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Competitive Pricing of Hydrogen as an Economic Alternative to Gasoline and Diesel for the Houston Transportation Sector

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Executive Summary

The preference for liquid transportation fuels like gasoline and diesel relates to their much greater energy density. However, greenhouse gas (GHG) emissions from combustion of gasoline and diesel in the transportation energy sector account for 27% of US emissions. Fuel cell electric vehicles (FCEVs) refuel with hydrogen (H_2) in 5 minutes and provide transportation range similar to internal combustion vehicles (ICEVs) without GHG emissions. This paper investigates how the cost of providing H_2 refueling in the Houston area would compare with current gasoline and diesel prices.

This paper compares three H_2 generation processes. The two processes that start with methane and water as feedstock are steam methane reforming (SMR) and SMR with carbon capture (SMRCC). The third process applies electrolysis using grid electricity and water as feedstock. The National Renewable Energy Laboratory (NREL) H2A tools provides cost estimates of H_2 generation by the analyzed pathways of SMR, SMRCC, and grid H_2. By grid H_2 this paper means H_2 generated from the Texas electric grid using electrolysis. The H_2 Delivery Scenario Analysis Model (HDSAM) created by Argonne National Laboratory generates the delivery model and costs. Our investigation of 45Q and 45V provides insight into the tax incentives producers could use to reduce their overall leveled cost of H_2.

This paper provides investors and policy makers with compelling evidence, based on aggregated capital, operating, and feedstock costs for H_2 generation, transportation and distribution, that gaseous H_2 can be supplied in the greater Houston area at a cost that is competitive with gasoline and diesel fuel. The levelized total cost (LTCH) of H_2 ranges from \$4.54 per kg H_2 (onsite SMR) to \$8.86 per kg H_2 (electrolysis). The option to reuse available transport, pipeline, road, and rail infrastructure for H_2 and natural gas would be cheaper than new construction and would provide an option for low-cost H_2 delivery by reducing capital expenditures (CAPEX) and operating expenditures (OPEX).

For as long as they exist, favorable 45V tax incentives can encourage investment in SMRCC H2 generation because the incremental cost (\$113.6 per ton CO_2) of storing CO_2 captured for SMRCC is less than the maximum 45V incentive (\$3 per kg $H_2 \approx$ \$300 per ton CO_2). While grid H_2 offers a more straightforward generation and delivery system, emissions from the grid electricity generation compare with emissions from ICEV transportation. At much lower cost than grid H_2, without tax credit incentive SMRCC H2 costs \$6.10 per kg H_2 at the pump. The customer breaks even paying about twice the price per gallon of gasoline and 1.8 times the price per gallon of diesel for a kg of H_2 on a cost per distance-traveled basis. At the current liquid fuel prices a supplier can profitably offer H_2 fuel at a price competitive with gasoline and diesel.

Introduction

The most common justification for the continued use of liquid transportation fuels is their high volumetric energy density. Volumetric energy density is an important attribute because transportation vehicles must transport both the size and weight of the onboard fuel in addition to passengers and/or freight. Transportation vehicles must also transport the propulsion mechanism, which for gasoline and diesel vehicles is an internal combustion engine (ICE).

Electric vehicles (EVs) may store onboard energy in batteries (BEVs) or as hydrogen (H_2) to power a fuel cell (FCEVs). To compare ICE vehicles (ICEVs) with EVs impartially, we must consider the volume and weight of their combined onboard fuel and propulsion mechanism along with the overall life cycle analysis (LCA) of the energy required to move the vehicle a particular distance. Further, markets must consider costs and consumer preferences, and modern societies may also favor environmental constraints on greenhouse gas (GHG) emissions.

California has declared that ICEVs will no longer be sold there after 2035, and 100% of medium-and heavy-duty vehicles will be zero emission vehicles (ZEV) by 2045 where feasible (Executive Department State of California 2020). They have already demonstrated that companies and consumers can manage EV transportation, but adoption rates have been low. Table 1 indicates that the EV adoption rates were only 2.8% of the total light-duty vehicle population at the end of 2021. A later report indicated that the total number of medium and heavy-duty ZEVs in commercial use was only 1,943. Industry near Houston, Texas generates more H_2 than anywhere else in the world. As such, Houston, and for that matter the state of Texas, may be well-positioned to promote a transition to H_2 as a transportation fuel. This paper investigates the merits of supplying Houston private and commercial consumers with access to H_2 for refueling vehicles.

The following sections detail hydrogen generation, transport, consumer sales, and the economic impact of adding CO_2 capture to SMR. We include a cost comparison and market considerations before concluding the study. For comparison purposes, we calculate several levelized costs culminating in a levelized total cost of hydrogen (LTCH). The LTCH is the total cost to produce and sell each kg of H_2 during a project's operational life. It includes all capital requirements as well as operation, transportation, and distribution costs. We obtain the LTCH from the following equation:

$$LTCH = LCOH + LCT + LCRS \quad (1)$$

where LCOH is the levelized cost of H_2 generation, LCT is the levelized cost of H_2 transportation, and LCRS is the levelized cost of H_2 associated with the costs refueling stations for consumer sales. We obtain LCOH from the following equation:

$$LCOH = LFC + LCC + LOM \quad (2)$$

where LFC is the levelized feedstock cost including electricity, LCC is the levelized capital cost, and LOM is the levelized operating and maintenance cost (this includes both fixed and variable costs). We will report everything in $ per kg H_2.

H_2 Generation

Several existing hydrogen generation pathways use various feedstock to produce H_2. In this paper, we analyze five pathways, steam methane reforming (SMR), steam methane reforming with carbon capture (SMRCC), electrolysis, onsite SMR, and onsite electrolysis. The first three pathways apply for hub generation, and the last two consider generation at or near a refueling location. We describe each pathway in this section.

In this section, we gather data from a variety of sources to derive the levelized cost of H_2 under multiple generation options. We use two recent NETL studies featuring H_2 generation facilities in the Midwest region with 30-yr operation periods, starting in 2023 (DOE/NETL 2022). They form the basis for some of our data on SMR and SMRCC facilities. We also use NREL data to assess the costs of both hub- and small-scale grid hydrogen, as well as small-scale SMR (Penev et al. 2018).

Table 1: Total Light-Duty Vehicle Population in California (California Energy Commission 2022)

	ZEV Population			Non-ZEV Population		
Description	Battery Electric (BEV)	Plug-in Hybrid (PHEV)	Fuel Cell (FCEV)	Gasoline	Gasoline Hybrid	Diesel
Percent Vehicles	2.61%	1.15%	0.04%	89.38%	4.76%	2.04%
Total Vehicles	763,557	335,574	11,897	26,188,730	1,394,237	598,147
Total Light-Duty Vehicles End of 2022	**1,111,028**			**28,189,748**		

Steam Methane Reforming (SMR)

The most common process for H_2 generation is steam methane reforming (SMR), which contacts steam (H_2O vapor) with methane (CH_4) to produce carbon monoxide (CO) and hydrogen (H_2), followed by a shift reaction that further generates hydrogen by reacting carbon monoxide (CO) with water to produce H_2 and CO_2. The latter process then emits the resultant carbon dioxide (CO_2) to the atmosphere. As well, usually CO_2 from combustion of methane to energize the steam generation emits additional CO_2.

Houston is home to many H_2 plants for industrial use, with several H_2 plants operated by Air Liquide, Air Products, and other commercial H_2 manufacturers. This work refers to H_2 generation using SMR with carbon capture and strict attention to methane containment as SMRCC. There have been recent developments in the SMRCC space, with Air Products retrofitting a H_2 generation plant, in Port Arthur, Texas, to enable CO2 capture (Air Products 2023).

While other known processes for hydrogen generation from natural gas include partial oxidation (POX), autothermal reaction (ATR), and methane pyrolysis, this study considers only SMR.

Grid H_2 Generation

Grid H_2 generation is H_2 generated with electricity supplied by the electric grid. Currently, several processes exist to generate grid H_2. In this paper, we analyze the economics of a proton exchange membrane (PEM) electrolyzer. A PEM electrolyzer passes an electrical current through an anode and a cathode to separate water into H_2 and oxygen (Holladay et al. 2009). PEM-based electrolyzers typically use platinum black, iridium, ruthenium, and rhodium for electrode catalysts and a Nafion membrane that separates the anode and cathode and acts as a gas separator (Holladay et al. 2009).

Costs of Resources and Feedstock for Hydrogen Generation

This section summarizes costs of water, natural gas, and grid resources in the greater Houston area as contributions to the LFC component of the LCOH in Eqn. (2). We will obtain LFC from the following information by adding the levelized cost results in Table 2, Table 3, and Table 4. mechanism, which for gasoline and diesel vehicles is an internal combustion engine (ICE).

Water

Houston has more than sufficient water resources and commercial filtering systems to support H_2 generation. The city of Houston treats an average of roughly 450 million gallons each day; industrial and manufacturing sectors use most of this water. The city owns the water rights to 1.2 billion gallons per day of surface water (City of Houston 2022). This provides an estimated excess supply of 750 million daily gallons, without including additional supplies managed by public utility districts (PUD). Groundwater supplies provide an additional 200 million daily gallons (City of Houston 2022) for a total of 1.4 billion gallons of water per day.

The Texas Department of Transportation reported that Houston had roughly 5.5 million registered vehicles in fiscal year 2022 (TxDOT 2022). If all these vehicles were FCEVs, using H_2 as fuel, the fleet would require 4 million kg of H_2 per day, based on an average consumption of 5 kg of H_2 per week per vehicle. Depending on the technology employed to generate H_2, this level of demand would consume between 15 and 33 million gallons of water per day (roughly 1.1% to 2.4% of Houston's 1.4 billion gallons of total daily water rights). Each H_2 generation pathway requires differing amounts of water.
The city of Houston charges at varying commercial rates depending on meter size (City of Houston 2022), and volume of water consumed, as well as for basic sewer services. Based on our research, we will use an approximation of $10.97 per 1,000 gallons of water. This results in levelized costs of water usage for hydrogen production ranging from $0.04 per kg H_2 (electrolysis) to $0.09 per kg H_2 (SMRCC).

