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Cost and Performance Comparison Of Stationary Hydrogen Fueling Appliances

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ABSTRACT

This work was funded by the Hydrogen Program Office of the U.S. Department of Energy under Grant No. DE-FG01-99EE35099 and represents the second task of three to be completed under this contract. The first task presented a broad overview of the costs for creating infrastructures to supply direct hydrogen, methanol, and gasoline to support fuel cell vehicles (FCV's). A conclusion of the report resulting from the first task was that "the costs of maintaining the existing gasoline infrastructure per vehicle supported are up to two times more expensive than the estimated costs of maintaining either a methanol or a hydrogen fuel infrastructure".

The second task, as detailed in this report, was to provide a detailed analysis of the cost of providing small-scale stationary hydrogen fueling appliances (HFA's) for the on-site production and storage of hydrogen from natural gas to fuel hydrogen FCV's. Four potential reforming systems were studied: 10-atmosphere steam methane reforming (SMR) with pressure-swing adsorption (PSA) as gas cleanup, 20-atm SMR with metal membrane gas cleanup, 10-atm autothermal reforming (ATR) with PSA gas cleanup, and 20-atm ATR with metal membrane gas cleanup. The full report for this work is available in pdf format at www.directedtechnologies.com/pubs/DTI_Task2_Report.html.

INTRODUCTION

Over several studies, Directed Technologies, Inc. has analyzed the costs of representative hydrogen fueling appliances (HFA's) to supply hydrogen to direct-hydrogen powered fuel cell vehicles (FCV's) and the cost of hydrogen produced by these HFA's. In previous studies we evaluated the impact of fuel choice on FCV, the cost of other sizes and quantities of HFA's, and the infrastructure maintenance costs of various fuels. In this study we analyze the costs for an intermediate production rate (250/year) of HFA's sized to support communities of 183 vehicles each (about one-eighth the size of the current average gasoline station, and suitable for refueling 20 vehicles per day). This small HFA is chosen to allow economical hydrogen production in the early years when there are low numbers of FCV's present in any geographical area. While the focus of this report is on the economics of hydrogen production at this small unit size, it is noted that significant hydrogen cost reductions can be achieved by scaling the HFA unit to a larger size. This report concludes by estimating the cost of an eight-fold capacity HFA that results in a 45% reduction in the cost of hydrogen.

COST ESTIMATION METHODOLOGY

The cost estimation methodology employed in this report is based on the Design for Manufacture and Assembly (DFMA) techniques developed by Boothroyd and Dewhurst, described in *Product Design for Manufacture and Assembly, 2nd edition* (Marcel Dekker, Inc., 2002). The DFMA process has been formally adopted by the Ford Motor Company (among others) as a systematic means for the design and evaluation of cost-optimized components and systems. These techniques are powerful and are flexible enough to incorporate historical cost data and manufacturing acumen that have been accumulated by Ford since the earliest days of the company. Directed Technologies has adapted and expanded the formal DFMA technique to include lessons from Ford and its own experience to develop a system of tools and methods for cost estimation of engineering designs. The DFMA approach used for this analysis provides a solid framework for the cost study and is the only fair method to compare the cost of potential HFA configurations.

The cost of each system component includes the cost of material, manufacturing, assembly, and markup. Markup refers to the additional cost percentage to account for general and administrative (G&A) expenses, material scrap, spending on research and development (R&D), overhead (OH), and profit. In this analysis, two levels of markup may be applied to each component of the final system (see Figure 1). The lower level represents the markup applied by a vendor who sells a manufactured component to the appliance manufacturer (the final assembler). The higher level is the markup applied by the appliance manufacturer. (The total markup on a component then depends on who performs the work: the vendor or the HFA manufacturer.) The final resulting "cost" is thus actually a projected "price" to the appliance purchaser (fueling station owner). In addition, the projected cost of hydrogen to the consumer (potentially a FCV motorist) is provided in this report, with inclusion of operating expenses to the reformer purchaser.

