Hydrogen Infrastructure Integration Study

Metropolitan ENERGY CENTER

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Executive Summary and Conclusion by Metropolitan Energy Center

TABLE OF CONTENTS

Executive Summary

As the nation grapples with the need to decarbonize the transportation sector, society must explore all available options. This "Hydrogen Infrastructure Integration Study" was funded by 501(c)3 nonprofit Metropolitan Energy Center under the project "Accelerating Adoption of Alternative Fuels in Mid-America". Conducted in 2022 by the University of Kansas, the intent of the study was to explore economic and design considerations associated with using Compressed Natural Gas (CNG) station locations for future hydrogen (H_2) fueling infrastructure deployment. Key component analysis identified five delivery pathways for hydrogen fuel, all of which deliver natural gas feedstock using existing pipelines. Initial economic analyses were conducted using the Hydrogen Analysis Tool (H_2A), a base model commonly used for evaluation by the U.S. Department of Energy. Initial H_2A results were combined with existing literature to develop inputs to the Hydrogen Financial Analysis Scenario Tool (H_2FAST).

In addition to the economic analysis, this study provides real-world operational considerations that must be accounted for when planning a transition from CNG to H_2 fueling. These considerations include different engineering standards, personnel training, and fueling procedures and practices.

It appears that the economics resulting from similar siting requirements do make co-location of CNG and H_2 facilities possible, primarily when considering blended CNG/H_2 pipelines. However, the differences in material and operational requirements are, on balance, detrimental to the economic feasibility of such a project.

Acknowledgments and Disclaimer

Contributions by Tami Alexander and other staff at Metropolitan Energy Center.

This material is based upon work supported by the U.S. Department of Energy's Office of Energy Efficiency and Renewable Energy (EERE) Vehicle Technologies Program under Award Number DE-EE0008262, *Accelerating Adoption of Alternative Fuels in Mid-America*.

Cover Photo: H2 Fueling Stations by National Renewable Energy Laboratory

1. Introduction

The transportation sector contributes to approximately 28% of the greenhouse gas (GHG) emissions in the United States (US) ([1]). About 93% of these emissions are caused by vehicles utilizing petroleum-based fuels with internal combustion engines. Fuel Cell Vehicles (FCVs) utilizing hydrogen (H_2) as the fuel have the potential to decarbonize the energy system and further lower GHG emissions ([2]). Moreover, utilizing H_2 as the fuel could aid in alleviating critical energy challenges typically associated with fossil fuels ([2]).

H_2 has a simple molecular structure; yet, it has the highest energy content by weight compared to other petroleum-based fuels. In addition, H_2 embedded in other elements, such as water and hydrocarbons, is abundantly available on Earth. However, challenges associated with its generation and transportation present significant hindrances to the long-term mass deployment of FCVs. Unlike gasoline, diesel, natural gas, and electricity, the availability of H_2 refueling stations is limited. In the US, currently, there are only about 45 H_2 retail stations which are mostly concentrated in California ([3]). In addition, there are only around 1600 miles of H_2 transportation pipelines ([4]). In comparison, approximately 1000 compressed natural gas (CNG) stations ([5]), and over 3 million miles of CNG transportation pipelines are available in the US [(6)]. Here, natural gas (NG) that is compressed to a higher pressure is commonly known as CNG. On first look, since both fuels can be stored as compressed gases, there is a possibility of using existing CNG components with hydrogen including compressors, storage tanks, and pipelines. Hence, there is rising curiosity regarding the possibility of converting the existing CNG pipeline and refueling station infrastructure to an H_2 fueling system. However, due to differences in their chemical and physical properties, specific attention must be given to CNG station components when upgrading for H_2; a few of these critical components are addressed in the following sections.

2. Challenges of Upgrading CNG Stations

First, it is important to identify the pathway of H_2 fueling. It has been well established that utilizing existing CNG pipelines to transport H_2 is unsafe as H_2 causes embrittlement and degradation to steel pipes that are typically used for natural gas (NG) transport causing H_2 leakage [7]. Thus, it is important to identify alternative pathways to obtain the desired H_2. In this avenue, the following are the primary conduits used to transport H_2 to a refueling station [7]:

