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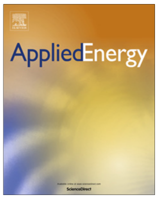

# Near-term analysis of a roll-out strategy to introduce fuel cell vehicles and hydrogen stations in Shenzhen China

Xinhai Xu [a,*], Ben Xu [b], Jun Dong [a], Xiaotong Liu [a]

[a] *School of Mechanical Engineering and Automation, Harbin Institute of Technology Shenzhen Graduate School, Shenzhen 518055, China*
[b] *Department of Mechanical Engineering, University of Texas Rio Grande Valley, Edinburg, TX 78539, USA*

## HIGHLIGHTS

- Fuel cell vehicle growth trend in Shenzhen in the near-term was predicted.
- Capital and O&M costs of different size $H_2$ stations were calculated.
- $H_2$ fuel price was calculated and compared with that of other traditional fuels.
- A roll-out strategy of $H_2$ station distribution in Shenzhen was proposed.
- $H_2$ was compared with other fuels regarding with cost and emissions.

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## ABSTRACT

The utilization of fuel cell vehicles can significantly reduce the greenhouse gas emissions in urban areas. However, huge investments are needed to construct the hydrogen infrastructure to produce, store and distribute hydrogen fuel to fuel cell vehicles. The present study conducted an analysis of a roll-out strategy to introduce fuel cell vehicles and hydrogen stations in Shenzhen, China between 2016 and 2025. An accurate estimation to develop hydrogen economy in Shenzhen in the near-term was provided. Three different scenarios of fuel cell vehicle penetration rate in the new car sales market were employed to predict the number of fuel cell vehicles and daily hydrogen demand in Shenzhen. The capital investment and operation/maintenance cost of on-site steam methane reforming hydrogen fueling stations was estimated. For a station with 100, 500 and 1000 kg/day capacity, the capital investment is $1.04, 4.15 and 7.84 million, respectively, while the corresponding hydrogen fuel price at 20 years of return on investment (ROI) is 7.7, 7.0 and 6.8 $/kg, respectively. A roll-out strategy of ten hydrogen stations in Shenzhen by 2020 was proposed, taking into consideration the population density, average income, locations of grocery stores and shopping malls, and locations of existing gas stations. The total capital investment required to construct 10 hydrogen stations is $19.7 million. The fuel costs and life cycle greenhouse gas emissions of hydrogen, gasoline and electricity vehicles were assessed to justify the benefits of introducing fuel cell vehicles in Shenzhen. Local industry and government can use the results to make decisions about possible future $H_2$ utilization and infrastructure construction.

## 1. Introduction

The fuel cell vehicle (FCV) is considered to be a promising alternative vehicle technology in our future society along with the electrical vehicle (EV). Due to its clean and energy efficient nature, FCVs are expected to significantly reduce gasoline dependence and greenhouse gas (GHG) emissions compared to the traditional internal combustion engine vehicles (ICEVs) [1]. Toyota has released the world's first commercial FCV - Toyota Mirai - into the market in December 2014 in Japan and October 2015 in USA [2,3]. However, one major obstacle which limits the commercialization of FCVs is the lack of existing $H_2$ refueling infrastructures across the world [4]. Without sufficient $H_2$ refueling stations, customers will have no incentive to purchase any FCVs. On the other hand, it is not economically viable to construct $H_2$ refueling stations without an adequate number of FCVs running on the road [5]. It is the classic "chicken and egg" problem for FCV penetration and the construction of $H_2$ refueling station [6,7].

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* Corresponding author.
*E-mail address:* xuxinhai@hitsz.edu.cn (X. Xu).

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## Nomenclature

| | |
|---|---|
| $a$ | coefficient in the logistic model |
| $b$ | coefficient in the logistic model |
| $d$ | discount rate (%) |
| $r$ | after-tax real rate of ROI (%) |
| $t$ | time (year) |
| $inf$ | annual inflation rate (%) |
| $\dot{m}_{H_2}$ | flow rate of $H_2$ (kg/h) |
| $\dot{m}_{cooling}$ | cooling water consumption rate of a compressor (L/h) |
| $C_{H2}$ | estimated $H_2$ fuel price ($/kg) |
| $C_{annual}$ | annualized cost of a $H_2$ station ($) |
| $C_{capital}$ | capital investment of a station ($) |
| $C_{O\&M}$ | yearly O&M cost ($) |
| $E_{comp}$ | power consumption of a compressor (kW) |
| $M_{H2}$ | yearly $H_2$ production capacity of a $H_2$ station (kg) |
| $P$ | designed $H_2$ storage pressure (bar) |
| $P_0$ | atmospheric pressure (bar) |
| $P_{op}$ | operating pressure of a compressor (bar) |
| $P_{ref}$ | reference pressure of a compressor (bar) |
| $P_{tb}$ | base pressure of a storage tank (bar) |
| $Y$ | expected number of years of ROI |
| $capital_{comp}$ | capital investment of a compressor ($) |
| $capital_{tank}$ | capital investment of a storage tank ($) |
| *compcool* | reference cooling water consumption rate of a compressor (L/kg $H_2$) |
| *compcost* | reference cost of a compressor ($/kW) |
| *compexp* | size component of a compressor |
| *compower* | compressor power consumption rate at the reference pressure (kW h/kg $H_2$) |
| *compsize* | reference power of a compressor (kW) |
| *storesize* | designed size of a storage tank (kg $H_2$) |
| *tankcost* | reference cost of a $H_2$ storage tank ($/kg $H_2$) |
| *tankexp* | size exponent of a storage tank |
| *tanksize* | reference size of a $H_2$ storage tank (kg $H_2$) |
| *pcexp* | pressure exponent of a compressor |
| *ptexp* | pressure exponent of a storage tank |

