Modeling Hydrogen Fuel Distribution Infrastructure  
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“…the first car driven by a child today could be powered by hydrogen and pollution-free”
--President Bush  
State of the Union Address  
January 28, 2003

Introduction and Motivation
As President Bush indicated in his State of the Union address in 2003, the future of transportation could dramatically shift in the next several decades from our current paradigm of using vehicles powered by internal combustion engines (ICEs) and fossil fuels to a system using fuel cell vehicles (FCVs) powered by hydrogen gas. The attraction of fuel cell vehicles is easy to understand: fuel cells have no moving parts, and are therefore more reliable than ICEs, they have virtually no emissions during operation, and they are thermodynamically more efficient, in terms of operational efficiency (though not necessarily in terms of Well-To-Wheels efficiency), than ICEs (Breeze).

However, the future outlook for FCVs is not entirely without problems. In addition to the daunting technical challenges in fundamental research required to produce cost-effective fuel cell stacks, there exists a substantial hurdle to overcome regarding the development of a hydrogen fuel delivery infrastructure. Whether or not such an infrastructure scheme takes root, there exists a fundamental, though tacit, paradox in the development of a transportation system based on hydrogen fuel:

In order to build fuel cell vehicles, there must be hydrogen fuel available to consumers, but in order to make a hydrogen fuel delivery infrastructure feasible, there must be enough market demand to maintain the expense of such a network (DOE Hydrogen Posture Plan).

Burns et. al, in “Vehicle of Change – How Fuel-Cell Cars Could Revolutionize the World”, also describe an on-site scheme for hydrogen distribution. The authors in this study present a broad overview of a possible hydrogen economy and they emphasize the need for further research, especially in the infrastructure development and fuel distribution sides of the problem. The authors also point out the corollary benefits in the realm of vehicle design in moving from an internal combustion engine design to a fuel cell system. GM has already produced its first hydrogen concept car, the “Hy-Wire” as a show case for potential technologies (Bigelow). The authors of the article believe that within a decade, there will be both hydrogen fueling stations and stationary power stations using steam methane reformation on site to produce hydrogen gas (Burns et al). Later, stationary applications may contribute electricity to rest of the power grid as part of a distributed power generation system. The authors believe that if the price per kg of hydrogen is at least double that of a gallon of gas, the fuel will become economically viable. Nevertheless, the assumption in the author’s works is twofold. First, the authors do not give credit for the increased efficiency of gasoline hybrid electric vehicles (GHEVs). Second, it is not clear that United States vehicle owners are concerned with fuel inefficiency as a factor in determining vehicle choice. In fact, one recent article
highlighted that gasoline could reach as high a $3 per gallon before consumers would change their driving habits or vehicle choices. (Woodward) Yet the authors of “Vehicles of Change”, all GM executives, work for a company that has chosen to invest $100M per year into R&D. (Bigelow)

In short, in addition to the many technical challenges confronting proponents of a fuel cell economy, there is a fundamental business and logistics issue facing practitioners – how to deploy an infrastructure to delivery fuel which must directly compete with a system that can deliver petroleum fuel for a landed cost less than that for a gallon of milk (Senate Hearing 108-16).

This thesis’ fundamental research question is to evaluate the structure of the hydrogen production, distribution, and dispensing infrastructure under various scenarios and to discover if any trends become apparent after sensitivity analysis. After reviewing the literature regarding the production, distribution, and dispensing of hydrogen fuel, a hybrid product pathway and network flow model is created and solved. In the literature review, an extensive analysis is performed of the forthcoming findings of the National Academy of Engineering Board on Energy and Environmental Systems (BEES). Additional considerations from operations research literature and general supply chain theory are applied to the problem under consideration. The second section develops a general model for understanding hydrogen production, distribution, and dispensing systems based on the findings of the BEES committee. The second chapter also frames the analysis that the thesis will review using the model. In the problem formulation chapter, the details of the analytic model at examined at length and heuristics solution methods are proposed. Three heuristic methodologies are described and implemented. An in-depth discussion of the final model solution method is described. In the fourth chapter, the model uses the state of California as a test case for hydrogen consumption in order to generate preliminary results for the model. The results of the MIP solutions for certain market penetration scenarios and the heuristic solutions for each scenario are shown and sensitivity analysis is performed. The final chapter summarizes the results of the model, compares the performance of heuristics, and indicates further areas for research, both in terms of developing strong lower bounds for the heuristics, better optimization techniques, and expanded models for consideration.