Table 2 lists levelized water costs for the five H_2 generation pathways and indicates which NREL spreadsheet was used for each of various numbers in the table.
The tool numbers refer to the following NREL spreadsheet names: Tool 1 is Current Central Steam Methane Reforming without CO2 sequestration (version Aug 22);
Tool 2 is Current Central Steam Methane Reforming with CO_2 sequestration (version

Table 2. Water Costs

Hydrogen Generation Pathway	Net Plant Capacity	Plant Production	Usage	Cost per Year	Contribution to LFC
SMR[1]	434,700 kg H_2/day	158,774,175 kg H_2/yr	4.344 gal/kg H_2	$7.57 M	**$0.05/kg H_2**
SMRCC[2]	434,700 kg H_2/day	158,774,175 kg H_2/yr	8.130 gal/kg H_2	$14.16 M	**$0.09/kg H_2**
Electrolysis[3]	54,805 kg H_2/day	20,017,526 kg H_2/yr	3.780 gal/kg H_2	$0.83 M	**$0.04/kg H_2**
Onsite SMR[4]	1,290 kg H_2/day	471,173 kg H_2/yr	5.770 gal/kg H_2	$0.03 M	**$0.06/kg H_2**
Onsite Electrolysis[5]	1,458 kg H_2/day	532,535 kg H_2/yr	3.780 gal/kg H_2	$0.02 M	**$0.04/kg H_2**

Price of $10.97/1000 gal for all calculations, [1]NREL Tool 1, [2]NREL Tool 2, [3]NREL Tool 3, [4]NREL Tool 4, [5]NREL Tool 5

[1] *To underscore the variability in electricity cost among the H_2 generation options, it is grouped with feedstock instead of operating costs.*
[2] *Electrolysis uses demineralized water as a feedstock; table uses tap water cost.*

Aug 22); Tool 3 is Current Central PEM Electrolysis (version Nov 20); Tool 4 is Current Distributed Hydrogen Production from Natural Gas (1500 kg/day) (version Apr 2022); Tool 5 is Current Distributed Hydrogen Production from PEM Electrolysis (version Apr 2022).

Natural Gas

Natural gas is abundant in Texas and in North America and is transported by pipeline throughout much of the US. BP 2020 indicates global natural gas reserves of 7,019 trillion cubic feet (TCF) with a reserves to production ratio of approximately 50 years (bp 2020). EIA reports proved natural gas reserves of 133 billion cubic feet (BCF) in Texas with a reserves to production ratio of approximately 14 years (EIA 2023). Reserve to production ratio is an economic measure and does not necessarily reflect the available resource size or duration. Each H_2 generation pathway consumes differing quantities of natural gas. Natural gas prices fluctuate based on market conditions and regional considerations. For the nation, in the first three months of 2023 the average industrial price of natural gas ranged from \$4.86 to \$7.03 per mmBTU, while for Texas the prices ranged from \$2.50 to \$4.55 (EIA 2023b). All calculations for this work assume that the purchase price of natural gas is at industrial prices. Based on the above data, we averaged the industrial prices for Texas for the first 3 months of 2023 for an approximation of \$3.32 per mmBTU of natural gas. This results in levelized costs of natural gas usage for hydrogen production from \$0.52 per kg H2 (SMR and Onsite SMR) to \$0.56 per kg H_2 (SMRCC). Table 3 provides levelized natural gas costs for the three SMR pathways.

Table 3. Natural Gas Costs.

Hydrogen Generation Pathway	Net Plant Capacity	Plant Production	Usage	Cost per Year	Contribution to LFC
SMR[1]	434,700 kg H_2/day	158,774,175 kg H_2/yr	0.158 mmBTU/kg H_2	\$83.18 M	**\$0.52/kg H_2**
SMRCC[2]	434,700 kg H_2/day	158,774,175 kg H_2/yr	0.168 mmBTU/kg H_2	\$88.44 M	**\$0.56/kg H_2**
Onsite SMR[3]	1,290 kg H_2/day	471,173 kg H_2/yr	0.156 mmBTU/kg H_2	\$0.24 M	**\$0.52/kg H_2**
Price of \$3.32/mmBTU for all calculations, [1]NREL Tool 1, [2]NREL Tool 2, [3]NREL Tool 4					

Electricity

The electricity mix in Texas is about 34% low or zero (from alternative energy resources) carbon intensity generation. The mix includes 50% natural gas, 21% wind, 16% coal, 7.5% nuclear, 5% solar, and 0.5% other fuels in 2022 (ERCOT 2023a). This power generation mix differs somewhat from that of the US as a whole, which includes 42% natural gas, 10% wind, 17% coal, 19% nuclear, 4% solar, and 8% other (EIA 9-23 Report). Texas generates about 12.5% of the total electricity in the US. We can approximate electricity prices in Texas with \$0.07 per kWh for industrial uses (EIA 2023). Each H_2 generation pathway draws a different quantity of electricity. With the above price, this results in levelized costs of electricity usage for hydrogen production from \$0.01 per kg H2 (SMR) to \$3.90 per kg H_2 (onsite electrolysis). Table 4 provides levelized feedstock cost (LFC) electricity cost values for the five pathways. It is worth noting the contrasts in electricity usage shown in Table 4. Either electrolysis pathway uses from 45 to nearly 450 times more electricity than the SMR pathways. Relying on grid power for hydrogen generation would add significant new load. We also note that the onsite SMR electricity usage value (nearly 10 times the electricity used for hub SMR) comes from an unexplained input in NREL Tool 4. Also, we note that studies do not usually include electricity as a feedstock.

Table 4. Electricity Costs.

Hydrogen Generation Pathway	Net Plant Capacity	Plant Production	Usage	Cost per Year	Contribution to LFC
SMR[1]	434,700 kg H_2/day	158,774,175 kg H_2/yr	0.13 kWh/kg H_2	\$1.46 M	**\$0.01/kg H_2**
SMRCC[2]	434,700 kg H_2/day	158,774,175 kg H_2/yr	1.50 kWh/kg H_2	\$16.70 M	**\$0.11/kg H_2**
Electrolysis[3]	54,805 kg H_2/day	20,017,526 kg H_2/yr	55.50 kWh/kg H_2	\$77.77 M	**\$3.89/kg H_2**
Onsite SMR[4]	1,290 kg H_2/day	471,173 kg H_2/yr	1.11 kWh/kg H_2	\$0.04 M	**\$0.08/kg H_2**
Onsite Electrolysis[5]	1,458 kg H_2/day	532,535 kg H_2/yr	55.80 kWh/kg H_2	\$2.08 M	**\$3.91/kg H_2**
Price of \$0.07/kWh for all calculations, [1]NREL Tool 1, [2]NREL Tool 2, [3]NREL Tool 3, [4]NREL Tool 4, [5]NREL Tool 5					

The Department of Energy (DOE) characterizes electricity as a variable operating cost and the EIA refers to electricity as a secondary energy source. However, we included it in this category because it is a major part of the cost of goods sold for electrolysis, and is more similar in nature to a feedstock in that process than Variable O&M where it would otherwise be included. This decision will not impact the findings of the paper.

Reminding the reader that Houston requires 4 million kg H_2 per day for a complete transportation fuel switch from liquid fuels to hydrogen, we note that SMR would require about 0.52 GWh per day or SMRCC about 6 GWh per day. By contrast, electrolysis would require 222 GWh per day. For reference, ERCOT expects the instantaneous maximum demand to exceed 82 GW during summer of 2023.

The total LFC component for each pathway is the sum of the levelized costs for the three feedstock components in Table 2, Table 3, and Table 4, as shown in Table 5. An alternative study, carried out by NETL in 2018, offered a similar market-ready system in the Midwest states that the levelized feedstock cost (LFC) are \$0.77 per kg H_2 for SMR and \$0.82 per kg H_2 for SMRCC (DOE/NETL 2022). Our LFC numbers for slightly different regional feedstock costs are \$0.58 per kg H_2 for SMR and \$0.75 per kg H_2 for SMRCC.

Table 5. Feedstock Costs.

Hydrogen Generation Pathway	Net Plant Capacity	Plant Production	Total Feedstock Cost per Year	LFC
SMR[1]	434,700 kg H_2/day	158,774,175 kg H_2/yr	\$92.20 M	**\$0.58/kg H_2**
SMRCC[2]	434,700 kg H_2/day	158,774,175 kg H_2/yr	\$119.30 M	**\$0.75/kg H_2**
Electrolysis[3]	54,805 kg H_2/day	20,017,526 kg H_2/yr	\$78.60 M	**\$3.93/kg H_2**
Onsite SMR[4]	1,290 kg H_2/day	471,173 kg H_2/yr	\$0.31 M	**\$0.66/kg H_2**
Onsite Electrolysis[5]	1,458 kg H_2/day	532,535 kg H_2/yr	\$2.10 M	**\$3.95/kg H_2**
[1]NREL Tool 1, [2]NREL Tool 2, [3]NREL Tool 3, [4]NREL Tool 4, [5]NREL Tool 5				

Capital Expenditure

Capital expenses required for H_2 generation are process dependent. Our analyses included major pieces and systems of equipment such as accessory electric plant, cooling water system, feedwater and miscellaneous balance of plant (BOP), flue gas cleanup, hydrogen production, instrumentation and control, reformer and accessories, syngas cleanup, stack capital costs, and mechanical and electrical BOP. This section considers costs for SMR (both hub scale and onsite), SMRCC, and grid H_2 generation equipment (both hub scale and onsite). Capital costs vary from \$0.23 per kg H_2 (SMR) to \$0.85 per kg H_2 (onsite electrolysis) for the different hydrogen generation pathways (Table 6). For example, the total capital cost for the studied SMR is \$283.66 million; this is equivalent to ~\$0.23 per kg H_2.

Appendix 1 includes a detailed breakdown of the capital cost for each process we summarize in Table 6. The comparable 2018 NETL study states that levelized capital costs (LCC) are \$0.14 per kg H_2 for SMR and \$0.33 per kg H_2 for SMRCC (DOE/NETL 2022). The NETL calculation incorrectly treats debt as though it linearly reduces project capital cost. Accounting for the 60% debt they used in their calculation makes these numbers reasonably consistent with the numbers in Table 6.

Table 6: Capital Costs (LCC), see Appendix 1 for more details

Hydrogen Generation Pathway	Net Plant Capacity	Plant Production	Plant Life	Total Capital Cost	LCC
SMR[1]	434,700 kg H_2/day	158,774,175 kg H_2/yr	40 yr	\$283.66 M	**\$0.23/kg H_2**
SMRCC[2]	434,700 kg H_2/day	158,774,175 kg H_2/yr	40 yr	\$802.84 M	**\$0.63/kg H_2**
Electrolysis[3]	54,805 kg H_2/day	20,017,526 kg H_2/yr	40 yr	\$86.41 M	**\$0.59/kg H_2**
Onsite SMR[4]	1,290 kg H_2/day	471,173 kg H_2/yr	20 yr	\$1.76 M	**\$0.55/kg H_2**
Onsite Electrolysis[5]	1,458 kg H_2/day	532,535 kg H_2/yr	20 yr	\$3.13 M	**\$0.85/kg H_2**
[1]NREL Tool 1, [2]NREL Tool 2, [3]NREL Tool 3, [4]NREL Tool 4, [5]NREL Tool 5					

Operating Costs

Our analyses for the LOM component of the LCOH in Eqn. (2) for fixed operating and maintenance (O&M) included annual operating labor, maintenance labor, administrative and support labor, property taxes and insurance. The levelized fixed operating cost varies from \$0.09 per kg H_2 (SMR) to \$0.34 per kg H_2 (electrolysis), as summarized in Table 7. Our analyses included maintenance material, consumables, and water disposal for variable operating and maintenance (O&M) costs. The levelized cost varies from \$0.02 per kg H_2 (onsite SMR) to \$0.27 per kg H_2 (SMRCC), as summarized in Table 8. The comparable 2022 NETL study states that levelized operating and maintenance costs (LOM) are \$0.16 per kg H_2 for SMR and \$0.39 per kg H_2 for SMRCC (DOE/NETL 2022). Adding costs in Table 7 and Table 8, our numbers become \$0.11 per kg H_2 for SMR and \$0.48 per kg H_2 for SMRCC.

