INTERNATIONAL JOURNAL OF HYDROGEN ENERGY XXX (2018) 1–12

Available online at www.sciencedirect.com

ScienceDirect

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

Well-to-wheel analysis of hydrogen fuel-cell electric vehicle in Korea

Eunji Yoo, Myoungsoo Kim, Han Ho Song *

Department of Mechanical Engineering, Seoul National University, 1 Gwanak-ro, Gwanak-gu, Seoul 08826, South Korea

ARTICLE INFO

Article history:
Received 4 May 2018
Received in revised form
2 August 2018
Accepted 14 August 2018
Available online xxx

Keywords:
Well-to-wheel analysis
Automotive fuels
Hydrogen
Fuel-cell electric vehicle
Greenhouse gas emission
Naphtha cracking

ABSTRACT

This study provides methodologies, data collection and results of well-to-wheel greenhouse gas analysis of various H_2 production pathways for fuel-cell electric vehicle (FCEV) in Korea; naphtha cracking, steam methane reforming, electrolysis and coke oven gas purification. The well-to-wheel (WTW) greenhouse gas emissions of FCEV are calculated as 32,571 to 249,332 g-CO_2 eq./GJ or 50.7 to 388.0 g-CO_2 eq./km depending on the H_2 production pathway. The landfill gas (on-site) pathway has the lowest GHG emissions because the carbon credit owing to use landfill gas. The electrolysis with Korean grid mix (on-site) pathway has the highest GHG emissions due to its high emission factor of the power generation process. Furthermore, the results are compared with other powertrain vehicles in Korea such as internal combustion engine vehicle (ICEV), hybrid electric vehicle (HEV) and electric vehicle (EV). The averaged WTW result of FCEV is 35% of ICEV, is 47% of HEV, and is 63% of EV.

Introduction

Energy resource depletion and climate change have become global issues, mainly caused by the increased use of fossil fuels and accompanying greenhouse gas (GHG) emissions. One of the most responsible causes is the rapid growth in energy use in the transportation sector [1]. This has led to the development of non-conventional fuels and energy conversion systems for automotive applications, which require new judgment tools to better compare them with their conventional counterparts in terms of environmental friendliness or energy efficiency.

Life cycle analysis (LCA) is a method that estimates the energy use and GHG emissions associated with a product during all stages of its life. Specifically, as a part of LCA for automotive fuels, well-to-wheel (WTW) analysis has been given significant attention and can be divided into two groups of processes: well-to-tank (WTT) and tank-to-wheel (TTW) processes. WTT includes processes such as feedstock recovery, fuel production, fuel storage, distribution to fueling stations and refueling. TTW represents vehicle operation whereby fuel is consumed to power the vehicle. A number of research groups have performed WTW analysis, mostly in the U.S., Canada, and European Union (EU) [2–5].

In Korea, Jang et al., Choi et al., and Kim et al. performed WTW GHG emission analysis on major automotive fuels in Korea, i.e., gasoline, diesel, and compressed natural gas, as well as on newly introduced fuels, i.e., naphtha-based hydrogen and electricity [6–9].

In this study, we focus on the WTW GHG emissions analysis of production pathways of gaseous hydrogen (H_2) fuel for

* Corresponding author.
E-mail address: hhsong@snu.ac.kr (H.H. Song).

https://doi.org/10.1016/j.ijhydene.2018.08.088

fuel-cell electric vehicles (FCEVs) considered in South Korea. According to the specific fulfillment plans of controlling fine dust, there is a plan to expand the number of supplied FCEVs in Korea from 100 in 2016 and to 10,000 in 2020 [10]. The H_2 production pathways, currently in use or expected to be used, are included in the scope of analysis in this paper. The most recent literatures on comparative evaluation of environmental impacts of hydrogen production methods are summarized in Table 1.

Many previous studies of life cycle analysis of H_2 production pathways have still focused on SMR, electrolysis, and coal gasification pathways and some researches covered the H_2 production pathways with biomass. Furthermore, most of recent researches are focused on the case of European countries and U.S.