1. On-site steam methane reforming (SMR): This pathway includes NG supplied through a pipeline to a fuel processing station where the NG is passed through a dryer and a filter. Subsequently, H_2 is produced using NG as the feedstock through the SMR reaction. The H_2 is then compressed to a pressure of 5,000 to 10,000 psi and stored at the refueling station.
2. Central SMR: In this pathway, NG is delivered through pipelines to a central plant that converts NG into H_2 through SMR or other methods. Based on the method utilized to transport H_2 from the central plant to the refueling station, this avenue can be subcategorized as:
    a. H_2 pipeline delivery: Gaseous H_2 (GH_2) is delivered to the refueling stations through pipelines at comparatively high pressures. This GH_2 is further compressed onsite to 5,000 to 10,000 psi and stored in heavy-duty tanks.
    b. GH_2 truck: GH_2 is compressed and stored at a central plant. The high-pressure gaseous H_2 is transported to the refueling station through trucks where the H_2 gas is further compressed to 5,000 to 10,000 psi and stored in heavy-duty storage tanks before dispensing.
    c. Liquified H_2 (LH_2) truck: The H_2 generated in the central plant is liquified and stored. This LH_2 is transported using trucks to the refueling station where it is pumped, vaporized, and stored at high pressure in a buffer storage unit.
    d. Blends of CNG and H_2: The feedstock CNG is added to the GH_2 at a blend station and transported through existing NG pipelines to the refueling station. At the refueling station, the gaseous H_2 is separated from the blend, and the H_2 is compressed and stored for subsequent dispensing.

Based on these options, the key components that are necessary to transport H_2 to the refueling station are described in **Table 1**. Additionally, the primary differences between the NG and H_2 routes are categorically identified using unique pathway numbers. Finally, detailed discussions of these differences highlighted in various colors in **Table 1** will be the focus of this study.

3. Details of Key Components Requiring Updating

To begin with, a series of assumptions are considered for component upgrading and associated cost analysis for each pathway since the source H_2 supply location and the H_2 dispensing units are unique for each pathway:

- Pathway 2 – Onsite SMR: No additional equipment or costs are required for the supply of NG to the onsite SMR.
- Pathway 3A – Default values provided by H_2FAST are considered for H_2 pipeline costs. Note: the H_2FAST spreadsheet is discussed later in this document.
- Pathway 3B and 3C – Default values provided by H_2FAST are considered for H_2 transportation costs through trucks; however, costs at truck fueling terminals are not included.
- Pathway 4 – Components and costs of the NG/H_2 blend stations are not included.

Based on these assumptions, the following are the key components that require upgrading:

1. H_2 compressor: H_2 is typically compressed to around 350 to 700 bars which is significantly higher compared to the CNG storage pressure that is about 200 to 250 bars [7]. Unfortunately, a CNG compressor is not ideal to handle H_2 as its physical properties, such as density and viscosity, are relatively different compared to CNG [7]. In addition, an extra compression stage is necessary to match the higher pressure required for H_2. Furthermore, upgrades to valves and seals are required to ensure safety.
2. Compressed H_2 (CH_2) storage: H_2 requires heavy-duty storage, and the storage material utilized must avoid embrittlement and degradation [7]. Stainless steel is traditionally used to store CNG fuel. However, to overcome embrittlement and degradation, stainless steel storage tanks with an interior polymer lining are used for high-pressure H_2 storage [7].
3. H_2 pipeline: As mentioned earlier, the existing CNG pipelines cannot be used for transporting H_2 due to issues related to embrittlement and subsequent leaks. Details of the material requirements, and the design specifications for H_2 pipeline can be found in the Hydrogen piping and pipelines code B31 by ASME [8].
4. LH_2: Alternatively, when pathway 3B is selected, stand-alone LH_2 pump, storage, and vaporizer are necessary. Additionally, since most vehicles are designed for GH_2, LH_2 must be vaporized and stored at high pressures prior to dispensing.
5. Blend separation (5 to 15% by volume): Existing CNG pipelines could be utilized to safely transport CNG blended with 5 to 15% by volume of H_2. However, the maximum percentage of H_2 by volume that could be used has to be computed on a case-by-case basis [9]. Specifically, factors such as embrittlement, leaks, gas flow rate measurement equipment, end-user application, and the type of transmission lines being used for transporting the blended mixture

need to be studied to ensure safety [7]. Pressure Swing Adsorption (PSA) extraction of H_2 at 300 psi of 10% NG/H_2 blend could add between $3.20/kg of H_2 and $8.20/kg of H_2. Importantly, this separation cost is exclusive to the production and transportation costs of H_2. For simplicity, an average of $5.50/kg of H_2 is considered as the added cost for NG/H_2 separation [9].

Importantly, several other comparatively smaller systems such as dispensing units, flow meters, leakage detectors, alarm systems, etc. also require upgradation due to the differences in the physical and chemical properties of CNG and H_2. Additionally, there are significant differences in welding, brazing, heat treatment, forming and testing requirements for H_2 pipelines compared to CNG. However, these meticulous details are not included due to the broader focus of this study and timeline restrictions. Nevertheless, a brief comparison on the code requirements of CNG and H_2 is provided in section 5.3.

Table 1: H_2 fuel delivery pathways in contrast with CNG pathway.

