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Hydrogen infrastructure: resource evaluation and capacity modeling

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HYDROGEN INFRASTRUCTURE: RESOURCE EVALUATION AND CAPACITY MODELING

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ABSTRACT

A hydrogen economy could offer energy stability, economical, and environmental benefits. Several issues are involved in the design and implementation of a hydrogen economy such as the selection of feedstocks, generation and storage technologies, transportation methods, appropriate equipment capacity, codes/standards and public awareness. The design of a hydrogen infrastructure may seem insurmountable; however, as the system is deconstructed a proper design can be achieved. In order to better understand how a hydrogen system for light duty vehicles might operate, both hydrogen resource and capacity analysis and modeling is conducted. Specifically, an evaluation of leading near term production and distribution technologies is presented. A hydrogen system based on wind-generated electricity is then presented as a viable component in a hydrogen transition strategy. In support of this strategy, the theoretical hydrogen generation capability of a wind-hydrogen system on a state level basis is determined.

A newsvendor framework is utilized to determine the optimal capacity for hydrogen filling stations based upon consumer behavior. The utility of this approach is expanded by including the effects of a competitive business environment by providing an alternative to the consumer and by including a consumer placed utility for hydrogen. The consumer placed utility represents the value to the consumer that the higher energy efficiency and environmental benefits hydrogen is perceived to provide. The results from a parametric analysis of key variables are presented in regards to inventory levels. The presented work provides an understanding as how a complex hydrogen economy might operate in the future. Finally, future areas for model expansion are presented.

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1. INTRODUCTION

1.1. WHY HYDROGEN?

The need to initiate an economy based on sustainable energy sources is more compelling than ever, and is key to the evolution of an economically and environmentally stable world. Numerous and diverse drivers are leading the United States and other countries toward the development of hydrogen infrastructures. Among these reasons are the interrelated areas of increased energy stability and the expanded usage of renewable energy sources.

Energy stability is of particular importance to the United States and to many other countries whose economies are severally dependent on foreign oil. Because the United States both consumes and imports more oil than any other country, it is in a perilous position (though not alone). Further, as a vast majority of the proven oil reserves are in geopolitically sensitive areas, crude oil prices are not insulated from large price fluctuations. The growing dependence on imported oil and natural gas increases the strategic vulnerability of many countries. Further, competition among importing countries will increase as the major emerging economies of India and China will spur additional demand. These trends, coupled with increased worldwide interest in hydrogen and fuel cell technology, provide a warning that if the U.S. is to remain competitive, it must lead in technology innovations related to this new economy.

The use of hydrogen also addresses stability through diversity. As hydrogen can be generated by many different pathways and at a variety of different quantities the technological pathway for a particular region might not be the best choice for an adjoining region. As a result, the production of hydrogen will most likely be much more distributed than the current petroleum infrastructure. The distributed production reduces the impact of a disturbance, as compared to the centralized production used in the refining of petroleum. An example of such a disturbance can be found in 2005 when Hurricane Katrina had a devastating impact on the nation’s ability to pump and refine crude oil.

The effects felt nationally from such a disaster would be lessened if the sourcing of raw materials and production of energy would be on a more distributed scale. The decentralized nature of a hydrogen economy could also provide a more reliable energy supply. By using fuel cells with independent hydrogen sources, power outages could be averted, saving the tens of thousands to millions of dollars of revenues that are lost from a single hour without power [ADL, 2000].

Hydrogen also provides a pathway for the expanded use of domestically produced intermittent renewables, thereby creating the possibility of a drastically reduced carbon producing economy. The electricity generated from renewable sources such as wind, solar, and hydro can be used to produce hydrogen using the electrolysis process. Hydrogen can then be stored until it is needed as fuel for either mobile applications or local stationary power generation sources, or it can be transferred into electricity and fed into the electrical power grid. The interconversion of hydrogen and electricity by means of water is a perceivable indicator of a future integrated energy mix.

As the largest emitter of carbon dioxide, the U.S. accounts for almost one quarter of all energy-related carbon emissions worldwide. The continuation of such releases will only exacerbate global environmental problems attributed to greenhouse gas emissions. Further, the environmental impacts caused by the continued use of carbon emitting energy sources can be witnessed on a more local scale. In 2005, the United States had one of the largest urban populations in the world. Between 2005 and 2030, the annual world urban growth rate is projected to be twice as high as the projected rate for the overall world total population (1.8 per cent versus almost 1 per cent). This projection results in roughly 60 percent of the world's population living in urban areas by 2030. The increases in urban population will likely indirectly result in an increase in personal vehicles in these areas unless a change in public attitude occurs with respect to mass transportation. This, among other unsustainable patterns of transportation, especially in urban areas, is the root cause to many significant and interrelated public health and environmental issues. Approximately, 800,000 deaths annually worldwide can be attributed to urban pollution of which a significant portion is generated by vehicles [Kenworthy et al., 2002].

Another potential benefit from using hydrogen as transportation fuel can be found in the form of noise reduction. If hydrogen is utilized in conjunction with a fuel cell, the noise created by vehicles could be drastically reduced. This is achieved since the car is powered by an electric motor and thus does not have any of the vibration or exhaust noise created by a typical internal combustion engine vehicle. Some of the effects caused by noise pollution can include hearing loss, cardiovascular problems, and inherent unpleasantness.

Globally, the pace of research and development on hydrogen infrastructure technologies is being accelerated. As the complexity of transitioning from a well-entrenched energy system has become apparent, the focus has switched from generating ultimate visions to transitions strategies. Currently, government organizations, such as the U.S. Department of Energy (DOE) and U.S. Department of Transportation (DOT), are researching, developing, and validating hydrogen pathways in an effort to establish a business case. For example, working with industry, academia, and the national labs, the DOE developed a long-term plan for moving toward widespread implementation of hydrogen technologies. In addition, to support the expanded use of hydrogen vehicles, the DOT Research and Innovative Technology Administration (RITA) is pursuing hydrogen infrastructure research that analyzes various production and delivery concepts in order to assess the United States' ability to reliably supply adequate amounts of hydrogen.

1.2. HISTORY OF TRANSPORTATION ENERGY

From the beginning of time, wood was used to provide light and energy for cooking. As time progressed, it was found that by transforming wood into charcoal, a higher and cleaner flame could be produced. During the 1700s and 1800s, coal became the favored fuel as it provided a higher energy density per weight, even higher flame temperature, and did not require vast forest resources. These attributes provided the energy needed to power the first steam powered machinery, which brought about the Industrial Revolution. The use of steam for power also ushered in the production of the first self propelled car on record in 1769. By 1807, Francois Issac de Rivaz invented the first internal combustion powered automobile designed to burn hydrogen. Unfortunately, the designed proved to be unsuccessful. During the 1830s, the first electric car became a reality and later gained widespread support by the late 1800s. In 1885, Gottleb Daimler invented what is recognized as the prototype of the modern gasoline engine. A year later, Karl Benz received the first patent for a gasoline fueled car. Initially, electric vehicles out sold all other types as they did not produce the vibration, smell and noise problems associated with steam and gasoline propelled cars. By the 1920s, gasoline had become the leading source of power as a result of providing a longer driving range between refuelings. The utility of this attribute was magnified as the road system in the United States improved during this same period. The quest for an alternative to gasoline began in 1970s due to the energy crisis. During the time period, both natural gas and hydrogen garnered attention as potential vehicle fuels. After the energy crisis receded, the use of natural gas vehicles in niche markets continued as there was already a distribution network for natural gas. Production of hydrogen vehicles never went past singular production due to storage issues and the lack of fueling infrastructure. In the 1990s, interest in hydrogen began again for a variety of political and environmental reasons. Currently, interest in hydrogen and all electric vehicles has gained support from a diverse group of stakeholders and has the potential to change the paradigm by providing an energy efficient and clean future.

1.3. HISTORY OF HYDROGEN

Hydrogen was first recognized as a distinct substance in 1766 by English chemist and physicist Henry Cavendish. The first large scale use of hydrogen was in early the 1800s. Town gas, a combination of hydrogen, methane and carbon dioxide, was manufactured from coal and supplied light and heat for parts of America and Europe until the mid 1900s. Town gas is still in use in parts of Europe and Asia. Natural gas displaced town gas when large natural gas fields were discovered and the pipeline networks to deliver it were installed. A related event occurred in 1845 when Sir William Grove demonstrated Christian Friedrich Schoenbein’s discovery of the combination of hydrogen and oxygen to produce water and electricity on a practical scale by creating what he termed a “gas battery”. Hydrogen later found another large scale industrial application when, in 1910, Chemist Carl Bosch commercialized the process developed by Fritz

Haber in 1908 to manufacture ammonia from hydrogen and nitrogen gases. This innovation lead to the development of synthetic fertilizers which has had a profound impact on agriculture and is still in use today for making ammonia. In addition, hydrogen is also used in the food processing, semiconductor, glass, and steel industries, as well as by electric utilities as a coolant for large turbine generators.

The first proposal of a hydrogen-based renewable energy economy was made by J.B.S. Haldane at a meeting of the Heretics at Cambridge University in 1923 where he proposed a network of hydrogen-generating windmills [Haldane, 1923]. In addition, German engineer Rudolf Erren, converted internal combustion engines in trucks, buses, and submarines to use hydrogen and hydrogen mixtures during the 1920s. These events spurred some interest, which later faded during World War II. The second wave of interest was initiated by the development of the first practical fuel cell by Francis T. Bacon in 1959. Later in the same year, the first fuel cell vehicle, a 20 horsepower tractor was first demonstrated. Interest continued through the 1960s and 1970s due partly to NASA's use of hydrogen for rocket propulsion, and in conjunction with fuel cells to power the space capsules and later the space shuttle. The other major event that continued interest in hydrogen happened in 1973 when the OPEC embargo sent a supply shock through the world, which demonstrated the need for alternative fuels. But again, support dwindled in the 1980s after the 1970s energy crisis subsided.

In the late 1990s, researchers began to make strong arguments advocating hydrogen as an alternative fuel. The differentiating factor with the current wave of interest is that, unlike the previous two, it has gained support from industrial companies, as well as from a continuously growing level of government backing. An example of such support includes the U.S. Congress's passage of the Spark M. Matsunaga Hydrogen Research, Development, and Demonstration Act in 1990, which created a blueprint for hydrogen research and development in the United States. Another major sign of government support can be found in the 2003 State of the Union Address which announced a $1.2 billion hydrogen fuel initiative. In addition, the Energy Policy Act of 2005 and the Energy Independence and Security Act of 2007 are providing continued support. Signs of industrial support can be found in the numerous and continuously improved upon fuel cell powered vehicles that have been introduced by various vehicle manufacturers throughout the last decade.

1.4. TRANSITION STRATEGIES FOR A HYDROGEN ECONOMY

Although many scenarios, visions, backcasts and forecasts have developed many potential hydrogen based systems, few studies have presented truly comprehensive transitional roadmap strategies. The use of scenarios, visions, and similar methods does provide a means of handling the uncertainty in the areas of energy and transportation, which have long planning horizons. In addition, the publication of research exploring the future potential of hydrogen energy contributes to the propagation of ideas and aids in the development of common expectations of a hydrogen system.

The great strength to roadmaps is that they identify barriers and solutions with target dates attached to key events. The roadmap itself also provides a common plan that can increase stakeholder confidence, while at the same time be used to measure progress. In addition, the process of constructing a roadmap is beneficial as it brings stakeholders together in a common forum where roles and timing of significant decisions can be agreed upon. Within the U.S., the Department of Energy (DOE) [DOE, 2002] and the National Hydrogen Association (NHA) [NHA, 1999] each have produced a hydrogen roadmap.

1.4.1. Department of Energy Roadmap. The Department of Energy’s vision and roadmap identify a four phase transitional plan. Phase one highlights the need for significant research progress, specifically to reduce the cost/power output of fuel cells. During this phase, continued demonstrations of hydrogen vehicles, especially in non-attainment areas, is expected. In addition, the use of hydrogen in stationary applications to provide heat and power is mentioned. A final significant point mentioned is the need for liability, permitting, and codes and standards to be addressed. Currently, the U.S. is transitioning forward from phase one. During phase two, a continued decrease in fuel cell costs is expected due to the development of large scale manufacturing. It is also anticipated that natural gas reforming will remain the predominated supply feedstock even though the first use of renewables is expected to take place. The introduction of power parks and fueling stations with distributed hydrogen production systems is expected to take place. Federal and state governments are expected to begin to serve as early first adopters of hydrogen technology. During phase three, market penetration of fuel cell vehicles is anticipated to be widespread. It is expected that most of the research will focus on advanced hydrogen storage techniques. Expansion from local pockets of hydrogen development into a national infrastructure is also projected to take place. Additionally by this time, siting and permitting will be streamlined in order to aid in expansion of infrastructure. The beginning of phase four signals the mass adoption of hydrogen for most end-use energy market applications. Expanded usage of renewable energy will take place with remaining carbon generating facilities either sequestering or utilizing the carbon in other applications.

1.4.2. National Hydrogen Association Roadmap. The National Hydrogen Association roadmap is constructed around two central markets – transportation and stationary power generation [NHA, 1999]. Specific goals for transportation market adoption are included with the expectation that 50% of all new buses be hydrogen powered by 2010. However, currently it is expected that this target will not be met. The report also identifies key barriers to market penetration in the transportation sector, including high initial costs and the need for coordination of infrastructure and vehicle deployments. It is mentioned that locations near hydrogen plants and by-product hydrogen sources provide opportunities for early market entry.

The goals for fixed power generation include, by 2015, 10% of all new electrical generation capacity should be from hydrogen power cogeneration fuel cell systems. The market barriers for stationary usage are not expected to be as overwhelming as hydrogen transportation is not required. In addition, the permitting and safety concerns are expected to be less since the power plants would be operated by trained utility workers. Although these benefits would suggest a focus on stationary cogeneration systems, such systems would not significantly contribute to a reduction in oil imports or reduce air pollution as they are typically fueled by natural gas.

In general, the NHA roadmap focuses more on the near term and midterm with only specific goals set out to 2015. In contrast to DOE plans, portable power systems are not mentioned as taking part in the introduction of the hydrogen economy. In summary, the completeness of the roadmap can best be summarized by the self description “It should be considered a skeleton, outlining the direction, with details to filled in..”.

1.5. RATIONALE FOR STUDY

Although many arguments demonstrate the role hydrogen could play in addressing pressing dilemmas such as energy stability, economic competiveness, and environmental concerns. The design of an economically feasible hydrogen infrastructure has been perceived as an insurmountable hurdle that will inhibit the introduction of hydrogen vehicles. Further, the National Academy of Engineering [NAE, 2004] noted that the evaluation of a combination of generation technologies and distribution methods to determine which systems should be utilized on a local and regional basis needed to be completed. The development of a high quality hydrogen supply chain is also exacerbated by the high costs and energy requirements required to distribute hydrogen. These costs represent a significant fraction of the total “at the pump” costs if central production is utilized and are heightened during the introduction period due to the likely dispersed demand locations. Finally, the timing of infrastructure deployment including the use of centralized and decentralized production, the interaction between stakeholders, and safety regulations are chief among the various policy issues that also need to be addressed. These concerns could slow the penetration of hydrogen into the transportation market even if production cost and energy efficiency targets could be met and were highlighted in [NAE, 2004].

This work investigates both hydrogen production and usage. First, the work evaluates near term production and delivery technologies. Next, analysis on a wind-based hydrogen system to determine the theoretical hydrogen generation capability of a wind-hydrogen system on a state level basis is presented. In addition, the ability of the system to internally meet the demand for hydrogen created by the conversion of light duty vehicles (LDV)s to hydrogen vehicles is considered. A cost comparison of transmission and distribution methods is also presented. A transitional scenario based on a combination of existing hydrogen production and a wind-hydrogen system is also discussed.

The third section of this work specifically addresses hydrogen fueling stations. The design of a hydrogen station network involves several aspects including identifying the optimal location and time to construct the station, as well as, the appropriate size. Related to the station size is the station utilization rate, which has a significant effect on the local hydrogen price. The costs associated with over sizing a station have to be balanced with lost sales. For example, the size of the station cannot be under sized to insure high utilization without risk of alienating drivers who are unable to be serviced due to a lack of fuel. Further, fueling stations need to be sized to include future anticipated fueling needs as component, planning, and construction lead times for hydrogen facilities can be significant, often adding delays and increased expenses. The cost target for delivered hydrogen also has a complementary role in the proper sizing of a station. As the price of hydrogen exhibits an inverse feedback interaction with the adoption rate of fuel cell vehicles, this behavior has a compounding cyclical effect [Keles et al., 2008]. These conditions highlight the importance of properly designing the initial network of hydrogen fueling stations. This work will address the aforementioned issues by determining optimized hydrogen station capacities based on market conditions. The modeling utilizes a newsvendor framework with an outside option. The outside option creates a realistic environment where the consumer has the ability to select between hydrogen and another fuel. Finally, a summary of the conclusions from this work and areas for future research is presented.

2. THE FORCES AFFECTING THE ADOPTION OF HYDROGEN

This section provides additional background on the previously mentioned drivers of technological competiveness, energy stability, and current focus on expanding the usage of renewable sources of energy. The section also briefly addresses consumer attitudes towards hydrogen.