Although hydrogen element on earth is always in water, hydrocarbons, hydrides or other forms, gaseous $H_2$ can be obtained from multiple sources through various technical pathways. Commonly $H_2$ can be produced either from fossil fuels through methods such as steam methane reforming (SMR) and coal gasification, or from water by means of including electrolysis, photolysis and thermolysis [5,8]. Water splitting methods employing electric power from wind, solar, or nuclear are the long-term choices for $H_2$ production. Nevertheless, they are not as competitive as the reforming methods in the near-term mainly due to economic concerns [9,10]. Katikaneni et al. [9] conducted a techno-economic assessment to compare the steam reforming method and the electrolysis method to produce $H_2$. It was found that the overall thermal efficiency of the electrolysis process was almost 40% less than that of the steam reforming process. Moreover, the capital investment of the electrolysis process was more than 3 times higher than that of the stream reforming process. The operation and maintenance (O&M) cost of the electrolysis process was also much higher.

To date the most matured $H_2$ production technologies are based on fossil fuels, and 90% of the currently used $H_2$ is from fossil fuel sources in the amount of 45 billion kg [11]. Among all the fossil fuel based methods, coal gasification produces the highest GHG emissions; whereas SMR emits the least [5,12]. Furthermore, SMR is a relatively cost effective method compared to the water splitting methods used to produce $H_2$ [5]. A shorter payback time and a higher return on investment (ROI) can be obtained by SMR [13]. Besides, natural gas is an easily accessed raw material in the short-term for $H_2$ production. Finally, failure risks in a SMR station are relatively low compared to that in an electrolysis station [14].

Centralized $H_2$ production followed by pipe or truck delivery to a station and decentralized on-site $H_2$ production are two basic types of $H_2$ refueling stations [9]. Both types have been evaluated thoroughly, and it is well accepted that on-site $H_2$ production is a more technologically feasible option [13]. Transportation of natural gas is also safer because natural gas has a much higher boiling point and a lower compression pressure compared to $H_2$ [15,16]. In the past decade the number of $H_2$ refueling stations has increased steadily. By 2009, more than 70 refueling stations have been built in USA, Germany and Japan [13]. By 2013, 224 $H_2$ refueling stations have been constructed in over 28 countries and areas, 43% of which are located in north and South America, 34% in Europe, and 23% in Asia. Out of the 224 $H_2$ refueling stations, 42 are based on SMR [5]. On-site $H_2$ production occupies more than 60% of the currently operating stations [5]. The largest existing on-site SMR $H_2$ refueling station is located in Oakland, CA. It started to operate in 2006 with the ability to generate and store 150 kg $H_2$/day. Two dispensers at 350 bar are equipped at this station [17].

Government's policies significantly promote the construction of $H_2$ refueling stations. Several countries and areas have announced roadmaps to construct $H_2$ stations and promote FCVs. California, USA has forged ahead in the world to build $H_2$ stations. In 2009, the California Fuel Cell Partnership (CaFCP) issued a plan calling for $181.5 million to build 50–100 stations by 2017 [18,19]. By 2013, there were 18 existing or planned stations in California. The CaFCP also recommended building another 50 stations to form a network with 68 stations in total [19]. In Asia, the Fuel Cell Commercialization Conference of Japan (FCCJ) planned to construct 1000 $H_2$ stations by 2025 in order to introduce 20 million FCVs on the road [20]. The HyWays Project set the aim of $H_2$ station construction in Europe [21]. $H_2$ Mobility launched in Germany in 2009 had a plan to build 1000 $H_2$ stations by 2030 [22].

As for China, no official roadmap to FCVs and $H_2$ stations has been announced. In total 6 $H_2$ stations (3 in Beijing, 2 in Shanghai, 1 in Guangzhou, and 1 in Hong Kong) are operating in China by 2015 [23]. However, the National Development and Reform Commission (NDRC) and the National Energy Administration (NEA) jointly issued the "Action Plan for Energy Technology Revolution and Innovation (2016–2030)" in March 2016 [24]. The standardization, promotion and application of $H_2$ stations and FCVs are included in this official governmental plan. In June 2016, Shanghai Sunwise New Energy System Co., Ltd. and the Shanghai government signed an agreement to invest in the $H_2$ station construction in Shanghai. By the end of 2020, five stations are expected to be completed [25].

As the fourth most developed city in China mainland according to the economic output, Shenzhen was selected by the central government in 2009 as one of the 13 national pilot cities for new energy vehicles, and it has grown to a world EV leader by now [26,27]. However, the deployment of FCVs is far behind EVs in the market, and no $H_2$ refueling station has been constructed yet in Shenzhen. However, the conditions required to construct $H_2$ refueling stations are prime in Shenzhen, because this city is rich in natural gas resources. China's first liquefied natural gas (LNG) project launched in 2006 – the Guangdong Dapeng LNG Pilot Project, is located in Shenzhen. The natural gas supply in Shenzhen has

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