Pathway	Primary feedstock	Central fuel processing		Delivery to station		Station fuel processing	Compression/ Storage		Dispenser
1 - CNG	NG via pipeline			NG Pipeline		Dryer/Filter	NG compressor	CNG storage	CNG dispenser
2 - Onsite SMR	NG via pipeline			NG Pipeline		Dryer/Filter Small SMR	H_2 compressor	CH_2 storage	CH_2 dispenser
3A - Central SMR H_2 pipeline	NG via pipeline	Dryer/Filter H_2 compressor	Central SMR bulk GH_2 storage	H_2 Pipeline			H_2 compressor	CH_2 storage	CH_2 dispenser
3B - Central SMR GH_2 truck	NG via pipeline	Dryer/Filter H_2 compressor	Central SMR bulk GH_2 storage	GH_2 truck terminal	GH_2 truck		H_2 compressor	CH_2 storage	CH_2 dispenser
3C - Central SMR LH_2 truck	NG via pipeline	Dryer/Filter H_2 liquefier	Central SMR bulk LH_2 storage	LH_2 truck terminal	LH_2 truck		LH_2 pump and vaporizer LH_2 storage	CH_2 storage	CH_2 dispenser
4 - Blended NG/H_2 delivery w/H_2 separation	NG via pipeline	Dryer/Filter H_2 compressor blend station to add H_2	Central SMR bulk GH_2 storage	NG pipeline with blended H_2		H_2 Separation equipment	H_2 compressor	CH_2 storage	CH_2 dispenser

4. Economic Analysis of Upgrading a CNG to H_2 Refueling Station

The Hydrogen Analysis (H_2A) tool is used to compare the economics of the various pathways in Table 1 due to its simplicity and flexibility. Additionally, scores of research programs conducted by the Department of Energy utilize H_2A as the base model for evaluating the economics under varying assumptions and scenarios [10]. The H_2A Production Models analyze the technical and economic aspects of hydrogen production technologies and there are several H_2A models. Each H_2A model represents a different case study that is either a central or distributed model along with the primary production source (e.g., natural gas). The central model performs carbon capture and sequestration calculations. The distributed model calculates the optimal costs of compression, storage, and dispensing in a refueling station. For each case study, there are two options: current case and future case. The current case option is an analysis for construction in 2015; whereas the future case option is in 2040. The main outputs of H_2A models include the estimated hydrogen selling price by the time of construction and various total costs (e.g., operating costs, feedstock costs).

The Hydrogen Financial Analysis Scenario Tool (H_2FAST) provides quick and convenient in-depth financial analysis for hydrogen fueling stations. H_2FAST outputs projections of financial performance parameters (e.g., the break-even sale price of hydrogen) from 2021 to 2042. H_2FAST does not assume a particular station configuration, refueling pressure, or state of technology maturity, so it does not function as a cost estimation tool. There are basic and advanced user interface modes in the H_2FAST spreadsheet. For simplicity, this study will use the basic user interface mode of the H_2FAST spreadsheet.

The main difference between H_2A models and H_2FAST is that H_2A models break down various costs into their core elements, whereas H_2FAST requires one lumped value for the costs. For example, H_2A has a "Capital Costs" tab in its spreadsheet dedicated to recording the cost of each piece of equipment in the system. In the case of H_2FAST, there is only one input field for the costs of installed capital and each feedstock, respectively. Both H_2A models and H_2FAST assume the construction of a hydrogen fueling station from scratch instead of upgrading an existing natural gas station to one that supplies both natural gas and hydrogen or hydrogen only. Therefore, even though both H_2A models and H_2FAST have default values for most of their inputs, the case studies default values provided by H_2A models more accurately reflect the costs of upgrading the existing natural gas infrastructure through different pathways of producing hydrogen.

In this study, the total capital costs, the amount required of each feedstock and the associated feedstock costs, and the electricity needed will be extracted from H_2A models and literature, and these will serve as the inputs to H_2FAST. Details of the inputs (i.e., total equipment cost, electricity use, electricity unit price, natural gas use, natural gas unit price) and the corresponding output (i.e., estimated break-even leveraged price) of H2FAST of each hydrogen delivery pathway is presented in **Table 2**. The break-even hydrogen price is the net present unit selling price of hydrogen that would cover the investor contributions after a 10% after-tax discount rate. The lower the break-even price of a pathway, the less costly the pathway. According to **Table 2**, the costliness of each pathway follows the order: Central SMR, H_2 pipeline through central SMR (Pathway 3A); Onsite SMR (Pathway 2); GH_2 truck with central SMR (Pathway 3B); blended NG/H_2 (Pathway 4); LH_2 truck with central SMR (Pathway 3C). The "Total Capital Cost" H_2FAST input presented in **Table 2** accounted for the additional equipment needed in the case of integrating hydrogen delivery to existing natural gas stations, and the details of the capital costs for the various pathways are presented in **Table 2**. However, it does not include the cost of land associated with each pathway. Therefore, it is important to note that the break-even price of hydrogen (i.e., the costliness of a pathway) would be impacted if the cost of land was added to the "Total Capital Cost" input.