2.1. SOURCES OF HYDROGEN DEMAND

2.1.1. Stationary Applications. Cogeneration fuel systems are attractive as they provide heat and power, and in the future may provide a convenient source of hydrogen for transportation fueling. Most of the heat generated by the system is captured and may be used for heating either air or water. In addition, the increased efficiencies of such systems raise the economic prospectus of hydrogen usage. The overall process of converting natural gas to electricity in a fuel cell system is approximately 30% efficient without cogeneration. In comparison, if a cogeneration unit is utilized, total efficiency is increased to over 80% [UTC, 2009].

Backup power systems are used in many industries where operation of critical systems is required regardless of power availability. Mahadevan et al. [2007] indentifies that emergency response team radio towers, the consumer telecommunications industry, and government agencies such as the FAA, NOAA, DoD are where fuel cells provide a unique value proposition currently or in the near term. In order to gain an understanding of the effect these areas could have on the broader introduction of hydrogen usage, the U.S. market size for first responder towers is approximately 15,000 towers [Mahadevan et al., 2007].

2.1.2. Mobile and Transportation Applications. Mobile backup power units are a niche market where the properties of fuel cells offer unique advantages. Areas where rugged, highly-reliable, conditioned power is a requirement fuel cell units are useful. In addition, the near silent and relatively low heat signature of hydrogen fuel cells are attributes that have sparked interest by the DoD for use in reconnaissance missions where such features are key to maintaining a stealth profile. Mobile hydrogen fuel cells also can provide a critical power source for emergency responders where grid connected electricity is not always available.

Specialty vehicles such as forklifts and airport tugs are another source of demand for hydrogen fuel cells. The current market in the U.S. for such vehicles includes approximately the current use of 84,000 forklifts, 4,000 baggage tugs and 3,600 aircraft pushback tractors [Mahadevan et al., 2007]. The use of hydrogen fuel cells in forklifts chiefly addresses the long recharge times and recharging equipment space requirements indicative of battery systems which represent 58% of the total market. As the only emission from a hydrogen fuel cell is water, the use of fuel cell airport tugs also addresses air quality issues around airports. In addition, such vehicles have the power to tow heavy aircraft that battery only variations are unable to do. Another mobile application market consists of personal vehicles such as scooters and Segways. These vehicles have been mentioned due to their low power requirements. In addition, the use of hydrogen to power such vehicles avoids the battery recharging times since prototypes “recharge” by swapping hydrogen canisters.

The ultimate goal considered by many is the introduction of hydrogen as a fuel for transportation. Hydrogen fuel cell buses have been in use throughout the world in mass transit systems since 1998 when three fuel cell buses were incorporated into the Chicago mass transit system (Raman, 1999). The HyFleet: Clean Urban Transport for Europe (CUTE) demonstration project operated 47 hydrogen buses on three continents (HyFleet, 2009). In addition, select universities, including Missouri S&T, and shopping centers are operating shuttle services which utilize hydrogen powered buses. Such a viewpoint is based upon the ability of hydrogen usage in automobiles to address several diverse needs including reducing dependence on foreign oil and reduction of greenhouse gases.

2.1.3. Relationship Between Demand Sources. There are two prime connections between the stationary and mobile sectors. First, the economics and unique aspects of fuel cell systems in certain niche markets (cogeneration and backup power systems) are expected to increase demand for critical infrastructure components. The increase in demand is expected to decrease component costs, lowering the adoption costs in more price sensitive markets. The second connection is expansion of infrastructure and increased awareness. The introduction of hydrogen refueling infrastructure is considered the major factor that could limit the successful introduction and adoption of hydrogen vehicles. Cogeneration systems are able to be designed to serve two purposes 1) produce and store hydrogen for vehicle use and 2) provide hot water and electricity. The multifunction capability decreases investment risk, while providing critical initial fueling capability. In addition, it is anticipated that as more hydrogen systems are used, any public concerns over the use of hydrogen would decrease, increasing the adoption of hydrogen. The use of transit buses serves a similar purpose as they promote hydrogen to the masses through personal usage, while the central fueling locations add to the initial infrastructure. For these reasons, some including the Department of Energy feel the inclusion of markets other than automobile usage is critical in order to develop a sustainable hydrogen economy.

2.2. SUSTAINABILITY OF HYDROGEN

The development of a sustainable hydrogen infrastructure is multifaceted. Issues ranging from uncertain costs associated with production and delivery to government policy concerning energy and the environment will continue to affect the introduction and sustained use of hydrogen in the United States. However, the role and to what degree each issue will affect the decision is debatable [McDowall and Eames, 2006]. In addition, there is uncertainty as to what level the participation of social priorities will influence adoption and expanded usage of hydrogen. When evaluating the affect the presented issues have on potential hydrogen pathways, one must look at the feasibility and practicality both in the short and long term. Long term visions provide little if there is no viable transition pathway. Conversely, if only short term viewpoints are discussed, highly ideal solutions in the long term can prematurely be discarded and the effectiveness of continuous building in support of a long term goal can be lost. The possibility of disjointed efforts is only exacerbated by the likelihood that any transition from the entrenched fossil fuel energy system to one based upon hydrogen would take decades to evolve. Based upon this viewpoint, infrastructure/fuel costs and political and policy frameworks are the most important aspects for sustainability in the United States. This view point was first supported by the United Nations [UN, 1987].

What exactly "sustainability" means is in of itself a source of great debate. The most common definition of sustainable development was put forth by the World Commission on Environment and Development. In the commission's seminal report, "Our Common Future", they wrote "Humanity has the ability to make development sustainable – to ensure that it meets the needs of the present without compromising the ability of future generations to meet their own needs" [UN, 1987]. The commission also stated three core principles in relation to sustainability. The first is that humans have always and will continue to have an impact of Earth. Second, the human race will ultimately fail in common goals of family and community if we do not find sustainable ways to interact with the environment and each other. Third, and probably the most fundamental, is the belief that sustainable development has to focus on a triangular balance among environmental protection, social development, and economic development.

2.2.1. Economic Considerations. The uncertainty of supply feedstock prices certainly will have an effect on the adoption of hydrogen. Without reliable projections a choice of production technology is complicated as the final "at the pump" costs to the consumer must be competitive if general adoption is to occur. For example, although natural gas is considered a leading feedstock, the long term commitment to its usage is diminished as price uncertainly is high. This is due in part because the U.S. will increasingly have to compete with other countries as it continues to increase the amount of natural gas it imports and as developing countries' economies expand. The use of natural gas also exhibits seasonal price fluctuations that add additional short term uncertainty to the already insecure situation.

2.2.2. Infrastructure Costs. The sustainable development of hydrogen infrastructure may technically be feasible but, unless the resources exist to support the implementation, a "hydrogen economy" is only a concept. Investors are, in general risk adverse, thus a compelling business case needs to be present in order to draw attention and investment. Of course, in order to determine whether there the resources exist, you must first determine what the possible pathways are and what the cost would be to construct the various hydrogen pathways.

2.2.3. Political and Policy Frameworks. The effect policy frameworks have on the adoption of a hydrogen economy cannot be understated. The most commonly discussed strictly social perspective related to a hydrogen economy is the public acceptance of hydrogen as a fuel. This perspective is based upon the consensus that the public lacks knowledge about this alternative fuel. However, the issue of acceptance is usually taken in the context of a barrier to uptake not an issue related to sustainability. Thus it is expected that a comprehensive public education campaign on safety and refueling practices could address this issue.

A more important issue in regards to sustainability and politics is the need for a clear national energy strategy which commits to the large scale introduction of hydrogen. Such a strategy would also need to provide sustained, long term compelling incentives for all companies involved. Such actions would increase industry and public confidence in the national energy direction. If such policy existed it would promote the sustained use of hydrogen by reducing the risk automotive and hydrogen production companies would experience. It would accomplish this by increasing the potential payback due to the long term commitment on behalf of the government. In addition, the general public would also have greater confidence in purchasing a hydrogen vehicle as they would have confidence that refueling infrastructure would be in place for at least a fixed time before any mass decommissioning of stations took place. In addition, as the build up of a comparable hydrogen infrastructure could take several decades the involvement of government is necessary to add continuity to the transition as corporate budgets typically are conducted on a yearly basis.

2.3. CONSUMER ATTITUDES TOWARD HYDROGEN

Although it has been almost four decades since the term “hydrogen economy” was coined, research has only recently investigated the public perception of hydrogen. This is notable as many, including the DOE [2002], have identified it as a barrier for market entry. An early understanding of public acceptance allows potential objections to be identified and suitable alternatives to be developed in the early stages. Some of the potential key influences related to hydrogen acceptance include knowledge, experience, safety, additional cost and environmental concern. Most published studies have been conducted in conjunction with the introduction of hydrogen buses to the local region.

A study in London [O'Garra et al., 2005] conducted just prior to introduction of hydrogen buses found that less than half of the survey respondents had heard of hydrogen vehicles and just over one third were clearly in favor of hydrogen. In addition, awareness was tied to gender, age, education, and environment knowledge. The concern among the hydrogen community is that the general public is still concerned over safety issues. However, O'Garra et al. [2005] provides a surprising contrast to the traditional expert opinion of expected word associations made with hydrogen. Prior knowledge was identified as the main contributor for those who positively supported hydrogen. This is of note as 60% of the respondents stated that they needed more information before they could make a decision.

Similar results from studies conducted in other countries support the general public's positive notion of hydrogen. A Canadian study presents similar findings regarding overall support and little opposition [Hickson et al., 2007]. Maack and Skulason [2006] report a 93% positive viewpoint for the use of hydrogen as the main fuel in buses, cars, and ships in Iceland. In addition, a majority of respondents expressed they would be willing to pay 10-20% higher fare prices in order to support a hydrogen introduction. This viewpoint is supported by a study by O'Garra et al. [2007], which specifically investigated the willingness of the public to pay higher rates for hydrogen buses. The study involved four major European cities with results indicating a willingness to pay an extra €0.29 to €0.35 per single fare. In Sweden, a survey of fuel cell bus passengers reported 74% of respondents felt that the technology was safe [Haraldsson et al., 2006]. However, in contrast to the previously mentioned studies, although 64% of passengers expressed interest in the environment, more than half of them would not be willing to pay a premium to use a hydrogen bus. The authors attribute the difference to the way the question related to the topic was formulated. In all studies, respondents expressed an interest in receiving more information about hydrogen and how a hydrogen economy would work.

In a different approach Schulte et al. [2004] developed a qualitative model in order to investigate consumer opinions. The model identifies education, marketing, and exposure to product as the three factors that influence and have a direct affect on the "values", "wants", and "perceptions" of a potential consumer. A formal education plan is suggested for school age children in order to prepare them for the future and as means to reach some adults. It is suggested that, for most adults, marketing has the potential to be effective, although mobile information centers are also suggested as a means to reach the remaining adult population. The study also stresses that "hands-on" experience would be the most important method in educating and changing public opinion.

3. LITERATURE REVIEW

3.1. HYDROGEN INFRASTRUCTURE AND TRANSPORTATION

The latest wave of interest in hydrogen is rooted in the 1960s and 1970s [Gregory and Pangborn, 1976]. Starting in the late 1990s, researchers began to evaluate potential infrastructures, strongly advocating hydrogen as an alternative fuel [Thomas, 1997; Ogden, 1999a; Myers et al., 2002; Ogden et al., 2004]. Although many in the scientific community agree that hydrogen will begin to play a critical role in the energy sector, a number of questions concerning the realization of a hydrogen economy still remain [Thomas, 1997; Ogden, 1999a; Myers, 2002; Ogden et al., 2004; Edwards et al., 2008]. Chief among these dilemmas is the lack of an infrastructure that can satisfy the increased demands for hydrogen that would result from a transformation of the light duty vehicle (LDV) market. The magnitude of this dilemma is increased by the high costs and energy requirements required to distribute hydrogen. However, current research is addressing these areas with progress being made [DOE, 2008].

To develop a hydrogen infrastructure, a variety of production and distribution options are being considered, including centralized reforming of natural gas or gasification of coal or biomass, on-site reforming of natural gas or ethanol, electrolysis (potentially using renewable energy sources), industrial by-product hydrogen, and both liquid and gaseous storage/delivery [NAE, 2004; Martin and Grasman, 2006; Turner et al., 2008; Muradov and Veziroglu, 2008]. Ogden [1999a] presents prospects for building a hydrogen energy infrastructure and reviews the current status of technologies for hydrogen production, storage, transmission, and distribution and described potential areas for future research. Depending on the source, many infrastructures can be conceptualized. Mintz et al. [2003] describes several infrastructure alternatives and the associated cost of the delivered hydrogen. A self-reported limitation of the study is that the analysis assumes little effect from technology and infrastructure maturation nor phased technology development. Winebrake and Creswick [2003] performed a perspective-based scenario analysis of various production methods using the analytic hierarchy process. Although many concepts related to meeting the projected increase in hydrogen demands created by the introduction of hydrogen vehicles have been presented, the development of a hydrogen infrastructure is one of the main unsolved issues impeding migration to a sustainable hydrogen economy.

The National Academy of Engineering identified the four factors that will most significantly affect the cost of delivered hydrogen [NAE, 2004]: 1) the feedstock used to produce hydrogen, 2) the scale of the production unit and the transportation requirements, if any, 3) the level of technology readiness, and 4) the use of carbon dioxide (CO_2) by-product sequestration if fossil fuel is used as a feedstock. In addition, Melendez [2006] identified availability and high cost of alternative fuel infrastructure as key barriers that past alternative fuels have experienced and that hydrogen is expected to face. These studies highlight the complexity of balancing the availability of refueling infrastructure with production scales and transportation costs.

Many scientists champion introducing hydrogen into the transportation sector as a vehicle fuel. This view is supported not only by the economic and environmental feasibility, but also by major improvements in overall hydrogen vehicle efficiency and performance. Myers et al. [2002] concluded that the costs of maintaining the existing gasoline infrastructure are up to twice the estimated costs of maintaining a hydrogen infrastructure. Thomas et al. [2003] also presents a scenario that includes a hydrogen infrastructure that is less costly than the existing infrastructure. This possibility is especially significant, given that a potential pathway for meeting growing hydrogen demand is to replace existing gasoline infrastructure with hydrogen infrastructure at the end of the existing infrastructure’s useful life. Melendez and Milbrant [2006] also identified a minimum infrastructure to support the introduction of hydrogen vehicles in the United States.

Researchers have steadily developed a number of case studies primarily with the focus on estimating the number of fueling stations required [Ogden, 1999b]. Melaina [2003] estimates the number of initial hydrogen stations by comparison with the existing gasoline infrastructure. A minimum infrastructure to support the introduction of hydrogen vehicles with a focus on connecting cities along major highways was identified by Melendez and Milbrant [2006]. Nicholas et al. [2004] relates the number of stations to the location of stations using geographical information systems (GIS). Nicholas and Ogden

[2007] base the placement of stations on customer convenience which is taken into by considering the average travel time to the nearest station.

Increasingly, researchers have begun to include more complete systems into the scope of the models. For example, an optimized infrastructure for Southern California based on dynamic programming is presented in Lin et al. [2008]. Johnson et al. [2008] utilized GIS to analyze the deployment of a coal-based hydrogen infrastructure in Ohio. Internationally, Strachan et al. [2009] linked a GIS model to the UK MARKAL model in order to model infrastructure from a primary energy source to demand locations. Almansoori and Shah [2006] present a steady-state snapshot of a future hydrogen supply chain in Great Britain using mixed integer linear programming, and Lin et al. [2006] present a model with application to urban Beijing. The size and cost of a hydrogen delivery system in Europe is discussed in Tzimas et al. [2007]. In another mixed integer linear program, the design of a hydrogen infrastructure for South Korea is presented [Kim and Moon, 2008].

While little work has been done on modeling of phased infrastructure development, Thomas et al. [1998] provided some early thoughts on economically viable hydrogen infrastructure development, including the idea of combining electrolyzers and small steam methane reformers incrementally to match the growth in demand. However, actual models for implementation of the supply chain infrastructure are not discussed. More recently, Martin and Grasman [2009] present a transition scenario utilizing a combination of existing hydrogen production and wind-hydrogen systems. Yang and Ogden [2005] present an analysis for transitioning from distributed to centralized production (via natural gas) for an idealized city. In one of few quantitative models, Hugo et al. [2005] utilize mixed integer linear programming to identify optimal investment strategies and integrated supply chain configurations from many potential pathways. Using multi-objective analysis the paper addresses both investment and environmental criteria in order to provide tradeoffs representing conflicting design alternatives. Brey et al. [2006] present a plan for the gradual transition to a hydrogen economy in Spain. The multi-objective nonlinear programming model addresses hydrogen production, transportation and consumption, as well as renewable energy sources, for each region of Spain. Ball et al. [2007] discuss a mixed-integer linear optimization model which focuses on linking electricity and hydrogen generation in Germany. Schwoon [2007] utilizes a combination of agent based trip modeling and GIS to construct various snap shots of the initial distribution of hydrogen filling station in Germany with a focus on providing highway fueling. Of particular note is the HyTRANS model which is a dynamic non-linear model that focuses on the early hydrogen transition and incorporates hydrogen production, fuel cell vehicle manufacturing and consumer behaviors [Greene et al, 2007]. In addition, Struben and Sterman [2007] combine economic and behavioral aspects of drivers and potential hydrogen station owners to determine a critical threshold for sustained adoption of hydrogen as a vehicular fuel. A final transitional stage model of note is a computer agent-based model being developed by Mahalik et al. [2009], which focuses on the early dynamics of both potential fuel cell vehicle drivers and of hydrogen infrastructure investors.