**Literature Review**

In order to refine the scope of the document, it is important to narrow the field of topics to those which are relevant to the topic of hydrogen fuel production, distribution, and dispensing. Therefore, no effort is made to discuss the internal chemical interactions of fuel cell applications, the operational thermodynamics of fuel cell systems, or the difficulties in manufacturing such items in mass quantities. Instead, the thesis focuses on three areas of research as they pertain to the question of hydrogen fuel distribution. First, general supply chain articles which are relevant to the discussion of a fuel distribution infrastructure will be surveyed. Second, operations research articles that discuss solution methods to network flow models will be reviewed and salient points from such research will guide the solution method in later chapters. Finally, a review of the literature on hydrogen fuel distribution will be made with particular attention given to the BEES

Based on the DOE’s “Hydrogen Posture Plan” and the Roadmap model, the Board on Energy and Environmental Systems created a Committee on Alternatives and Strategies for Future Hydrogen Production and Use. The committee’s major finding is that, although hydrogen fuel has a long-term potential to transform the United State’s energy system, the short-term (25 years) impact on oil imports and CO₂ emissions will be minor. Since the two major motivations of the “Hydrogen Posture Plan” are to increase energy security by reducing the level of foreign imports and to reduce CO₂ emissions, the committee found that the hydrogen economy doesn’t provide a solution to the nation’s energy problems (HE 6-14). Nevertheless, the committee is optimistic that the nation can achieve a transition to a hydrogen economy if many technology breakthroughs occur in the next few decades. In regards to supply chain infrastructure, the committee makes the recommendation that infrastructure analysis should increase. Specifically, the committee recommends to “Accelerate and increase efforts in systems modeling and analysis for hydrogen delivery, with the objective of developing options and helping guide R&D in large-scale infrastructure development.”

**Methodology**
The thesis’ fundamental research question is to determine the Hydrogen distribution and production infrastructure under various scenarios and to discover any trends using
sensitivity analysis. To better understand the hydrogen fuel distribution system, a framework must be developed to model the system. The illustration below details a generalized model for the hydrogen fuel supply chain.

As can be seen above, the general hydrogen fuel supply chain model has three major components, production, distribution and dispensing. At each stage the precise route taken will vary based on the on technology pathway chosen to produce, distribute and dispense hydrogen fuel. In order to perform sensitivity analysis on the model, different demand scenarios and technology pathways were developed and tested in using the generalized hydrogen supply chain as a basis for comparison.

In order to examine the various technology pathways, a network flow model was created based on the generalized hydrogen supply chain diagram shown above. The network flow model has different nodes and arcs for different technology pathways which account for the production, distribution and dispensing technology choices brought into play in the system. The network is modeled analytically as a fixed-charge capacitated network flow problem and, therefore, is NP-Hard to solve via a mixed-integer program formulation.
Three heuristics were developed to arrive at solutions to the model developed in the thesis, a greedy heuristic, a capacity scaling heuristic and a capacity scaling heuristic with a unit cost subproblem.

Figure 3: Hydrogen Supply Chain Network Flow Model for One Mode of Transportation.

Since different heuristic algorithms were used to arrive at solutions to this problem, it is important to compare the results of the heuristics to one another and to compare the best results to an established lower bound. Only two scenarios, the pipeline only and the truck only models for the 1% market penetration scenario, were able to solve to MIP optimality. The rest of the scenarios were solved via heuristic methodologies. Since only two scenarios were able to solve to MIP optimality, there exists no lower bound for the heuristics in later stages. Therefore, the heuristic solutions for the demand scenarios under larger market penetration can be evaluated for insights but cannot provide conclusive results regarding the hydrogen supply chain at those levels of demand. Further work will be needed to see if these results extend to optimal MIP solutions of the hydrogen supply chain model.
Thesis Results Compared to the Literature

DOE Posture Plan

The DOE outlines a hydrogen fuel distribution system in their DOE 2002 and 2004 vision document. The DOE envisions a transition from truck to pipe to distributed production over the next several decades. The heuristics examined in this thesis tend to favor this trend. However, the timeline may be more exaggerated for high demand markets than the DOE projects. The DOE also believes that natural gas will give way to renewable production methods and later to nuclear thermochemical splitting of water. The future heuristic solutions do not contradict this vision in any significant fashion. Further research will be needed to establish whether the optimal solution to the hydrogen supply chain model follows the DOE Posture Plan.

NREL:2002

In Simbeck’s study, the authors determined the cryogenic liquid tanker truck was the best methodology for transporting hydrogen. In the study, the authors also assumed that the plants operated at 90% efficiency. The authors found that the costs of using the liquid tanker truck were insignificant when compared to the costs of the feedstock and production (including compression). The authors concluded that the total cost per kg of hydrogen from a central station using natural gas production and liquid tanker truck distribution was $3.66. Although the thesis model considered the variable costs of compression as part of the distribution costs of the system, the results of the thesis do not contradict the results of the NREL study which served as a precursor to the BEES study. Furthermore, some of the better results from both the heuristics and the MIP optimal models confirm the authors’ finding a “mix and match” strategy will work best during the low market penetration scenario.