Table 2: Inputs and outputs of H2FAST

	Input					Output
	Total Capital Cost ($2016)	**Electricity Use (kWh/kgH_2)**	**Electricity Unit Price ($2016/kWh)**	**Natural Gas Use (MMBtu/kgH_2)**	**Natural Gas Unit Price ($2016/MMBtu)**	**Estimated break-even leveraged price ($2021/kg)**
Pathway 2 – Onsite SMR	2,598,775	1.110	0.107	0.156	3.734	-0.940
Pathway 3A – Central SMR, H_2 pipeline	4,829,542	0.569	0.070	0.156	4.251	-0.210
Pathway 3B – Central SMR, GH_2 truck	5,555,529	0.569	0.070	0.156	4.251	0.030
Pathway 3C – Central SMR, LH_2	8,740,577	0.569	0.070	0.156	4.251	1.070
Pathway 4 – Blended NG/H_2 with H_2 separation	4,347,630	0.569	0.070	0.156	4.251	0.340

Table 3 shows the land use unique to each pathway and the associated land cost. It is assumed that the onsite SMR pathway takes place in the existing natural gas stations and would not incur an additional land cost. The cost of land associated with the blending station is unknown as there is virtually no information regarding the blending process of H_2 into natural gas stream as the project initiated by the Department of Energy – HyBlend – is still undergoing.

Table 3: Costs of land use for each H_2 delivery pathway:

Pathway	Cost of Land ($2016/1,500kg H_2)
Pathway 2 – Onsite SMR	0
Pathway 3A – Central SMR with H_2 pipeline	134,694
Pathway 3B – Central SMR with GH_2 truck	33,284
Pathway 3C – Central SMR with LH_2	768
Pathway 4 – Blended NG/H_2 with H_2 separation	-

5. Design Protocol, Training Requirements, and Refueling Station Practices

With respect to the design of the refueling station unit, the protocol established in SAE J2601 standard for H_2 fueling for light duty H_2 surface vehicles must be closely followed [11, 12]. A brief description of the SAE J2601 protocol is presented here. Most commercial on-vehicle H_2 storage tanks are rated to operate at a maximum temperature of 85°C. The temperature management of the fuel tank is challenging because the temperature of the tank gradually increases during the refueling of pressurized H_2. In addition, the temperature of the storage tank is unknown. Therefore, the dispensing unit should be capable to estimate the storage tank temperature using tank pressure and ambient temperature as known data. Furthermore, necessary venting and pressure relief systems are necessary to ensure that the dispensed H_2 does not exceed the maximum temperature and pressure (70 MPa for full tank or 35 MPa for a half-tank) limits for safe on-vehicle storage. Moreover, a target refueling duration that satisfies the customer is desirable. Finally, visual and audio aids to indicate the end of the fueling process are necessary to ensure that the personnel do not remove the refueling nozzle prematurely. SAE J2601 standard provides guidance for H_2 fueling protocol on the following criteria (**Figure 1**):

- Storage tank instantaneous temperature/pressure and maximum allowable temperature/pressure
- State of charge assessment
- Communication protocol between H_2 dispenser and storage tank
- Necessary pre-cooling of stored H_2 and corresponding definition of fuel station type
- Fueling rate and target pressure
- Technique to detect safe and leak free connection between the pump nozzle and fill port

5.1 Customer fueling training

Commercially available fuel cell electric vehicle car manuals provide detailed description of the fueling process. A brief description of the general method is presented here. Firstly, the car must be put into the parking mode and the vehicle must be turned off. Subsequently, the fuel filler door must be opened pressing the appropriate button/lever, and manually opening the fuel filler door. Initially, the H_2 dispensing unit asks the customer if they have been trained to use the H_2 dispensing equipment. If the response is "NO", the dispensing unit will present an instructional video describing the H_2 refueling methodology and provide a pin code unique to that retailer station., the appropriate payment must be completed at the H_2 dispensing station. If the response is "YES", the unit proceeds to the payment process.