The design of a hydrogen station network involves several aspects including identifying the optimal location and time to construct the station, as well as, the appropriate size. Related to the station size is the station utilization rate which has a significant effect on the local hydrogen price. The costs associated with over sizing a station have to be balanced with the underage costs. For example, the size of the station cannot be under sized to insure high utilization without risk of alienating drivers who are unable to be serviced due to a lack of fuel. Further, fueling stations need to be sized to include future fueling needs over a determined planning period as component, planning, and construction lead times for hydrogen facilities can lead to increased expenses. The cost target for delivered hydrogen also has a complementary role in the proper sizing of a station. A variety of cost models have been developed including work by Amos [1998], Simbeck and Chang [2002], Ogden et al. [2005], Weinert et al. [2006], Yang and Ogden [2007], and U.S. Department of Energy's H2A models [DOE, 2005]. However, the evaluated station sizes are either assumed to be identical or as a percentage of output of current gasoline stations. As the price of hydrogen exhibits an inverse feedback interaction with the adoption rate of fuel cell vehicles this behavior has a compounding cyclical effect [Keles et al. 2008]. These conditions highlight the importance of properly designing the initial network of hydrogen fueling stations.

3.2. WIND-HYDROGEN ENERGY SYSTEMS

General interest in a wind-hydrogen system has increased partly because the price of wind power has become competitive with traditional power generating sources in certain areas. Due to the characteristics of a wind-hydrogen system it has the potential to play a complementary role during the mass introduction of hydrogen [Elam et al., 2003; Sherif et al., 2005; Segura et al., 2007; Greiner et al., 2008]. Wind energy technology has vastly improved with systems now operating at efficiencies that reach up to 80% of the theoretical possible energy flow [Thresher et al., 2007]. Chen et al. [2008] provides a review of modern wind power systems.

Although there are inherent challenges to introducing wind power into power systems such as, extending transmission lines to remote areas, Georgilakis [2008] states that incorporation of up to 20% wind power into the electrical grid would only have a moderate impact on grid stability and operations. The generation of hydrogen can also be used to address stability concerns such as during otherwise idle wind farm periods [Mantz and Battista, 2008]. By providing a means of energy storage, hydrogen provides a mechanism to utilize excess energy, thereby increasing the productivity of wind farms. Further**,** the use of a wind-hydrogen system could provide a pathway in which to address reliability concerns related to high penetration rates of intermittent energy generation sources incorporated into the U.S. energy grid [NAERC, 2008]. Kruger [2008] identified a wind-hydrogen system as an appropriate technology for distributed hydrogen applications based upon specific energy, although there is concern what effect connected distributed systems would have on the current U.S. electrical grid. A temporary method to address capacity strain questions would be to generate and store hydrogen during off-peak times.

Combining wind energy and hydrogen also addresses sustainability issues. Wind-generated electricity prevents many negative environmental impacts and addresses other drawbacks that surround most other electricity generating technologies [Moriarty and Honnery, 2007]. These issues include storage of nuclear waste, need for cooling water, dedicated land use, greenhouse gas emissions, and depletion of nonrenewable fossil fuel resources. The combination also addresses transportation related issues involving greenhouse gas emissions and water management by providing a potentially zero carbon production and delivery pathway for hydrogen.

Further, the U.S. uses approximately 300 billion gallons of water per year in the production of gasoline compared to the estimated 100 billion gallons of water required for a complete conversion of the U.S. light-duty fleet of vehicles to electrolytic hydrogen [Turner, 2004]. Hydrogen produced utilizing wind energy can approach 3 USD per kilogram in the near future comparable to 0.79 USD per liter gasoline [Bockris and Veziroglu, 2007]. In addition, water and electricity are generally not as sensitive to political or seasonal concerns as other hydrogen production feedstocks. Prince-Richard et al. [2005] examined the key technical and economic parameters influencing the competitive position of electrolysis.

Although, there are efficiency penalties associated with hydrogen generation by electrolysis. Using wind-generated electricity in conjunction with electrolysis addresses future infrastructure concerns. An integrated system, provides a reliable design concept for distributed power and subsequent hydrogen generation. Onsite production of hydrogen would alleviate the need for mass transportation of hydrogen and reduce the impact of natural disasters by adding redundancy to the transportation fuel sector. The scalability of electrolysis affords the opportunity to better match demand since the efficiency of such a system is largely independent of size. In addition, wind energy systems can be designed to be installed in a modular fashion, creating flexibility for the energy company by avoiding the large single capital outlays typical of traditional power generating facilities.

4. A FEASIBILITY STUDY FOR HYDROGEN ECONOMY INFRASTRUCTURES

The development of a hydrogen infrastructure is one of the main unsolved issues impeding the migration to a hydrogen economy. Numerous methods have been presented in the literature on how to meet the projected increased hydrogen demands created by the introduction of fuel cell vehicles. One leading early method includes transporting hydrogen from existing hydrogen production facilities to key fueling points. In this paper, systems analysis will be employed in order to investigate possible hydrogen architectures. Short and long term feasibilities of various hydrogen alternatives, including currently available technologies and the dynamic design of sustainable architectures, will be discussed.

4.1. INTRODUCTION TO A HYDROGEN ECONOMY

A sustainable hydrogen energy industry is key if an environmentally and economically stable world is to evolve in the future. The establishment of a hydrogen economy is a multifaceted challenge with three general areas needing to be addressed: physical, economic and policy. Some of the physical concerns include geography, technology and environmental impact. For example, the use of a hydrogen generation technique in one region might not be the "best" option in another region. Studies need to be undertaken to evaluate the combination of generation technologies and transportation methods to determine which system should be utilized. Consumer cost for hydrogen and capital costs for development of the infrastructure are some of the economic items which need to be determined. These variables are key to a successful transition from a petroleum-based economy. A viable initial system must provide hydrogen at a competitive price, while utilizing a low initial investment infrastructure to encourage investment. The interaction between stakeholders and regulations are chief among the various policy issues that must be addressed. Government and organization officials must provide standards to provide assurance to equipment manufactures that propriety designs will be accepted in the future.

There are many advantages associated with this transformation, notably, decreased greenhouse gas emissions and dependence on foreign oil. As the largest emitter of carbon dioxide, the U.S. accounts for 23% of energy-related carbon emissions worldwide. In 2003, 1,112 teragrams of carbon dioxide were emitted in the U.S. as a result of the combustion of gasoline and diesel fuel in motorcycles, automobiles, light duty trucks and buses [EPA, 2005]. The continuation of such releases will only exacerbate global environmental problems attributed to greenhouse gas emissions. In 2004, 3.7 billion barrels of crude oil were imported into the U.S., of which approximately 45% was refined into gasoline. In perspective, if the fraction of imported oil used for gasoline production was no longer needed due to the use of hydrogen, then the crude oil savings on a yearly basis would be greater than twice that of the U.S. strategic petroleum reserve [DOE, 2005].

Many scientists champion that hydrogen should be introduced first in the transportation sector as a fuel for fuel cell vehicles (FCVs). Fuel cell vehicle development is progressing rapidly with major improvements in fuel cell power density and overall vehicle efficiency and performance. All fuel cells currently being developed for near-term use in road vehicles require hydrogen as a fuel. While onboard vehicle production can be accomplished by reforming methanol or gasoline, direct storage of compressed hydrogen for use as a fuel has many attractive advantages. The vehicle is less costly, more energy efficient, and simpler to design. In addition, hydrogen can be produced from a variety of sources if produced at a stationary source along with taking advantage of economies of scale. Determining the best hydrogen production method and timing for the introduction of a hydrogen economy are not trivial tasks; there exists a myriad of potential combinations of production technologies and delivery methods. These are summarized in Figure 4.1. Leading sources for hydrogen in the initial phase of infrastructure development are industrial-scale steam methane reforming (SMR), onsite electrolysis and SMR, and the use of excess and easily upgradeable commercial hydrogen production capacity.

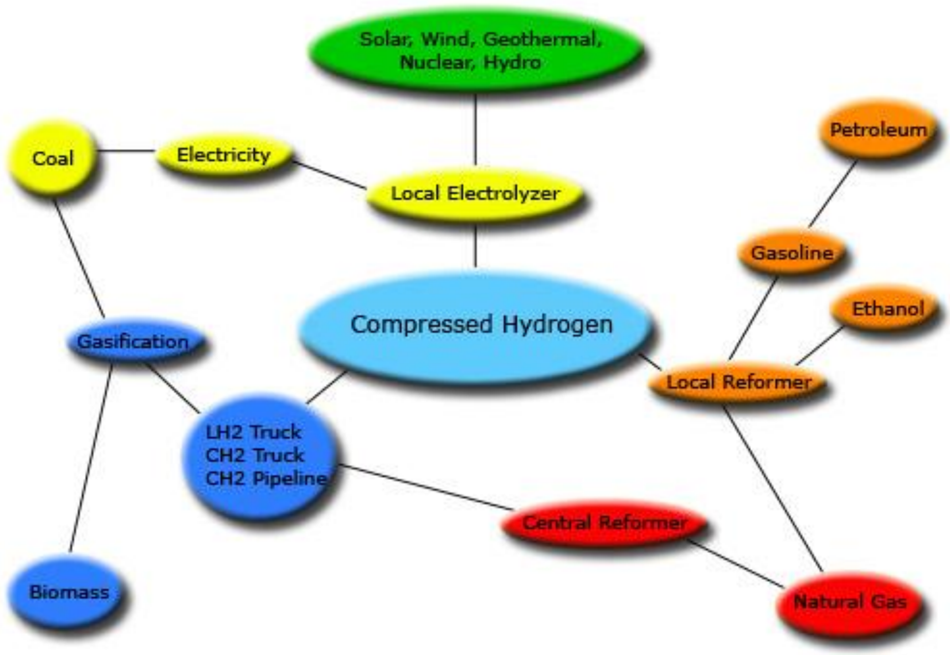

Figure 4.1 Hydrogen Production Techniques

4.2. LITERATURE ON HYDROGEN INFRASTRUCTURE

The scientific community is currently experiencing a renewed interest in hydrogen as an energy carrier. The first support for hydrogen began after a talk by J.B.S. Haldane at Cambridge in 1923, but interest slipped during World War II. The second wave was initiated by the development of the first practical fuel cell by Francis T. Bacon in 1959, but again support dwindled after the energy crisis in the 1970s subsided. The differentiating factor with this wave of interest, unlike the previous two, is that it has gained support from industrial companies, as well as from continuously growing government backing. However, a classic "chicken and egg" problem has deterred potential stakeholders from moving past developmental stages. Manufacturers are unwilling to produce vehicles without a refueling infrastructure in place and fuel producers are unwilling to invest considerable resources into an infrastructure when there is a high degree of uncertainty with respect to future demand. The design of an economically feasible hydrogen infrastructure has been perceived as an insurmountable hurdle that will inhibit the introduction of FCVs.

The latest wave of interest in hydrogen has its roots in the 1960s and 1970s [Gregory and Pangborn, 1976]. In the late 1990s, researchers began to evaluate potential infrastructures with strong arguments advocating hydrogen as an alternative fuel [Thomas, 1997] [Myers et al., 2002] [Ogden, 1999a] [Ogden et al., 2004]. As research progressed, researchers began to apply the developed scenarios to individual case studies. For example, Ogden [1999b] evaluated various centralized and distributed production methods for the Los Angeles Basin. The paper concluded that there were sufficient existing resources in the Los Angeles Basin to support potentially as many as 138,000 FCVs without building additional generation facilities. A study prepared for the California Fuel Cell Partnership [BKI, 2001] recommended that any early demonstration of FCVs entail the use of fleet or government vehicles. The study supported this position because it provided a means to increase public awareness and demand, which resulted in the study's FCV sales rate milestones of 40,000/yr and 100,000/yr to be met. The conclusions from a study on the feasibility of introducing FCVs in Italy also favored the introduction of fuel cells into buses and fleet vehicles as an initial phase [Mercuri et al., 2002], because of the centralized refueling practices of such systems. A recent study of the London bus system evaluated how an infrastructure might develop to support the conversion to fuel cell powered buses and how it might provide a suitable platform to expand upon in order to provide fuel to private vehicles [Joffe et al., 2004]. The model predicted fuel demands with accuracy and provided a rigorous assessment of different technology scenarios as it took into account refueling schedules and component flexibility.

In 2004, the National Academy of Engineering published one of the most thorough reports on hydrogen infrastructure and vehicle technologies [NAE, 2004]. This report indicated that there were four main challenges to introducing hydrogen vehicles: 1) development of inexpensive fuel cells and hydrogen storage methods; 2) development of a hydrogen refueling infrastructure; 3) required reductions of production costs from renewable resources; and 4) increased development in carbon sequestration and storage. In addition, the interaction of the technology related economic aspects with geography and competitive markets was not found to be understood with any proficiency. Also mentioned in the report was the inclusion of indirect variables in future analyses as it is speculated they would improve the understanding of how the technology pathways might unfold over time. Finally, the report mentioned that a systems analysis may be useful in assessing the interactions among the various components.

This section aims to initially present an overview of the critical requirements for an effective hydrogen infrastructure. Following the establishment of performance measures, a discussion of the leading production and transportation methods, including the pros and cons of each method, will be presented. The section will then conclude with an explanation of a viable introduction phase and areas of future work.

4.3. SYSTEM WIDE REQUIREMENTS

Consumers will likely be unwilling to travel excessive distances outside their normal routines to obtain fuel. As a result, any potential infrastructure will need to provide an acceptable level of convenience in order for it to be considered as a viable option. In order to provide effective coverage, the placement of fueling points must balance between demand locations, available sites, and costs. If FCVs are to gain mass acceptance with the general public over the long term, then the price of hydrogen must not inhibit growth. The consumer price of hydrogen must be comparable on a per mile basis to that of gasoline on a regional basis. A low initial infrastructure cost is an additional highly desirable attribute of any potential hydrogen delivery system. If an initial system with a low infrastructure can be designed a major barrier to bringing about a hydrogen economy will be overcome. The system also needs to increase public awareness and acceptance of hydrogen. Eventually, as demand for FCVs increases, manufacturers will increase production, thus lowering manufacturing costs and making them accessible to a greater percentage of the public. The technologies that potentially could be utilized in fulfilling the system wide requirements will now be discussed.

4.4. PRODUCTION METHODS

Three current leading sources of hydrogen will be presented in this section: steam methane reforming, electrolysis, and excess production capacity.

4.4.1 Steam Methane Reforming (SMR). Steam methane reforming involves four basic steps. Natural gas is first catalytically treated with hydrogen to remove sulfur compounds. It is then reformed by mixing it with steam and passing it over a catalyst, producing carbon monoxide and hydrogen. This step is followed by a catalytic water-gas shift to convert the carbon monoxide to hydrogen and carbon dioxide. Finally, the hydrogen gas is then typically purified using pressure swing adsorption (PSA).

The centralized SMR approach would entail construction of large commercial-scale production facilities, including storage tanks to ensure supply during shutdowns. Large commercial SMR plants already exist and currently provide a vast majority of the hydrogen used in the petroleum and chemical industries. Centralized production is more energy efficient than onsite production, but it is complicated by requiring a distribution network. If centralized production facilities are used, then carbon dioxide can be captured for sequestration, thus providing a semi-green option. The downside is that sequestration concepts and technologies are relatively new, and no universally accepted method to permanently store the carbon dioxide has been agreed upon.

Onsite SMR would entail using the same technology as central production, but on a smaller scale (see Figure 4.2). The capital costs per kilogram of hydrogen produced are considerably larger for a small steam reformer than for a central production operation. Onsite production also has safety considerations associated with producing hydrogen in urban areas. In addition, the need for a constant source of natural gas might limit feasible construction locations. Onsite does provide the benefit of distributed production, thus adding redundancy of supply points for each region. The use of onsite SMR also creates the opportunity to introduce hydrogen to a region utilizing a proven technology and with less initial construction costs.

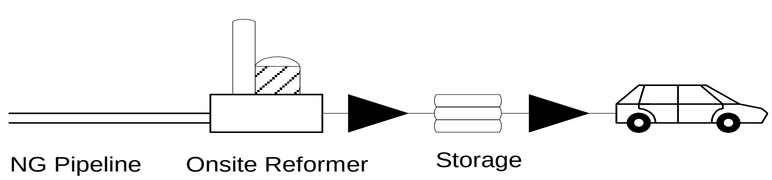

Figure 4.2 Onsite Natural Gas Reforming

Compared with other fossil fuels, natural gas is a cost-effective feed for producing hydrogen, in part because it is widely available, easy to handle, and has a high hydrogen to carbon ratio. However, natural gas is already imported into the United States, and thus an increased use of natural gas would only add strain to the current system. In addition, natural gas prices are volatile and are very sensitive to seasonal demand.

