INTERNATIONAL JOURNAL OF HYDROGEN ENERGY 40 (2015) 12905–12917

Available online at www.sciencedirect.com

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

Comparative life cycle assessment of hydrogen fuel cell passenger vehicles in different Canadian provinces

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A R T I C L E I N F O

Article history:
Received 5 June 2015
Received in revised form
30 July 2015
Accepted 31 July 2015
Available online 20 August 2015

Keywords:
Fuel cell
Hydrogen production
Light duty passenger vehicle
LCA

A B S T R A C T

A comprehensive life cycle assessment of hydrogen fuel cell passenger vehicles (FCVs) is conducted based on relevant conditions for four major Canadian provinces. Results are provided for three alternative hydrogen production methods, namely electrolysis, thermochemical water splitting, and steam methane reforming of natural gas, and compared against conventional gasoline vehicles as a reference case. Significant reductions in greenhouse gas and criteria air contaminant emissions are predicted from all three hydrogen production methods in all four provinces, except for electrolysis in Alberta where most electricity is generated from fossil fuels. Thermochemical hydrogen production shows the most favorable results in all provinces due to the prospective use of renewable waste heat, followed by electrolysis from renewable hydroelectric power in Quebec and British Columbia. The sweet spot in terms of life cycle emission reductions is obtained when a renewable energy source for production is combined with a low-emission electricity source for compression and distribution, for example by utilizing waste heat and electricity from nuclear power in Ontario. The lowest fuel costs are predicted for hydrogen produced from natural gas, which is abundant in Canada and can provide a reasonable balance between emission reductions and economic benefits for FCV implementation across all provinces.

Introduction

Worldwide energy usage has grown rapidly during the last several decades and fossil fuels such as coal, petroleum, and natural gas continue to be widely used despite the severe environmental problems that they cause. One of the major concerns of widespread use of fossil fuels is the greenhouse gases (GHGs) that are emitted to the environment from their use, contributing to global warming. On the other hand, renewable energy resources such as sunlight, wind, hydro, tidal, wave, and geothermal are naturally replenished on a human timescale and are essentially free from GHG emissions. In Canada, transportation accounts for approximately 31% of the total energy use and 37% of the GHG emissions, and gasoline and diesel internal combustion engines still play a

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http://dx.doi.org/10.1016/j.ijhydene.2015.07.147

dominant role in this sector [1]. In addition, these vehicles are known to have a negative impact on the overall health of residents of major urban areas by increasing the concentration of local air pollutants. Major criteria air contaminants (CACs) produced during combustion include mono-nitrogen oxides (NO_x), sulfur oxides (SO_x), carbon monoxide (CO), volatile organic compounds (VOCs), and particulate matter (PM); all of which may directly or indirectly affect the health of residents [2]. Consequently, significant efforts are made by individuals and governments to mitigate these problems by switching to cleaner burning fossil fuels as an intermediate solution and eventually to zero-emission fuels. However, the appropriate routes toward implementation of alternative vehicle solutions are often difficult to determine and put into practice; the delay of which may exacerbate the environmental problems.