HFA DESIGN ASSUMPTIONS

The HFA is composed of a reforming system (including the reformer, gas cleanup system, and peripheral components), a hydrogen compressor, storage tanks, and dispenser. For the baseline HFA, we compared the costs and efficiencies of two hydrogen-generation technologies (steam methane reforming and autothermal reforming) and two hydrogen purification technologies (pressure swing adsorption and metal membrane). Autothermal reforming (ATR) is generally considered the lower initial-cost option for hydrogen generation because of a simpler reactor design, and steam methane reforming (SMR) is generally the higher-efficiency option because of more complete methane conversion. The processing options chosen for this comparison emphasize the relative strengths of each process, with the result that there are many other potential variations that involve tradeoffs between capital cost and efficiency.

Category	**Markup up on Manufactured/Assembled Components**	**Markup on Pass Through Components**
Profit	15%	5%
OH	3%	3%
G&A	7%	3%
R&D	4%	2%
Scrap	2%	2%
Total	**31%**	**15%**

Figure 1. HFA Manufacturer Markup Rates

The basic processing steps are common to both SMR and ATR:

1. Natural gas compression
2. Natural gas purification (i.e., sulfur removal)
3. Catalytic steam reforming of methane to hydrogen and carbon monoxide (CO)
4. Water-gas shift to convert carbon monoxide (CO) to carbon dioxide (CO_2) and additional hydrogen
5. Hydrogen gas purification

The difference between SMR and ATR is how heat is provided to activate the endothermic steam reforming reaction. In SMR, the catalyst is contained in tubes that are heated by an external burner. In ATR, a portion of the natural gas is burned to raise the temperature of the process gas before it contacts the catalyst.

Pressure swing adsorption (PSA) is a commonly used industrial process for the purification of gas streams. The most common separation processes employing PSA are the purification of either oxygen or nitrogen from air and the purification of hydrogen from sources such as catalytic reformer off gas, coke oven gas, and ethylene plant effluent gas. Pressure swing systems are based on selective adsorbent beds. A gas mixture is introduced to the bed at an elevated pressure and the solid adsorbent selectively “adsorbs” certain components of the gas mixtures, allowing the unadsorbed components to pass through the bed as purified product gas. Multiple beds are cycled in the process, allowing the adsorbed pollutants to be periodically desorbed, cleaning the beds for the next cycle.

Hydrogen can also be separated from other gases by passing the gas mixture over a heated metal membrane such as palladium or palladium alloys at high pressure. The hydrogen molecule is first adsorbed on to a palladium site, and then is dissociated into hydrogen atoms. The hydrogen atoms then diffuse through the membrane at a speed determined by the hydrogen front-to-back partial pressures and metal temperature, and eventually these atoms recombine to form hydrogen molecules at the back surface of the metal membrane. As long as there are no leaks through or around the membrane, the output hydrogen is 100% pure, since no other gas can pass through a solid metal membrane. However, for effective mass transfer through the membrane, gas pressures far greater than those for the PSA are necessary.

Based on the evaluation of gas cleanup technologies, it was decided that a metal membrane gas cleanup was only feasible with a 20 atm reformer system. As a result, both the ATR and SMR HFA's were operated at 10atm for PSA gas cleanup and 20atm for metal membrane cleanup.

Each HFA system (SMR-PSA, SMR-membrane, ATR-PSA, ATR-membrane) was designed from the ground up using HYSYS^{TM} software, design calculations, and DFMA costing techniques. Although only current-day technology was assumed, an effort was made to carefully design each system for low cost and high performance.

The layout for an SMR system with PSA is shown in Figure 2. The reforming components fit on an eight-by-thirteen foot pallet, with the hydrogen compressor, storage system, and dispenser housed separately. This size of footprint offers generous room for the necessary vessels and to allow easy access for servicing the components. The reforming and shift reactors, and the HDS system are placed near the edges of the footprint, making them especially easy to service and remove for catalyst replacement. All of the reformer components are secured to the skid-mounted pallet for transportation and installation purposes. This pallet would be placed directly onto a concrete slab at the installation site, where a protective canopy and chain-link enclosure would be contructed. Similar layouts are possible for the SMR-membrane system and ATR systems.

The method and cost of hydrogen compression, storage, and dispensing is nearly identical for all four HFA designs studied. In each case, hydrogen is compressed to 7000psi and stored in fiber-wrapped composite vessels, before being dispensed to the HFCV's at 5000psi.