4.4.2. Electrolysis. Electrolysis chiefly consists of passing an electric current through water, which results in the disassociation of water into hydrogen and oxygen. The basic components of such a system would include an electrolyzer, compressor, intermediate storage tank and dispenser unit (see Figure 4.3). As the only resources required to operate are water and electricity, the possibility to install a fueling location exists virtually anywhere. Also, water and electricity are not as sensitive to political or seasonal concerns as natural gas.

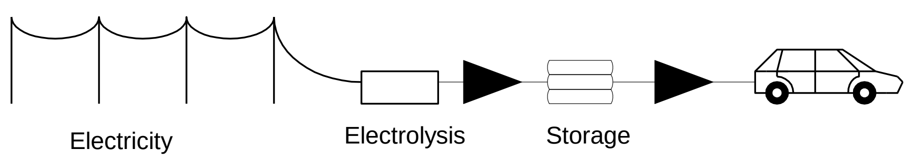

Figure 4.3 Onsite Electrolysis

In areas where the price of electricity is dependent on the time of day, an alternative would be to install increased storage capacity so the entire daily fuel demand could be generated during the lower priced off-peak times. By using renewable sources of energy such as solar, wind, and hydro power, the electrolysis option can produce hydrogen fuel without generating any carbon dioxide emissions. An electrolyzer's efficiency is independent of size; therefore it can be scaled to a variety of generation rates with marginal cost increases. The downside to this technology is that the overall energy efficiency is less than that of SMR. There is also concern regarding how the national power grid would handle the increased load.

4.4.3. Excess Production Capacity. The use of excess production hydrogen presents a low initial infrastructure investment option. Potential sources include ammonia, methanol and commercial hydrogen plants in addition to oil refineries (see Figure 4.4). In particular, refineries and commercial hydrogen production facilities could serve as the hydrogen source in California and Texas. Approximately, 275 vehicles/day could be refilled by using only 1% of the hydrogen produced at a typical oil refinery. In the Midwest, ammonia production plants could serve as the chief source for the region as hydrogen is produced as a feedstock. Finally, refineries in New Jersey and Pennsylvania could be used to supply the Northeast with hydrogen fuel.

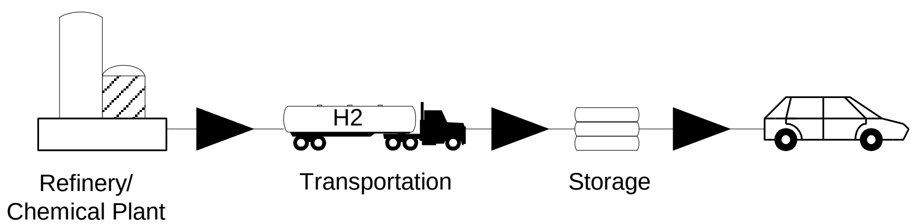

Figure 4.4 Excess Production Capacity Delivered by Trailer Truck

4.5. DISTRIBUTION METHODS

The currently available means of distribution are presented in the following section. In addition, any specific attributes about each method are also included to facilitate comparison among them.

4.5.1 Truck. The trucking option can be broken into two alternatives: cryogenic liquid and pressurized gas cylinders. The use of pressurized cylinders requires 4-8% of the energy content of hydrogen to compress it to 5000 psi. In contrast, it requires 30-40% of the energy content to liquefy and store hydrogen. Besides the increased energy demands, the transportation of liquid hydrogen requires additional equipment onsite in order to vaporize the liquid before filling of the storage system. The advantage of cryogenic liquids is that the energy density is more than twice that of compressed hydrogen on a volume basis. In addition, safety is increased because of the less destructive tendencies exhibited by liquid trailers involved in accidents when compared to gas cylinder trailers.

4.5.2 Pipeline. The installation of a pipeline system similar to the U.S. natural gas pipeline system would entail enormous initial capital expenditures and would require a large lead time for construction. There are also several technical issues associated with the pipeline option including durability and transmission costs. Depending on the composition of the steel used, embrittlement problems would have to be considered. Volumetric hydrogen flow rates are required to be about three times greater than natural gas for a given pipe size and pressure, in order to transport the same energy per cubic foot due the lower energy density of hydrogen. As the energy requirements for compressors depend on the volume of a gas, it requires three times more energy to compress hydrogen to achieve the same pressure than for natural gas. Even taking into account these disadvantages, pipeline transmission overall is the most energy efficient method to transport hydrogen.

4.5.3 Train/Ship. Currently a limited amount of liquid hydrogen is transported by train. Losses due to boil-off during transfer are approximately 10-20%. Two disadvantages when considering the use of rail include limited depot locations and the sparse amount of existing railcars. One key advantage is the capability of moving large quantities of hydrogen (over 9,000 kg liquid hydrogen per railcar) relatively efficiently. The use of ships to transport liquid hydrogen is currently not utilized. Preliminary designs include ships capable of carrying up to 14 million kg of liquid hydrogen, but the construction of such ships have been estimated to 3.5-4 times the cost of a comparable liquid natural gas transport ship.

4.6. CONCLUSIONS CONCERNING HYDROGEN INFRASTRUCTURE EXPANSION AND OPERATION

The need to initiate a hydrogen-based economy has never been more compelling than now. Instabilities in fuel prices caused by unpredictable events have far reaching effects throughout the nation’s economy. The first step toward a hydrogen economy might be to construct small commuter networks in large metropolitan areas. Two possible introductory locations for refueling networks are 1) between Los Angeles and San

Francisco and 2) between New York City and Washington D.C. These regions would provide sufficiently large populations of viable early adopters of FCVs to warrant the automotive and energy companies to make investments. These areas have shown a willingness to adopt leading technology as in the case with the sales of hybrid automobiles. The comparably higher gasoline prices in these regions will also increase the likelihood of public acceptance.

One viable system that could meet the needs of the proposed introduction phase would entail the installation of fueling points at existing conventional fueling stations. The fueling point would consist of a stationary hydrogen gas storage system that would be supplied by excess production, which is delivered by trailer truck. Two defining features of this design are the portability and scalability of the system. The system would initially consist of a minimal storage system, compressor and fuel dispenser. As demand grew, the storage system would progressively be replaced with sequentially larger systems within economical and physical constraints. The replaced storage system would then be relocated to a lower demand location. This system would achieve a decrease in the initial infrastructure costs by utilizing existing production capacity, by consistently using the original dispenser, and by matching storage size with demand.

As demand increases beyond the existing capacity in these introduction areas, onsite SMR generation might become the leading option. The use of natural gas reforming takes advantage of the already installed distribution system and further extends the time frame before large capital costs have to be incurred. As FCVs replace conventional automobiles as the predominate vehicle, demand will become sufficient enough to warrant investment in central production facilities including those based on completely green technologies. A pipeline network would then be used as the main means of distribution. This network will be created either by installing a new pipeline or by retrofitting the current natural gas pipeline network in order for hydrogen and natural gas to be transported concurrently. This combination of central production and pipeline transmission will provide for an energy efficient system.

A functionalist systems approach needs be undertaken when approaching this work. Appropriate system performance measures need to be evaluated using a variety of techniques. For example, by employing an analytical hierarchy process (AHP), trade-offs between the various economic and environmental benefits can be determined and analyzed. The use of incremental analysis will aid in determining the optimal amount of transportation vehicles required to meet demand constraints. Once an appropriate model is developed, robustness analysis needs to be completed to evaluate the model's capabilities to handle uncertainty. In addition, any future viable model needs to calculate key costs and determine the associated cost drivers, while noting any emergent properties.

5. AN ASSESSMENT OF WIND HYDROGEN SYSTEMS FOR LIGHT DUTY VEHICLES

A hydrogen economy could offer energy stability, economical, and environmental benefits. In this section, a hydrogen system based on wind generated electricity is presented as a viable component in a hydrogen transition strategy. The strengths of a wind-hydrogen system are exhibited in its modular design, exploitation of existing technology, and utilization of a renewable resource. Specifically, a state level assessment of wind power was conducted in order to determine the ability of individual states to meet light-duty vehicle hydrogen fueling demands while utilizing the proposed system. Additionally, analysis related to existing hydrogen resources is presented in order to form a transition scenario.

5.1. INTRODUCTION TO HYDROGEN FOR LIGHT DUTY VEHICLES

The need to initiate an economy based on sustainable energy sources is more compelling than ever, and is key to the evolution of an economically and environmentally stable world. Numerous and diverse drivers are leading the United States and other countries toward the development of hydrogen infrastructures. Among these reasons are the interrelated areas of increased energy stability and the expanded usage of renewable energy sources.

Energy stability is of particular importance to the United States and to many other countries whose economies are severally dependent on foreign oil. Because the United States both consumes and imports more oil than any other country, it is in a perilous position (though not alone). Further, as a vast majority of the proven oil reserves are in geopolitically sensitive areas, crude oil prices are not insulated from large price fluctuations. The growing dependence on imported oil and natural gas increases the strategic vulnerability of many countries. Further, competition among importing countries will increase as the major emerging economies of India and China will spur additional demand. These trends coupled with increased worldwide interest in hydrogen and fuel cell technology, provide a warning that if the U.S. is to remain competitive, it must lead in technology innovations related to this new economy. The use of hydrogen also addresses stability through diversity. Hydrogen generated through multiple pathways could provide a more reliable energy supply.

Hydrogen provides a pathway for the expanded use of domestically produced intermittent renewables, thereby creating the possibility of a drastically reduced carbon producing economy. The electricity generated from renewable sources such as wind, solar, and hydro can be turned into hydrogen using the electrolysis process. Hydrogen can then be stored until it is needed as fuel for either transportation applications or local stationary power generation sources, or it can be transferred into electricity and fed into the electrical power grid. The interconversion of hydrogen and electricity by means of water is a perceivable indicator of a future integrated energy mix.

Globally, the pace of research and development on hydrogen infrastructure technologies is being accelerated. As the complexity of transitioning from a well-entrenched energy system has become apparent, the focus has switched from generating ultimate visions to transitions strategies. Currently, government organizations, such as the U.S. Department of Energy (DOE) and U.S. Department of Transportation (DOT), are researching, developing, and validating hydrogen pathways in an effort to establish a business case. For example, working with industry, academia, and the national labs, the DOE developed a long-term plan for moving toward widespread implementation of hydrogen technologies. In addition, to support the expanded use of hydrogen vehicles, the DOT Research and Innovative Technology Administration (RITA) is pursuing hydrogen infrastructure research that analyzes various production and delivery concepts in order to assess the United States' ability to reliably supply adequate amounts of hydrogen.

5.1.1 Review of Hydrogen Infrastructure and Transportation. The latest wave of interest in hydrogen is rooted in the 1960s and 1970s [Gregory and Pangborn, 1976]. Starting in the late 1990s, researchers began to evaluate potential infrastructures, strongly advocating hydrogen as an alternative fuel [Thomas, 1997; Ogden, 1999a; Myers et al., 2002; Ogden et al., 2004]. To develop a hydrogen infrastructure, a variety of production and distribution options are being considered, including centralized reforming of natural gas or gasification of coal or biomass, on-site reforming of natural gas or ethanol, electrolysis (potentially using renewable energy sources), industrial by-product hydrogen, and both liquid and gaseous storage/delivery [NAE, 2004; Martin and Grasman, 2006; Muradov and Veziroglu, 2008; Turner et al., 2008].

Depending on the source, many infrastructures can be conceptualized. Mintz et al. [2003] describes several infrastructure alternatives and the associated cost of the delivered hydrogen. A self-reported limitation of the study is that the analysis assumes little effect from technology and infrastructure maturation nor phased technology development. Winebrake and Creswick [2003] performed a perspective-based scenario analysis of various production methods using the analytic hierarchy process. Although many concepts related to meeting the projected increase in hydrogen demand created by the introduction of hydrogen vehicles have been presented, the development of a hydrogen infrastructure is one of the main unsolved issues impeding migration to a sustainable hydrogen economy.

The National Academy of Engineering identified the four factors that will most significantly affect the cost of delivered hydrogen [NAE, 2004]: 1) the feedstock used to produce hydrogen, 2) the scale of the production unit and the transportation requirements, if any, 3) the level of technology readiness, and 4) the use of carbon dioxide (CO2) by-product sequestration if fossil fuel is used as a feedstock. In addition, Melendez [2006] identified availability and high cost of alternative fuel infrastructure as key barriers that past alternative fuels have experienced and that hydrogen is expected to face. These studies highlight the complexity of balancing the availability of refueling infrastructure with production scales and transportation costs.

Many scientists champion introducing hydrogen into the transportation sector as a vehicle fuel. This view is supported not only by the economic and environmental feasibility, but also by major improvements in overall hydrogen vehicle efficiency and performance. Myers et al. [2002] concluded that the costs of maintaining the existing gasoline infrastructure are up to twice the estimated costs of maintaining a hydrogen infrastructure. Thomas et al. [2003] also presents a scenario that includes a hydrogen infrastructure that is less costly than the existing infrastructure. This possibility is especially significant, given that a potential pathway for meeting growing hydrogen demand is to replace existing gasoline infrastructure with hydrogen infrastructure at the end of the existing infrastructure's useful life. Melendez and Milbrant [2006] also identified a minimum infrastructure to support the introduction of hydrogen vehicles in the U.S..

5.1.2. Aims of This Section. This section will expand on previous work by providing analysis of a wind-based hydrogen system to determine the theoretical hydrogen generation capability of a wind-hydrogen system on a state level basis. In addition, the ability of the system to internally meet the demand for hydrogen created by the conversion of light duty vehicles (LDV)s to hydrogen vehicles is considered. A cost comparison of transmission and distribution methods is also presented. Finally, a transitional scenario based on a combination of existing hydrogen production and a wind-hydrogen system is discussed.

5.2. WIND-HYDROGEN SYSTEMS

General interest in a wind-hydrogen system has increased partly because the price of wind power has become competitive with traditional power generating sources in certain areas. Due to the characteristics of a wind-hydrogen system it has the potential to play a complementary role during the mass introduction of hydrogen [Elam et al., 2003; Sherif et al., 2005; Segura et al., 2007; Greiner et al., 2008]. Wind energy technology has vastly improved with systems now operating at efficiencies that reach up to 80% of the theoretical possible energy flow [Thresher et al., 2007]. Chen et al. [2008] provides a review of modern wind power systems.

Although there are inherent challenges to introducing wind power into power systems such as, extending transmission lines to remote areas, Georgilakis [2008] states that incorporation of up to 20% wind power into the electrical grid would only have a moderate impact on grid stability and operations. The generation of hydrogen can also be used to address stability concerns such as during otherwise idle wind farm periods [Mantz and Battista, 2008]. By providing a means of energy storage, hydrogen provides a mechanism to utilize excess energy, thereby increasing the productivity of wind farms. Further, the use of a wind-hydrogen system could provide a pathway in which to address reliability concerns related to high penetration rates of intermittent energy generation sources incorporated into the U.S. energy grid [NAERC, 2008]. Kruger [2008] identified a wind-hydrogen system as an appropriate technology for distributed hydrogen applications based upon specific energy, although there is concern what effect connected distributed systems would have on the current U.S. electrical grid. A temporary method to address capacity strain questions would be to generate and store hydrogen during off-peak times.

Combining wind energy and hydrogen also addresses sustainability issues. Wind-generated electricity prevents many negative environmental impacts and addresses other drawbacks that surround most other electricity generating technologies [Moriarty and Honnery, 2007]. These issues include storage of nuclear waste, need for cooling water, dedicated land use, greenhouse gas emissions, and depletion of nonrenewable fossil fuel resources. The combination also addresses transportation related issues involving greenhouse gas emissions and water management by providing a potentially zero carbon production and delivery pathway for hydrogen.

Further, the U.S. uses approximately 300 billion gallons of water per year in the production of gasoline compared to the estimated 100 billion gallons of water required for a complete conversion of the U.S. light-duty fleet of vehicles to electrolytic hydrogen [Turner, 2004]. Hydrogen produced utilizing wind energy can approach 3 USD per kilogram in the near future comparable to 0.79 USD per liter gasoline [GE, 2006; Bockris and Veziroglu, 2007; DOE, 2007]. In addition, water and electricity are generally not as sensitive to political or seasonal concerns as other hydrogen production feedstocks. Prince-Richard et al. [2005] examined the key technical and economic parameters influencing the competitive position of electrolysis.

Although, there are efficiency penalties associated with hydrogen generation by electrolysis. Using wind-generated electricity in conjunction with electrolysis addresses future infrastructure concerns. An integrated system, such as the one shown in Fig. 5.1, provides a reliable design concept for distributed power and subsequent hydrogen generation. Onsite production of hydrogen would alleviate the need for mass transportation of hydrogen and reduce the impact of natural disasters by adding redundancy to the transportation fuel sector. The scalability of electrolysis affords the opportunity to better match demand since the efficiency of such a system is largely independent of size. In addition, wind energy systems can be designed to be installed in a modular fashion, creating flexibility for the energy company by avoiding the large single capital outlays typical of traditional power generating facilities.