Table 7: Fixed Operating Costs, see Appendix 2 for more details

Hydrogen Generation Pathway	Net Plant Capacity	Plant Production	Fixed Operating Costs	Contribution to LOM
SMR[1]	434,722 kg H_2/day	158,782,211 kg H_2/yr	\$13.56 M	**\$0.09/kg H_2**
SMRCC[2]	434,700 kg H_2/day	158,774,175 kg H_2/yr	\$32.66 M	**\$0.21/kg H_2**
Electrolysis[3]	54,805 kg H_2/day	20,017,526 kg H_2/yr	\$4.80 M	**\$0.24/kg H_2**
Onsite SMR[4]	1,290 kg H_2/day	471,173 kg H_2/yr	\$0.10 M	**\$0.21/kg H_2**
Onsite Electrolysis[5]	1,458 kg H_2/day	532,535 kg H_2/yr	\$0.18 M	**\$0.34/kg H_2**
[1]NREL Tool 1, [2]NREL Tool 2, [3]NREL Tool 3, [4]NREL Tool 4, [5]NREL Tool 5				

Table 8: Other Variable Operating Costs (Component of LOM), see Appendix 2 for more details

Hydrogen Generation Pathway	Net Plant Capacity	Plant Production	Other Variable Operating	Contribution to LOM
SMR[1]	434,722 kg H_2/day	158,782,211 kg H_2/yr	\$2.70 M	**\$0.02/kg H_2**
SMRCC[2]	434,700 kg H_2/day	158,774,175 kg H_2/yr	\$42.12 M	**\$0.27/kg H_2**
[1]NREL Tool 1, [2]NREL Tool 2				

H_2 Transport

This section provides capital and operating costs for H_2 transport options.

H_2 Transport Options

It will take a long time to build a national H_2 delivery infrastructure and doing so will be challenging (EERE 2023). Delivery infrastructure requirements and resources will vary by region because of differing market types and conditions. Infrastructure options will also change as the demand for H_2 grows and as improved delivery technologies develop (EERE 2023).

In this paper, we analyze three delivery options that can transport H_2 from central locations to various refueling stations: pipelines, compressed truck, and liquid truck. Pipelines with various metallurgy can carry H_2 in gaseous form under 100 bar (Javaheri 2023). Trucks transport H_2 in gaseous form under high pressure (Compressed Truck) or in liquid phase (Liquid Truck). Onsite generation, either by SMR or electrolysis, does not require substantial transportation costs. In a 2007 study, Yang and Ogden analyzed three options for H_2 deliveries by modeling different flow rates and distances to market. They derived an analysis whereby the lowest-cost transportation option could be selected based on city population and radius, population density, size and number of refueling stations and expected market penetration of fuel cell vehicles (Yang and Ogden 2007). Their work culminated in the results indicated in Figure 1 which shows that pipelines have the best economics at any distance under 500 kilometers (km) if the H_2 flow rates exceed 78,000 kg H_2 per day (78 tonne/d in the figure). As a reminder, Houston needs 4 million kg per day for 100% market penetration; their study would predict that pipelines would be the preferred transport option for the city.

Pipeline

Pipelines can transport H_2 from the generation plant to a distribution center or point of use. From the distribution center, additional pipelines transport H_2 to refueling stations (EERE 2023). Houston does not have H_2 specific pipelines within the city limits.

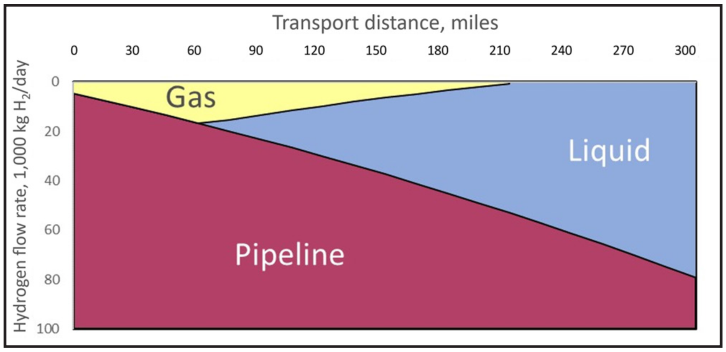

Figure 1: H_2 Flow Rate versus Transport Distance for Gaseous H_2 Trucks, Liquid H_2 Trucks, and Pipelines (Adapted from Yang and Ogden 2007)

Existing dedicated H_2 transport pipelines in the region exist only for industrial applications (Air Liquide 2005). Air Liquide owns a 34 mile 14-inch pipeline running from Freeport to Texas City and a 130 mile 8-inch pipeline running from Corpus Christi to Three Rivers (Figure 2). Air Products owns over 600 miles of bidirectional pipelines that transport hydrogen from the Houston Ship Channel to New Orleans. The company has the capacity to supply up to 1 billion cubic feet of H_2 per day, or approximately 2.3 million kg H_2 per day (Figure 3). Linde's (formerly Praxair) H2 pipeline system runs along the U.S. Gulf Coast and spans approximately 300 miles from Freeport, Texas to Lake Charles, Louisiana (Figure 4).

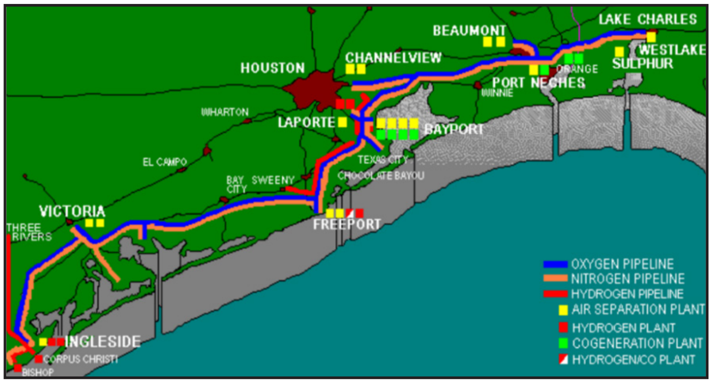

Figure 2: Air Liquide H2 Pipelines (Air Liquide 2005).

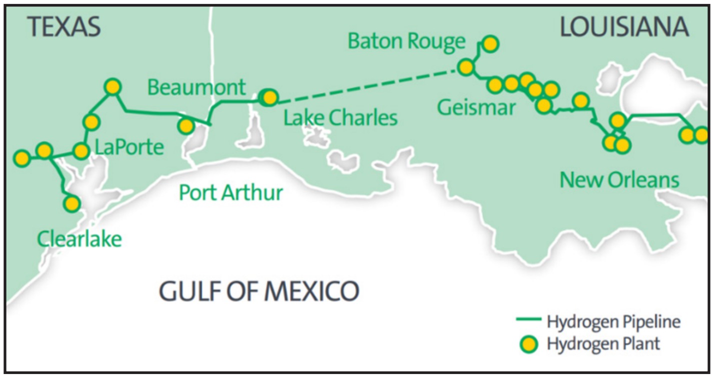

Figure 3: Air Products H2 Pipelines (Ehlig-Economides and Hatzignatiou 2021)

Figure 4: Linde (Formerly Praxair) H2 Pipelines (Ehlig-Economides and Hatzignatiou 2021)

Ehlig-Economides and Hatzignatiou 2021 indicate that new H_2 pipelines require high capital costs and constitute a major barrier to expanding the infrastructure of H_2 delivery. One alternative is to repurpose existing natural gas pipelines. Repurposing existing natural gas pipelines could cut investment costs by 50-80% when compared to new, but doing so requires considerable reconfiguration and modification, and few companies have the practical experience (IEA 2022). Projects are already under development to repurpose thousands of miles of natural gas pipelines to carry 100% H_2, and there are examples of past projects that have been successfully completed. In particular, the Air Liquide pipelines shown in Figure 2 illustrate completed repurposing projects in 1996 and 1998 (Air Liquide 2005).

Road

H_2 transport by road uses compressed gas or liquid trucks (EERE 2023). Houston's extensive and well-maintained road system would be acceptable for H_2 transport. Compressed gas trucks transport pressurized hydrogen at pressures ranging from 180 bar (~2,600 psig) to an allowable maximum pressure of 250 bar (~3,675 psig) in long cylinders stacked on trailers hauled by the trucks (EERE 2023). Each truck has a capacity ranging from 560 to 900 kg of H_2. With a 100% market penetration demand of 4 million kg of H_2 per day for Houston, this would require a truck fleet of between 4,000 and 7,200 trucks assuming one delivery per truck per day. Where space permits, trucks might unhitch the trailers at the refueling stations and return for additional cargo, thereby reducing the required number of trucks. Logistical concerns add to the complexity of managing truck fleets. Liquid trucks deliver hydrogen in a liquified state, cooled below -423 degrees Fahrenheit (EERE, 2023). These trucks can carry far more H_2 than compressed gas trucks. However, they face boiling off challenges during delivery and incur high relative CAPEX and OPEX. Liquid trucks are better suited for longer distances, or where pipelines are not an option. With presence of nearby H_2 generation plants, liquid trucks would not be economical in the city of Houston.

Capital Expenditure

Our analyses considered three H_2 transport options as possible LCT components of the LTCH in Eqn. (1). The one for liquid H_2 transport included liquefier, terminal, tractor-trailer, and H_2 terminal. The one for compressed gas transport included compressed H_2 truck-tube trucks and surface storage. The one for pipeline transport included transmission pipeline, distribution pipeline, central compressor, and surface storage. Table 9 considers the three H_2 transport options for two different distances. The levelized cost varies from $0.76 per kg H_2 (50 km pipeline) to $1.56 per kg H_2 (liquid truck traveling 100 km).

Table 9: Capital Costs for 3 H_2 Transport Options

Delivery Type	Capital	
	50km	100km
Pipeline	$0.75/kg H_2	$0.76/kg H_2
Compressed Truck	$1.00/kg H_2	$1.04/kg H_2
Liquid Truck	$1.55/kg H_2	$1.56/kg H_2

Operating Costs

Our analyses for the LCT component of the LTCH in Eqn. (1) for transport O&M costs included operating, maintenance, energy, and fuel costs for the same delivery types and distances as for capital costs. The levelized cost varies from $0.15 per kg H_2 (50 km pipeline) to $1.12 per kg H_2 (liquid truck traveling 100 km, as seen in the Table 10 and Table 11.

