Energy Policy 115 (2018) 317–329

Contents lists available at ScienceDirect

Energy Policy

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

Natural gas as a bridge to hydrogen transportation fuel: Insights from the literature☆

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ARTICLE INFO

Keywords:
Natural gas
Hydrogen
Fuel cell vehicles
Alternative transportation fuels
Power to gas
Energy infrastructure transition

ABSTRACT

Natural gas has been proposed as a possible “bridge” fuel to eventual use of hydrogen in zero emission fuel cell vehicles. This literature review explores whether the natural gas system might help enable a transition to longer-term use of hydrogen in transportation. Two transition strategies are reviewed: adapting natural gas refueling infrastructure for future use with H2 and blending renewable hydrogen into the NG system.

Our review suggests it is not attractive to re-purpose or overbuild NG fueling station equipment for future hydrogen service. Transporting H2/NG blends in the NG pipeline grid appears technically possible at modest fractions of 5–15% hydrogen by volume, but requires careful case by case assessment and could be expensive. Blending does not enable major reductions in GHG emissions from transport, unless “green” hydrogen can be cost effectively separated from the blend and delivered to highly efficient fuel cell vehicles. Ultimately, blend limits could make it difficult to utilize the existing NG system to deliver hydrogen at the scale needed to achieve deep cuts in transportation related GHGs. A dedicated renewable hydrogen system would be needed, if zero emission fuel cell vehicles play a major role in a future low carbon world.

1. Introduction

Recent energy/economic modeling studies suggest that reaching a “2 degree” climate scenario will require significant electrification of the light duty vehicle sector over the next several few decades, with large roles emerging for both hydrogen fuel cell vehicles (FCVs) and plug-in battery electrics (PEVs) (IEA, 2012, 2015; NRC, 2013). Natural gas is often discussed as a possible “bridge” fuel to eventual use of hydrogen in zero emission fuel cell vehicles, technologies which might play an important long term role in achieving deep cuts in transportation-related carbon emissions.

Both fuels are currently under development for transportation applications. Natural gas is already widely used as a transportation fuel for fleet vehicles, medium duty trucks including class 4–6 urban last mile delivery trucks and class 7–8 short-haul drayage trucks. LNG is being developed for long-haul freight applications (Scheitrum et al., this issue; Fan et al., 2017).

Hydrogen fuel cell vehicles (FCVs) began commercialization in light duty markets, in 2014. About 5500 FCVs are on the road today (PR Newswire, 2017), concentrated in a few early adopter areas, and initial regional networks of hydrogen refueling stations are being built (E4Tech, 2016). Hydrogen fuel cells have also been proposed for zero emissions medium and heavy duty vehicles and a few dozen fuel cell buses and trucks are now being demonstrated (CAFCP, 2016; Ohnsman, 2017; Stewart, 2017; Hall-Geisler, 2017).

Fuel availability is a key barrier facing large scale introduction of hydrogen vehicles. Unlike natural gas or electricity, there is currently no widespread infrastructure bringing hydrogen to consumers, and building a new hydrogen supply system is seen as expensive and risky. This has generated interest in hydrogen transition strategies that might utilize existing energy systems, especially natural gas infrastructure.

It is logical to look for synergies between hydrogen and natural gas.

Abbreviations: bar, 1 atm of pressure = 14.7 psia (pressure unit); CAFCP, California Fuel Cell Partnership; CCS, carbon capture and sequestration; CH2, compressed hydrogen gas; CNG, compressed natural gas; FCV, fuel cell vehicle; FCB, fuel cell bus; gge, gallon gasoline equivalent energy (energy unit) = 121.7 MJ (lower heating value); GHG, greenhouse gas; GW, gigawatt (10^9 W); H2, hydrogen; HD, heavy duty; HHV, higher heating value; ICEV, internal combustion engine vehicle; kg, kilogram; LCFS, low carbon fuel standard; LDV, light duty vehicle; LH2, liquid hydrogen; LHV, lower heating value; LNG, liquefied natural gas; MD, medium duty; MJ, Megajoule (energy unit); NG, natural gas; NGV, natural gas vehicle; NRC, National Research Council; PEM, proton exchange membrane; PEV, plug-in electric vehicle; psia, pounds per square inch absolute (pressure unit); RNG, renewable natural gas; scf, standard cubic foot (volume unit); SMR, steam methane reformer; VRE, variable renewable electricity (e.g. solar, wind); ZEV, zero emission vehicle

☆ *This article is part of a Virtual Special Issue entitled "The Potential of Natural Gas as a Sustainable Transportation Fuel".*

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https://doi.org/10.1016/j.enpol.2017.12.049
Received 17 February 2017; Received in revised form 24 December 2017; Accepted 28 December 2017
0301-4215/

Most hydrogen today is produced from natural gas. Natural gas and hydrogen have physical similarities: both fuels can be stored as compressed gases or cryogenic liquids and many of the components in a natural gas infrastructure (such as compressors, storage tanks and pipelines) are analogous to those for hydrogen. Given ongoing expansion of both natural gas and hydrogen in transportation applications, planners and policymakers have asked whether some or all the existing natural gas infrastructure might be re-used or designed for compatibility with the emerging hydrogen infrastructure (Jaffe et al., 2017; Sandia National Laboratories, 2014).