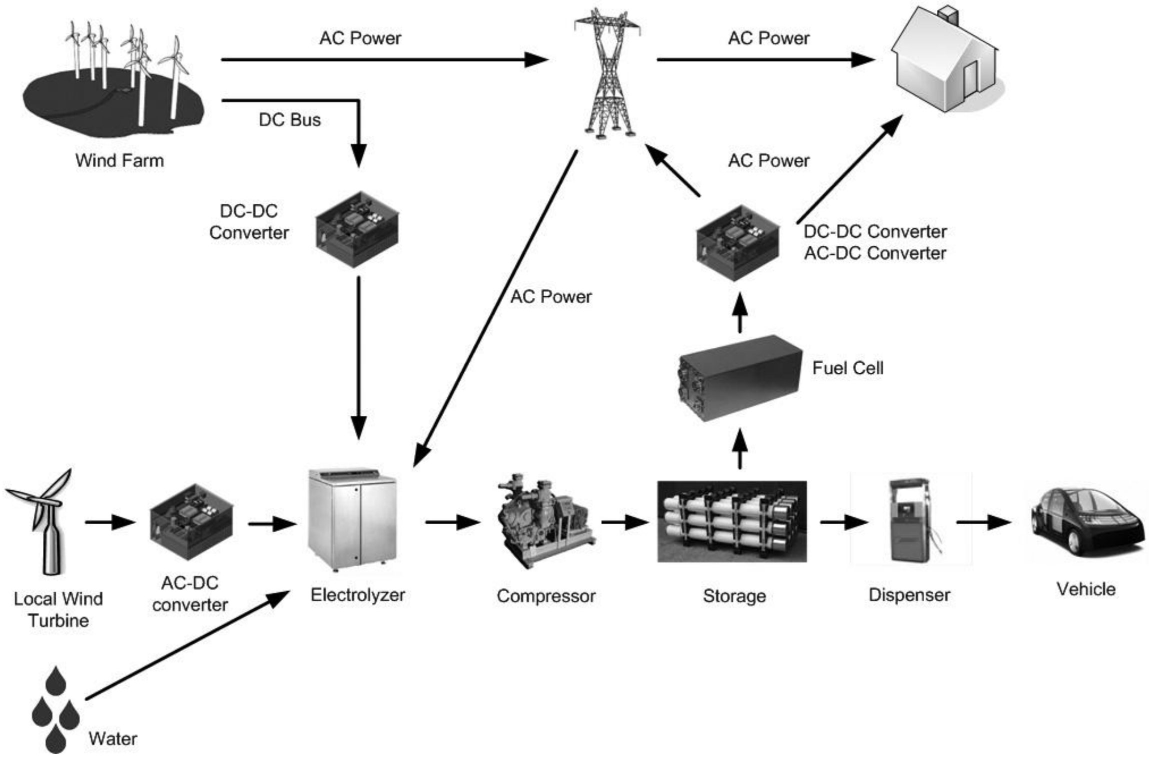

Figure 5.1. Wind-Hydrogen System

Although the previously mentioned strategic and environmental factors demonstrate the role hydrogen and wind could play in addressing the pressing dilemmas the U.S. and other countries are facing, feasible concepts need to be developed. One such idea is a wind-hydrogen system designed to produce fuel for hydrogen vehicles. The use of hydrogen for vehicles has gained momentum due to increases in vehicle efficiencies and zero vehicle emissions.

5.3. REGIONAL ASSESSMENT OF WIND RESOURCES FOR TRANSPORTATION USAGE

5.3.1. Methodology. An assessment of the potential for wind-generated hydrogen to meet light duty fuel demands was conducted. To make this determination, geographical information system (GIS) data [NREL, 2009] was utilized in conjunction with parameters such as electrolyzer efficiencies and wind farm capacity/installation factors to calculate the total theoretical amount of hydrogen that could be generated. In Eq. (5.1), the theoretical maximum power produced is calculated by determining the area covered by wind classes three through seven (A_i), which is then multiplied by an installed capacity factor per area (I) and by corresponding capacity factors (K_i) to determine actual expected power output. Wind classes i = 1 and 2 were not used in the calculations due to insufficient potential. To determine the hydrogen production capability for each state, the projected power output was multiplied by an average electrolyzer efficiency factor.

$$M = \sum_{i=3}^{7} A_i K_i ICT \qquad (5.1)$$

$M =$ Total mass of hydrogen [kg]
$A_i =$ In-state area with wind power class i [km^2]
$K_i =$ Capacity (productivity) factor for wind power class i
$I =$ Installed wind turbine capacity [kW/km^2]
$C =$ Electrolyzer efficiency factor [kg/kWh]
$T =$ Yearly hours [hrs]

The demand for internal transportation related hydrogen is then determined by using Eq. (5.2).

$$T_S = \frac{N_S * D}{F} \qquad (5.2)$$

$T_S =$ Total LDV demand for hydrogen in state s [kg]
$N_S =$ Number of LDVs in state s [vehicles]
$D =$ Distance traveled per vehicle [km/vehicle]
$F =$ Fuel economy [km/kg]

A comparison among states is made by determining the number of miles every registered light duty vehicle within each state could drive versus the number of LDVs whose fuel demands could be met on hydrogen generated from wind within the respective state. In addition, the ability for states to meet internal hydrogen demands for various wind energy utilization factors is also presented.

5.3.2. Data Assumptions. Where NREL validated high resolution data were not available, low resolution 1987 U.S. wind resource data were used except for Texas. The Texas Renewable Energy Resource Assessment provided estimates of coverage by wind class for the State of Texas [Frontier Associates, 2008]. All wind speed data used in the analysis were based upon yearly averages. The use of average wind speed results in a conservative estimate of hydrogen production. In addition, the aggregate data analysis limits the identification and sizing of an appropriate storage system for a specific location to address the daily and seasonal stochastic behaviors; however, the analysis is appropriate for the macro production planning stage, thus stochastic analysis is an opportunity for future work. A value of 52.5 kWh/kg was used to represent the electrolyzer efficiency which is a 75% efficient system based upon the higher heating value of hydrogen. The projected fuel demands are based on 2005 statistics for public and private light duty vehicles from the U.S. Department of Transportation [2006]. An efficiency of 50 miles per kilogram (80 km per kilogram) of hydrogen [Marcinkoski et al., 2008] and an annual mileage of 12,000 miles (approximately 20,000 km) were assumed for each vehicle. The states were categorized by U.S. census regions. Although all results are presented at the state level or other aggregated level, analysis at the county level or higher resolution is feasible if it were required by a practical application such as metropolitan areas or electric utility coverage areas that cross state borders. The economic analysis utilized the DOE H2A models and standard assumptions [DOE, 2009].

5.3.3. Theoretical Projections. From Fig. 5.2 it can be seen that the theoretical projections of potential terrestrial wind generated hydrogen are greater than projected requirements for each region. The U.S. has the potential to generate over 400 billion kilograms of hydrogen by utilizing only terrestrial wind as the electricity resource for electrolysis. Since the U.S. would need approximately 57 billion kilograms of hydrogen to meet 2005 private and public car and truck transportation needs capturing and distributing only 15% of the total potential would be required. However, the electricity and hydrogen distribution would pose challenges as sources do not correspond to demand locations in all cases.

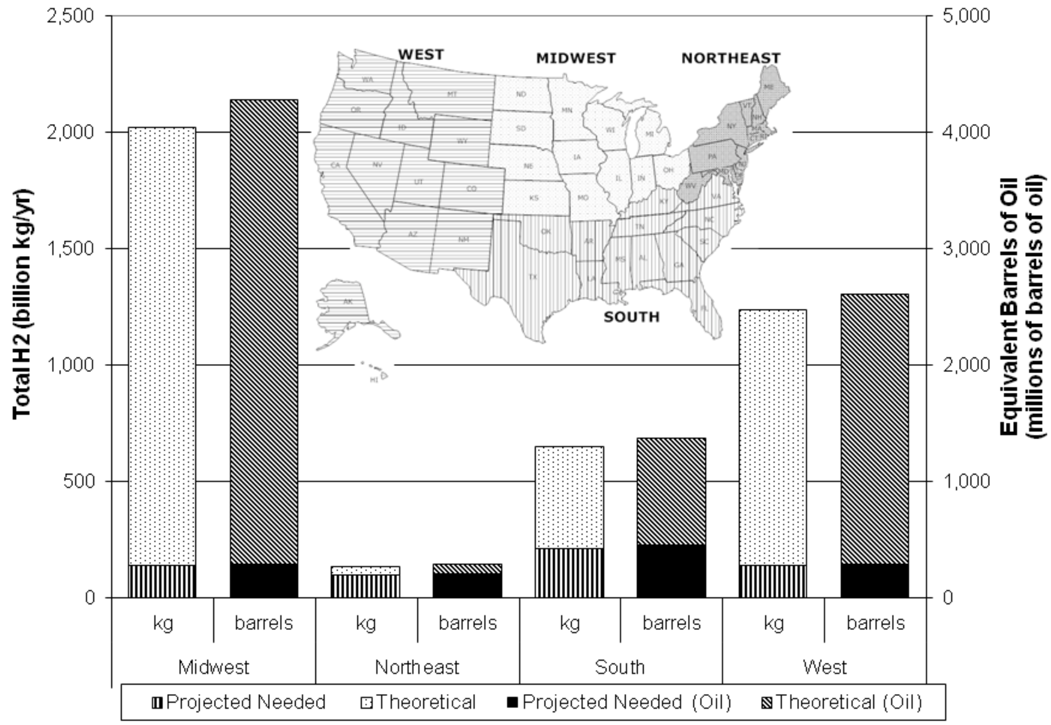

Figure 5.2. Comparison of Theoretical Wind Generated H_2 vs. Projected Required to Meet Light Duty Vehicle Demands

5.3.4 Regional and State Level Results. Fig.5.3 lists the available kilometers per registered vehicle versus the maximum hydrogen vehicle capacity within each state provided the theoretical maximum of instate wind-hydrogen generation is utilized for transportation. The solid delineation line demonstrates the states which can internally meet the hydrogen fuel demands of 20,000 km/instate vehicle.

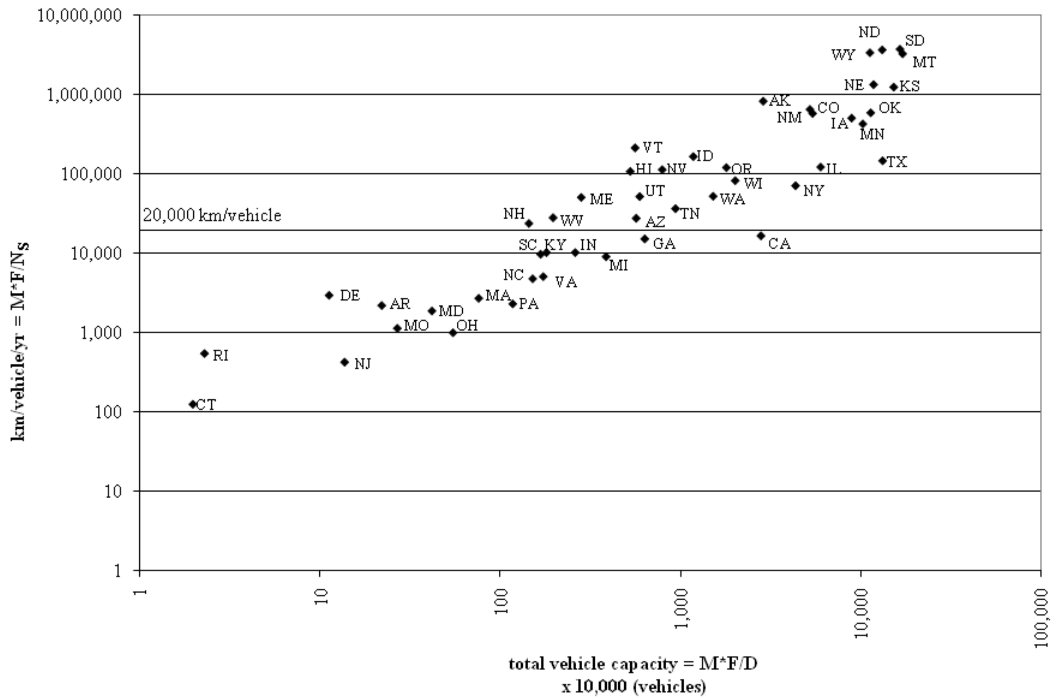

Figure 5.3. States Able to Internally Meet Transportation Demand Utilizing Available Wind Resources

Figure 5.4 provides a representation of the individual state’s ability to meet internal demand for four scenarios based upon the percentage of theoretical maximum wind-hydrogen generation used for transportation. States within the inner most circle would require only 10% of the theoretical maximum wind-hydrogen generation capability in order to support a complete conversion of the internal LDV fleet.

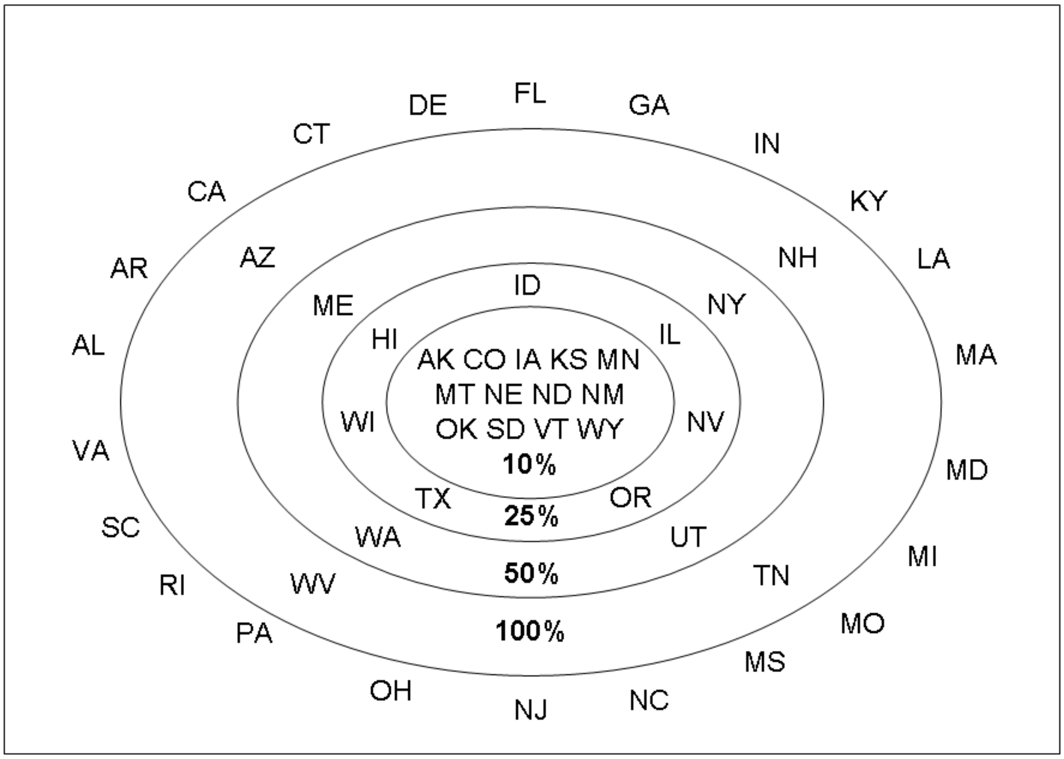

Figure 5.4. Ability to Meet Demand for Various Wind Energy Utilization Factors

The Midwestern United States has the most potential excess capacity with 188 billion kilograms per year of surplus capability. The Midwest also contains a majority of the concentrated power generating (kWh/km^2) states. Among the seven Midwest states that are within the top ten producers in the U.S., the average potential is greater than 150,000 kg H_2/ km^2 /yr or over 600 vehicles/ km^2. Because costs for new transmission lines can be up to $1 million/mile ($621 k/km) depending on terrain and transmission capacity, the concentration of wind power resources is a significant factor to consider. Even with this potential collective excess, Missouri, Michigan, Indiana, and Ohio are only able to meet less than half of their respective internal demands for all registered vehicles at an average of 20,000 km/vehicle. However, three of these states have access to offshore wind from the Great Lakes that could provide additional electricity for hydrogen generation. In addition, resources from Minnesota, Iowa, and Kansas are within an economically viable transportable range should demand require additional resources.

Although, the Northeastern United States is currently projected to be able to meet current demand, additional future capacity is limited. The Northeast, like the Great Lake states, has excellent offshore wind resources available. Much like the Midwest, the wind resources are concentrated within a smaller subdivision of the region (Maine, New Hampshire, and Vermont). Although Connecticut, in absolute terms, has the least capacity among all potential wind derived hydrogen producing states, it would be able to offset 19,000 vehicles using internal resources.