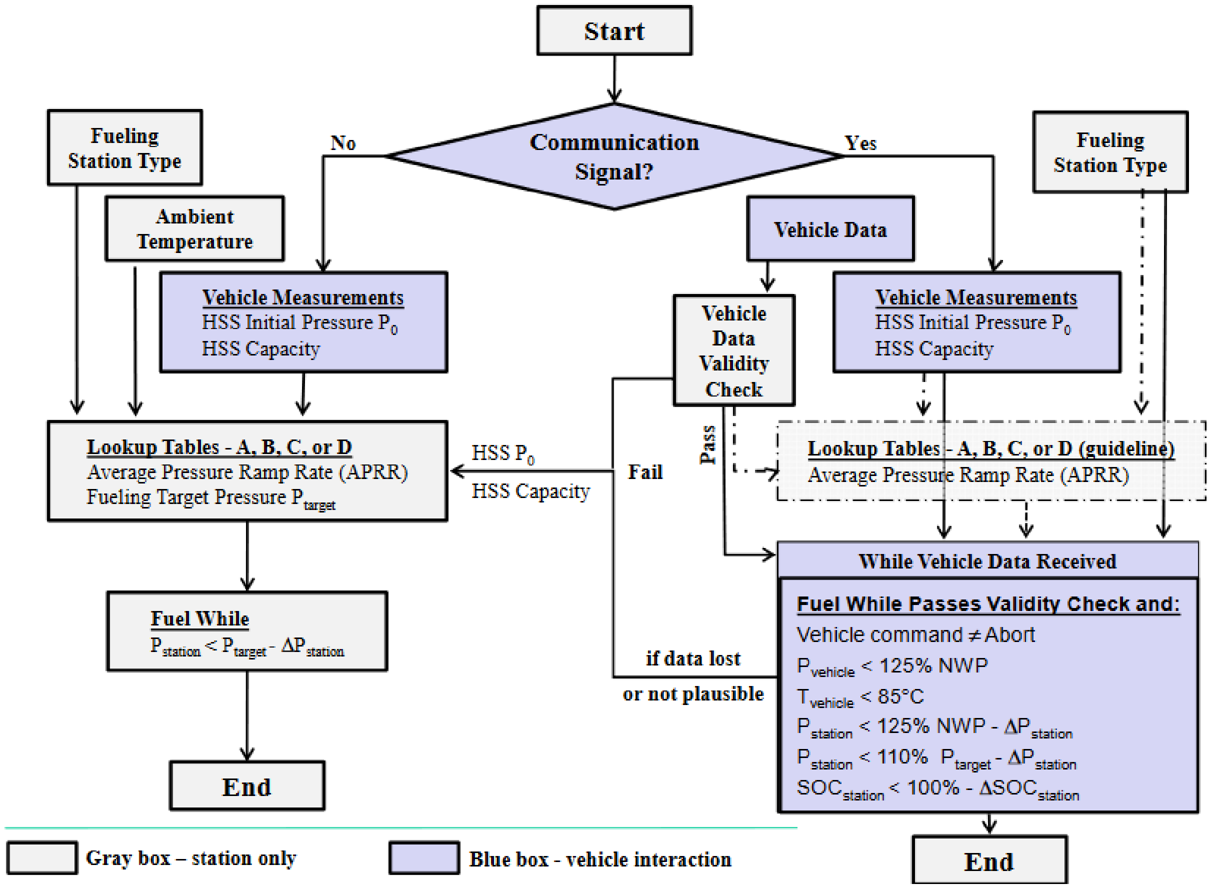

Figure 1: J2601 fueling procedure summary [11].

Consequently, the nozzle from the corresponding dispenser should be secured on to the receptacle and the lever on the dispenser must be squeezed until the latch is engaged. Gently pull on the nozzle to ensure that the connection is secure. This process locks the nozzle and receptacle together; but the fuel dispensing does not begin until the lever on the dispensing unit is lifted and the corresponding fueling level is selected. There are two levels of fueling that can be selected - H70 and H35. The numbers 70 and 35 represent the final pressure of the storage tank on-board of the vehicle in MPa. Selecting H70 correlates to filling the tank to a 100% capacity, and H35 fills the tank to a 50% capacity. Once the required fueling level is selected, the dispenser in conjunction with the vehicle's infrared sensors check for leaks in the connection before beginning fueling. If there are any leaks detected, the dispenser will indicate the same and necessary adjustments to the connection between the nozzle and the receptacle are necessary. After fueling is complete, lower the lever and replace the nozzle on to the dispenser unit, and replace the fuel filler cap and close the fuel filling door. It is possible for some vehicles to provide on-board apps that help the driver find functioning H_2 fueling stations in the vicinity.

5.2 Personnel training

It is important for users or employees working at the H_2 dispensing stations to adhere to pre-determined standards, codes, and guidelines for H_2 systems. The personnel at the H_2 refueling station must go through mandatory training on the following topics [13]:

1. Familiarity with physical and chemical properties of H_2.
2. Certification for handling GH_2 and LH_2.
3. Fire prevention, evacuation, and fire safety training as described in section 406 of International Fire Code (International Code Council, 2009) [14].
4. Maintenance and inspection procedures [15]:
5. Dealing with incidents related to:
    a. Evacuation procedure and capability to handle alarm systems, and regular safety drills.
    b. Emergency protocols during H_2 leakage and handling the hazards of H_2 associated with loading and storage systems, purge systems, control sampling and analytical systems, alarm/warning signal systems, ventilation requirements, fire and personnel protection, and system schematics and emergency procedures.
6. Procedures post emergency evacuation.
7. Procedures related to medical emergencies and rescue protocols.
8. Procedures of reporting all incidents.

