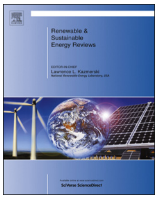
Renewable and Sustainable Energy Reviews 48 (2015) 483–499

Contents lists available at ScienceDirect

Renewable and Sustainable Energy Reviews

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



Automotive hydrogen fuelling stations: An international review

Jasem Alazemi [a,b,*,1], John Andrews [a,2]

[a] School of Aerospace, Mechanical and Manufacturing Engineering, RMIT University, Melbourne, Australia
[b] College of Technological Studies, Automotive Engineering, Kuwait

ARTICLE INFO

Article history:
Received 20 October 2014
Received in revised form
3 February 2015
Accepted 8 March 2015

Keywords:
Hydrogen production techniques
Hydrogen fuelling stations
Energy security
Greenhouse gas
Sustainable energy
On-site Hydrogen production

ABSTRACT

Hydrogen produced from low-emission primary energy sources, particularly renewable energy, is a potential alternative transport fuel to gasoline and diesel that can contribute to reducing greenhouse gas emissions and improving global energy security. Hydrogen fuelling stations are one of the most important parts of the distribution infrastructure required to support the operation of hydrogen fuel cell electric vehicles and hydrogen internal combustion engine vehicles. If there is to be substantial market penetration of hydrogen vehicles in the transport sector, the introduction of commercial hydrogen vehicles and the network of fuelling stations to supply them with hydrogen must take place simultaneously. The present paper thus reviews the current state of the art and deployment of hydrogen fuelling stations. It is found that by 2013, there were 224 working hydrogen stations distributed over 28 countries. Some 43% of these stations were located in North and South America, 34% in Europe, 23% in Asia, and none in Australia. The state of the art in the range of hydrogen production processes is briefly reviewed. The importance of producing hydrogen using renewable energy sources is emphasised for a transition to hydrogen fuel cell vehicles to contribute to greenhouse gas emission reduction targets. 2.3–5.8/H_2kg for SMR A classification of hydrogen refuelling stations is introduced, based on the primary energy source used to produce the hydrogen, the production process, and whether the hydrogen is made on site or delivered to the site. The current state of deployment of hydrogen fuelling stations in each major region of the world is then reviewed in detail. The costs of producing hydrogen vary from $1.8 to 2.9/$H_2$ kg for Coal gasification, 2.3–5.8/H_2 kg for SMR, $6–7.4/$H_2$ kg for wind power and $6.3–25.4/$H_2$ kg depending on the cost of the PV system. The lowest cost of hydrogen is nearing competitiveness with petroleum fuels. Finally conclusions are drawn about the progress to date in establishing this crucial component of the infrastructure to enable hydrogen-powered vehicles to become a commercial reality.

Contents

---

* Corresponding author.
E-mail addresses: jasem.alazemi@rmit.edu.au, ramthan@hotmail.com (J. Alazemi), john.andrews@rmit.edu.au (J. Andrews).
[1] Tel.: +61 399256242.
[2] Tel.: +61 3 9925 6085; fax: +61 3 9925 6108.

http://dx.doi.org/10.1016/j.rser.2015.03.085
1364-0321/

1. Introduction

The increase in energy demand in all sectors, the growth of the world's population, and the declining availability of low-cost fossil fuel sources are some of the most important issues the world faces in the 21st century. Fossil fuels such as oil, natural gas and coal are rapidly being depleted and polluting our environment, and they cannot be considered permanent and sustainable solutions to global energy requirements [1]. Consequently, any shortage of these types of energy sources could lead to fluctuations in oil prices and threaten global energy security and the world's economy [2]. As fossil fuels usage increases worldwide, local air quality falls and greenhouse gas (GHG) emissions increase. 33% of emissions in the USA are emitted by transportation (road, air, marine, and other), with just over three quarters of this amount coming from road transport; a further 41% are emitted by power stations, 16% from industry and agriculture, and 10% from other sources [3]. The latter are clearly leading to an increased world's mean surface temperature [4]. Marcinkoski [5] noted that some studies have estimated the cost of transportation-related emissions on public health to be between $40 billion and $60 billion every year.

For these reasons there is considerable interest in using hydrogen produced from low-emission primary energy sources, particularly renewable energy, as an alternative transport fuel to gasoline and diesel, and as an energy store to ensure reliable and continuous supply from intermittent and variable renewable energy sources. A growing number of studies see hydrogen as having a crucial role to play in a global sustainable energy strategy that on the one hand effectively reduces the threat of climate change and on the other provides a zero-emission fuel for transport to allow a gradual transition away from depleting gasoline resources.