BEES

In the BEES study, the authors believe that small scale plants should be prominent in short term, followed by a transition to large factories in the long term with pipeline transmission. The heuristics developed in the model trend with small plants in the initial market penetration, central stations in the low-mid market penetration of counties and small plants at market saturation. It remains to be seen whether the optimal network flow favors the BEES representation or upholds the results of this thesis.

BEES focuses on unit costs from the factory versus total system costs when determining cost per unit. Under the optimal solutions for pipeline only and truck only, the unit costs for a kg of hydrogen were $6.15 and $5.97, respectively, versus approximately $2 in BEES. The causes for the disparity may lie with BEES’ assumptions regarding transportation and capacity utilization. As previously mentioned, the low demand in the initial market penetration scenario makes the 90% utilization rate assumption for plants unlikely. However, at higher levels of demand, the plant utilization may adhere to the BEES assumption. It is important for further research to evaluate the unit cost value per
kg of hydrogen because the unit cost of fuel will be a major factor in the adoption of fuel cell technology.

A major difference between BEES and the results of the heuristics in this study is that BEES advocates using larger plant sizes as demand for hydrogen grows beyond its initial market penetration. The optimal solutions tended to favor smaller plants at the initial levels of demand while the heuristics favored smaller plants at maturity. It is unclear how optimal solutions will size plants at maturity.

Supply Chain Considerations

In spite of the assumption in both this thesis and the BEES study that the hydrogen supply chain will be vertically integrated, it is likely that the supply chain will, in fact, have different companies specializing in different aspects of the supply chain. Therefore, it is important to understand how general supply chain processes will affect the hydrogen fuel distribution network – especially given how important vehicular fuel is to the working of the economy and how critical it will be to avoid fuel shortages.

Some supply chain management principles which one should consider when developing this network are discussed below:

- Supply chain strategy should be focused on service and constrained by cost due to the necessity of preventing fuel stock outs
- Vendor-Supplier Relationships will be important because there will be considerable risk in this venture for both fuel producers and distributors
- Organizational alignment between parties is important both contractually and procedurally
- Understanding principles such as risk management and inventory management is essential for every supply chain
- Risk-Pooling between parties can be beneficial in the face of uncertain customer demand.
- Inventory Policies for finished goods and raw materials at plants is an important consideration
- Reverse logistics of solid state storage containers and empty truck miles on backhauls may be further areas to improve overall supply chain efficiency

Tanker Truck Contract Costs versus Model

One factor worth mentioning is the reality of tanker truck contracts. Rarely does one company have vertical integration of its entire supply chain from energy production to distribution and dispensing operations. Furthermore, when calculating transportation costs for tanker trucks the common practice to give prices quotes is by dollar cost per mile per truckload. These price quotes implicitly incorporate the fixed and variable costs of distribution, as well as profit taking on the part of the carrier. Therefore, the model does not adequately reflect the business model of the industry. However, it is necessary to incorporate fixed costs in the model it give an estimate for true transportation costs because there exists no market for gathering price quotes for wide-scale tanker truck
deliveries of hydrogen. The thrust of this thesis was to analyze how much capital infrastructure would be required for a tanker truck distribution network to be put in place in order to give future suppliers a general idea of the size of fleets required to deliver goods. In the 1% market penetration with truck only distribution scenario, the network required 120 vehicles. This represents a capital expense of $72M and an amortized expense at 25%, including O&M, of $18M.

Another factor to consider is that the 500km distance limit does not favor mid-sized or central station plants because such plants may operate at less than full capacity and yet not be able to service far-flung counties which otherwise would have to be serviced by their own distributed plant because the distance from the main plant to the county is beyond the threshold. The maximum distance threshold is a major limitation on the effectiveness of tanker truck distribution. In the BEES model, the maximum distance was merely 150km times a 40% “Blob” factor to account for fact that roadway distances are nonlinear and that multiple stops may have be made along a given route.

Conclusion

Given the interest in hydrogen fuel by both industry and the government, it is prudent to begin examining the structural issues surrounding the distribution infrastructure requirements for hydrogen fuel distribution. Many technology pathways seem to have potential as candidates for implementing a large-scale infrastructure for hydrogen fuel production, distribution and dispensing, but no one technology pathway has been shown to be an optimal choice. There is some confusion regarding the optimal size of plants in the network and whether a distributed on-site model of production is preferable over a centrally located large-scale plant. The methodology used to amortize the fixed cost of transportation assets, such as specialized cryogenic tanker trucks, needs more research. More general research is needed to understand these fundamental questions regarding hydrogen fuel infrastructure.