Table 10: Transport Options Operating Costs for 50 km

Delivery Type	O&M	Energy/Fuel	Total
Pipeline	$0.11/kg H_2	$0.04/kg H_2	**$0.15/kg H_2**
Compressed Truck	$0.44/kg H_2	$0.31/kg H_2	**$0.75/kg H_2**
Liquid Truck	$0.39/kg H_2	$0.71/kg H_2	**$1.10/kg H_2**

Table 11: Transport Options Operating Costs for 100 km

Delivery Type	O&M	Energy/Fuel	Total
Pipeline	$0.11/kg H_2	$0.04/kg H_2	**$0.15/kg H_2**
Compressed Truck	$0.49/kg H_2	$0.35/kg H_2	**$0.84/kg H_2**
Liquid Truck	$0.40/kg H_2	$0.72/kg H_2	**$1.12/kg H_2**

Using similar assumptions to our own and an estimated city-of-Houston radius of 32 km, Yang and Ogden found that pipelines would be the lowest-cost distribution mode for the city, assuming a 100% market penetration rate and 3,000 kg H_2/day station sizes (Yang and Ogden 2007). The authors estimated a levelized delivery cost of approximately $0.84/kg H_2 using these parameters. This is consistent with our findings suggesting a total levelized delivery cost of $0.91/kg H_2, calculated by adding OPEX to CAPEX.

H_2 Consumer Sales

Houston has roughly 2,600 ICEV refueling stations (Luck 2019). Where there is sufficient land area the owners of these stations could retrofit them with Hequipment to provide consumers the ability to refuel H_2 vehicles. Station owners must consider the costs and time for retrofitting as well as possible disruption to current revenue streams. New construction by current or prospective owners requires purchasing land and obtaining the appropriate permits from the City of Houston.

Capital Expenditure

Our analyses for the capital portion of the LCRS component of the LTCH in Eqn. (1) included the compressor, surface storage, dispenser, refrigeration, electrical, controls, and other equipment. The levelized cost varies from $1.45 per kg H_2 (compressed truck) to $1.90 per kg H_2 (pipeline), as seen in Table 12.

Table 12: Refueling Station Capital Cost Breakdown, see Appendix 4 for more details

Delivery Type	Capital
Pipeline	$1.90/kg H_2
Compressed Truck	$1.45/kg H_2
Liquid Truck	$1.89/kg H_2

Operating Costs

Our analyses for the O&M portion of the LCRS component of the LTCH in Eqn. (1) included the operating, maintenance, energy, and fuel costs for the compressor, surface storage, dispenser, refrigeration, controls, and other equipment. The levelized cost varies from $0.82 per kg H_2 (compressed truck) to $1.37 per kg H_2 (liquid truck), as seen in Table 13.

Table 13: Refueling Station Operating Cost Breakdown, see Appendix 4 for more details

Delivery Type	O&M	Energy/Fuel	Total
Pipeline	$0.67/kg H_2	$0.54/kg H_2	**$1.21/kg H_2**
Compressed Truck	$0.62/kg H_2	$0.19/kg H_2	**$0.82/kg H_2**
Liquid Truck	$0.90/kg H_2	$0.47/kg H_2	**$1.37/kg H_2**

Economic Impact of adding CO_2 Capture to SMR

This section focuses on the added costs associated with adding CO_2 capture and storage to H_2 generation, as required for SMRCC. CO_2 capture increases the total cost of H_2 production significantly.

CO_2 Capture, Transportation, and Storage

Table 14 shows the total incremental costs to capture, transport, and store carbon dioxide and their impacts on the levelized cost of H_2. NREL estimates that a yearly production of ~160 million kg of H_2 would result in ~1.6 million tons of CO_2 emissions, i.e., 1 ton of CO_2 per 100 kg of H_2 (NREL 2023). Based on calculations using the NREL spreadsheet the table shows that the total incremental levelized cost of CO_2 capture, transport, and storage amount to $0.77/kg H_2 in 2016 $US, i.e., approximately $78.54 per tonne of CO_2 (NREL 2023). The NREL model indicates that the bare erected costs of capture equipment for removal, compression, drying, aftercooler, and gas cleanup foundations are $188 million for 96.2% CO_2 capture. The calculations in Table 14 assumes CO_2 emissions of 1,581,600 metric tonnes per year and plant production of 158,774,175 kg H_2 per year for a 40-year plant life. This results in an incremental levelized cost of $0.22 per kg H_2 for including CO_2 transport and storage (T&S).

Table 14: Capture, Transport, and Storage Costs for Carbon Dioxide for SMRCC (*Estimated)

Capture Cost (CAPEX)	US$40.00 / tonne CO_2*	$0.40/kg H_2
Capture Cost (Fixed O&M)	US$12.07 / tonne CO_2	$0.12/kg H_2
Capture Cost (Variable O&M)	US$24.92 / tonne CO_2	$0.25/kg H_2
Water Cost	US$4.17 / tonne CO_2	$0.04/kg H_2
Electricity Cost	US$9.64 / tonne CO_2	$0.10/kg H_2
Transport Cost	US$6.41 / tonne CO_2	$0.06/kg H_2
Storage Cost	US$16.38 / tonne CO_2	$0.16/kg H_2
Total Incremental Costs	**US$113.60 / tonne CO_2**	**$1.13/kg H_2**

Operating Costs

Our analyses for the O&M portion of the LCRS component of the LTCH in Eqn. (1) included the operating, maintenance, energy, and fuel costs for the compressor, surface storage, dispenser, refrigeration, controls, and other equipment. The levelized cost varies from $0.82 per kg H_2 (compressed truck) to $1.37 per kg H_2 (liquid truck), as seen in Table 13.

Subsurface CO_2 Storage

The Intergovernmental Panel on Climate Change (IPCC) estimated CO_2 geologic storage costs (Intergovernmental Panel on Climate Change 2005). The cost is site-specific and leads to a high degree of variability. The type of storage, depth, reservoir formation, and location affect the number, spacing, and cost of wells, as well as the costs of facilities. Depth increases storage and compression costs. Storage reservoir formation characteristics (reservoir thickness, permeability, and effective radius) affect the amount and rate of CO_2 injection. Unit costs are higher offshore.

Table 15: Average CO_2 Storage Cost per Region (NPC 2019)

Region	Average Cost	Storage Volume
California	$7 / tonne CO_2	11 gigatonnes CO_2
Midwest	$7 / tonne CO_2	54 gigatonnes CO_2
North Central	$11 / tonne CO_2	85 gigatonnes CO_2
Gulf Coast	$7 / tonne CO_2	135 gigatonnes CO_2
South Central	$8 / tonne CO_2	129 gigatonnes CO_2
Overall Average/total	**$8 / tonne CO_2**	**413 gigatonnes CO_2**

Table 15 shows the default cost computations made by the National Petroleum Council (NPC) using the GaffneyCline cost assessment tool (NPC 2019). The tool is based upon the September 2017 version of the FE/NETL CO2 Saline Storage Cost Model from NETL. GaffneyCline assessment took 684 individual subsurface formations and aggregated them into 5 storage regions. The NPC assumed that operators would direct the captured CO_2 to the lowest cost storage formations within each region. While average storage costs vary, they are dwarfed by CO_2 capture cost.

[3] *NREL refers to bare erected costs (BEC) as the cost of process equipment, on-site facilities and infrastructure that support the plant (e.g., shops, offices, labs, road), and the direct and indirect labor required for its construction and/or installation.*

Figure 5 and Figure 6 highlight key elements in the SMR and SMRCC H_2 cost breakdowns.

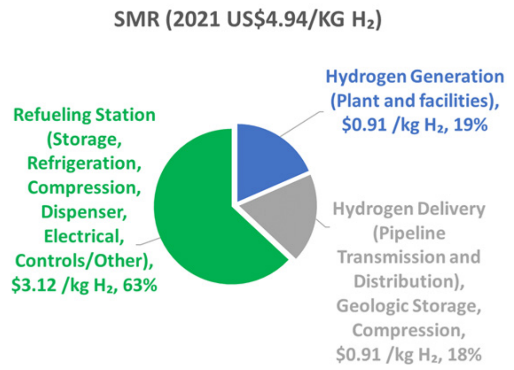

Figure 5: SMR H_2 Product Delivery Costs (LTCH) (ANL 2022 and NREL 2023)

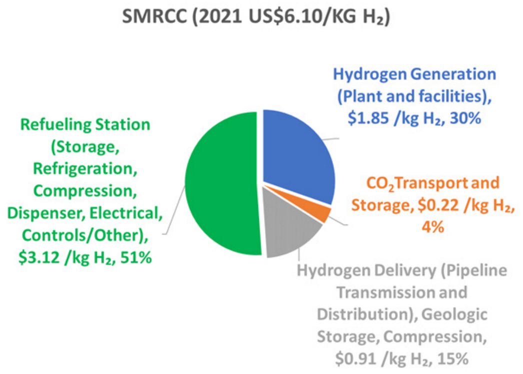

Figure 6: SMRCC H_2 Product Delivery Costs (LTCH) (ANL 2022 and NREL 2023)

Figure 7, Figure 8, and Figure 9 illustrate costs for various product delivery elements for SMR, SMRCC, and electrolysis pathways.

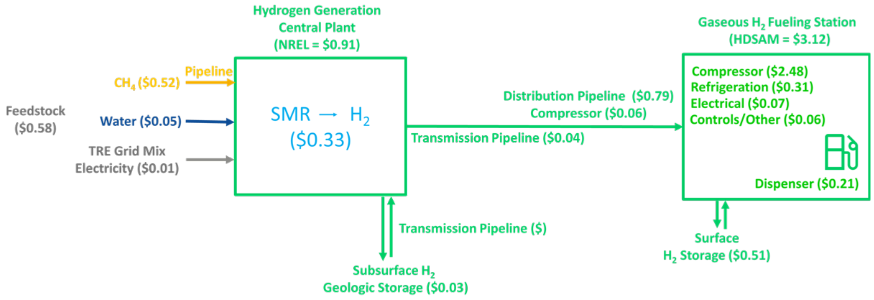

Figure 7: SMR H_2 Product Delivery Cost (LTCH) (ANL 2022 and NREL 2023)

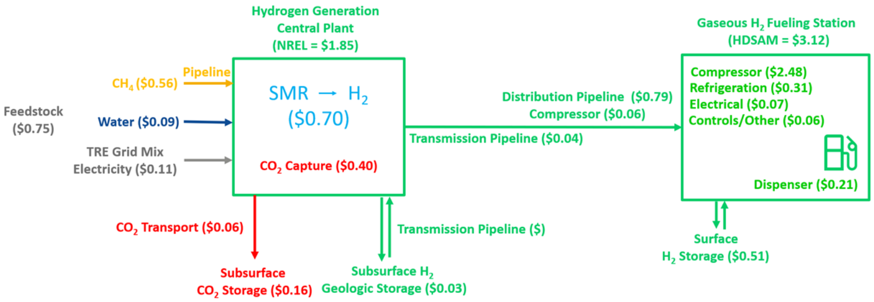

Figure 8: SMRCC H_2 Product Delivery Cost (LTCH) (ANL 2022 and NREL 2023)

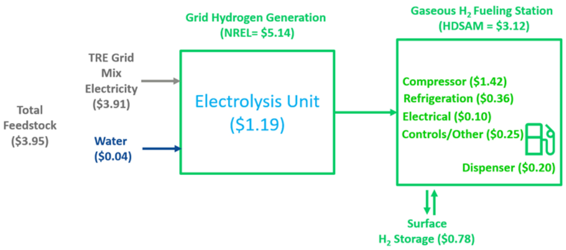

Figure 9: Pathway to Onsite Electrolysis H_2 (LTCH) (ANL 2022 and NREL 2023)

Government Tax Credit Impact

H_2 fuel generation may qualify for one or the other of two types of tax credits. Companies earn 45Q credits based on carbon tons captured and used or stored by a project on a per ton basis. Companies earn 45V credits based on quantities of hydrogen produced on a per kg basis. Companies cannot earn both at the same time for the same actions. In 2022, the Inflation Reduction Act (IRA) created a production tax credit (PTC) for H_2 under the Internal Revenue Code (IRC) Section 45V entitled "Credit for Production of Clean H_2" (Internal Revenue Service (IRS) 2022). The H_2 PTC applies to H_2 produced after December 31, 2022, for a 10-year term, starting on the date a qualified clean H_2 production facility begins service. The facility must begin construction prior to January 1, 2033. Under the same bill, Congress also increased 45Q tax credits (originally established in 2008 at $10 per tonne for CO_2 captured and stored via enhanced oil recovery (EOR) and $20 per tonne of CO_2 stored in geologic formations) to $85 per tonne of CO_2 (only $60 if CO_2 is used for CO_2 enhanced oil recovery).