The Southern states collectively exceed demand, but pose a unique situation because the four state region of Louisiana, Mississippi, Alabama, and Florida has no commercially viable terrestrial wind resources at a 50 m height. As a result, renewable electricity would have to be transmitted to the region most likely from Texas. Otherwise, the use of solar electricity where economical or off shore wind-generated electricity could also be utilized. The South is collectively skewed by the presence of Texas and Oklahoma, which both on absolute terms and a per vehicle basis possess potentially large amounts of excess production capability (a combined 58 billion kilograms per year potential). In contrast, the South Atlantic region, which consists of eight states, has a combined 3 billion kilograms per year of potential with only West Virginia able to internally meet LDV fuel demands.

Western states, with the exception of California, are all potentially self-sufficient. Although California is not able to fully (85% internally met) support its vehicle fleet based solely on terrestrial wind, it has vast off shore wind resources and solar resources. In addition, the neighboring states of Oregon, Nevada, and Arizona have excess capability totaling approximately five times the amount of hydrogen California would need to fully meet demands based on 2005 vehicle registrations. In addition, Hawaii provides a unique opportunity for hydrogen introduction because it would not require a vast infrastructure network to achieve acceptable refueling capabilities. In addition, the state experiences among some of the highest gasoline prices on average in the United States. Hawaii's tourism could further introduce this technology to other states because the typical tourist rents a vehicle while visiting and has an above average disposable income. This combination could provide an opportunity for potential early market adopters to try hydrogen vehicles without having to commit to purchasing them, while also providing an opportunity for Hawaii to promote its “green” image.

5.3.5. Economic Analysis. Figure 5.5 compares the total costs including generation, transportation (if needed) and station costs for three scenarios.

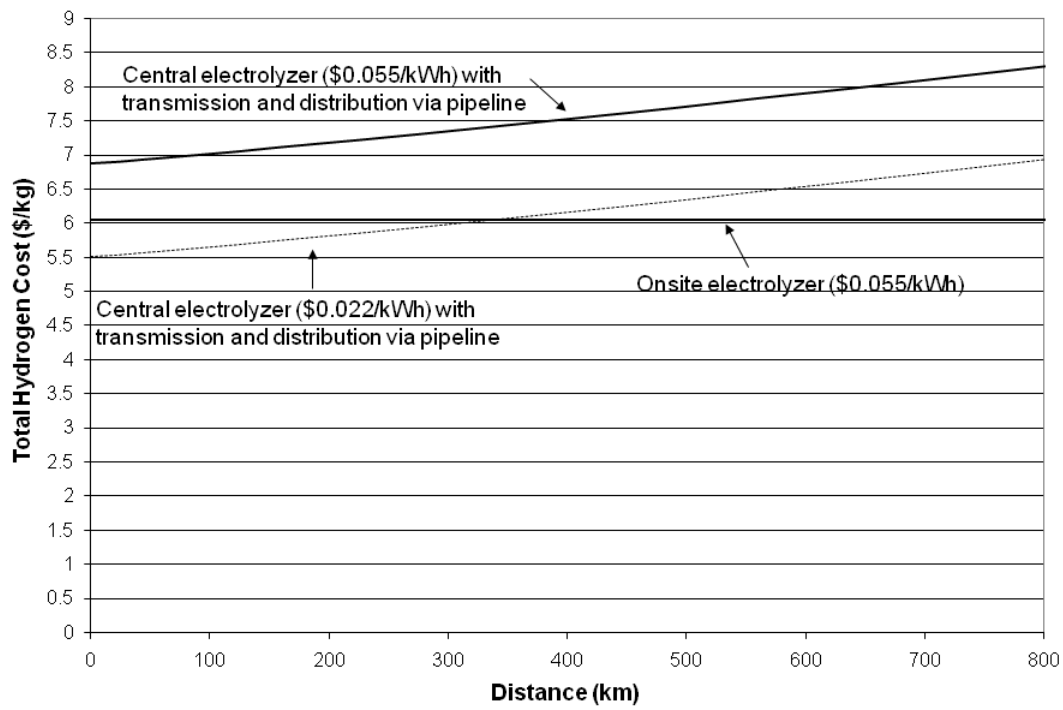

Figure 5.5. Wind-Hydrogen Costs

Scenario one generates 1,500 kg of hydrogen per day using on site electrolysis and storage and electricity at $0.055/kWh. This scenario is indicative of a standard rural commercial fueling station. Scenario two generates 52,300 kg of hydrogen per day using a bank of electrolyzers deployed in a centralized fashion with on site buffer storage and electricity at $0.055/kWh with hydrogen transmission and distribution taking place using a pipeline. The central production size was selected to be indicative of a regional production facility. Scenario three is identical to scenario two, however the electricity price has been changed to $0.022/kWh. The availability of lower priced electricity represents a case for instance where the grid could not accept power generated from a wind farm and in order to maintain a high capacity factor the electricity is utilized to generate hydrogen at the wind farm and then transported via pipeline. The comparison of scenarios 1 and 2 demonstrate that onsite electrolysis is more cost effective for all distances than utilizing a centralized production method and transporting the generated hydrogen via pipelines when the cost of electricity is the same. However, when the cost of electricity is reduced, as in case 3, there exists a range of distances where centralized production with pipeline production is more economical. Based upon Fig. 5.5, it appears that the generation and distribution of hydrogen on a regional basis utilizing excess wind energy provides an interesting concept. The centralized system addresses many current issues such as grid balancing and the buildup of regional networks while addressing environment concerns. Scenario three poses the possibility of seeing clusters of hydrogen fueling stations constructed within an approximate 300 km radius of wind farms. Further, if the wind farm and hydrogen station were owned by the same entity the reduced electricity generation profit would be offset by the sale of the generated hydrogen.

5.4. TRANSITION STRATEGY DISCUSSION

A company's operational strategy differs depending on where the individual company and its industry are in their respective business cycles. Because the introduction of hydrogen as a fuel is in its infancy, there is much speculation about how it will function, what its rate of adoption will be, and what market size it will eventually achieve. There is also great debate about what the technology landscape will consist of in the future. Stakeholders also face whether to take a regional or national approach concerning raw material supplies and, therefore, production technologies. A wind-hydrogen system is conducive to an expansion strategy because it provides product flexibility and modular installation both of which grant the ability for stakeholders to better follow the demand for hydrogen during the transition phase. In addition, due to increases in efficiency, wind power is at, or is approaching, competitive generation rates compared to traditional electricity generation methods.

Excess or by-product hydrogen production presents a low initial infrastructure investment option that can be used during a transition to a renewable hydrogen system. Potential sources include ammonia, methanol, coke, and commercial hydrogen plants, in addition to oil refineries. The total availability of these sources in the U.S. is approximately 8.5 billion kg/yr (approximate values include oil refineries 3.5 billion kg/yr, ammonia production plants 3.0 billion kg/yr, merchant 1.5 billion kg/yr, coke production plants 500 million kg/yr). If 10% of the total output of the previously mentioned sources were utilized, a fleet of over 3.5 million vehicles could be maintained. This amount is equivalent to 45% of U.S. car sales in 2006. However these sources are only available on a regional basis and would not provide a lasting solution. Increasingly, the use of electrolysis could be used to address demands for hydrogen in regions where an existing source does not exist or where demand has surpassed existing supply.

Combining hydrogen and wind power creates an almost totally renewable nonpolluting pathway that addresses the perceived drawback of most renewables in general: the fluctuating nature of power generation. In the past, utilities have been reluctant to introduce wind into the generation mix not only due to cost per kilowatt hour, but also because of the additional strain due to the variable generation. In a wind-hydrogen system, electricity can be generated and either fed into the power grid to be used at a distant demand or used to generate hydrogen near the wind farm, from which it could be transported to local fueling stations.

Such a system would provide flexibility and redundancy and would support a majority of the U.S. transportation fuel demand. On a regional basis, sufficient resources exist to meet internal regional transportation demands with 28 states. Further, an additional 6 states would be able to offset at least half of their registered light duty vehicles. In order to generate enough electricity using wind to meet total LDV demand would require approximately 1.8-3.5% of the total land area of the United States. In comparison, it would require 13.7% of the total land in the U.S. to meet the same demand utilizing E85. Further, replacement of gasoline with E85 would also require a nearly 400% increase in the amount of land used to grow corn, assuming current productivity could be maintained. Nationally, a wind-hydrogen system could result in an excess production capacity of approximately 3,500 billion kilograms of hydrogen after meeting light duty vehicle demands.

5.5. CONCLUSIONS ABOUT THE ROLE OF WIND-HYDROGEN SYSTEMS

Energy, in general, is key to economic growth, and diversification of the U.S. energy supply is critical to national security. The continued reliance on imported crude oil from geopolitically sensitive areas has a tremendous effect on worldwide markets due to the unpredictable nature of natural disasters and other supply disturbances. These effects are magnified because nearly half of every barrel of crude oil in the U.S. is used to produce gasoline. In addition, concerns about the effects of fossil fuels on the environment are continually increasing. A wind-hydrogen system would address both the emissions from most utility power generation plants and millions of vehicles. These issues will most likely be magnified because the demand for transportation increases as economies grow. The use of a wind generated hydrogen as a fuel for the transportation sector can address the aforementioned issues simultaneously.

6. AN INVENTORY MODELING APPROACH FOR HYDROGEN FUELING STATION CAPACITY

A newsvendor framework is utilized to determine the optimal capacity for hydrogen filling stations based upon consumer behavior. The utility of this approach is expanded by including the effects of a competitive business environment by providing an alternative to the consumer and by including a consumer placed utility for hydrogen. The consumer placed utility represents the value to the consumer that the higher energy efficiency and environmental benefits hydrogen is perceived to provide. The results from a parametric analysis of key variables are presented in regards to inventory levels.

6.1. INTRODUCTION TO HYDROGEN FUELING STATION MODELING

While hydrogen can be utilized in various applications including personal, mobile and stationary power generation, the use of hydrogen specifically in the transportation sector is of particular interest due to potential environmental, energy efficiency, and security benefits. In the United States, the transportation sector represents 28% of greenhouse gas emissions with petroleum being the primary energy source for 97% of the transportation sector nationwide. A report by the Global Humanitarian Forum estimates that climate change is responsible for affecting 325 million people, along with a loss of 125 billion USD each year, worldwide as a result of climate change [Global Humanitarian Forum, 2009]. In addition, various government agencies have expressed concerns over the effects that price shocks and an increased demand on petroleum would have on industrial investment, unemployment, and trade deficits. These concerns will only heighten as the International Energy Agency (IEA) predicts that global demand for energy will increase by 45% by 2030, with fossil fuels dominating energy source options [IEA, 2008].

Although many in the scientific community agree that hydrogen will begin to play a critical role in the energy sector, a number of questions concerning the realization of a hydrogen economy still remain [Thomas, 1997; Ogden, 1999a; Myers, 2002; Ogden et al., 2004; Edwards et al., 2008]. Chief among these challenges is the lack of an infrastructure that can satisfy the increased demands for hydrogen that would result from a transformation of the light duty vehicle (LDV) market. The magnitude of this dilemma is increased by the high costs and energy requirements required to distribute hydrogen. However, current research is addressing these areas with progress being made [DOE, 2008]

The design of a hydrogen station network involves several aspects including identifying the optimal location and construction timing, as well as, the appropriate size. Related to the station size is the station utilization rate, which has a significant effect on the local hydrogen price. The costs associated with over sizing a station have to be balanced with potential for lost sales. For example, the size of the station cannot be under sized to achieve high utilization without risk of alienating drivers who are unable to be serviced due to a lack of fuel. Further, fueling stations need to be sized to include future anticipated fueling needs as component, planning, and construction lead times for hydrogen facilities can be significant, often adding delays and increased expenses.

The cost target for delivered hydrogen also has a complementary role in the proper sizing of a station. A variety of cost models have been developed including work by Amos [1998], Simbeck and Chang [2002], Ogden et al. [2005], Weinert et al. [2006] , Yang and Ogden [2007], and U.S. Department of Energy's H2A models [DOE, 2009]. As the price of hydrogen exhibits an inverse feedback interaction with the adoption rate of fuel cell vehicles this behavior has a compounding cyclical effect [Keles et al. 2008]. These conditions highlight the importance of properly designing the initial network of hydrogen fueling stations.

The remainder of this section will present a review of the relevant literature followed by the hydrogen station sizing model and results. The modeling utilizes a newsvendor framework with an outside option. The outside option creates a realistic environment where the consumer has the ability to select between hydrogen and another fuel. The section will conclude with a discussion of the results and areas for future research.

6.2. LITERATURE REVIEW ON HYDROGEN INFRASTRUCTURE

Ogden [1999a] presents prospects for building a hydrogen energy infrastructure including hydrogen production, storage, transmission, and distribution and described potential areas for future research. Although challenges and issues are discussed in this study, analysis of the infrastructure development is not presented. Myers et al. [2002] states that the costs of maintaining the existing gasoline infrastructure could be up to twice the estimated costs of maintaining a hydrogen fuel infrastructure. Thomas et al. [2003] supports this viewpoint by presenting a hydrogen infrastructure that is lower cost than the existing gasoline infrastructure. This is significant given that a potential transition could include replacing the existing gasoline infrastructure with hydrogen infrastructure at the end of its useful life.

Many studies recommend that any early demonstration of hydrogen vehicles entail the use of fleet or government vehicles in order to provide a means to increase public awareness and demand, as well as because of the centralized refueling practices of such systems. The conclusions from studies in Italy [Mercuri et al., 2002], London [Joffe et al., 2004; O'Garra et al., 2005], Spain [Brey et al., 2006], and China [Lin et al., 2006] all support this view. Farrell et al. [2003] presents a strategy that calls for introducing a small number of relatively large vehicles that are operated along point-to-point routes within a small geographical region. However, these approaches will likely have limited influence since they do not provide convenience to the individual consumer. Further, the earliest signs of a sustained hydrogen economy are most likely going to be witnessed in the form of regional networks potentially supplied by existing industrial production infrastructure [Gross et al., 2007].

Researchers have steadily developed a number of case studies focusing on estimating the number of fueling stations required [Ogden, 1999b]. Melaina [2003] estimates the number of initial hydrogen stations by comparison with the existing gasoline infrastructure. A minimum infrastructure to support the introduction of hydrogen vehicles with a focus on connecting cities along major highways was identified by Melendez and Milbrant [2006]. Nicholas et al. [2004] relates the number of stations to the location of stations using geographical information systems (GIS). Nicholas and Ogden

[2007] bases the placement of stations on customer conveniences which is taken into consideration by the average travel time to the nearest station.

Increasingly, researchers have begun to include more complete systems into the scope of the models. For example, an optimized infrastructure for Southern California based on dynamic programming is presented in Lin et al. [2008]. Johnson et al. [2008] utilize GIS to analyze the deployment of a coal-based hydrogen infrastructure in Ohio. Internationally, Strachan et al. [2009] link a GIS model to the UK MARKAL [2009] model in order to model infrastructure from primary energy sources to demand locations. Almansoori and Shah [2006] present a steady-state snapshot of a future hydrogen supply chain in Great Britain using mixed integer linear programming, and Lin et al. [2006] present a model with application to urban Beijing. The size and cost of a hydrogen delivery system in Europe is discussed in Tzimas et al. [2007]. In another mixed integer linear program, the design of a hydrogen infrastructure for South Korea is presented [Kim and Moon, 2008].

While little work has been done on modeling of phased infrastructure development, Thomas et al. [1998] provided some early thoughts on economically viable hydrogen infrastructure development, including the idea of combining electrolyzers and small steam methane reformers incrementally to match the growth in demand. However, actual models for implementation of the supply chain infrastructure are not discussed. More recently, Martin and Grasman [2009] presents a transition scenario utilizing a combination of existing hydrogen production and wind-hydrogen systems. Yang and Ogden [2005] presents an analysis for transitioning from distributed to centralized production (via natural gas) for an idealized city. Hugo et al. [2005] utilizes mixed integer linear programming to identify optimal investment strategies and integrated supply chain configurations from many potential pathways. Using multi-objective analysis the paper addresses both investment and environmental criteria in order to provide tradeoffs representing conflicting design alternatives. Brey et al. [2006] presents a plan for the gradual transition to a hydrogen economy in Spain. The multi-objective nonlinear programming model addresses hydrogen production, transportation and consumption, as well as renewable energy sources, for each region of Spain. Ball et al. [2007] discusses a mixed-integer linear optimization model that focuses on linking electricity and hydrogen generation in Germany. Schwoon [2007] utilizes a combination of agent based trip modeling and GIS to construct various snapshots of the initial distribution of hydrogen filling station in Germany with a focus on providing highway fueling. Of particular note is the HyTRANS model which is a dynamic non-linear model that focuses on the early hydrogen transition and incorporates hydrogen production, fuel cell vehicle manufacturing and consumer behaviors [Greene et al., 2007]. In addition, Struben and Sterman [2007] combine economic and behavioral aspects of drivers and potential hydrogen station owners to determine a critical threshold for sustained adoption of hydrogen as a vehicular fuel. A final transitional stage model of note is an agent-based model being developed by Mahalik et al. [2009], which focuses on the early dynamics of both potential fuel cell vehicle drivers and of hydrogen infrastructure investors.

