INTERNATIONAL JOURNAL OF HYDROGEN ENERGY 37 (2012) 1184–1203

Available online at www.sciencedirect.com

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journal homepage: www.elsevier.com/locate/he

Re-envisioning the role of hydrogen in a sustainable energy economy

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ARTICLE INFO

Article history:
Received 24 July 2011
Received in revised form
26 September 2011
Accepted 27 September 2011
Available online 28 October 2011

Keywords:
Hydrogen economy
Global sustainable energy strategy
Renewable energy
Fuel cell vehicles
Battery vehicles
Energy security

ABSTRACT

This paper addresses the fundamental question of where hydrogen might fit into a global sustainable energy strategy for the 21st century that confronts the three-pronged challenge of irreversible climate change, uncertain oil supply, and rising pollution. We re-envision the role of hydrogen at national and international strategic levels, relying entirely on renewable energy and energy efficiency. It is suggested the time for an exclusive ‘hydrogen economy’ has passed, since electricity and batteries would be used extensively as well. Yet hydrogen would still play a crucial role: in road and rail vehicles requiring a range comparable to today’s petrol and diesel vehicles; in coastal and international shipping; in air transport; and for longer-term seasonal storage on electricity grids relying mainly on renewables. Hydrogen fuel cell vehicles are proposed where medium and long distance trips are required, with plug-in battery electric vehicles reserved for just short trips. A hierarchy of spatially-distributed hydrogen production, storage and distribution centers relying on local renewable energy sources and feedstocks would be created to limit the required hydrogen pipeline network to the main metropolitan areas and regions by complementary use of electricity as a major energy vector. Bulk hydrogen storage would provide the strategic energy reserve to guarantee national and global energy security in a world relying increasingly on renewable energy. It is recommended that this vision next be applied to specific countries by conducting detailed energy-economic-environmental modeling to quantify its net benefits.

1. Introduction

Where does hydrogen fit into a sustainable energy economy? To the forebears of the hydrogen economy, the answer to this core question was clear. The electrochemist, John Bockris, describes the genesis of this concept of a hydrogen economy in his pioneering book *Energy: The Solar Hydrogen Alternative* first published in 1975 [1] as follows:

Abbreviation: A, Aircraft; AC, Alternating Current; AHC, Autonomous Hydrogen Center; B, Bus; BEV, Battery Electric Vehicle; C, Cycle; CCS, Carbon Capture and Storage; CHC, Coastal Hydrogen Center; DC, Direct Current; DoE, Department of Energy; EERE, Energy Efficiency and Renewable Energy; EO, Electric Overhead; EU, European Union; HE, Hydrogen Economy; HFC, Hydrogen Fuel Cell; HFCV, Hydrogen Fuel Cell Vehicle; HHV, High Heating Value; HISE, Hydrogen in a Sustainable Energy (strategy); IHC, Inland Hydrogen Center; IPCC, Intergovernmental Panel on Climate Change; JetLH, Liquid Hydrogen Jet Fuel; kWh_e, Kilowatt Hours (electrical); LHV, Low Heating Value; LPG, Liquid Petroleum Gas; NHA, National Hydrogen Association; OHC, Off-shore Hydrogen Center; PV, Photovoltaic; R, Rail; R&D, Research and Development; RE, Renewable Energy; S, Ship; T, Tram; UPT, Urban Public Transport; W, Walking; WWS, Wind, Water, and Sunlight.

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doi:10.1016/j.ijhydene.2011.09.137

"The phrase 'A Hydrogen Economy' arose for the first time in a discussion between Bockris and Triner of the General-Motors Technical Center, 3 February 1970.They had been discussing (along with others in a Group) the various fuels which could replace polluting gasoline in transportation and had come to the conclusion that hydrogen would be the eventual fuel for all types of transports. The discussion went to other applications of hydrogen in providing energy to households and industry, and it was suggested that we might live finally in what could be called 'A Hydrogen Society'. The phrase 'A Hydrogen Economy' was then used later in the same conversation".

The original vision for such a Hydrogen Economy (HE) was conceived at a time when concerns about running out of oil, natural gas, and ultimately coal in the face of exponential growth in global primary energy use, and the associated rising pollution levels, were first being raised [1,2]. The seminal meeting described above took place just before the release of the Club of Rome's controversial *Limits to Growth* report [3], and three years before the first major oil crisis occurred leading to a major hike in the price of crude oil and risks about the security of future supplies from the Middle East. Presciently, Bockris in his 1975 book [1] does refer to the fact that increasing coal consumption could lead to increasing carbon dioxide in the atmosphere and global warming. But it is a cursory mention, since the threat of looming climate change was then only dimly recognized, and in no way a driving force behind the transition to a HE as it is today.