The IRC Section 45V offers a PTC of $0.60 per kg of qualified clean H_2. To be eligible for 20% of the PTC (i.e., $0.12 per kg H_2), lifecycle greenhouse gas emissions cannot exceed 4 kg of carbon dioxide equivalent (CO_{2e}) per kg H_2 produced. The applicable rate can increase to 100% of the PTC (i.e., $0.60 per kg H_2) if the company achieves an emissions rate below 0.45 kg of CO2e per kg H_2. The emission rate calculation includes well-to-gate (point of production) emissions, i.e., all emissions from feedstock (this would include emissions from electricity generation), production, transportation, etc. prior to the output of H_2 from the facility (IRS 2022). If the facility also meets prevailing wage and apprenticeship requirements, as defined in the tax code, it can receive a bonus that multiplies the base PTC by five. This results in an applicable amount that ranges from $0.12 to $3.00 per kg of clean H_2 produced; all rates will be adjusted for inflation (IRS 2022). The bill prevents companies from earning 45V, under IRC Section 45V(d)(2), and 45Q, under IRC Section 45Q, credits at the same time for the same facility. This is to prevent taxpayers from stacking credits (IRS 2022). While the value of 45V credits can exceed the value of 45Q credits under certain circumstances, without added, hard-to-economically-quantify actions, 45Q credits, at $85 per tonne of CO2, equate to $0.85 per kg H_2 and are therefore often worth more. We will use 45Q credits within our model to save on complexity, but it is worth noting that the economics could be better under 45V credits in many cases.

Tax Credit Impact on SMRCC H_2 Viability

Based on our calculated incremental costs of $1.13 per kg H_2 and a tax credit of $85 per tonne of CO_2, i.e., ~$0.85 per kg H_2, the tax credit levelized value is less than the levelized cost associated with earning it. When companies can use or sell the tax credits, they may choose to produce with carbon capture, but in many cases, this will represent a loss of profitability.

Unlike 45Q, with 45V PTCs, the value of the credits can exceed the cost to obtain them (reminder: a 45V PTC could be as much as $3/kg H_2). Again, not all companies will be able to use the credits, but assuming they can sell them at or near full price, capturing and disposing of the produced CO_2 would be profitable. It is worth noting that, regardless of the potential value under 45Q or 45V, the increased capital requirements may be too much of a barrier. In the example within this paper, the SMRCC needs about $520 million more capital investment than the SMR (for the same H_2 production) just for the facility (see Table 6), has added associated costs for CO_2 storage and transportation (see Table 14), and may also have complex requirements for geolocation (i.e., a need for proximity to CO_2 storage facilities). These differences could make funding SMRCC projects much more difficult despite the potential financial advantages. Grid H_2 cannot qualify for 45V, but electricity supplied by dedicated off-grid renewable energy would qualify. The economics of this option are beyond the scope of this paper.

Additional Tax Adjustments

There are other tax incentives that we did not integrate into the economic analysis of the paper. As a result of The Alternative Fuel Infrastructure Tax Credit, as of January 1, 2023, fueling equipment for H_2 is eligible for a tax credit of 30% of the cost or 6% in the case of property subject to depreciation, not to exceed $100,000 (117th Congress 2022). Covered expenses do not include permitting and inspection fees. The Alternative Fuel Excise Tax Credit incentive was initially set to end on December 31, 2021, but has been extended through December 31, 2024 by Public Law 117-169 (117th Congress 2022). This incentive is available for alternative fuel that is sold for use or used as a fuel to operate a motor vehicle. A tax credit of $0.50 per gallon (we estimate this to be ~$0.148 per kg H_2)[4] is available for liquefied H_2 among other types of fuel.

Cost Comparison among H_2 Generation Pathways

For each of the various hydrogen generation pathways, we consolidate the costs related to feedstock which aggregates the water, natural gas, and electricity components, capital, and fixed and other variable operating and maintenance costs to find levelized cost of H_2 (LCOH) in Table 16. For example, for the cheapest hydrogen generation pathway, SMR, the LCOH is $0.91 per kg H_2. The low cost for SMR stems from its low capital, fixed O&M, variable and feedstock costs per kg H_2 relative to the other options.

Table 16: Total Levelized Cost of H_2 Generation (LCOH)

Hydrogen Generation Pathway	Feedstock	Capital	Fixed O&M	Other Variable O&M	Total Levelized Cost
SMR[1]	$0.58/kg H_2	$0.23/kg H_2	$0.09/kg H_2	$0.02/kg H_2	**$0.91/kg H_2**
SMRCC[2]	$0.75/kg H_2	$0.63/kg H_2	$0.21/kg H_2	$0.27/kg H_2	**$1.85/kg H_2**
Electrolysis[3]	$3.93/kg H_2	$0.59/kg H_2	$0.24/kg H_2	-	**$4.76/kg H_2**
Onsite SMR[4]	$0.66/kg H_2	$0.55/kg H_2	$0.21/kg H_2	-	**$1.42/kg H_2**
Onsite Electrolysis[5]	$3.95/kg H_2	$0.85/kg H_2	$0.34/kg H_2	-	**$5.14/kg H_2**

[1]NREL Tool 1, [2]NREL Tool 2, [3]NREL Tool 3, [4]NREL Tool 4, [5]NREL Tool 5

[4] *Gal cost to kg cost based on Universal Industrial Gas (UIG) conversion http://www.uigi.com/h2_conv.htm*

Table 17 replicates data from two tables in the DOE/NETL 2022 study for the midwestern region.

Table 17: LCOH for H, generated by SMR and SMRCC (DOE/NETL 2022)

Hydrogen Generation Pathway	Feedstock	Capital Costs	Fixed O&M	Other Variable O&M	Total Levelized Cost (Excluding T&S)	CO_2 T&S	Total Levelized Cost (Including T&S)
SMR	\$0.77/kg H_2	\$0.14/kg H_2	\$0.07/kg H_2	\$0.09/kg H_2	**\$1.06/kg H_2**	\$0.00/kg H_2	**\$1.06/kg H_2**
SMRCC	\$0.82/kg H_2	\$0.33/kg H_2	\$0.15/kg H_2	\$0.24/kg H_2	**\$1.54/kg H_2**	\$0.10/kg H_2	**\$1.64/kg H_2**

Our analysis indicates that the onsite electrolysis LCOH is \$4.87 per kg H_2 (Table 16) NREL provided a cost estimate of \$5.14 per kg H_2 for a 1,500 kg of H_2 per day distributed H_2 production system (James et al. 2013) A DOE case study that we would categorize as onsite electrolysis estimated grid costs between ~\$5 to ~\$6 per kg H_2 (Vickers et al. 2020). The study assumes H_2 production using polymer electrolyte membrane electrolyzers, existing technology, grid electricity prices of \$0.05/kWh to \$0.07/kWh, and low volume electrolyzer capital costs up to \$1,500/kW. In addition to their own study, they provided H_2 cost results from other studies as referenced in Table 18 (Vickers et al. 2020) ATB is the Annual Technology Baseline provided by NREL.

Table 18: Grid H2 Generation Costs (LCOH) (Vickers et al. 2020)

Low	High	Year	Electricity Cost	Capacity Factor	System CapEx	System Efficiency	Reference
\$4.00/kg H_2	\$6.00/kg H_2	2020	\$0.04-0.10/kWh	20-30%	\$750.00/kW	65 % LHV	Hydrogen Council 2020
\$3.75/kg H_2	\$5.10/kg H_2	2018	ATB	ATB	\$1,124.00/kW	63% LHV	Energy + Environmental Economics 2020
\$2.70/kg H_2	\$6.80/kg H_2	2018	\$0.023-0.085/kWh	26-48%	\$840.00/kW	65 % LHV	International Renewable Energy Agency 2019
\$2.50/kg H_2	\$6.80/kg H_2	2019	\$0.0350.045/kWh	-	\$1,400.00/kW	-	Bloomberg New Energy Finance 2020

At-scale, the price of produced H_2 via electrolysis would likely be higher than stated in Table 18 because of increased demand pressure on future available electricity supply and its impact on electricity prices (a key input to electrolysis). Table 19 aggregates the results of the assorted studies and tools used in this paper, such as NREL's H2A and Argonne National Laboratory's HDSAM, and combines them with the costs associated with H_2 transportation and distribution via pipeline assuming 100km distance and a matched refueling station to receive and sell the gas. The table summarizes the levelized total costs (LTCH) of the supply chain elements of the five hydrogen generation pathways

Assuming 700 bar cascade dispensers used by light duty vehicles, the total levelized cost (LTCH) of H_2 ranges from \$4.54 per kg H_2 (Onsite SMR) to \$8.86 per kg H2 (electrolysis) Throughout this paper, inflation adjustments were made using the Gross Domestic Product: Implicit Price Deflator from FRED hosted by the Federal Reserve Bank of St. Louis (Federal Reserve Bank of St. Louis 2023) The SMRCC cost in the table does not reflect any tax credit incentive. As noted previously, the SMRCC cost with tax credit incentive is lower than SMR without CO_2 capture and storage.