The hydrogen compressor design selected for cost estimation is based upon industrial compressor designs, adapted to a hydrogen flow rate of 4.8 kg/hr (115 kg/day) to match the hydrogen reformer unit H_2 production. A key feature of the baseline compressor system is cost reduction through parts commonality with existing internal combustion engines (ICE's). Specifically, adaptation of an existing V-6 or V-10 engine into a compressor is proposed. This concept has already been successfully demonstrated by the CNG 90 compressor from Hurricane Compressors.

The on-site hydrogen dispensable storage capacity is set at 58% of daily average production capacity for two purposes: 1) to serve as an overnight storage reservoir when vehicle refueling may not take place and 2) to allow for demand surges, i.e., multiple cars arriving simultaneously at the service station. A cascade filling storage system is assumed and consists of charged banks of pressure vessels sequentially filling the vehicle tanks. Typically, three or four cascades are used. The advantage of this approach is preservation of high-pressure gas in at least one of the storage vessels so that the vehicular tank can be filled to design pressure (34.5 MPa/5,000 psia) efficiently. A disadvantage of the approach is low hydrogen recovery factor: only 58% of the hydrogen in each tank is cycled in and out of the tank. Composite pressure vessels are estimated to be the lowest cost system primarily due to the lower cost of the tanks themselves. The composite pressure vessel cost of $356/kg H_2 is judged to be achievable due to a moderately high rate of manufacture, use of a HDPE plastic liner that is much cheaper to form than a metal liner, and use of mid-grade composite fiber that has been steadily decreasing in price due to economies of scale. The cost of appropriate valving for the system is added to the storage cost.

The dispensing equipment is based on prototype fast-fill hydrogen dispensing equipment from Kraus Group Inc. Due to the electronic complexity of the dispensing unit, a detailed DFMA analysis was not conducted. Instead, price quotes were obtained for Kraus' prototype hydrogen dispensers and Tulsa Gas Technologies Inc.'s commercial compressed natural gas dispensers. The estimated price was adjusted to reflect the 7000 psig requirement, the inclusion of a credit card reader, and control valving for the cascade storage system.

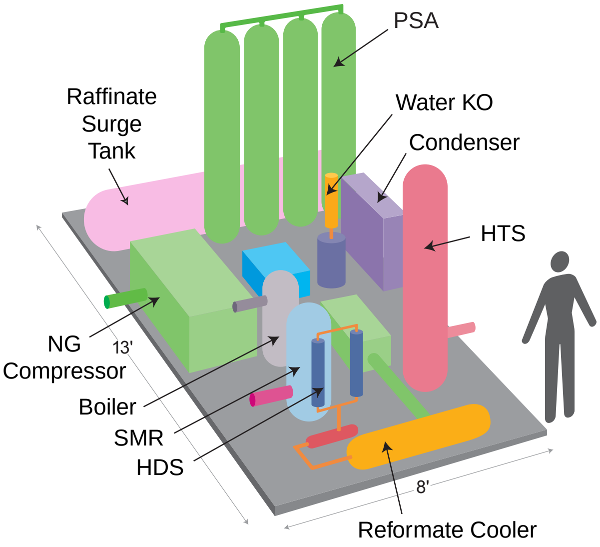

Figure 2. Proposed Layout of 10 atm SMR Reformer System (Cylindrical vessels are secured in racks (not shown), and all components are attached to a skid-mounted pallet.)

RESULTS

Based on this study we conclude that ***the most cost-effective option as determined by the wholesale cost of hydrogen is steam methane reforming (SMR) with pressure swing adsorption (PSA) hydrogen purification.*** The initial capital cost to install the preferred SMR-PSA to support 183 vehicles is $253,014 per unit. The wholesale cost of hydrogen for this option including storage and dispensing but excluding sales taxes (state and federal highway taxes) and retail markup is $3.38/kg, or $1.55 per gallon of gasoline equivalent (based on a 2.2 fuel efficiency gain over conventional gasoline internal combustion engines). Autothermal reforming (ATR) of natural gas is a lower initial-cost option, but the resulting cost of hydrogen is higher ($3.59/kg) because the ATR is less efficient than the SMR. The capital costs for the four primary options studied, assuming a ten-year lifetime, are listed in Figure 3. (For reference, the hydrogen production capacity required to support 183 vehicles at 69% equipment utilization is 115 kg/day, or 2,000 standard cubic feet per hour.)