Reducing greenhouse gas (GHG) emissions from transportation is a major motivation for adopting hydrogen FCVs. Thus, a critical long term issue is how to provide hydrogen transportation fuel at large scale from zero or near-zero carbon supply pathways. Today most hydrogen comes from fossil sources, usually natural gas, which emits greenhouse gases during hydrogen production (Nguyen et al., 2013). But ultimately, a switch to low carbon hydrogen pathways will be needed. A proposed strategy, currently being demonstrated, is "power-to-gas". Here hydrogen is produced electrolytically, for example, from low-cost curtailed solar or wind electricity in a renewable intensive electric grid. The produced hydrogen could be blended into natural gas pipelines and transported to users, without having to build a costly dedicated hydrogen infrastructure. This strategy offers multiple potential benefits: it could create a market for uneconomic excess renewable power, provide a way of storing and transporting renewable hydrogen, reduce carbon content of the NG/H2 gaseous blend fuel and ultimately help enable use of zero emission hydrogen in transportation, assuming the hydrogen could be cost effectively separated from the blend and dispensed to vehicles. Alternatively, electrolytic hydrogen could be combined with a renewable source of carbon via methanation (Goetz et al., 2016) to make renewable methane, which could be blended with natural gas. Or hydrogen might be delivered in a dedicated hydrogen infrastructure. A key question is under what conditions a hydrogen blending strategy that utilizes the natural gas system might help enable widespread use of zero emission hydrogen fuel cell vehicles, and whether a parallel dedicated hydrogen system will be preferred.

A number of recent technical articles have addressed particular aspects of how natural gas might relate to a hydrogen transition. These articles represent various perspectives: near term to mid-term planning for alternative transportation fuels; energy/economic analysis of potential roles for NG and H2 in low carbon, renewable-intensive energy futures; power to gas technology assessments; and fuel infrastructure technologies and transitions (Alliat et al., 2009; Brydol et al., 2017; Bünger et al., 2014, 2015; European Commission, 2015a, 2015b, 2015c; Fan et al., 2017; Goetz et al., 2016; IEA 2003, 2015; Jaffe et al., 2017; JRC, 2014; Judd and Pinchbeck, 2015; Melaina et al., 2013a; Sandia National Laboratories, 2014; Scheitrum et al., 2018; Schiebahn et al., 2015; Steen, 2015).

In this article, we undertake a comprehensive literature review, drawing on these diverse perspectives. Topics reviewed include natural gas vehicle markets and infrastructure options; hydrogen fuel cell vehicle introduction and infrastructure options; compatibility of natural gas and hydrogen infrastructures; technical aspects of using hydrogen blends in the natural gas system; power to gas for transport applications; scenarios for low carbon future transportation; and power to gas concepts for capturing renewable energy. Our overall goal is to distill insights from this broad literature review about how and when the natural gas system might facilitate adoption of hydrogen in transportation. We focus on several questions:

- What are the likely roles of natural gas and hydrogen in various transport applications?
- What infrastructure options could supply natural gas or hydrogen to vehicles? Could a future hydrogen refueling infrastructure grow "organically" from natural gas infrastructure? Could natural gas refueling equipment be re-purposed or designed for future hydrogen compatibility?
- How might the growth of natural gas and hydrogen transportation markets impact infrastructure development and synergies? How much might natural gas and hydrogen infrastructures "overlap" geographically and over time?
- Is it technically feasible to use hydrogen or hydrogen blends in the natural gas system?
- What is the role of renewable "power-to-gas" for low-carbon transportation? Is blending renewable hydrogen into natural gas pipelines an attractive path toward carbon-free hydrogen transportation or is a parallel hydrogen infrastructure needed?

Two transition approaches are reviewed where H2 transportation fuel infrastructure might grow out of the NG infrastructure 1) overbuilding or re-purposing natural gas refueling infrastructure for future use with H2; 2) blending renewable hydrogen into the NG pipeline system (e.g. electrolytic H2 is produced from curtailed variable renewable electricity). In many of the papers we reviewed, these are compared to a third option of building a dedicated hydrogen refueling infrastructure.

We first review which transportation applications are most promising for natural gas and hydrogen. Possible infrastructure supply chains for refueling natural gas and hydrogen vehicles are then described. We draw some general conclusions about the near to mid-term potential for overlap between natural gas and hydrogen infrastructures and assess whether components of the natural gas refueling supply system might be repurposed or built for forward-compatibility with hydrogen.

We review studies on the technical issues for using hydrogen or hydrogen blends in existing natural gas infrastructure. We discuss how blending renewable hydrogen into natural gas might reduce greenhouse gas emissions from transportation via "power to gas", as well as the technical limits to this approach.

We review a recent case study for how natural gas and hydrogen infrastructures in California might co-evolve over the next two decades (Jaffe et al., 2017). We also review studies from the European Union that take a longer term view, exploring the role of renewable "power to gas" in a transition to zero emission hydrogen, and its applicability in transportation markets (Alliat et al., 2009; Bünger et al., 2014, 2015; European Commission, 2015a, 2015b, 2015c; Rudd and Pinchbeck, 2015; Schiebahn et al., 2015).

Finally, we discuss the implications of our review and suggest areas for future research.

2. Literature review of vehicle and infrastructure options

2.1. Natural gas in transportation

The literature on natural gas vehicles has typically focused on light duty, transit and refuse vehicles applications, while only a few studies include long haul trucking applications. Rood-Werpy (2010) concludes that high costs, limited refueling infrastructure, and uncertain environmental performance constitute barriers to widespread adoption of natural gas as a transportation fuel in the United States but, in another substantial contribution to the literature, Krupnick (2011) finds that the move from a long-haul route structure to a "hub and spoke" structure could facilitate the development of natural gas refueling infrastructure in the highway system.

Kuby et al. (2009) found that early adopters of light duty natural gas vehicles may be willing to refuel more frequently and farther from home than gasoline drivers, but more so on work-based trips and less on home-anchored trips. In another study, Kelley and Kuby (2013) find CNG users favored refueling CNG along routes used frequently rather than closer to their homes. Both studies suggest CNG is more appealing for commercial applications including by captive fleets than for passenger vehicles. This matches with findings by the Boston Consulting