Table 19: LTCH for Various Hydrogen Generation Pathways

Hydrogen Generation Pathway	Hydrogen Generation (Plant and facilities)	CO_2 Transport and Storage	Hydrogen Delivery (Pipeline Transmission and Distribution), Geologic Storage, Compression	Refueling Station (Storage, Refrigeration, Compression, Dispenser, Electrical, Controls/Other)	Total (2021 \$US)
SMR	\$0.91 /kg H_2	\$ -	\$0.91 /kg H_2	\$3.12 /kg H_2	**\$4.94 /kg H_2**
SMRCC	\$1.85 /kg H_2	\$0.22 /kg H_2	\$0.91 /kg H_2	\$3.12 /kg H_2	**\$6.10 /kg H_2**
Electrolysis	\$4.76 /kg H_2	\$ -	\$0.91 /kg H_2	\$3.12 /kg H_2	**\$8.79 /kg H_2**
Onsite SMR	\$1.42 /kg H_2	\$ -	\$ -	\$3.12 /kg H_2	**\$4.54 /kg H_2**
Onsite Electrolysis	\$5.14 /kg H_2	\$ -	\$ -	\$3.12 /kg H_2	**\$8.25 /kg H_2**

Cost Comparison between Gaseous H_2 and Liquid Transportation Fuels

Early remarks in this paper noted the volumetric energy density advantage of liquid transportation fuels and the need to consider the combined volume and weight of onboard fuel and the vehicle propulsion mechanism along with the overall life cycle analysis (LCA) of the energy required to move the vehicle a particular distance. This section shows how energy efficiency relates to overall emissions and factors into an equivalent H_2 price. A final subsection compares gaseous H_2 and liquid transportation fuel emissions.

Energy Efficiency

Ehlig-Economides and Hatzignatiou (2022) showed that pump to wheels (PTW) energy use for FCEVs is around 2 MJ per mi compared to 4.4 MJ per mi for ICEVs (Ehlig-Economides and Hatzignatiou 2022). Hence, FCEVs are about 2.2 times as efficient on an energy usage basis. H_2 has an energy density of 120 MJ per kg, while gasoline and diesel have 45.8 and 45.5 MJ per kg, respectively (EERE 2023). A gallon of gasoline weighs 2.84 kg, and gallon of diesel weighs 3.22 kg (Martinez 2023). Therefore, diesel and gasoline hold 130 and 147 MJ per gallon, respectively. Using the above information, the customer breaks even paying about 2.0 times the price per gallon of gasoline and 1.8 times the price per gallon of diesel for a kg of H_2 on a cost per distance-traveled basis. The following equation summarizes the previous remarks:

$$\frac{\mathbf{120\ MJ\ per\ kg}}{\mathbf{130\ MJ\ per\ gal}} \cdot \frac{\mathbf{4.4\ MJ\ per\ mi}}{\mathbf{2\ MJ\ per\ mi}} \approx \mathbf{2}\ \frac{\mathbf{gal}}{\mathbf{kg}}$$

Equivalent Pricing for H_2

In Houston, consumers paid an average of \$2.91 per gallon of gasoline for the first 3 months of 2023. Over the same period, they paid \$4.12 per gallon of diesel in the Gulf Coast area (EIA 2023c). As referenced earlier in the paper, this is the period we used for our feedstock price input for natural gas. The equivalent H_2 price accounting for doubled efficiency would range from \$5.82 (gasoline) to \$8.24 (diesel). The H_2 cost range from \$4.54 for onsite SMR to \$6.10 for SMRCC (with no tax credit) in Table 19, along with the multiplier discussed above (which divides the per kg price by 2), shows that H_2 fuel price is competitive with gasoline and diesel at current prices.

In California, consumers paid \$26.75 per kg H_2 at Shell light vehicle refueling stations in Northern California since April 2023 (Shell Hydrogen 2023) and \$24.99 per kg H2 at Iwatani refueling stations since November 2022 (Iwatani 2022). These prices are hard to justify based on costing, and are not likely to be sustainable in Houston, or continue in California as the regional market expands (see Appendix 5). For reference, the average price for regular unleaded gasoline in California was \$4.48 per gallon (\$8.96 for an equivalent kg H_2), and for diesel was \$5.38 per gallon (\$9.68 for an equivalent kg $H_{2)}$ in the first 3 months of 2023 (EIA 2023c).

Cost per Mile

Table 20 presents the varying costs per mile for ICEVs (overall average, and trucks only), FCEVs, and BEVs. The costs in this table reflect operating costs and do not include vehicle costs. The FCEV cost in the table is for SMRCC, the highest hydrogen cost considered in this report. The unit price for H_2 does not include fuel tax. Average mileage data in the table come from EPA estimates 2022. We note that the 2X multiplier suggested in the previous Energy Efficiency discussion is conservative relative to this table.

The table shows that BEVs have significantly lower operating cost per mile. Liquid fuel tax is levied mainly to finance roadway maintenance, and currently electricity for BEV charging does not include this tax. As well, electricity costs may increase as BEVs add enough load to the grid to induce a need for additional power generation. Also, while BEV cost per mile is less than FCEV cost, it is useful to note that electricity cost may change (increase or decrease) in a fully decarbonized grid, while the FCEV fuel cost we use is for already decarbonized fuel. In any case, the focus of this report is the cost comparison between H_2 and liquid fuels.

Table 20: Cost per Mile for ICEV, ICEV (Trucks only), FCEV, and BEV (Environmental Protection Agency (EPA) 2022)

Category	Average Mileage	Unit Price	Cost per Mile
ICEV	26 miles per gal	\$2.91/gal	\$0.11/mile
ICEV (Trucks only)	20 miles per gal	\$2.91/gal	\$0.15/mile
FCEV	67 miles per kg	\$6.10/kg H_2	\$0.09/mile
BEV	2.86 miles per kWh	\$0.07/kWh	\$0.02/mile

Emissions

Table 21 details CO_2 emissions per mile for ICEVs (overall average, and trucks only), FCEVs using SMR H_2, and BEVs using Texas grid electricity. Our numbers reflect the Texas grid, but national emission levels per kWh of electricity are comparable (ERCOT 2023b). Gasoline and diesel combustion emissions are 8.8 and 10.2 kg/gal (EIA 2023a). Hub scale H_2 generation emits 10.2 kg CO_2/kg H_2 (NREL 2023). Interestingly, FCEV using SMR without GHG capture and BEV emissions per mile are essentially the same. We note that SMRCC produces almost no emissions (i.e., ~0 kg/mi).

Table 21: CO2 Emissions per Mile for ICEV, ICEV (Trucks only), FCEV, and BEV (Average mileage from (Environmental Protection Agency (EPA), 2022))

Category	Average Mileage	CO_2 Emission	CO_2 Emission per Mile
ICEV	26 miles per gal	8.9 kg/gal	0.3 kg/mi
ICEV (Trucks only)	20 miles per gal	8.9 kg/gal	0.4 kg/mi
FCEV	67 miles per kg	10.0 kg/kg H_2	0.1 kg/mi
BEV	2.86 miles per kWh	0.37 kg/kWh	0.1 kg/mi

Consumer Preferences

Consumers are accustomed to refueling vehicles in 5 minutes and demand abundant, reliable, and affordable fuels. Consumer access to H_2 refueling stations and FCEVs in models like those currently available as ICEVs may easily satisfy consumer refueling preferences. In addition, EVs are much simpler vehicles with lower maintenance costs.

BEV owners that do not have access to dedicated overnight or workplace charging spots will need more than 30 minutes for each vehicle recharging stop if and only if BEV super chargers become as available as gasoline and diesel refueling stations. Commonly available BEV charging stations take many hours to recharge a vehicle. The reward for the extra time required for charging is much lower cost per mile, at least for now.

The current automobile industry offers only a few options for light-duty FCEVs and is waiting for H_2 to be more widely adopted before producing more FCEV vehicles (Ehlig-Economides and Hatzignatiou 2022). Toyota's sedan line includes the Mirai LE, SLE, and limited editions while Hyundai markets the NEXO Fuel Cell Limited and NEXO Blue as SUVs. These vehicles are currently available in select markets such as northern and southern California with access to H_2 fueling stations. In 2022, the Port of Houston began piloting a H_2 fuel cell electric truck (Webb 2022).

Conclusions

The analysis in this report confirms the ability to profitably supply H_2 for transportation refueling in the greater Houston area at gasoline and less than diesel prices. Grid H_2 is considerably more expensive and relies on a carbon intensive grid (which may or may not be able to expand rapidly enough to meet BEV demands). Current tax credit incentives can accelerate net-zero H_2 generation from the abundant natural gas supply. However, since we did not need to adjust SMRCC prices downward to account for these credits, tax credits are evidently not required to create competitively priced zero-carbon H_2 fuel. Existing natural gas pipeline infrastructure makes the greater Houston area an ideal location for demonstrating the promise of a gradual switch from liquid fueled ICEVs to H_2.

The $6.10 per kg H_2 price associated with SMRCC provides essentially zero carbon fuel at a cost of $0.09 per mile to the consumer. This price is within the range that consumers currently pay for gasoline and diesel while eliminating CO_2 emissions for both generation and use of the H_2. Assuming H2 supply and FCEV availability, H_2 is a superior fuel that mimics the liquid fuel consumer refueling experience without unduly impacting the consumer bottom line.

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APPENDIX 1: H_2 Generation Property, Plant & Equipment Details

The following tables provide CAPEX details for hub scale SMR, SMRCC, CO_2 capture, and electrolysis and onsite SMR and electrolysis.

Table 22: Capital Cost for SMR and SMRCC

	SMR			SMRCC		
Major pieces/systems of equipment	Capital Costs in Model	Percent of Total	Contribution to LCC	Capital Costs in Model	Percent of Total	Contribution to LCC
Accessory Electric Plant	$4.04 M	1%	$0.00/kg H_2	$6.58 M	1%	$0.01/kg H_2
Cooling Water System	$6.91 M	2%	$0.01/kg H_2	$25.04 M	3%	$0.02/kg H_2
Feedwater & Miscellaneous BOP Systems	$45.00 M	16%	$0.04/kg H_2	$57.38 M	7%	$0.05/kg H_2
Flue Gas Cleanup	-	-	-	$173.50 M	22%	$0.14/kg H_2
Hydrogen Production	$16.71 M	6%	$0.01/kg H_2	$16.71 M	2%	$0.01/kg H_2
Instrumentation & Control	$8.73 M	3%	$0.01/kg H_2	$10.99 M	1%	$0.01/kg H_2
Reformer & Accessories	$57.01 M	20%	$0.05/kg H_2	$60.56 M	8%	$0.05/kg H_2
Syngas Cleanup	$8.22 M	3%	$0.01/kg H_2	$27.48 M	3%	$0.02/kg H_2
Direct Capital Cost	**$146.62 M**	**52%**	**$0.12/kg H_2**	**$378.25 M**	**47%**	**$0.30/kg H_2**
Site Preparation	$23.44 M	8%	$0.02/kg H_2	$24.34 M	3%	$0.02/kg H_2
Engineering & design	$17.01 M	6%	$0.01/kg H_2	$51.97 M	6%	$0.04/kg H_2
Process contingency	$0.00 M	0%	$0.00/kg H_2	$41.91 M	5%	$0.03/kg H_2
Project contingency	$36.33 M	13%	$0.03/kg H_2	$152.82 M	19%	$0.12/kg H_2
Other (Depreciable) capital	$38.47 M	14%	$0.03/kg H_2	$96.80 M	12%	$0.08/kg H_2
One-time Licensing Fees	$0.00 M	0%	$0.00/kg H_2	$0.00 M	0%	$0.00/kg H_2
Up-Front Permitting Costs	$17.01 M	6%	$0.01/kg H_2	$51.97 M	6%	$0.04/kg H_2
Total Contingency and Other	**$132.25 M**	**47%**	**$0.11/kg H_2**	**$419.80 M**	**52%**	**$0.33/kg H_2**
Land Cost	**$4.79 M**	**2%**	**$0.00/kg H_2**	**$4.79 M**	**1%**	**$0.00/kg H_2**
Total for LCC Calculation	**$283.66 M**	**100%**	**$0.23/kg H_2**	**$802.84 M**	**100%**	**$0.63/kg H_2**

