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A Simplified Integrated Model for Studying Transitions to a Hydrogen Economy

Authors
Yang, Christopher
Ogden, Joan M

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A Simplified Integrated Model for Studying Transitions To A Hydrogen Economy

Christopher Yang[a], Joan Ogden[a,b]
University of California, Davis
[a] - Institute of Transportation Studies
[b] - Department of Environmental Science and Policy

Abstract

Many past studies of the 'Hydrogen Economy' have presented a steady-state portrait of a mature pathway from hydrogen production and distribution through utilization. One of the key problems surrounding the hydrogen economy is the large cost of building the infrastructure. The desire to reduce these costs associated with hydrogen infrastructure development leads to models and analysis of the dynamics of how a hydrogen supply infrastructure might grow over time, as demand for hydrogen increases in the transportation sector. To fully model hydrogen transitions is immensely complex, involving not only matching hydrogen supply and demand, but also how hydrogen interacts with the rest of the energy system, the economy, the environment and policy.

As a first approach to understanding transitions, we are developing a simplified model of the hydrogen economy – including alternative feedstocks, production technologies, distribution modes and demand scenarios. This model will be used to estimate infrastructure transition costs as a function of relatively small number of parameters for various demand scenarios. We plan to study how transition costs depend on factors such as the size and geographic density of demand, the market penetration rate, resource availability and technological progress. The goal is provide insights into low cost paths for moving our transportation fuel infrastructure from its current state to one based on large-scale use of hydrogen fuel. In this paper, we describe our overall approach and present initial results.

1. INTRODUCTION

1.1 Background and motivation

Hydrogen offers significant future benefits, when used in applications such as light duty vehicles and stationary power. These include significant or complete reductions in point-of-use criteria emissions, lower overall life-cycle CO_2 emissions, high efficiency, and a shift (with respect to transportation fuels) to a wide range of domestic feedstocks [1-3]. Despite the potential benefits of a hydrogen economy, there are many challenges as well. Hydrogen end-use technologies such as fuel cells and hydrogen storage need additional development to reduce cost and improve durability. In addition, there are tremendous costs and investments associated with developing and transitioning to an extensive transportation network based upon hydrogen. The widely-discussed "chicken and egg" problem focuses on these costs and the difficulty in building hydrogen supply to meet a small and growing demand. Many current studies of the 'Hydrogen Economy' present a steady-state portrait of a mature energy system including H_2 production, distribution and utilization [4-7]. These studies permit comparative assessments of the likely environmental and economic characteristics of particular supply options, but they do not adequately describe the technical and economic difficulties of building up the required infrastructure as H_2 demand increases in the transportation sector.

Modeling the transition to a hydrogen economy is difficult because of dynamic nature of the problem. The transition costs will be determined, in large part, by the size of the production, distribution and other infrastructure components and the economies of scale associated with these components and with the major shift in the transportation sector. Some believe that in the near-term, infrastructure will be built up by means of distributed production of hydrogen at refueling stations by fuel processors or electrolyzers. Only after significant maturation and market penetration of vehicles will the hydrogen demand be large enough to take advantage of the economies of scale associated with large centralized plants dedicated to hydrogen energy production [7]. In general, there is a trade-off between production costs and distribution costs in deciding when to move from distributed to centralized hydrogen production plants. We plan to explore how and when this and other possible transitions could occur in future work.

1.2 Scope of paper

We are examining many aspects of a transition to large-scale use of hydrogen in transportation under the Hydrogen Pathways Program at the Institute of Transportation Studies at UC Davis (ITS-Davis). The goal of the infrastructure modeling work is to provide insights into low cost paths for moving our transportation fuel infrastructure from its current state to one based on large-scale use of hydrogen fuel. This paper presents initial results from a simplified model for understanding hydrogen infrastructure transitions. Several distribution-related infrastructure models will be discussed:

- Optimal distribution mode - this analysis calculates distribution costs for compressed gas and liquid trucks and gas pipelines and determines minimum costs as a function of two parameters (distance and flow rate).
- Idealized city hydrogen distribution network - this model develops an idealized city where the number and location of refueling stations is varied to investigate the distance between users and the nearest stations and the length of the hydrogen distribution network to supply the stations.
- Growth dependent pipeline cost - this model calculates the costs associated with adding pipeline capacity of different size increments to meet various demand growth profiles.