In essence, Bockris' HE vision centered on the production of hydrogen by electrolysis of fresh and sea water by electricity generated by large-scale solar power stations located in hot remote parts of the world – most notably the desert regions of North Africa, Saudi Arabia, and Australia – and/or by nuclear fission reactors. The hydrogen produced would then be transmitted to distant population centers by long pipelines for consumption in all sectors of the economy.

Now that we confront the three-pronged threat of irreversible climate change, a deficit between oil demand and supply, and rising levels of pollution generally, the original HE concept needs re-envisioning. In transport applications, there have been significant developments in battery technology, with lithium ion and lithium polymer batteries becoming available with much higher gravimetric and volumetric energy densities than traditional lead acid batteries [4]. Hence there is a major effort worldwide to commercialize electric vehicles, particularly cars and light commercial vehicles, as an alternative to conventional gasoline and diesel vehicles. If electric vehicles are to be a true zero-emission mode of transport, however, the electricity for battery charging must come from renewable energy (RE) sources of electricity (or the more problematic nuclear, or fossil fuel power stations with carbon capture and storage). Yet the very same is the case for the electricity to produce hydrogen by electrolysis, the most likely early production technology, for use in hydrogen fuel cell vehicles. Why then traverse the apparently more circuitous and energy lossy route of converting electricity to hydrogen, transporting and storing it, and then reconverting it back to electricity on board a vehicle in a fuel cell, rather than simply charging batteries in vehicles using grid electricity generated from renewables? With batteries, it is electricity in and electricity out directly from the one electrochemical device.

Another alternative that has emerged to hydrogen as a transport fuel is biofuel, including principally ethanol, various bio-oils and biodiesel. All such biofuels are produced from organic materials – starch, sugar or cellulosic plants, or algae – that have absorbed carbon dioxide from the atmosphere by photosynthesis during their growth phase so that on combustion the same quantity of carbon dioxide is emitted once again. Provided then the energy used to produce and distribute these biofuels is also obtained from renewable resources, they are a zero-emission option like hydrogen produced from renewables. Biofuels for transport can be used as blends with existing fuels without any modification to today's internal combustion engines, the remainder of vehicle technology, and fuel distribution, storage and delivery infrastructure, and as 100% alternatives with relatively minor changes to existing engines and fuel distribution infrastructure. To many, biofuels are thus seen as a much more readily implementable substitute for petroleum fuels than taking on the apparently herculean challenge of switching to hydrogen, which indeed would require a completely new fuel distribution, storage and dispensing infrastructure, as well as a radical change in vehicle motive power systems and associated vehicle design.

In the original HE, hydrogen further played the critical role of providing the energy storage that would allow continuous base-load electricity supply in a system relying substantially on intermittent and variable RE sources such as solar, wind and ocean power. In recent years this role for hydrogen too has come under strong challenge from a number of alternatives, including batteries, supercapacitors, thermal storage, and multiple RE inputs geographically distributed over a large-scale grid.

Over the past decade, there have been many notable and useful works (e.g. [5–9]) that have sought to develop and modify the original vision of a hydrogen economy to reflect more recent environmental, resource, and political-economic contexts, and technological developments. In the area of more specific and quantitative scenario-based studies, the International Energy Agency [10] researched the consequences of introducing hydrogen globally, finding that hydrogen and fuel cells could reduce carbon dioxide emissions by a further 5% (1.4 Gt/year) by 2050 compared to just deploying efficiency measures (such as petrol-electric hybrid vehicles) and alternative fuels like ethanol.

One of the most thorough studies of the potential role of hydrogen in a sustainable energy economy conducted to date has been the HyWays [11] European hydrogen roadmap supported by the European Union (EU) and ten of its member countries. In the high policy support, fast learning, hydrogen-emphasis scenario evaluated by Hyways, the penetration of hydrogen fuel cell vehicles in passenger transport rises rapidly from 3% in 2020, to 25% in 2030, and tends towards saturation at just under 75% in 2050. The corresponding hydrogen production mix in 2030 is 31% from nuclear fission power, 27% from RE sources, 26% from steam reforming of natural gas, and 14% from coal via integrated gasification combined cycle plants and carbon capture and storage. In this scenario,