In contrast to previously mentioned models, an alternative formulation for sizing hydrogen stations can take the form of a classic inventory problem. The newsvendor problem consists of a decision-maker that decides the order quantity of a product in order to maximize the expected reward. This problem forms the building block of many capacity planning problems in supply chain systems [Agrawal and Seshadri, 2000]. See Porteus [1990], Khouja [1999], and Petruzzi and Dada [1999] for reviews of general newsvendor problems. The pricing decision with a risk neutral decision maker was first studied by Whitin [1955]. More recently, Kalyanam [1996] demonstrates that the optimal price of a risk-averse retailer is lower than that of a risk-neutral retailer. More recently, the newsvendor problem has been used to investigate various aspects including multiple periods [Bensoussan et al., 2007], in-period price adjustment [Chung et al., 2009], and risk aversion [Chen et al., 2009]. Of particular note is the work by Dana and Petruzzi [2001], which considers a model that provides an outside option for the customer. This outside option models the customer choice to visit the firm without knowing if product will be available, and is used in this section to compare the utility provided to the customer from investing in alternative fuels.

6.3. HYDROGEN STATION MODELING

As the deployment of hydrogen fueling stations is expected to take place in the coming years, it is critical to meet early adopter expectations in order for a full deployment of hydrogen infrastructure to take place. Thus, the inclusion of consumer behavior is critical when discussing issues related to the transition. This model explicitly considers consumer behavior by including a distribution function which represents the value consumers associate with hydrogen.

6.3.1 Model Development. The newsvendor model is a classical inventory model in which a decision maker chooses a stocking level to account for uncertain demand. Several factors affect the inventory level including: the cost and selling price of the item, salvage value of the item, the cost of customer goodwill due to stockouts, and the demand distribution. The standard newsvendor problem has been expanded to include an outside option. For this case, the hydrogen station represents a firm selling hydrogen on a unit mass basis. The outside option is considered by providing an alternative to the consumer and by including a consumer placed value for hydrogen. The consumer placed value represents the utility that the higher energy efficiency and environmental benefits among, other attributes, that the consumer perceives hydrogen provides.

6.3.2. Generalized Model. General results for the presented model can be found in Dana and Petruzzi [2001]. Here, the model will be adopted for purposes of including customer behavior into the capacity decision.

Let the station have capacity, C, a cost per unit c, and selling price, p. The station will experience an aggregate demand, D, where $F(d)$ is the cumulative distribution function of D and $f(d)$ must be a strictly positive bounded probability density function with mean $\bar{d}$ and limits $[d^-,d^+]$. The consumer receives utility, u, which has a corresponding cumulative distribution function $O(u)$ and is continuously differentiable on $\boldsymbol{R}^+$, if the outside option is selected. The value the customer places on hydrogen is defined as v. Let $\hat{u}$ be the utility of the consumer who is neutral between visiting the station and selecting the outside option. Then, define $E[Sales(C,\hat{u})]$ as the expected sales for a given capacity , and $E[Demand(\hat{u})]$ as the expected demand when considering the utility of an outside option. It follows that

$$E[Sales(C,\hat{u})] = \bar{d}O(\hat{u}) - E[DO(\hat{u}) - C]^{+} \text{, and} \tag{6.1}$$

$$E[Demand(\hat{u})] = \bar{d}O(\hat{u}) \tag{6.2}$$

The firm's fill rate, or the percentage of demand met, is defined as

$$r(C,\hat{u}) = \frac{E[Sales(C,\hat{u})]}{E[Demand(\hat{u})]} = \frac{\bar{d}O(\hat{u}) - E[DO(\hat{u}) - C]^{+}}{\bar{d}O(\hat{u})} = \frac{\bar{d} - E[D - C/O(\hat{u})]^{+}}{\bar{d}} . \tag{6.3}$$

Let, the stocking factor s proposed by Petruzzi and Dada [1999] which is related to the safety factor [Silver and Peterson, 1985] be defined as

$$s = \frac{C}{O(\hat{u})}, \tag{6.4}$$

then, as the fill rate depends only on C and $\hat{u}$, substituting (6.4) into (6.3) yields

$$r(C,\hat{u}) = r(s) = 1 - \frac{E[D-s]^{+}}{\bar{d}} \text{, where} \tag{6.5}$$

$$E[D-s] = \int_{s}^{d^{+}} (1 - F(x))\mathrm{dx} . \tag{6.6}$$

6.3.3 Hydrogen Model. It is assumed that the demand distribution for hydrogen will be similar to that witnessed for gasoline. Therefore, a triangular distribution is selected for *f(d)* with lower limit d^{-}, upper limit d^{+}, and mode $\hat{d}$ based on the station demand distribution data presented in Melaina [2005]. Thus,

$$f(d) = \begin{cases} \dfrac{2(d - d^{-})}{(d^{+} - d^{-})(\hat{d} - d^{-})} & d^{-} \le d \le \hat{d} \\ \dfrac{2(d^{+} - d)}{(d^{+} - d^{-})(d^{+} - \hat{d})} & \hat{d} \le d \le d^{+} \end{cases} . \tag{6.7}$$

The value of the neutral outside option, $\hat{u}$, is equal to the ex ante expected probability that a consumer who visits the station will be served, multiplied by the utility received from purchasing hydrogen. Therefore,

$$\hat{u} = r(s)(v - p) . \tag{6.8}$$

The standard critical ratio *cr* [Nahmias, 2005] in a newsvendor problem is defined as

$$cr = \frac{p-c}{p} \tag{6.9}$$

assuming the salvage value of the product is zero.

The profit function is defined as

$$P(s,\hat{u}) = pE[Sales(C,\hat{u})] - cC \tag{6.10}$$

As $C = s\,O(\hat{u})$ and $p = v - \hat{u}/r(s)$ the profit function can be expressed as

$$P(s,\hat{u}) = \left[v - \frac{\hat{u}}{r(s)}\right] O(\hat{u}) \left[\bar{d} - \int_s^{d^+} 1 - F(x)\mathrm{d}x\right] - csO(\hat{u}). \tag{6.11}$$

The solution to the profit function for a triangular distribution is found using $F^{-1}(s)$ thus

$$s = \begin{cases} d^- + \sqrt{cr\left(d^+ - d^-\right)}\left(\hat{d} - d^-\right) & \text{cr} \le \dfrac{\hat{d} - d^-}{d^+ - d^-} \\ d^+ + \sqrt{\left(d^+ - d^-\right)}\left(d^+ - \hat{d}\right)(1 - cr) & \text{cr} \ge \dfrac{\hat{d} - d^-}{d^+ - d^-} \end{cases}. \tag{6.12}$$

For a triangular distribution the fill rate is

$$r(s) = \begin{cases} 1 - \dfrac{\int_s^{\hat{d}} 1 - \left(\dfrac{\left(\mathrm{x} - d^-\right)^2}{\left(d^+ - d^-\right)\left(\hat{d} - d^-\right)}\right) d\mathrm{x} + \int_{\hat{d}}^{d^+} 1 - \left(1 - \dfrac{\left(d^+ - \mathrm{x}\right)^2}{\left(d^+ - d^-\right)\left(d^+ - \hat{d}\right)}\right) d\mathrm{x}}{\bar{d}} & \mathrm{s} < \hat{d} \\ 1 - \dfrac{\int_s^{d^+} 1 - \left(1 - \dfrac{\left(d^+ - \mathrm{x}\right)^2}{\left(d^+ - d^-\right)\left(d^+ - \hat{d}\right)}\right) d\mathrm{x}}{\bar{d}} & \mathrm{s} \ge \hat{d} \end{cases}. \tag{6.13}$$

The capacity of the station can then be determined by

$$C = O(\hat{u})s. \tag{6.14}$$

6.4. EXPERIMENTATION

For all instances, the station capacity was plotted versus the ctitical ratio to provide the ability to identify the station capacity for any combination of production and selling prices provided the selling price is greater than the cost to produce. If the consumer attaches a utility to hydrogen less than the selling price the station capacity is set to zero. Finally, a normal distribution was selected for the outside option, $O(\hat{u})$, with a standard deviation , σ , and a mean, $\bar{u}$.

6.4.1. Fragmented Outside Option Market. Figure 6.1 examines the effect a fragmented outside option market has on station capacity. All paramter values were constant with $\bar{u}$ and *v-p=1* and varying only σ .

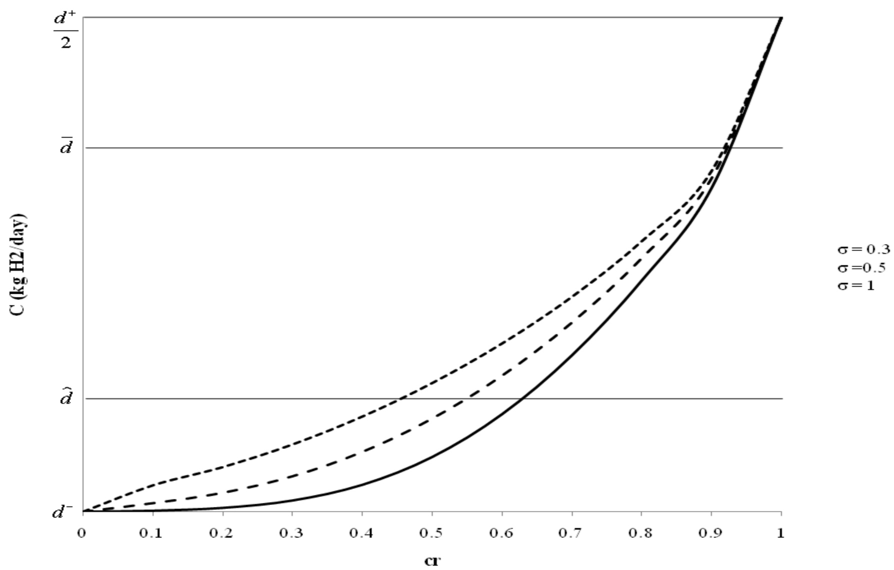

Figure 6.1. Station Capacity versus Critical Ratio $\bar{u}$ =1 and *v-p=1*

As σ increases, representing disagreement among consumers on the value of the outside option, the station capacity increases. Thus from a public policy stand point, if actions can be taken that introduce a change in consumer beliefs concerning the option, hydrogen would benefit.

6.4.2. Outside Option Utility. Figure 6.2 investigates the effect the average utility of the outside option has for a fixed value of a *v-p* equal to one. All parameters were fixed including σ =0.3 and *v-p=1* with only $\bar{u}$ being varied. As the difference between *v-p* and $\bar{u}$ increases, the station capacity increases. Conversely, assuming an operating point, *cr*=0.4, this experiement demonstrates the difficulites of overcoming a relatively highly valued outside option e.g. gasoline.

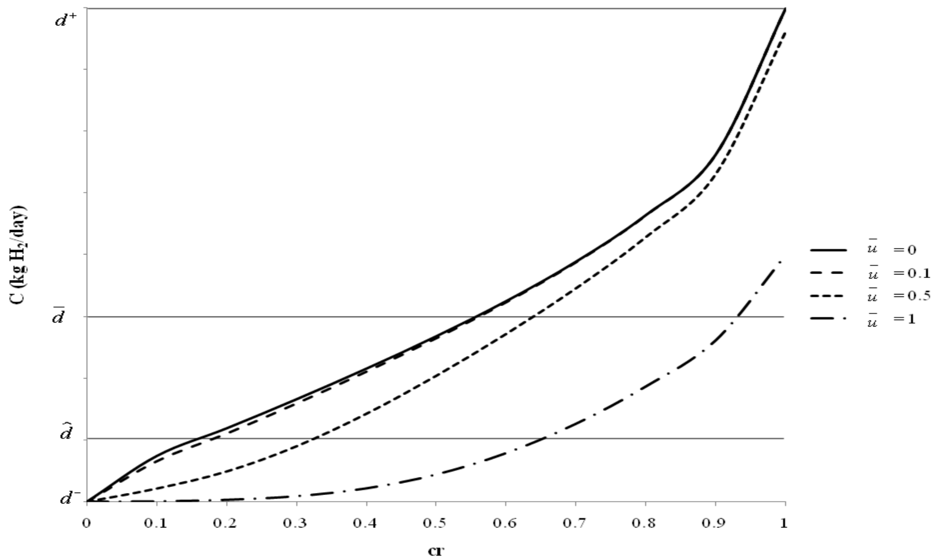

Figure 6.2: Station Capacity versus Critical Ratio σ =0.3 and *v-p=1*

This example also demonstrates the significant effect production cost has on station size. However, future demand forecasts would need to be included into the ultimate station size decision in order to balance current and future demands with the additional capital cost required for the expansion. This poses the need for stations to be designed in a modular fashion so that supply can follow demand more closely, thus maximizing the fueling station profits. This need is increased if onsite production is selected as each station operates independently, thus reducing the benefits of demand averaging over a larger pool of customers.

6.4.3. Consumer Added Hydrogen Utility. In certain environemnts consumers might place different values on hydrogen. Therefore, an experiemnt was conducted to determine the affect added hydrogen utility has on station capapcity. See Fig. 6.3. Only *v-p* was varied with all remaining paramters fixed including $\bar{u}$ =0 and σ =0.3. The neutral case (*v-p=0*) is indicative of when the value of hydrogen to the consumer is identical to the selling price set by the firm. An increasing *v-p* represents various degrees in which consumers place added value to hydrogen beyond it current selling price as a result of consumer beliefs including energy efficiency, environmental benefits and the need to refuel at that specific location.

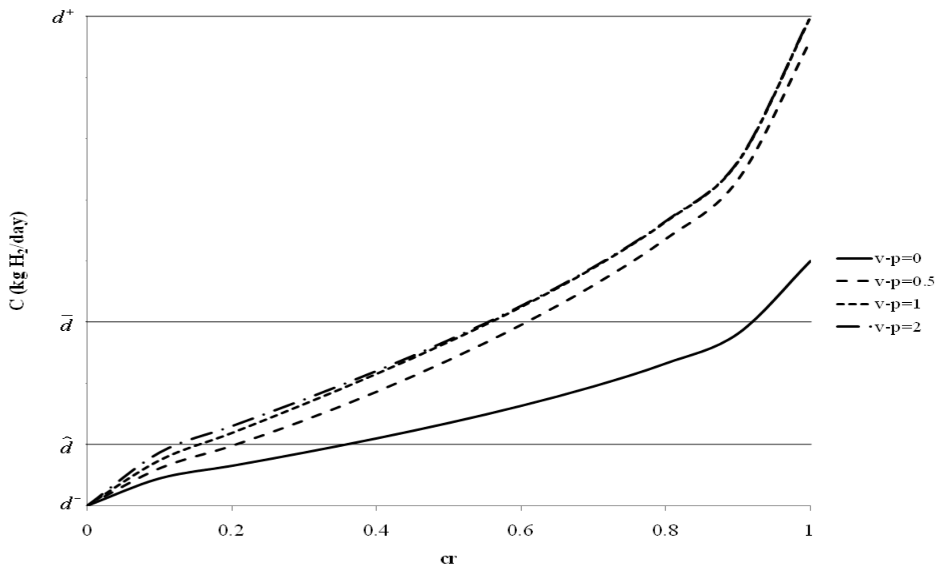

Figure 6.3. Station Capacity versus Critical Ratio $\bar{u}$ =0 and σ =0.3

A relatively small added utility has a significant impact on the station capacity. For example, at a critical ratio of 0.4, which represents a potential future operating point, station capacity is nearly twice for an added value difference *v-p=0.5*. This result has policy implications as it demonstrates the need for consumers to be educated about hydrogen which may have a significant impact on the adoption of hydrogen. As well, this experiment demonstrates that if consumers believe they must fill at this location, station capacities will increase significantly.

6.4.4. Numerical Example. Values of d^-=0, $\hat{d}$ = 3,333 and d^+=26,664 were selected based on data presented in Melaina [2005]. A value of σ =0.3 represents a public which can relatively agree what the utility of the outside option e.g. gasoline provides to them. The neutral case where, $\bar{u}$ =*(v-p)*=1, was selected in order to minimize the effect from outside values other than price. Thus, utilizing the presented model and assuming the U.S. Department of Energy's hydrogen production cost target between \$2.00-3.00/kg and a selling price of \$3.50/kg the station capacity would approximately be between 50-

850 kg/day. However, if the difference between *(v-p)* and $\bar{u}$ is 0.5 assuming all remaining parameters are identical the station size would approximately be 180-3,500 kg/day. This result demonstrates the significant affect that a change in consumer attitude on hydrogen could have on hydrogen demand.

6.5. CONCLUSIONS ON CONSUMER BELIEFS ON HYDROGEN STATION CAPACITY AND FUTURE WORK

A number of issues have to be addressed in order for a hydrogen economy to become a reality, including addressing the need to expanded the hydrogen infrastructure system to accommodate vehicular needs. Assuming a future hydrogen infrastructure would operate in a similar fashion as the current gasoline delivery system, with customers visiting fueling stations in order to refuel, the design of these new hydrogen stations must need future customer expectations. The design of a hydrogen station is a complex problem that entails the determination of numerous operating parameters including the overall hydrogen fueling station capacity while incorporating consumer behavior. A newsvendor formulation was selected to form the basis of the presented model. The classical formulation was expanded to include an outside option with customer placed added value to hydrogen. The results highlight the effect consumers have on demand as the optimal station size can differ significantly depending on consumer beliefs. The results also provide some insight into optimal introductory station sizes. Future work could expand the presented model by including multiple periods and salvage values for hydrogen. Further, multiple inventories representing a network of stations could be aggregated to be used in order to determine production capacity levels to investigate centralized production costs more thoroughly.