Though these results are still preliminary, they permit some early insights into the hydrogen infrastructure transition. After the model is complete, it will ultimately yield a greater understanding and insights into the optimal and low cost paths for moving our transportation fuels infrastructure from its current state to one based largely on hydrogen fuel. The most attractive transition pathways, in terms of capital investment, hydrogen cost, emissions and pathway flexibility, will depend on the scale of the location and time-dependent H_2 demand. Understanding if and when the transition makes economic sense and the factors that will influence that transition can help guide efficient decision making for policy, research and development directions and investments by government and industry.

2. MODEL, METHODS AND PRELIMINARY RESULTS

2.1 Integrated Infrastructure Transition Model

Researchers at the Hydrogen Pathways program at ITS-Davis are developing a series of integrated hydrogen system models for the entire chain of processes that occur between feedstock conversion to consumer utilization. The main goal is to understand how a transition to hydrogen could occur both temporally and spatially as demand grows over time. The model will incorporate the work of other researchers in the Pathways program with detailed projects relating to specific components of the hydrogen economy including hydrogen vehicle demand [8-10], production and distribution technologies and reliability, refueling station design and siting [11] and end-use technologies and their performance and environmental impacts [12], as well insights from other ongoing systems studies such as the H2A project [13].

Pathways that will be investigated include large-scale and distributed production of hydrogen via different primary energy sources including fossil fuels, biomass, and renewables, distribution of hydrogen via trucks (compressed gas and liquid) and pipelines, storage of hydrogen, and dispensing in hydrogen refueling stations of different configurations. These pathways will be studied for their suitability and cost-effectiveness to meet various growth scenarios for demand in different representative geographic regions. The usefulness of such a model is to help identify pathways that can lower the initial and aggregate costs of building the necessary hydrogen production, distribution and dispensing facilities in the near and medium term. The goal of this model is to investigate the lowest cost pathways for providing hydrogen over a range of conditions. We would like to understand the cost and environmental implications of different possible future scenarios, regionally specific attributes that affect infrastructure buildup, and alternative processes and primary energy resources. This can provide a focal point for planning the transition to a hydrogen economy, for example, by identifying system components that are most in need of improvements.

The key outputs of the model will be cost and environmental impact. Sub-models are currently being developed to describe technical performance and costs associated with feedstock choices, hydrogen production technologies, distribution modes, storage options and refueling station designs as a function of scale and operating conditions. We plan to integrate these sub-models into a coherent pathway model that can investigate transition issues as demand grows. Important issues include the transition between distributed vs centralized hydrogen production, costs related to underutilized capital, replacement costs and stranded assets when moving to higher capacity equipment, and environmental impacts during the transition. We will attempt to model the impact on costs to uncertainties in future demand. Because the transition model is a long-term ongoing project still in development, extensive results are not yet available. Below we discuss results from some of these sub-models, which will be integrated to produce the infrastructure transition model.