The goal of this paper is to build a database to evaluate the environmental impact of FCEVs through the analysis of well-to-wheel greenhouse gas emissions for various H_2 production pathways in Korea. In particular, this is the first comprehensive study of WTW analysis on H_2 produced by naphtha cracking and comparison to other H_2 production technologies. In addition, the WTW results can be compared with other types of fuel and powertrain vehicles, such as internal combustion engine vehicles (ICEVs), hybrid electric vehicles (HEVs) and electric vehicles (EVs), and it is possible to evaluate which H_2 production paths are suitable for such application.

Method

WTW processes of various H_2 production pathways

The annual production of H_2 in Korea is 2.1 million tons, with 1.4 million tons of by-product H_2 [24]. More than 90% of by-product H_2 produced is consumed as a process fuel within the boundary of the corresponding production plant, and the remaining H_2 is shipped out for sale. Table 2 shows the average H_2 production rate of various technologies for sale in Korea [24]. Naphtha cracking is the main technology for H_2 production for sale in Korea. In particular, it is noted that the gross production rate from COG is 2.1 million m^3/hr from the Korean steel industries, although only 300 m^3/hr is available for sale.

Table 2 – Hydrogen production rate for sale in Korea [24].

H_2 production rate	For sale (m^3/hr)	Percentage (%)
Naphtha cracking	161,900	54.1
Electrolysis	67,500	22.6
Steam methane reforming	51,600	17.2
Coke oven gas purification	300	0.1
Propane dehydrogenation	14,000	4.7
Methanol reforming	4000	1.3
Total	299,300	100

Fig. 1 shows the well-to-wheel processes from feedstock recovery to FCEV operation in Korea. In this study, the WTW processes are classified by their feedstock (COG, naphtha, NG, landfill gas (LFG) or electricity) and the site of H_2 production (off-site or on-site). Finally, seven representative pathways for use in FCEVs are selected for the analysis, and the details are as below.

Off-site production corresponds to the situation whereby H_2 is produced at a location distant from where it is used, typically with a relatively large production capacity, and then distributed to a gas station for final usage. On the other hand, on-site H_2 production refers to the production at an H_2 gas station achieved by installing a H_2 generator directly at the station. The first to fourth rows in Fig. 1 show the pathways of the off-site production, and the remaining three rows represent the pathways of the on-site production.

The 'Upstream process' in Fig. 1 represents the processes that are associated with producing the feedstock for each H_2 production process. In the case of Elec. (off-, on-site), the first process is 'upstream for feedstock'. There are several types of resources for power generation, e.g., coal, NG, uranium, residual oil, and renewable energy. Therefore, the pathways producing each resource are grouped together as 'upstream for feedstock'. Detailed descriptions of these upstream processes are given in Section Upstream process.

Another dashed line box indicates the H_2 production process from each feedstock. In Section Hydrogen production,

Table 1 – The most recent literatures on comparative evaluation of environmental impacts of hydrogen production methods [11–23].

Resources	Biomass	Coal	Electricity	NG
Region	U.S [22] Portugal [13] Sweden [12] Germany [18]	U.S [22] Portugal [13] EU [11] Germany [18] China [17]	U.S [14,22] Portugal [13] Sweden [12] Germany [18] EU [15] China [16,17] Mexico [20] No regional classification [19]	U.S [14,21,22] Portugal [13] Sweden [12] Germany [18] EU [15] China [16,17] No regional classification [19]

Notes
- Some papers analyzed not only GHG emissions but also other environmental impact categories, e.g., acidification potential, human toxicity, ozone layer depletion, PM emissions, radiation, cost, system energy efficiency [11,12,15,19,22]
- Woody is included in the 'Biomass' category
- Hydrogen produced from 'Coal' resources used coal gasification technology
- Electricity is not a feedstock for hydrogen, but it is required resource for electrolysis process
- Some papers covered renewable electricity [12–15,18,22]

Please cite this article in press as: Yoo E, et al., Well-to-wheel analysis of hydrogen fuel-cell electric vehicle in Korea, International Journal of Hydrogen Energy (2018), https://doi.org/10.1016/j.ijhydene.2018.08.088