5.3 Comparison of CNG and H_2 refueling station practices

Irrespective of the pathway selected for H_2 production and delivery, it is important to meet the piping and siting requirements of H_2 to obtain the necessary permits. In this context, the key similarities and differences in the piping and siting requirements between NG and H_2 as suggested by the American Society of Mechanical Engineers (ASME) B31 committee are presented in **Table 4**.

Table 4: Similarities and differences in natural gas and H_2 piping and siting requirements [8, 16].

Component description	Section no.		Similarities and differences in the codes and requirements
	NG	H_2	
Scope and Intent	802	GR-1.1 through GR-1.5	There are some differences in the structure of these sections; however, the content is comparable There is an exclusive section describing the terms and definitions related to plastic in the natural gas requirements
Piping Systems Definitions	803		
Piping Systems Component Definitions	804		
Design, Fabrication, Operation, and Testing Terms and Definitions	805		
Quality Assurance	806		

Component description	Section no.		Similarities and differences in the codes and requirements
	NG	H_2	
Training and Qualification of Personnel	807		
Materials and Equipment	810	GR-2.1	Significant differences in the material requirements described, their manufacturing standards, temperature specifications, and material index requirements NA = Equivalent requirements not presented for hydrogen
Qualification of Materials and Equipment	811	GR-2.2	
Materials for Use in Low-Temperature Applications	812	GR-2.1.2	
Marking	813	NA	
Material Specifications	814	GR-2.1.1	
Equipment Specifications	815	NA	
Transportation of Line Pipe	816	NA	
Conditions for the Reuse of Pipe	817	NA	
Welding	820	GR-3.2	Comparable introductions to the chapter describing welding process and definitions
General	821	GR-3.1	
Preparation for Welding	822	GR-3.4.3	Significant differences in the preparation requirements; specifically, the number of codes described in the hydrogen requirements are comparatively exhaustive for each of these sections in this chapter
Qualification of Procedures and Welders	823	GR-3.2.4	
Preheating	824	GR-3.5	
Stress Relieving	825	GR-4.2	
Weld Inspection Requirements	826	GR-4.3	
Repair or Removal of Defective Welds in Piping Intended to Operate at Hoop Stress Levels of 20% or More of the Specified Minimum Yield Strength	827	PL-3.0	
Piping System Components	831	PL-2.2	Significant differences in the descriptions of (a) valves and pressure-reducing devices, (b) flanges, and (c) fittings other than valves and flanges requirements Similar descriptions of (a) reinforcement of welded branch connections, (b) reinforcement of multiple openings, and (c) extruded outlets requirements
Expansion and Flexibility	832	PL-2.5	Comparable requirements
Design for Longitudinal Stress	833	PL-2.6	Comparable requirements
Supports and Anchorage for Exposed Piping	834	PL-2.7	Comparable requirements
Anchorage for Buried Piping	835	PL-2.8	Comparable requirements
Liquid Removal Equipment	836	NA	Exclusive description of liquid removal requirements provided for natural gas
Design, Installation, and Testing	840	PL-3.1	Differences in the details of gas composition and additives used Exclusive damage control requirements for H_2 Hydrogen sulfide, oxygen, and water vapor content requirements for H_2 missing Comparable requirements for (a) buildings intended for human occupancy, (b) Considerations Necessary for Concentrations of People in Location Class 1 or 2, and (c) intent Exclusive (a) risk assessment [PL-3.5] and (b) location class and changes in the number of buildings intended for human occupancy [PL-3.6] requirements provided for H_2

Component description	Section no.		Similarities and differences in the codes and requirements
	NG	H_2	
Steel Pipe	841	PL-3.7	Significant differences in formulas related to steel piping systems design requirements Comparable requirements for installation of steel pipelines and mains with the following exceptions: -Exclusive pipe installation inspection provisions provided for natural gas; -Additional requirements of hot taps for H_2 included; -Differences in precautions to prevent combustion of H_2-air mixtures during construction operations Several differences in the testing after construction requirements Comparable commissioning of facilities requirements
Materials Used for Pipes Other Than Steel	842	NA	No description of requirements for materials used for pipes other than steel provided for hydrogen
Compressor Stations	843	Appendix I	Comparable requirements except for the following differences in the subsections: -Few differences in the compressor station equipment code requirements -Exclusive section on the liquid removal for gas treating facilities provided for natural gas -Exclusive requirements for air piping, lubricating oil, water piping, steam piping, and hydraulic piping described for natural gas
Pipe-type and Bottle-type Holders	844	PL-3.12	The pipe-type and bottle-type holders requirements are comparable with the following exceptions: -Special provisions applicable to (a) bottle-type holders only and (b) general provisions applicable to both pipe-type and bottle-type holders requirements are different
Control and Limiting of Gas Pressure	845	PL-3.13	Significantly different requirements for control and limiting of gas pressure Similar design of pressure relief and pressure-limiting installations requirements Several differences in (a) capacity of pressure-relieving and pressure-limiting station and devices requirements An exclusive section describing the instrument, control, and sample piping requirements provided for natural gas
Valves	846	PL-3.15	Comparable requirements for required spacing of valves
Vaults	847	PL-3.16	Significant differences in (a) structural design and (b) drainage and waterproofing requirements Similar (a) accessibility and (b) vault sealing, venting, and ventilation requirements
Customers' Meters and Regulators	848	PL-3.17	Significant differences in customers' meters and regulators requirements Several subsections of 848 defined for natural gas missing in H_2 requirements

