from coal with near-zero greenhouse gas emissions. Since growing biomass consumes CO<sub>2</sub> from the atmosphere, producing hydrogen through biomass gasification releases near-zero net greenhouse gases.

#### *Renewable Liquid Reforming*

Biomass can also be processed to make renewable liquid fuels, such as ethanol or bio-oil, which are relatively convenient to transport and can be reacted with high-temperature steam to produce hydrogen at or near the point of use. Researchers are also exploring a variation of this technology known as aqueous-phase reforming.

#### *Nuclear High-Temperature Electrolysis*

Heat from a nuclear reactor can be used to improve the efficiency of water electrolysis to produce hydrogen. By increasing the temperature of the water, less electricity is required to split it into hydrogen and oxygen, which reduces the total energy required.

#### *High-Temperature Thermochemical Water-Splitting*

Another water-splitting method uses high temperatures generated by solar concentrators (mirrors that focus and intensify sunlight) or nuclear reactors to drive a series of chemical reactions to split water into hydrogen and oxygen through a series of chemical reactions. All of the intermediate process chemicals are recycled within the process.

#### *Biological*

Certain microbes, such as green algae and cyanobacteria, produce hydrogen by splitting water in the presence of sunlight as a byproduct of their natural metabolic processes. Other microbes can extract hydrogen directly from biomass.

#### *Photoelectrochemical*

Hydrogen can be produced directly from water using sunlight and a special class of semiconductor materials. These highly specialized semiconductors absorb sunlight and use the light energy to completely separate water molecules into hydrogen and oxygen.

### **What Are the Challenges?**

The greatest technical challenge to hydrogen production is cost reduction. For transportation, a key driver for energy independence, hydrogen must be cost-competitive with conventional fuels and technologies on a per-mile basis. This means that the cost of hydrogen — regardless of the production technology,

including the cost of delivery — must be in the range of \$2-\$4/gallon gasoline equivalent (untaxed and dispensed).

### **Research Directions**

Hydrogen production technologies are in various stages of development. Some technologies, such as steam methane reforming, are well-developed and can be used in the near term, and R&D in this area is no longer being funded by DOE. Others, such as high-temperature thermochemical water-splitting, biological, and photoelectrochemical, are in early stages of laboratory development and considered potential pathways for the long-term.

To reduce overall hydrogen cost, research is focused on reducing capital equipment, operations, and maintenance costs, as well as improving the efficiency of hydrogen production technologies. Related research includes developing new hydrogen delivery methods and infrastructure, improving carbon sequestration technology to ensure that coal-based hydrogen production releases almost no greenhouse gas emissions, and improving biomass growth, harvesting, and handling to reduce the cost of biomass resources used in hydrogen production.

### **For More Information**

More information on the Fuel Cell Technologies Program is available at <http://www.hydrogenandfuelcells.energy.gov>.