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Wind energy and the hydrogen economy—review of the technology

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Abstract

The hydrogen economy is an inevitable energy system of the future where the available energy sources (preferably the renewable ones) will be used to generate hydrogen and electricity as energy carriers, which are capable of satisfying all the energy needs of human civilization. The transition to a hydrogen economy may have already begun. This paper presents a review of hydrogen energy technologies, namely technologies for hydrogen production, storage, distribution, and utilization. Possibilities for utilization of wind energy to generate hydrogen are discussed in parallel with possibilities to use hydrogen to enhance wind power competitiveness.

Keywords: Hydrogen energy; Wind energy; Fuel cells; Solar energy; Hydrogen production; Hydrogen storage

1. Hydrogen energy system

The transition to a hydrogen economy may have already begun. The US Department of Energy has initiated a "National Hydrogen Vision and Roadmap" process in response to recommendations made in President George W. Bush's National Energy Policy. Representatives from hydrogen-related industries, universities, environmental organizations, and government agencies participated in the "Vision Meeting" and in a subsequent "Roadmap Workshop" to outline the next step in America's transition to a *hydrogen economy*. At present, there are a large number of companies working on technologies pertaining to hydrogen production, storage, and utilization. For example, several hydrogen-powered prototype vehicles are already being demonstrated together with hydrogen refueling stations.

Regardless of the energy sources of the future there will always be a need for convenient, clean, safe, efficient and versatile energy carriers or forms of energy that can be delivered to the end user. One of these energy carriers is electricity, which is already being used worldwide. Electricity is a convenient form of energy, which can be produced from various sources and transported over large distances. It is clean, although its production from

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fossil fuels is not. Hydrogen is another clean, efficient and versatile energy carrier, which supplements electricity very well. Together these two carriers may satisfy all the energy needs and form an energy system that is permanent and independent of energy sources (Bockris, 1975; Bockris and Veziroglu, 1985; Bockris et al., 1991).

Hydrogen has some unique characteristics that make it an ideal energy carrier (Veziroglu and Barbir, 1992), namely:

- It can be produced from and converted into electricity at a relatively high efficiency.
- Raw material for hydrogen production is water, which is available in abundance. Hydrogen is a completely renewable fuel, since the product of hydrogen utilization (either through combustion or through electrochemical conversion) is pure water or water vapor.
- It can be stored as liquid, gas, or solid (metal hydrides).
- It can be transported over large distances using pipelines, tankers, or rail trucks.
- It can be converted into other forms of energy in more ways and more efficiently than any other fuel, i.e., in addition to flame combustion (like any other fuel) hydrogen may be converted through catalytic combustion, electro-chemical conversion, and hydriding.
- Hydrogen as an energy carrier is environmentally compatible. It produces small amounts of NO_x if it is burned with air at high temperatures.

Fig. 1 shows a global energy system in which electricity and hydrogen are produced from available energy sources and used in many applications. Both hydrogen and electricity complement renewable energy sources particularly well, by presenting them to the end user in a convenient form and at a convenient time. Depending on location, electricity may be used directly or transformed into hydrogen. For large-scale storage, hydrogen can be stored underground in ex-mines, caverns or aquifers. Fuel cells may be available in MW power plant size or several kW suitable for distributed power generation. Together with renewable energy sources, such as solar and wind, electricity and hydrogen form a clean energy system capable of permanently satisfying all the energy needs of human civilization.

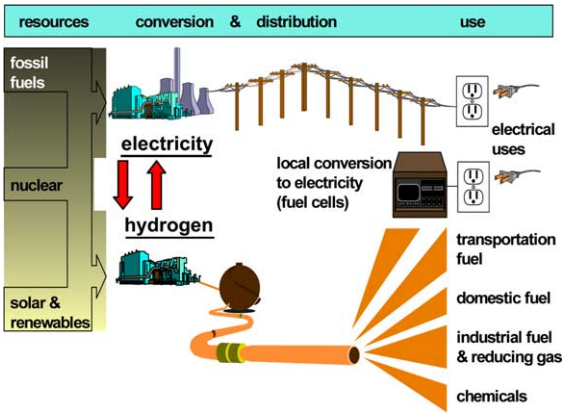

Fig. 1. Hydrogen/electricity energy system.

1.1. Hydrogen energy technologies

Most of the technologies required for hydrogen production, storage, and utilization have already been developed. Few of them are at a level where they can compete with the existing energy technologies. The following is a review of the technologies for hydrogen production, storage, distribution, and utilization.

1.1.1. Technologies for hydrogen production

Production of hydrogen requires feedstock (logical sources being hydrocarbon fuels, C_XH_Y, and water, H_2O) and energy. The amount of energy required to produce hydrogen is always greater than the energy that can be released by hydrogen utilization.

Presently, hydrogen is mostly being produced from fossil fuels (natural gas, oil, and coal). Hydrogen is used in refineries to upgrade crude oil (hydrotreating and hydrocracking), in the chemical industry to synthesize various chemical compounds (ammonia, methanol, etc.), and in metallurgical processes as a reduction or protection gas.

Technologies for hydrogen production from fossil fuels have been developed and are used to produce industrial hydrogen. These include steam reforming of natural gas, partial oxidation of hydrocarbons and coal gasification. Depending on the cost of fuel, hydrogen can be produced for 6–14 $/GJ (Steinberg and Cheng, 1988). However, these technologies depend on fossil fuels and emit CO_2. The only method that can generate hydrogen from fossil fuels without generation of CO_2 is direct thermal and catalytic cracking of hydrocarbons. This method has been used to produce carbon, but for cost effective hydrogen generation it is still in the early development phase (Muradov, 1998).

Water electrolysis is relatively efficient (>70%), but because it needs electricity, hydrogen produced by water-electrolysis is expensive (>$20/GJ assuming a cost of about $0.05/kW h). However, there is a potential to generate relatively inexpensive hydrogen from hydropower and nuclear plants.

Water electrolysis is particularly suitable to be used in conjunction with photovoltaics (PVs) and wind energy. In general, there is a good match between the polarization curves of PV cells and electrolyzers. Experience from PV/electrolysis pilot plants shows that they