Component description	Section no.		Similarities and differences in the codes and requirements
	NG	H_2	
Gas Service Lines	849	PL-3.18	Comparable gas service lines requirements except for the following subsections that have several differences: - Installation and service lines - Exclusive excess flow valve installation requirements provided for natural gas - Exclusive ductile iron, plastic, and copper service lines requirements, and their connection to mains requirements provided for natural gas - Exclusive requirements listed for categories such as (a) inspection and examination, (b) repair or removal of defective welds in piping intended to operate at hoop stress levels of 20% or more of the specified minimum yield strength, and (c) steel pipeline service conversions for hydrogen
Operating and Maintenance Procedures Affecting the Safety of Gas Transmission and Distribution Facilities	850	GR-5.2	Significant differences in general operation and maintenance plans
Pipeline Maintenance	851	GR-5.2	Comparable pipeline maintenance requirements except for the following differences: - Significant differences in repair procedures for piping and pipelines - Additionally, the distribution of the subsections is not similar; moreover, the specific requirements are different
Distribution Piping Maintenance	852	GR-5.18	Comparable requirements for leakage investigation and action, and leakage survey requirements Significant differences in the description of requirements for abandoning, disconnecting, and reinstating distribution facilities Exclusive description of plastic pipe maintenance provided in natural gas requirements
Miscellaneous Facilities Maintenance	853	GR-5.23	Comparable requirements for all subsections An exclusive section on maintenance and testing of gas detection and alarm systems, and monitoring effects of pulsation and vibration requirements provided for natural gas
Location Class and Changes in Number of Buildings Intended for Human Occupancy	854	PL-3.6	Comparable requirements for all subsections with few differences in the subsection addressing the requirements related to concentrations of people in location classes 1 and 2
Pipeline Service Conversions	855	PL-3.21	Significant differences in the steel pipeline service conversion requirements
Odorization	856	GR-5.20.3	Exclusive description of odorization and related requirements provided for natural gas Limited requirements on odor or indications from foreign sources provided for hydrogen
Uprating	857	PL-3.14	Significant differences in the uprating requirement descriptions
Composition	4.2	NA	Exclusive description of the composition of natural gas provided

Component description	Section no.		Similarities and differences in the codes and requirements
	NG	H_2	
System approvals	4.3	5.2	Comparable requirements; however few specific differences related to generators, dispensers, and gas detection equipment
Design and construction of containers	4.4	5.3	Differences in the design, fabrication, testing, and marking of cylinders, containers, and tanks Natural gas is required to follow ASME compliance, and H_2 to follow US Department of Transportation compliance Similar pressure vessel design requirements
Pressure relief devices	4.5	5.4	Significant differences in the design requirements of cylinders, portable tanks, boiler, and pressure relief devices.
Vent Pipe Termination	NA	5.5	Exclusive description of the vent pipe termination requirements provided for H_2
Pressure gauges	4.6	5.6	Similar pressure gauge capability description Specific restriction on gauge opening inlet connection sizing for H_2
Pressure regulators	4.7	5.7	Comparable requirements
Fuel Lines	4.8	5.8	ASME B31.3 to be used in the design and fabrication of fuel piping Differences in safety factors used Specific restrictions on the material used for various components for natural gas
Valves	4.9	5.9	Similar valve and shut-off valve design requirements Several differences in materials that could be used in the valves
Hose and Hose Connections	4.10	5.10	Comparable requirements
Vehicle fueling connections	4.1	5.11	Natural gas fueling connections to comply with ANSI/IAS NGVI, the standard for compressed natural gas vehicle fueling connection devices, and H_2 fueling connection to comply with SAEJ2600, compressed hydrogen surface refueling connection devices
System Siting	8.4	9.3	Following are the differences in the siting requirements: - Exclusive description of minimum distance from outdoor gaseous hydrogen systems to exposures (U.S. units) provided - Exclusive description on separation distance based on alternative pipe or tube internal diameters provided for H_2 - Exclusive description on separation distances for outdoor gaseous hydrogen dispensing systems provided for H_2 - Outdoor storage, ventilation, rooms within buildings, room ventilation, warning signs, fire detection and safety, and gas detection system requirements are different
Indoor Fast-Fill Fueling, Outdoor Storage, and Compression	8.5	NA	An exclusive section describing the requirements for an indoor fueling station provided for H_2