Natural gas is a promising alternative vehicle fuel due to its relatively low carbon content compared to other fossil fuels and abundance worldwide. Sufficient infrastructure is available to obtain and distribute natural gas, which essentially consists of methane that produces combustive emissions of relatively low ozone forming potential. Zhang et al. [3] investigated the emissions generated by light-duty in-use flexible-fuel vehicles fueled with gasoline and compressed natural gas (CNG). The results showed that using CNG as an alternative fuel can lead to a 30% reduction of CO, 15% reduction of hydrocarbons, and 7% reduction of NO_x emissions for the same travel distance. However, other studies indicated an increase of nitrogen oxides [4–6]. CNG is a methane based fuel which has a higher heating value of 54,552 kJ kg^{-1}. Combustion of methane produces 2 mol of water and 1 mol of carbon dioxide. Compared to gasoline which consists of hydrocarbons with between 5 and 12 carbon atoms per molecule with a higher heating value of 42,307 kJ kg^{-1} and produces 3 mol of water and 6 mol of CO_2, CNG delivers 1.6 times more energy for the same amount of CO_2 emission [7]. One of the main drawbacks of using CNG as an alternative fuel is the greater amount of space required for fuel storage than for conventional, liquid phase gasoline. Therefore, CNG tanks usually take up additional trunk space of a car or bed space of a pickup truck compared to liquid fuels. This problem is solved in factory-built CNG vehicles that install the tanks under the body of the vehicle, thereby reserving the other spaces for their originally intended purposes. However, the problem still exists for heavy duty vehicles due to longer travel distances and higher fuel consumption per km of travel. In order to overcome this issue, liquefied natural gas (LNG) is another alternative for heavy duty vehicles used for long distance travel where the size of the CNG tank would otherwise be prohibitively large. Although both CNG and LNG have attracted substantial interest, the production and distribution of these two alternative fuels is still limited. Besides, natural gas combustion generates substantial CAC emissions at the site of vehicle operation as well as considerable, albeit lower GHG emissions.

Hydrogen powered fuel cell vehicles (FCVs) offer a promising option for sustainable transportation systems due to their ability to generate zero GHG and CAC emissions at the point of use. Fuel cells operate by means of a non-combustive electrochemical reaction between hydrogen and oxygen from ambient air and the only emission produced is water vapor. The electrical energy generated from the cell reaction is delivered to an electric or hybrid electric drivetrain. The key benefits of hydrogen FCVs are summarized as follows:

- Due to the high efficiency of the electrochemical cell reaction, FCVs can utilize 40–60% of the energy stored in the hydrogen fuel, compared to internal combustion engines which currently use only about 20% of the energy from gasoline [8].
- Fuel cell engines completely eliminate GHG and CAC emissions during vehicle operation, which is ideal for urban transport.
- FCVs share many of the benefits of electric vehicles, including rapid acceleration due to the high torque generated by the electric motor, low operating noise, and regenerative braking – again, ideal for urban driving.

Most major automotive OEMs are currently working to develop technologies that efficiently exploit the potential of hydrogen energy for use in motor vehicles, and commercial units have started to appear on the market. In many jurisdictions, automakers, fuel distributors, and governments are cooperating on enabling the technology and supporting infrastructure. For example, Japan's strategic plans include dedicated resources to enable the world's fastest dissemination of FCVs and hydrogen refueling stations, targeting two million FCVs and over one thousand hydrogen stations by 2025 [11]. In addition, European cities and bus OEMs have demonstrated their commitment to fuel cell bus commercialization by signing an agreement that anticipates around 500–1000 fuel cell buses in service in urban centers across Europe by 2017–2020 [9]. However, hydrogen fuel does not occur naturally on Earth and thus is not an energy source; rather it is an energy carrier. It is most frequently made from methane or other fossil fuels, but it can also be produced using renewable sources such as wind and solar using a wide range of methods including biomass conversion, steam methane reforming (SMR), and water splitting by photocatalysis, thermochemical cycles, and electrolysis [10]. Each hydrogen production method has its own characteristics for production, storage, and delivery. In addition, the environmental impact assessment of each method varies depending on the availability of resources and the results may become convoluted and difficult to use in the decision-making process.

Life cycle assessment (LCA) is a reliable methodology for analysis of the relative merits of various options for passenger mobility and freight. LCA represents a comprehensive approach to assess environmental and economic impacts at each step of a vehicle and its fuel “life” cycle from raw materials and production to usage and disposal or recycling. Without this comprehensive approach, false conclusions on environmental impact and economics may be reached, especially for new emerging vehicle and fuel technologies [11]. Our group recently used the LCA methodology to assess CNG as an alternative fuel to diesel for heavy duty refuse collection vehicles [11] and light duty commercial vehicles [12]. The results showed that replacing the incumbent diesel vehicles with new CNG vehicles could reduce the life cycle GHG emissions by 24% and 34%, respectively. Karman [13]