For example, Dougherty and Kartha [4] investigated the transition to hydrogen energy in the United States of America (USA) for light- and heavy-duty vehicles, marine vessels and trains as a central plank of a sustainable energy strategy. The study found that hydrogen fuel cell electric vehicles (FCEVs), in conjunction with electric and other low-emission vehicles, could reduce GHG pollution by 80% in 2100 compared with that of 1990. Further, it would enable the USA to remove almost all controllable air pollution in urban areas and become essentially independent of gasoline fuel by the 2100s. IPCC (2011) – Summarise from Andrews and Shabani [6]. Balta-Ozkan and Baldwin [7] studied the role of a hydrogen economy and showed how it could meet the United Kingdom (UK) government's climate and energy policy goal to reduce 80% of national GHG emissions by 2050.

Andrews and Shabani [8] proposed six principles to guide the use of hydrogen in sustainable energy strategies globally and nationally and contribute to the transition to a hydrogen economy, and recently reviewed the role being projected for hydrogen currently [8].

Although hydrogen is not a primary energy source, it can, like electricity, serve as an energy carrier, and thus can replace fossil fuels in a wide range of applications [9]. Hydrogen can release energy through several different methods: direct combustion, catalytic combustion, steam production and fuel cell operations [10]. Among these methods, the fuel cell is generally the most efficient and cleanest technology for releasing energy from hydrogen [11].

In a fuel cell, hydrogen and oxygen are combined in a catalysed electrochemical reaction to produce an electrical current, water and heat. This process can achieve efficiencies that are two to three times those of internal combustion engines [11], while being quiet and pollution free. Further, developing hydrogen technology for producing, storing, distributing and using hydrogen energy can create many new jobs, as well as contribute to GHG reduction and assist in securing energy supplies, nationally and globally. Kohler and Wietschel [12] noted that ‘results from the ASTRA model (Infrastructure investment for a transition to hydrogen automobiles) show that a transition to hydrogen transport fuels would lead to an increase in GDP, employment and investment’. According to McDowall and Eames [13], a transition to a hydrogen future would ameliorate carbon dioxide emissions, and FCEVs, in particular, can contribute significantly to the reduction of carbon emissions from the transport sector in the long term.

The most concern in using hydrogen is about safety issues. It is important to note, however, that exactly the same situation existed in the early years of using gasoline and diesel [14]. Hydrogen gas is nontoxic, environmentally safe, and has low radiation level, which reduce the risk of a secondary fire [15]. But special care must be taken since hydrogen burns with a colourless flame that may not be visible. Hydrogen has a faster laminar burning velocity (2.37 m/s), and a lower ignition energy (0.02 mJ) than gasoline (0.24 mJ) or methane (0.29 mJ) [10]. The explosion limits by volume for hydrogen in air of 18.3–59% are much higher than those for gasoline (1.1–3.3%) and natural gas (5.7–14%) [14]. The self-ignition temperature of hydrogen (585 °C) is significantly higher than for gasoline (228–501 °C) and natural gas (540 °C) [10]. It is almost impossible to make hydrogen explode in an open area due to its high volatility [16]. Since hydrogen is 14 times lighter than air, it rises at 20 m/s if gas is released [14]. Hydrogen is thus usually safer than other fuels in the event of leaks [17]. Cold burns and increased duration of leakage are a concern about liquid hydrogen, although hydrogen disperses in air much faster than gasoline [15].

Hydrogen is as safe as other fuels if appropriate standards and safe working practices are followed [18]. When stored at high pressures, the usual regulations and standards for pressurised gas vessels and usage must be implemented, and detection systems need to be employed to avoid any accident or components failure due to hydrogen attack (HA) or hydrogen embrittlement (HE) [10,17]. All components used in hydrogen fuelling stations must be certified by the appropriate safety authority. The California Energy Commission has identified 153 failure modes at hydrogen delivery stations (using liquid hydrogen and/or compressed hydrogen stations), and at on-site hydrogen production stations (using SMR and electrolysis hydrogen production) [17].

Stations with liquid hydrogen delivery have the most serious potential failures due to factors such as collisions, overfilling tanks, and relief valve venting [17]. For stations with electrolysers there are two low-potential failure modes and one medium failure mode [17]. The low failure modes are related to the electrolyser leak (oxygen, hydrogen, or KOH) and high voltages electrocution hazard. The medium failure is related to the dryer failure, which causes moisture to go into downstream components. Station with SMR has one medium-frequency rating failure, which is condensate separator failure that can cause fire or explosion [17]. Other SMR station failures are rated low frequency. Tube trailers have