2.2 Demand inputs

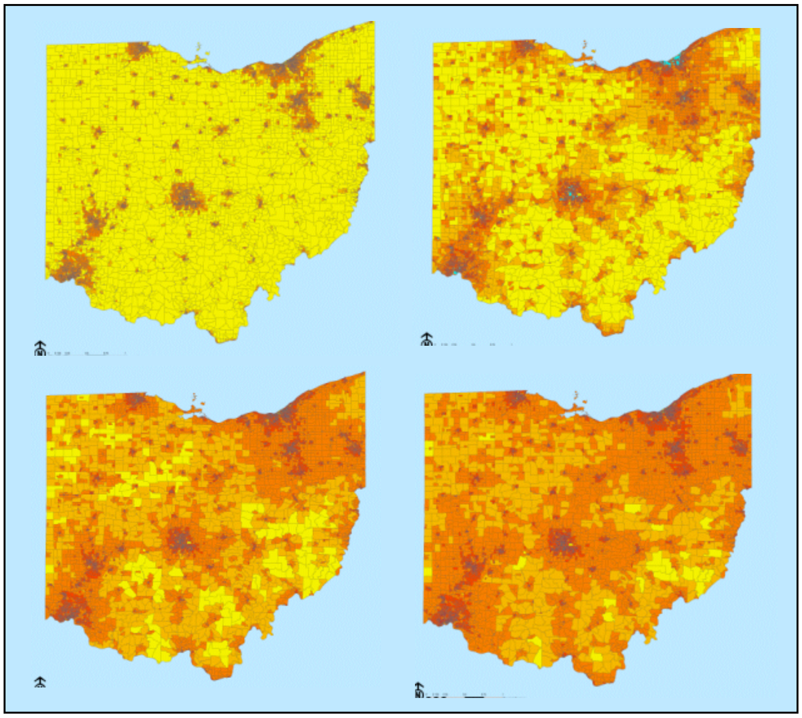

Figure 1 GIS figure showing hydrogen demand changes over time (Year 1, 5, 10 and 15) for the state of Ohio in response to a increase in hydrogen vehicles (25% of LDV sold per year).

In the transition model, hydrogen demand is specified exogenously from the other components of the model. The model then finds the lowest cost pathway to meet the specified demand. To develop a range of credible demand scenarios, we are incorporating a number of key variables, including geographic factors (population distribution and density), market factors (market penetration rate which depends on the competitiveness of hydrogen vehicle technologies and policies to reduce externalities), and siting (number of refueling stations needed).

An early attempt to model demand geographically over time is shown in Figure 1. Here Geographic Information System (GIS) data on population and vehicle ownership for different types of regions (e.g. urban, suburban, rural) is used to provide an estimated vehicle density (vehicles/km^2) in a region. We use exogenously determined market penetration curves for H_2 vehicles to estimate hydrogen demand over time. Given the growth in percentage of LDVs that run on hydrogen and estimates on the vehicle miles traveled (VMT) and fuel efficiency of these vehicles, one can calculate a hydrogen demand (kg H_2/km^2/day) that is a function of location and time. From these GIS maps, a network of refueling stations and the distribution network to supply hydrogen to these stations can be designed and sited. We are investigating other methods for modeling demand in for idealized cities (see section 2.4 below), and for particular locations [11].

2.3 Optimal delivery mode

Distribution is one of the critical elements of a hydrogen infrastructure and has been the initial focus of our model development efforts. This calculation attempts to quantify the costs associated with delivery of hydrogen from a central plant to the city gate (between two points) and the least-cost mode is determined as a function of two input variables: transport distance and flow rate. Models for estimating the costs of each delivery mode were developed based upon previous work of Simbeck and Chang, Amos, Ogden and other pipeline equations for natural gas and other fluids [5, 6, 14-16]. This study and previous studies have attempted to estimate cost of large-scale hydrogen transportation and storage based upon current commercially available technologies.

These models help to determine the technical performance and economic costs of the range of technologies with which to deliver hydrogen. This delivery analysis does not incorporate the wide range of factors to describe the spatial and temporal evolution of demand growth. Rather, this model represents the hydrogen demand by two variables: transport distance [km] and hydrogen flow rate [kg/day]. While this ignores the complexity associated with a distributed and growing hydrogen demand, it allows each transport mode to be readily comparable with other transport modes and provides a simplification so that a detailed analysis of a region need not be a prerequisite of identifying the most likely low-cost pathway.