The range of capital costs ($225,000 to $275,000, depending on the HFA option) corresponds to a total annual investment of $56.25-$68.75 million per year to support the introduction of ~50,000 new FCV's per year.

This study indicates that ***with current technology, pressure swing adsorption (PSA) is more cost effective and reliable than metal membrane hydrogen purification.*** The higher costs of membrane units relative to PSA's are not justified by the potential for better hydrogen recovery and smaller size.

A breakdown of factors making up the capital costs is provided in Figure 4. The combined costs for hydrogen compression, storage, and dispensing are roughly equal to the cost for the reformer and purification system.

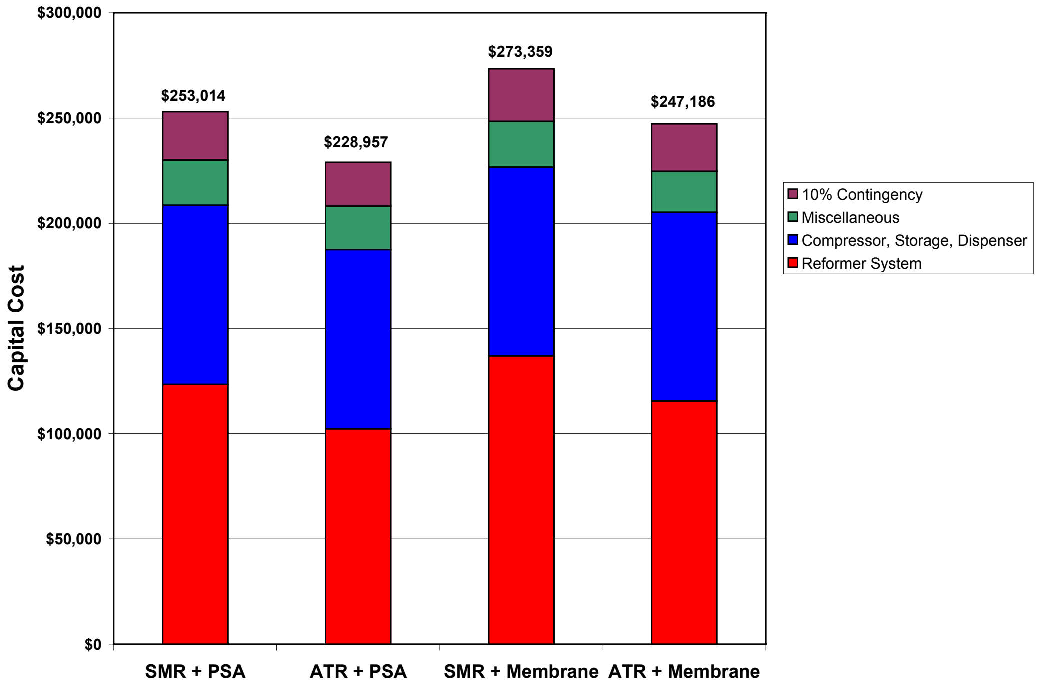

Figure 3. Contribution of Subsystems to Capital Cost for 115 kg/day HFA's. The "Miscellaneous" category includes on-site installation, freight, taxes & insurance, and initial spares. The "Reformer System" category includes the hydrogen production and gas cleanup subsystems.

Capital recovery (i.e., amortization of the initial investment over the life of the HFA) accounts for ~48% of the cost of hydrogen for SMR and ~40% of the cost of hydrogen for the ATR. The other contributors to the cost of hydrogen are the cost of natural gas, the cost of electricity, operation and maintenance expenses (O&M), and taxes and insurance.