7. OPPORTUNITES FOR FUTURE RESEARCH

Significant challenges still exist in order to completely model a realistic deployment of hydrogen infrastructure. For instance, current models do not address the dynamic nature of transitional infrastructure development due to changes in technological and economic conditions. This section presents models that capture the benefits of phased development, while addressing the questions related to early feasible introduction locations, and how the introduction of hydrogen technologies in these locations affects continued introduction of hydrogen technologies on a local, regional, and national basis. First, some general background on factors affecting supply chain modeling is presented. Next, a hydrogen demand model based on intrinsic and extrinsic factors is formulated to accurately predict demand growth. The section concludes by proposing the incorporation of the enhanced hydrogen demand model with hydrogen supply models into a stochastic model to determine the timing of the introduction of hydrogen infrastructure components.

7.1. SUPPLY CHAIN CONSIDERATIONS

As globalization occurs more enterprises are entering into strategic partnerships with suppliers, subcontractors, and customers. This trend has only heightened some of the strengths and weaknesses of centralized and decentralized decision making. With centralized decision making, all decisions are made at a single location usually far removed from raw material sourcing or production sites. This can lead to a delay in transferring of information to the decision makers and can lengthen response time. An advantage of such a system is that the central decision making authority has a global view and can optimize the placement of resources, production levels, among other operating parameters for the entire supply chain. However, the globally optimized parameters are not guaranteed to be optimized for each party involved. Thus for competitive reasons individual companies tend to follow alternative policies which are optimized only for their production. This myopic point of view tends to result in a lower overall system efficiency.

Overall, the resource acquisition decision is one of the most critical factors that determines a firm's success. The decision to invest in large capital projects are usually characterized by long lead times, uncertain future demands and, in some cases, uncertain raw material feedstock availability or composition. One strategy to handle such uncertainties is to build flexibility into the supply chain in order to effectively match supply with demand. Additional benefits can be found in utilizing several different production and delivery technologies in order to diversify supply channels.

The optimal resource investment mix depends on several factors, including cost structure, market characteristics, demand characteristics, and risk management strategy. Investment and operating cost targets provide direction for the cost structure strategy. For an emerging industry such as a hydrogen energy system, these decisions are critical as the market conditions are highly variable. For example, although hydrogen is currently produced at a commercial scale by using a steam methane reformer, such a system would require a large capital outlay. In addition, the potential of serving a singular purpose, increases investment risk as the expansion rate for hydrogen usage is highly debatable. Such a decision emphasizes the complexity of investment decisions.

The main source of price disparity experienced by the consumer is due to the more efficient supply chain that exists for gasoline. Hydrogen can be produced onsite, which alleviates most of the supply chain costs. However, production costs rise as a result of losing economies of scale. The demand characteristics of such an industry further complicate the decision of what cost structure is most appropriate, as uncertainty, variability, and the unpredictability of the willingness of customers to adopt a new technology are significant.

The final factor that has an affect on optimal resource investment strategy is the overall risk management strategy. For instance, this would have a profound impact on the decision to invest in a large central production facility with lower production costs early in the introduction phase in hopes that the lower cost would generate demand at a higher rate or to take a more conservative approach and to invest in higher operating cost, lower output onsite generation technologies.

Although hydrogen has been used commercially for over a hundred years, a vast majority of this hydrogen has been captive use or for use by long term contractual customers. As a result, robust delivery channels, including intermediate storage depots, are not preexisting. Therefore if delivery of hydrogen from a central facility is required, the delivery system will have to be designed based upon economic and service level parameters. Currently, hydrogen delivery is constrained by the number of delivery methods available and the relatively small amount of existing delivery infrastructure. A sound corporate strategy for an emerging market must strive to make it easy for the consumer to try the product; hence, product availability is a key concern. Therefore, hydrogen outages, especially during the introduction phase, have to be minimal, while at same time the production pathway and scale have to remain economically viable. Aforementioned product availability is but one concern of the customer service strategy. The response time to fill a demand at a local station if central production is utilized is another parameter that needs to be considered. Both of these parameters have to be compared to profitability targets while at the same time minimizing the logistics cost.

The placement of most existing hydrogen existing has been based upon political and economical reasons that might not result in optimal placement or timing during the introduction period. As construction costs for individual stations can reach well above one million dollars, the optimal placement of initial stations is critical in order to create a backbone from which an encompassing support network can grow. Previous work has focused on the placement of stations within a particular city or region. These studies must be expanded in order to capture the attributes of the larger system otherwise the current model limitations could lead to the development of only clusters of stations. The clustering of stations to form “islands” could have a detrimental affect resulting in an overall collapse of the infrastructure over the long term if stations connecting these high concentration areas do not materialize.

In response to these conditions, a model that captures the benefits of phased development while addressing the questions related to early feasible introduction locations and how the introduction of hydrogen technologies in these locations affects continued introduction is proposed. Another key point related to the presented model is the incorporation of the interaction among locations within local regions and the effect of these interactions on future decisions. The inclusion of this behavior provides a more realistic representation of the multiple forces that affect the decision to install hydrogen infrastructure components. Further, identification and understanding of how key variables affect the design and growth of a future infrastructure can also be addressed through parametric studies.

7.1.1 Hydrogen Demand Modeling. The demand growth model incorporates three distinct forces – intrinsic demand, demand created by the presence of adjacent hydrogen facilities (e.g., production or fueling), and the additional potential demand created by the connection of independent networks – which are expected to have an effect on the potential demand for hydrogen at a particular location. The inclusion of this behavior is expected to provide a more realistic representation of the multiple forces that affect the decision to install a fueling station. In particular, the interaction among nodes within local regions is incorporated into the decision process. The projected demand growth for location *i* at time *t*, D_i^t (in kilograms), is modeled by:

$$D_i^t = \alpha_i^i + \beta_i^i + \gamma_i^i \text{, where} \tag{7.1}$$

α_i^i = intrinsic demand at location i at time t

β_i^i = adjacent demand at location i at time t

γ_i^i = network connection demand at location i at time t.

The intrinsic demand is based upon the population of the location and an exogenously derived hydrogen vehicle growth rate. In this case, a differentiating factor is that the growth rate is dynamic in nature. Overall, intrinsic demand (in kilograms) is calculated by:

$$\alpha_i^t = \phi_i^t \theta_i^t \upsilon^t \rho^t \xi^t \text{, where} \tag{7.2}$$

ϕ_i^t = population of location i at time t [people]

θ_i^t = number of per capita vehicles at location i at time t [vehicle/people]

ν^t = hydrogen vehicle growth rate at time t [%]

ρ^t = fuel usage rate at time t [kg/mile]

ξ^t = vehicle mileage at time t [miles/vehicle].

The presence of a fueling station has an effect on the demand of adjacent locations due to public awareness. This effect is based upon on the duration that the neighboring station has existed and the distance between the locations. Although, the distance at which the infrastructure may influence other potential locations is limited. The spatial behavior could be represented by a few distinct distributions for instance either a multimodal or a normal distribution. A multimodal distribution could be elected to represent a situation where drivers exhibit a high probability of refueling after driving a fixed trip length and again as they approach an empty tank. In either case, the time behavior is modeled using an exponential recovery function. For a normal distribution, the spatial behavior takes the form of equation 7.3. Thus,

$$\beta_i^t = \sum_{j=1}^{N} \alpha_j^t D_{ij} T_{ij}^t x_j \text{ , where} \tag{7.3}$$

D_{ij} is the distance effect the adjacent station at node j has on node i.

$$D_{ij} = \frac{\lambda_{ij}}{\sigma\sqrt{2\pi}} e^{\frac{-(\lambda_{ij}-\mu)^2}{2\sigma^2}} \text{ , for } \begin{array}{l} \lambda_{ij} \le d^t, D_{ij} = D_{ij} \\ \lambda_{ij} > d^t, D_{ij} = 0 \end{array} \tag{7.4}$$

where T_{ij} is the time effect a station at node j has on node i.

$$T_{ij}^t = R(1 - e^{-\frac{t-t_j}{R}}) \tag{7.5}$$

R is the adjacent station time effect scaling factor. Where,

$$R = \frac{\phi_i^t}{\left|\phi_i^t - \phi_j^t\right|} \tag{7.6}$$

x_j^t = 0/1if station is present at location j at time t

t_j = time station located at location j [yr]

λ_{ij} = distance between locations i and j

μ = mean distance [miles]

σ = standard deviation [miles]

d_t= vehicle driving range [miles].

The increased utility generated from the connection of independent nodes is calculated by distributing the traffic counts from each node to each secondary node and multiplying these counts by the combined distance traveled and the fuel usage rate. Thus,

$$\gamma_i^t = \rho^t \sum_{j=1}^{N} \sum_{\substack{k=1 \\ k \neq j}}^{N} \left[\frac{v^t \varepsilon_j^t \varepsilon_k^t \left(\lambda_j + \lambda_k\right) x_j^t x_k^t}{\sum_{j=1}^{N} \varepsilon_j^t} \right],\ \lambda_{ij} + \lambda_{ik} \leq 2d^t (\gamma_i^t = 0 \forall i, j, k \exists \lambda_{ij} + \lambda_{ik} > 2d^t) \tag{7.7}$$

ε_j^t = traffic counts between locations i and j at time t [vehicles].

The presence of x_j^t and x_k^t ensure the existence of a station at each node.

7.1.2 Stochastic Integrated Supply and Demand Network Modeling. Strategic planning and implementation activities related to exploring both near-term and renewable options for hydrogen infrastructure development and deployment suggest that effective national hydrogen infrastructure planning requires cooperative and collaborative efforts at the local and regional levels. A key assumption in modeling will be that deployment will grow outward from key local and regional nodes. With this in mind, this objective entails incorporating the outcomes from supply and demand models into comprehensive models for determining the optimal timing for the introduction of hydrogen infrastructure components, e.g., production, distribution, storage, or fueling station.

Either discrete stochastic dynamic programming or stochastic programming could be used to model the development of infrastructure. In either case, an efficient method to evaluate expansion candidates is to use threshold modeling to take into account the conflicting priorities of multiple decision makers, and would entail the automatic consideration of a component based on achieving a desired threshold. Factors included in the threshold model are derived from the supply/demand network modeling presented earlier, plus other socioeconomic or political considerations factors that are yet to be included. Thus, the index would be represented by *V(xt, Dt,…)*, and the action set, *A(xt)*, would include all locations *j* where

$V_j\left(x_j^t, D_j^t, \ldots\right) \geq T_j^t$, where T_j^t is the threshold criterion for location j at time t.

The first approach is to model the development as a stochastic dynamic program similar to an "arm acquiring restless bandit". A decision to expand to more than one location may be made (restless bandit) and at each stage, new locations become available for expansion (arm-acquiring) based on threshold modeling. In this case, the decision maker chooses a location for expansion based on the current state, x^t, and the rewards, *Ri t(xt)*, for each state. When an action from $A(x^t)$ is taken, the state transitions, $x^t \rightarrow x^{t+1}$ based on the uncertain nature of the supply/demand networks. The objective would be to maximize the expected (discounted) reward:

$$E\left[\sum_{t=1}^{\infty} R^t\left(x^t\right) e^{-\rho t}\right]. \tag{7.8}$$

Gittins Indices have been shown to optimally solve similar problems [Gittins, 1979], and a number of other researchers have utilized these results. Thus, Gittins Indices may be used to set the threshold criteria, T_j^t

The second approach is the use of multistage stochastic programming with recourse. In this case, potential expansion candidates could again be determined using threshold modeling. An example is where the decision maker chooses a location or locations for expansion in the first stage, and determines a distribution pattern in the second stage (after cost and demand uncertainty is resolved). A simplified objective of this model would be:

$$\max_{a(x^t)\in A(x^t)} R^t\left(x^t\right) - E_\xi\left[q^t\left(\omega^t\right)y^t\left(\omega\right)\right], \text{ where} \qquad (7.7)$$

E_ξ = expected recourse from action $a\left(x^t\right)\in A\left(x^t\right)$.

In this instance, *Rt(xt)* is a function of the supply network, while $q^t\left(\omega^t\right)$ is a function of the demand network, and $y^t\left(\omega\right)$ is a function of the integrated supply/demand network.

To formulate the problem mathematically, following notation is intorduced:

Inputs (primary dependent on supply/demand modeling)

f_j^t = fixed cost for establishing facility j at time t [$]

g_j^t = variable cost for establishing facility j at time t [$]

c_{ij}^t = production and distribution cost for satisfying demand at location i from facility j at time t [$]

p_i^t = unit profit for meeting demand at location i at time t[$]

D_i^t = projected demand growth for location i at time t[%]

Decision Variables

x_j^t = 0/1 if a facility is present at location j at time t

y_{ij}^t = fraction of location i demand supplied from facility j at time t [%]

z_j^t = size of facility j at time t [kg].

Using these definitions, a stochastic dynamic facility location problem can be formulated:

$$Max - \sum_t e^{-\rho t}\sum_j g_j^t z_j^t - \sum_t e^{-\rho t}\sum_j f_j^t x_j^t + E_\xi \max_y\left[\sum_t e^{-\rho t}\sum_i d_i^t \sum_j \left(p_i^t - c_{ij}^t\right) y_{ij}^t\right] (7.8)$$

Subject to

$$x_j^t \in \{0,1\}, \forall j,t \qquad \sum_i d_j^t y_{ij}^t \le z_j^t, \forall j,t$$

$$z_j^t \ge 0, \forall j,t \qquad y_{ij}^t \le x_j^t, \forall i,j,t$$

$$\sum_j y_{ij}^t \le 1, \forall i,t \qquad y_{ij}^t \ge 0, \forall i,j,t.$$

The random variable ξ is defined as $\xi = \{p,C\}$, where *p* is the vector of profits from demands and *C* is a vector of transportation costs c_{ij}^t.

The establishment of a hydrogen infrastructure is a multifaceted challenge. The key question is how to achieve feasible supply pathways in order to satisfy hydrogen demand growth. A chief differentiation point concerning the proposed models is that they utilize dynamic and stochastic methodology to quantitatively include non-stationary parameters related to supply, demand, and supply chain modeling. Another key point is the incorporation of the interaction within local regions and the effect of these interactions on future decisions, which provides a more realistic representation of the multiple forces that affect the decision to install hydrogen infrastructure, e.g., a production, storage or fueling facility. Supply chain interactions resulting from strategic and phased infrastructure development can also be explored.

8. CONCLUSIONS REGARDING HYDROGEN RESOURCES AND CAPACITIES

Energy, in general, is key to economic growth. A sustainable hydrogen energy industry could provide the pathway for an environmentally and economically stable world to evolve in the future. However, the establishment of a hydrogen economy is a multifaceted challenge with physical, economic and policy issues requiring to be overcome. In response, an assessment of leading near-term sources of hydrogen is presented in order to support future hydrogen adoption. For example, excess or by-product hydrogen production presents a low initial infrastructure investment option that can be used during a transition period.

A hydrogen system based on wind generated electricity is also presented as a viable component in a hydrogen transition strategy. The strengths of a wind-hydrogen system are exhibited in its modular design, exploitation of existing technology, and utilization of a renewable resource. Such a system would also provide flexibility and redundancy and would support a majority of the U.S. transportation fuel demand.

In order to better understand hydrogen station capacities required to fulfill potential demand, an inventory model which determines expected demand at local hydrogen fueling stations was constructed. A classical newsvendor formulation was expanded to include an outside option with customer placed added utility to hydrogen. The results highlight that the optimal station size can differ significantly depending on consumer beliefs. The results also provide some insight into optimal introductory station sizes. Results fom the model also show if actions can be taken that introduce a change in consumer beliefs concerning hydrogen demand could significantly increase.

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VITA

Kevin Braun Martin was born on September 14, 1979 in Mt. Vernon, Illinois. He received a Bachelor of Science in Chemical Engineering in 2002 from the University of Missouri – Rolla. He later received a Master of Science in Chemical Engineering in 2005 from the University of Missouri – Rolla. His master's research entailed the characterization of the polymer electrolyte membrane (PEM) fuel cell catalyst layer utilizing scanning electron, transmission electron, and atomic force microscopes. He has participated in many areas involving hydrogen, including the design, construction and daily management of a one of kind facility, the E^3 (E-Cubed) Commons. This facility includes a uniquely designed hydrogen fueling station, hydrogen vehicle research garage, and a building demonstrating environmentally friendly technologies including an integrated renewable energy system. Most recently, he became the initial chief executive officer of the Missouri S&T EcoCAR team. EcoCAR is North America's premier collegiate automotive competition. The Missouri S&T team, which is the only U.S. hydrogen fuel cell team in the competition, has the target of achieving a production ready vehicle by 2011. He received a Ph.D. in Engineering Management in December 2009.