Table 23: Capital Cost for Electrolysis

Major pieces/systems of equipment	Capital Costs in Model	Percent of Total	Contribution to LCC
Stack Capital Cost	$45.49 M	53%	$0.31/kg H_2
Mechanical BoP Capital Cost	$4.29 M	5%	$0.03/kg H_2
Electrical BoP Capital Cost	$10.90 M	13%	$0.07/kg H_2
Direct Capital Cost	**$60.68 M**	**70%**	**$0.41/kg H_2**
Site Preparation	$1.21 M	1%	$0.01/kg H_2
Engineering & design	$6.07 M	7%	$0.04/kg H_2
Process contingency	$0.00 M	0%	$0.00/kg H_2
Project contingency	$9.10 M	11%	$0.06/kg H_2
Other (Depreciable) capital	$0.00 M	0%	$0.00/kg H_2
One-time Licensing Fees	$0.00 M	0%	$0.00/kg H_2
Up-Front Permitting Costs	$9.10 M	11%	$0.06/kg H_2
Total Contingency and Other	**$25.48 M**	**29%**	**$0.17/kg H_2**
Land Cost	**$0.25 M**	**0%**	**$0.00/kg H_2**
Total for LCC Calculation	**$86.41 M**	**100%**	**$0.59/kg H_2**

Table 24: Capital Cost for Onsite SMR

Major pieces/systems of equipment	Capital Costs in Model	Percent of Total	Contribution to LCC
Water Feed System	$0.01 M	0%	$0.00/kg H_2
Primary Feed System	$0.01 M	1%	$0.00/kg H_2
Boiler	$0.04 M	2%	$0.01/kg H_2
Superheater	$0.01 M	0%	$0.00/kg H_2
HDS & Absorbent Bed	$0.01 M	0%	$0.00/kg H_2
Burner	$0.00 M	0%	$0.00/kg H_2
Reformer	$0.26 M	15%	$0.08/kg H_2
Water Gas Shift	$0.22 M	12%	$0.07/kg H_2
HDS Preheater	$0.00 M	0%	$0.00/kg H_2
Primary Air Feed System	$0.01 M	0%	$0.00/kg H_2
Reformate Cooler	$0.04 M	2%	$0.01/kg H_2
Condenser	$0.05 M	3%	$0.01/kg H_2
Air Feed System for Condenser	$0.00 M	0%	$0.00/kg H_2
Pressure Swing Adsorption Unit	$0.09 M	5%	$0.03/kg H_2
Water Purification	$0.05 M	3%	$0.01/kg H_2
Structural Supports	$0.03 M	1%	$0.01/kg H_2
Controls System	$0.05 M	3%	$0.01/kg H_2
System Assembly	$0.27 M	15%	$0.08/kg H_2
Miscellaneous	$0.11 M	6%	$0.04/kg H_2
Direct Capital Cost	**$1.24 M**	**70%**	**$0.39/kg H_2**
Site Preparation	$0.23 M	13%	$0.07/kg H_2
Engineering & design	$0.06 M	4%	$0.02/kg H_2
Process contingency	$0.00 M	0%	$0.00/kg H_2
Project contingency	$0.19 M	11%	$0.06/kg H_2
Other (Depreciable) capital	$0.00 M	0%	$0.00/kg H_2
One-time Licensing Fees	$0.00 M	0%	$0.00/kg H_2
Up-Front Permitting Costs	$0.04 M	2%	$0.01/kg H_2
Total Contingency and Other	**$0.52 M**	**30%**	**$0.16/kg H_2**
Land Cost	**$0.00 M**	**0%**	**$0.00/kg H_2**
Total for LCC Calculation	**$1.76 M**	**100%**	**$0.55/kg H_2**

APPENDIX 1 (cont'd): H_2 Generation Property, Plant & Equipment Details

Table 25: Capital Cost for Onsite Electrolysis

Major pieces/systems of equipment	Capital Costs in Model	Percent of Total	Contribution to LCC
Stack Capital Cost	$1.37 M	44%	$0.37/kg H_2
Mechanical BoP Capital Cost	$0.43 M	14%	$0.12/kg H_2
Electrical BoP Capital Cost	$0.48 M	15%	$0.13/kg H_2
Direct Capital Cost	**$2.28 M**	**73%**	**$0.62/kg H_2**
Site Preparation	$0.43 M	14%	$0.12/kg H_2
Engineering & design	$0.05 M	2%	$0.01/kg H_2
Process contingency	$0.00 M	0%	$0.00/kg H_2
Project contingency	$0.34 M	11%	$0.09/kg H_2
Other (Depreciable) capital	$0.00 M	0%	$0.00/kg H_2
One-time Licensing Fees	$0.00 M	0%	$0.00/kg H_2
Up-Front Permitting Costs	$0.03 M	1%	$0.01/kg H_2
Total Contingency and Other	**$0.85 M**	**27%**	**$0.23/kg H_2**
Land Cost	**$0.00 M**	**0%**	**$0.00/kg H_2**
Total for LCC Calculation	**$3.13 M**	**100%**	**$0.85/kg H_2**

Alternative Methodologies to Calculate LCC or Equivalent Measures

We note that some institutions compute LCC as

$$LCC = \frac{TC}{Q} * \frac{r}{1-(1+r)^{-T}} * (1+r)^t \qquad (A1)$$

where TC is the total capital cost of the investment in dollars (for simplicity we assume the entire investment is paid at time 0), Q is the average yearly production in kg, t is the years required to build the facility, T is the productive life of the facility in years, and r is the discount rate. To better match the results of prior research and avoid discussions beyond the scope of this paper we have assumed a discount rate of 10%. Table 26 includes LCC calculated using the NREL tools, using Eq. (A1), and an alternative measure obtained by dividing the upfront capital costs by the operational lifetime for the facility.

Table 26: Standard Levelized Capital Cost (LCC) with 8% Discount Rate

Hydrogen Generation Pathway	Total Capital Costs	Plant Production	Plant Life	Years Construction	NREL LCC	Standard LCC	Annualized Capital
SMR[1]	$283.66 M	158,774,175 kg H_2/day	40 yr	3	0.23	$ 0.19	**$0.04/kg H_2**
SMRCC[2]	$802.84 M	158,774,175 kg H_2/day	40 yr	3	0.63	$ 0.53	**$0.13/kg H_2**
Electrolysis[3]	$86.41 M	20,636,625 kg H_2/day	40 yr	1	0.59	$ 0.38	**$0.10/kg H_2**
Onsite SMR[4]	$1.76 M	547,875 kg H_2/day	20 yr	1	0.55	$ 0.35	**$0.16/kg H_2**
Onsite Electrolysis[5]	$3.13 M	532,535 kg H_2/day	20 yr	1	0.85	$ 0.65	**$0.29/kg H_2**

[1]NREL Tool 1, [2]NREL Tool 2, [3]NREL Tool 3, [4]NREL Tool 4, [5]NREL Tool 5

APPENDIX 2: H_2 Generation Operating Cost Details

Fixed O&M costs include annual operating labor, maintenance labor, administrative and support labor, and property taxes and insurance. Other variable O&M costs consist of maintenance material, consumables with initial fill and water disposal.

Table 27: Fixed Operations and Maintenance Costs for SMR for plant size 483,000 kg H_2 per day with capacity factor 0.9

Description	Annual Cost	
Annual Operating Labor	$1.67 M	$0.01/kg H_2
General and Administrative (G&A)	$0.33 M	$0.00/kg H_2
Maintenance Labor	$1.95 M	$0.01/kg H_2
Administrative & Support Labor	$1.01 M	$0.01/kg H_2
Material Costs for Maintenance and Repairs	$2.92 M	$0.02/kg H_2
Property Taxes and Insurance	$5.67 M	$0.04/kg H_2
Fixed Operating Costs Total	**$13.56 M**	**$0.09/kg H_2**

Table 28: Other Variable Operations and Maintenance Costs for SMR for plant size 483,000 kg H_2 per day and capacity factor 0.9

Description	Annual Cost	
Maintenanance Material	$2.68 M	$0.02/kg H_2
Water Disposal	$0.02 M	$0.00/kg H_2
Other Variable Operating Costs Total	**$2.70 M**	**$0.02/kg H_2**

Table 29: Fixed Operations and Maintenance Costs for SMRCC for plant size 483,000 kg H_2 per day with capacity factor 0.9

Description	Annual Cost	
Annual Operating Labor	$2.04 M	$0.01/kg H_2
General and Administrative (G&A)	$0.41 M	$0.00/kg H_2
Maintenance Labor	$7.36 M	$0.05/kg H_2
Administrative & Support Labor	$1.89 M	$0.01/kg H_2
Material Costs for Maintenance and Repairs	$4.90 M	$0.03/kg H_2
Property Taxes and Insurance	$16.06 M	$0.10/kg H_2
Fixed Operating Costs Total	**$32.66 M**	**$0.21/kg H_2**

Table 30: Other Variable Operations and Maintenance Costs for SMRCC for plant size 483,000 kg H_2 per day with capacity factor 0.9

Description	Annual Cost	
Maintenanance Material	$5.92 M	$0.04/kg H_2
CO2 sequestration O&M costs and credits	$36.13 M	$0.23/kg H_2
Water Disposal	$0.07 M	$0.00/kg H_2
Other Variable Operating Costs Total	**$42.12 M**	**$0.27/kg H_2**

Table 31: Fixed Operations and Maintenance Costs for Electrolysis for plant size 56,500 kg H_2 per day with capacity factor 0.97

Description	Annual Cost	
Annual Operating Labor	$1.04 M	$0.05/kg H_2
Maintenance Labor	$1.82 M	$0.09/kg H_2
Administrative & Support Labor	$0.21 M	$0.01/kg H_2
Property Taxes and Insurance	$1.73 M	$0.09/kg H_2
Fixed Operating Costs Total	**$4.80 M**	**$0.24/kg H_2**

Table 32: Fixed Operations and Maintenance Costs for Onsite SMR for plant size 1500 kg H_2 per day with capacity factor 0.86

Description	Annual Cost	
Annual Operating Labor	$0.00 M	$0.00/kg H_2
Maintenance Labor	$0.06 M	$0.13/kg H_2
Rent	$0.00 M	$0.01/kg H_2
Administrative & Support Labor	$0.00 M	$0.00/kg H_2
Property Taxes and Insurance	$0.04 M	$0.07/kg H_2
Fixed Operating Costs Total	**$0.10 M**	**$0.21/kg H_2**

Table 33: Other Variable Operations and Maintenance Costs for Onsite SMR for plant size 1500 kg H_2 per day with capacity factor 0.86

Description	Initial Fill	Annual Cost	
Maintenanance Material		$0.00 M	$0.00/kg H_2
Consumables	$0.00 M	$0.00 M	$0.00/kg H_2
Water Disposal		$0.00 M	$0.00/kg H_2
Other Variable Operating Costs Total	**$0.00 M**	**$0.00 M**	**$0.00/kg H_2**

Table 34: Fixed Operations and Maintenance Costs for Onsite Electrolysis for plant size 1695 kg H_2 per day with capacity factor 0.86

Description	Annual Cost	
Annual Operating Labor	$0.00 M	$0.00/kg H_2
Maintenance Labor	$0.11 M	$0.21/kg H_2
Licensing, Permits, and Fees	$0.00 M	$0.00/kg H_2
Rent	$0.00 M	$0.01/kg H_2
Administrative & Support Labor	$0.00 M	$0.00/kg H_2
Property Taxes and Insurance	$0.06 M	$0.12/kg H_2
Fixed Operating Costs Total	**$0.18 M**	**$0.34/kg H_2**

APPENDIX 3: H_2 Transport CAPEX Details

Although not all areas have available salt caverns, Houston has access to both natural and manmade ones drilled through salt deposits. The HDSAM tool indicates that H_2 storage in salt caverns with compressors costs 2016 US$0.03/kg H2 (Table 35). The tool bases its analysis on data gathered from the US EPA Federal Register Documents, Duke Energy, and Natural Resources Canada. For this paper, we assume that this storage price is representative of the region surrounding Houston.