6. Conclusion

Conversion of CNG fueling stations to H_2 fueling or co-locating CNG and H_2 fueling is indeed possible. It will be important to consider the various options and costs for H_2 delivery to determine the financial feasibility of such a project. Similarities in siting requirements for H_2 and CNG would help to keep costs down with a conversion or co-location project however, equipment requirements are quite different and therefore would not transfer from CNG usage to H_2. Blended pipeline NG/H_2 could be an affordable option.

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Appendix: Capital Cost Details for All Pathways

Table 5: Capital cost details for all pathways

Pathway 2 – Onsite SMR			
Components	**Price ($2016)**	**Comments**	**Source**
Reformer	260,945		[17]
H_2 compressor	814,070		[17]
CH_2 storage	915,000		[7]
CH_2 dispenser	367,551		[17]
Pathway 3A – Central SMR, H_2 pipeline			
Central SMR	1,687,882	Inflation adjusted, 1,500kg/day out of 27,000kg/day	[18]
Central H_2 compressor	25,887	1500kg/day out of 66,599kg/day flow rate to one compressor	[19]
Bulk GH_2 storage	673,877	1500kg/day out of 141,609kg/day	[19]
H_2 pipeline	490,162	1500kg/day out of 141,757kg/day, including labor	[19]
H_2 compressor	814,070		[17]
CH_2 storage	826,128	Inflation adjusted	[20]
CH_2 dispenser	367,551		[17]
Pathway 3B – Central SMR, GH_2 truck			
Central SMR	1,687,882	Inflation adjusted, 1,500kg/day out of 27,000kg/day	[18]
Central H_2 compressor	25,887	1500kg/day out of 66,599kg/day flow rate to one compressor	[19]
Bulk GH_2 storage + GH_2 terminal	1,355,237	1500kg/day out of 141,609kg/day	[19]
GH_2 truck	534,789	Trailer delivery capacity = 1042 kg/trip	[19]
H_2 compressor	814,070		[17]

CH_2 storage	826,128	Inflation adjusted	[20]
CH_2 dispenser	367,551		[17]
Pathway 3C – Central SMR, LH_2			
Components	**Price ($2016)**	**Comments**	**Source**
Central SMR	1,687,882	Inflation adjusted, 1,500kg/day out of 27,000kg/day	[18]
Central H_2 liquefier	5,485,615		[17]
Bulk LH_2 storage + LH_2 terminal	1,265,911	Inflation adjusted, 1,500kg/day out of 27,000kg/day	[18]
LH_2 truck	1,054,926	Inflation adjusted, 1 truck with min. capacity = 3610 kg/trip	[18]
LH_2 pump	713,619	3 pumps operating at 360kg/hr	[19]
LH_2 vaporizer	12,130		[21]
LH_2 storage	271,329	min. storage capacity = 4020 kg	[19]
CH_2 storage	826,128	Inflation adjusted	[20]
CH_2 dispenser	367,551		[17]
Pathway 4 – Blended NG/H_2 with H_2 separation			
Central SMR	1,687,882	Inflation adjusted, 1,500kg/day out of 27,000kg/day	[18]
Central H_2 compressor	25,887	1500kg/day out of 66,599kg/day flow rate to one compressor	[19]
Bulk GH_2 storage	673,877	1500kg/day out of 141,609kg/day	[19]
Blend station	-	Will need info from HyBlend, an undergoing project initiated by DOE	-
H_2 separation equipment	8,250	Used the unit separation cost of $5.5/kg at a 10% H_2 mixture	[7]
H_2 storage	814,070		[17]
CH_2 storage	826,128	Inflation adjusted	[20]
CH_2 dispenser	367,551		[17]

Metropolitan
ENERGY CENTER

Metropolitan Energy Center, MEC, is a Missouri 501(c)3 nonprofit. Founded in 1983, our mission is to create resource efficiency, environmental health and economic vitality in Kansas City and beyond. A catalyst for community partnerships focused on energy conservation, MEC works primarily through its Building Performance and Sustainable Transportation programs. Every energy dollar conserved through MEC's work remains available for investment in the local economy.

MEC also acts as an aggregator and funder for local projects that achieve energy efficiency in Kansas and Missouri, distributing nearly $20 million in the last decade, helping to reduce greenhouse gas emissions by more than 300 tons.

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