Costs in \$/kg H_2	SMR/PSA	ATR/PSA	SMR/Membrane	ATR/Membrane
Hydrogen Cost	**$3.38**	**$3.59**	**$3.74**	**$4.28**
Capital Recovery	1.66	1.50	1.78	1.62
Natural Gas	0.95	1.17	1.01	1.44
Electricity	0.23	0.41	0.37	0.68
O&M	0.33	0.31	0.33	0.33
Taxes & Insurance	0.23	0.20	0.24	0.22
Gasoline equiv. ($/gal)	**$1.55**	**$1.65**	**$1.72**	**$1.96**

- HFA is assumed to run an average of 69% of capacity with 98% availability.
- Capital Recovery assumes a 10% after-tax return on investment over its 10-year life. A 38% marginal tax rate (34% federal, 4% state and local) is included in the return on investment calculation.
- Natural gas price is based on the 19-year national average commercial rate of $5.34 per thousand scf.
- Electricity price is based on the 10-year national average commercial rate of 7.5¢ per kW-hr.
- The cost for water usage is negligible.
- O&M includes yearly hydrogen desulfurization bed replacement and reformer and shift catalyst replacement after five years. It also includes general maintenance for compressors, valves, etc.
- Tax and Insurance costs refer to annual property taxes at 1.5% of capital investment and annual insurance premiums at 1% of capital investment. Highway/road sales taxes are not included.
- Gasoline equivalent price is based on an efficiency gain of 2.2 for hydrogen FCV's over current gasoline ICEV's.

Figure 4. Cost of Hydrogen Produced from the 2,000 scfh HFA Options

We conclude that the wholesale cost of hydrogen produced from early-year HFA's (i.e. 2000scfh HFA's produced in 250 per year quantities) will be nearly competitive with the retail price of gasoline on a per vehicle-mile basis, especially in regions with reformulated gasoline requirements. We feel that this comparison of the untaxed cost of hydrogen with the taxed price of gasoline is valid for the near to mid-term as hydrogen is unlikely to be taxed until it begins to significantly displace gasoline road-tax revenues. When there are sufficient FCV's to justify a larger number of higher-volume stations, the cost of hydrogen is expected to decrease significantly by taking advantage of economies of scale.

Based on the results of the baseline HFA analysis, we estimated the reduced hydrogen cost that results by increasing the size of the HFA from 2,000 scfh to 16,000 scfh. An HFA of this size would support roughly 1464 vehicles, which is comparable to current gasoline stations. A breakdown of the estimated cost of hydrogen for this HFA is given in Figure 5. Using scale-up factors common to chemical processes, the capital cost of this 8x HFA was estimated to be $1.16 million, resulting in a hydrogen cost of $1.87-$2.48/kg (dependent on assumptions about utility discounts, natural gas feedstock cost, and equipment life). Thus, the 1x HFA derived hydrogen cost of $3.38/kg is appropriate when discussing the early introduction of fuel cell vehicles where many small stations need to be distributed over the country to support a sparse FCV population, and the significantly lower hydrogen cost of $1.87-$2.48/kg, resulting from an 8x HFA, is appropriate for the latter years when the FCV population and population density is much higher.

Costs in $/kg H_2	**16,000scfh SMR/PSA HFA**
Hydrogen Cost	**$1.87**
Capital Recovery	$0.77
Natural Gas	$0.59
Electricity	$0.15
O&M	$0.24
Taxes & Insurance	$0.13
Gasoline equiv. ($/gal)	**$0.85**

- Estimates are based on a scaled-up version of a 2,000scfh HFA. Scale-up may not retain accuracy of original analysis.
- HFA is assumed to run an average of 69% of capacity with 98% availability.
- Capital Recovery assumes a 10% after-tax return on investment for a 15-year life. A 38% marginal tax rate (34% federal, 4% state and local) included in the return on investment calculation.
- Natural gas price is based on the 19-year national average industrial rate of $3.30 per thousand scf.
- Electricity price is based on the 10-year national average industrial rate of 4.65¢ per kW-hr.
- The cost for water usage is negligible.
- O&M includes yearly hydrogen desulfurization bed replacement and reformer and shift catalyst replacement every five years. It also includes general maintenance for compressors, valves, etc.
- Tax and Insurance costs refer to annual property taxes at 1.5% of capital investment and annual insurance premiums at 1% of capital investment. Highway/road sales taxes are not included.
- Gasoline equivalent price is based on an efficiency gain of 2.2 for hydrogen FCV's over current gasoline ICEV's.

Figure 5. Cost of Hydrogen from 16,000 scfh (8x) SMR/PSA HFA with Optimistic Assumptions

More details of the system design and cost analyses are available in the full report, available from the Directed Technologies website at www.directedtechnologies.com/pubs/DTI_Task2_Report.html.