An analysis using HDSAM produced the results captured in Table 35 to Table 40. The model estimates a total cost of $0.91/kg H_2 for the city of Houston with a population of approximately 6 million, geologic/gaseous storage, 1,500 kg H_2/day dispensing rate, with pipelines for transmission and distribution, and a high production volume. In contrast to Census 2020 data showing 1,389 people per square kilometer, the analysis uses an estimated population density of 1,150. A 100% penetration rate is used for the scenario of a complete switch from liquid fuels.

Table 35: HDSAM Analysis Levelized Cost Results for Pipeline and 50km

Description	Transmission Pipeline	Distribution Pipeline	Central Compressor	Geologic Storage	Total
Capital	\$0.01/kg H_2	\$0.69/kg H_2	\$0.01/kg H_2	\$0.03/kg H_2	**\$0.75/kg H_2**
Other O&M	\$0.00/kg H_2	\$0.09/kg H_2	\$0.00/kg H_2	\$0.01/kg H_2	**\$0.11/kg H_2**
Energy/Fuel	\$0.00/kg H_2	\$0.00/kg H_2	\$0.04/kg H_2	\$0.00/kg H_2	**\$0.04/kg H_2**
Total Cost	**\$0.02/kg H_2**	**\$0.79/kg H_2**	**\$0.06/kg H_2**	**\$0.03/kg H_2**	**\$0.90/kg H_2**

Table 36: HDSAM Analysis Levelized Cost Results for Pipeline and 100km

Description	Transmission Pipeline	Distribution Pipeline	Central Compressor	Geologic Storage	Total
Capital	\$0.03/kg H_2	\$0.69/kg H_2	\$0.01/kg H_2	\$0.03/kg H_2	**\$0.76/kg H_2**
Other O&M	\$0.01/kg H_2	\$0.09/kg H_2	\$0.00/kg H_2	\$0.01/kg H_2	**\$0.11/kg H_2**
Energy/Fuel	\$0.00/kg H_2	\$0.00/kg H_2	\$0.04/kg H_2	\$0.00/kg H_2	**\$0.04/kg H_2**
Total Cost	**\$0.04/kg H_2**	**\$0.79/kg H_2**	**\$0.06/kg H_2**	**\$0.03/kg H_2**	**\$0.91/kg H_2**

Table 37: HDSAM Analysis Levelized Cost Results for Compressed Truck and 50km

Description	GH_2 Terminal	Geologic Storage	Compressed H_2 Truck-Tube	Total
Capital	\$0.61/kg H_2	\$0.03/kg H_2	\$0.36/kg H_2	**\$1.00/kg H_2**
Other O&M	\$0.14/kg H_2	\$0.01/kg H_2	\$0.29/kg H_2	**\$0.44/kg H_2**
Energy/Fuel	\$0.21/kg H_2	\$0.00/kg H_2	\$0.11/kg H_2	**\$0.31/kg H_2**
Total Cost	**\$0.96/kg H_2**	**\$0.04/kg H_2**	**\$0.76/kg H_2**	**\$1.76/kg H_2**

APPENDIX 3 (cont'd): H_2 Transport CAPEX Details

Table 38: HDSAM Analysis Levelized Cost Results for Compressed Truck and 100km

Description	GH_2 Terminal	Geologic Storage	Compressed H_2 Truck-Tube	Total
Capital	\$0.61/kg H_2	\$0.03/kg H_2	\$0.40/kg H_2	**\$1.04/kg H_2**
Other O&M	\$0.14/kg H_2	\$0.01/kg H_2	\$0.34/kg H_2	**\$0.49/kg H_2**
Energy/Fuel	\$0.21/kg H_2	\$0.00/kg H_2	\$0.14/kg H_2	**\$0.35/kg H_2**
Total Cost	**\$0.96/kg H_2**	**\$0.04/kg H_2**	**\$0.88/kg H_2**	**\$1.88/kg H_2**

Table 39: HDSAM Analysis Levelized Cost Results for Liquid Truck and 50km

Description	Liquefier	Terminal	Tractor-Trailer	Total
Capital	\$1.19/kg H_2	\$0.24/kg H_2	\$0.12/kg H_2	**\$1.55/kg H_2**
Other O&M	\$0.24/kg H_2	\$0.05/kg H_2	\$0.11/kg H_2	**\$0.39/kg H_2**
Energy/Fuel	\$0.68/kg H_2	\$0.00/kg H_2	\$0.03/kg H_2	**\$0.71/kg H_2**
Total Cost	**\$2.10/kg H_2**	**\$0.29/kg H_2**	**\$0.26/kg H_2**	**\$2.64/kg H_2**

Table 40: HDSAM Analysis Levelized Cost Results for Liquid Truck and 100km

Description	Liquefier	Terminal	Tractor-Trailer	Total
Capital	\$1.19/kg H_2	\$0.24/kg H_2	\$0.13/kg H_2	**\$1.56/kg H_2**
Other O&M	\$0.23/kg H_2	\$0.05/kg H_2	\$0.12/kg H_2	**\$0.40/kg H_2**
Energy/Fuel	\$0.68/kg H_2	\$0.00/kg H_2	\$0.04/kg H_2	**\$0.72/kg H_2**
Total Cost	**\$2.10/kg H_2**	**\$0.29/kg H_2**	**\$0.30/kg H_2**	**\$2.68/kg H_2**

APPENDIX 4: H_2 Refueling Station Details

The H2A case study for distributed generation (Parks et al. 2020) assumes a cost of $54,000 for a two-hose 700-bar H_2 dispenser. The study indicates that dispensing costs are $0.17 per kg H_2. By comparison, the HDSAM and the H_2 Refueling Station Analysis Model (HRSAM), which we used for our economic analysis, estimate the costs for the various parts of the refueling station with a dispenser between $0.20 per kg H2 and $0.22 per kg H_2. These numbers are consistent with each other, and our is more conservative. Table 41 detail the HDSAM computations and their relative impacts on the levelized cost of H_2 associated with the costs refueling stations for consumer sales (LCRS), a component of the total cost to produce and sell each kg of H_2 during a project's operational life (LTCH). The figures combine both capital expenditures and operational costs. HDSAM estimates total refueling station cost at $3.12 per kg H_2 for pipeline, $2.27 per kg H_2 for compressed truck, and $3.27 per kg H_2 for liquid truck.

Table 41: Refueling Station Cost Details (LCRS)

Delivery Type	Compressor	Storage	Dispenser	Refrigeration	Electrical	Controls/Other	Total
Pipeline	$1.42/kg H_2	$0.78/kg H_2	$0.20/kg H_2	$0.36/kg H_2	$0.10/kg H_2	$0.25/kg H_2	**$3.12/kg H_2**
Compressed Truck	$0.94/kg H_2	$0.40/kg H_2	$0.21/kg H_2	$0.37/kg H_2	$0.10/kg H_2	$0.25/kg H_2	**$2.27/kg H_2**
Liquid Truck	$1.28/kg H_2	$0.72/kg H_2	$0.22/kg H_2	$0.39/kg H_2	$0.17/kg H_2	$0.49/kg H_2	**$3.27/kg H_2**

APPENDIX 5: California H_2 Price Reduction Potential

Shell New Energies compared H_2 costs at the dispenser to gasoline in California (Shell 2022). Their assumptions included 70% station utilization, $100 per tonne CO_2 low carbon fuel standard (LCFS), no taxes on H_2 sales, no infrastructure subsidy, and $3.50 per gallon with 35 miles per gallon (MPG). Their conclusion was that regional H_2 prices would be at or below parity with gasoline, i.e., at or below $7 per kg H_2, once the regional demand serviced greater than 70,000 H_2-fueled cars.

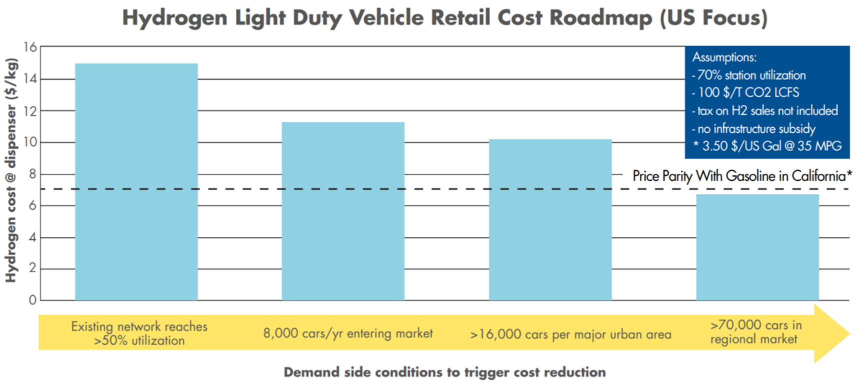

Figure 10: Shell's US H_2 Light Duty Vehicle Retail Cost Roadmap (Shell 2022)

ABOUT UH ENERGY

UH Energy is an umbrella for efforts across the University of Houston to position the university as a strategic partner to the energy industry by producing trained workforce, strategic and technical leadership, research and development for needed innovations and new technologies.

That's why UH is the Energy University.

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UH Energy has partnered with faculty and thought leaders across the University of Houston to bring you the White Paper Series. This series is a collaboration of research reports examining pertinent topics throughout the energy sector and aims to provide leaders from industry, nonprofits and regulatory agencies with information they need to navigate the changing energy landscape.

While UH Energy already offers a popular symposium series focusing on key issues in the field and a blog hosted by Forbes.com intended to reach a wide audience, the White Paper Series, in contrast, is focused on distilling information on a variety of energy-related topics in a way that can help industry leaders prepare for the future.

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