In addition to the unit delivery cost of hydrogen [$/kg], other important criteria are included such as energy losses (which relate to overall system energy efficiency) and CO_2 emissions. There are, of course, many other potentially important variables and metrics that are not discussed in detail here such as delivery mode flexibility, mode reliability, amount and timing of total capital investment and other environmental impacts (life-cycle emissions). Although these factors are not explicitly incorporated into the simple model presented here, they can play a large role in decision making for the transition to a hydrogen economy. The following sections describe the different hydrogen delivery modes that are considered and the basis for the cost estimates, including compressed gas and liquid hydrogen trucks and gas pipeline.

2.3.1 Pipelines – gaseous H_2

In this model, pipeline cost is composed of several components, pipeline materials, right-of-way, installation, compressor, operations and maintenance, and energy costs. The cost of pipeline materials is determined by the length of pipe, diameter of pipe and maximum pipeline pressure. A detailed pipeline flow model is used to determine the appropriate diameter and thickness to supply a specified flowrate and pressure of hydrogen at the lowest cost [5, 16]. The pipeline materials costs are calculated based upon the pipeline diameter, length and thickness. These costs were compared to a study of natural gas pipelines and the installation and right-of-way costs were assumed to be similar on a cost-per-mile basis to natural gas pipelines (described in detail by Nathan Parker at ITS-Davis). The levelized cost of unit H_2 distribution ($/kg) through pipeline systems is mainly dependent on the fixed pipeline and compressor capital and installation costs (which account for between 66 and 75% of the annual costs for a fully utilized pipeline). Compression and pumping energy make up only 7 – 15% of the delivery costs. This dependence on capital costs makes the pipeline capacity and how well it matches with the actual flow capacity an important factor. The design capacity of the pipeline will likely be higher than actual/instantaneous flow rate due to non-constant flow conditions on an hourly or daily basis or due to built-in flexibility/capacity growth or both. This can lead to underutilized capital (pipeline and compressor) which increases the cost of hydrogen delivery.

2.3.2 Trucking – compressed and liquefied H_2

The levelized cost of truck delivered hydrogen is based upon the capital costs of trucks, liquid or compressed gas tanks, compressors and liquefaction equipment, operating and maintenance and fuel costs. These costs were based upon studies at NREL and SFA Pacific to determine costs for trucks and O&M [5, 6]. The model costs are strongly dependent upon the hydrogen capacity of the trucks. The capacity of compressed gas tube trailers is fairly small (~300 kg/truck). Because liquid hydrogen has much more energy density, hydrogen trucks carrying cryogenic hydrogen can carry perhaps 3000-4000 kg/truck or about 10 times the amount of hydrogen as the compressed gas trucks. This leads to significantly reduced capital costs for trucks and fuel and labor costs, although energy costs for liquefaction are higher than for compression.

2.3.3 Model results

This model calculation determined the levelized delivery cost ($/kg) for each of three technologies (truck delivery of gaseous H_2, truck delivery of liquid H_2, and pipeline delivery of gaseous H_2) over the range of transport distances and flowrates. The transport distance refers to the length along one specific route. Distribution to multiple stations is not calculated so the costs are not representative of the distribution costs for a network of refueling stations. For pipeline distribution, we include costs for compression and storage at the central hydrogen production plant, plus pipeline costs. For liquid hydrogen trucks, we include capital and operating costs associated with the trucks and liquefaction and LH2 storage at the central plant. For compressed gas trucks, we include capital and operating costs for the trucks and compression from production pressure (150 psia) to truck tube trailer pressure 2600 psi at the central plant.

Figure 2 shows a representation of which mode is the lowest cost method for a given set of conditions (transport distance and flowrate). It shows that trucking gaseous H_2 make sense for low flowrates and short distances, but that as you increase transport distance, other modes can become the lowest cost method. Because the capacity of tube trailers is very low, liquid delivery makes more sense at longer distances, where reductions in diesel fuel costs more than make up for increased capital and storage energy costs. Pipeline becomes the dominant low-cost mode, as the flowrates increase and the delivered costs are greatly reduced as the volume increases.

Flowrate [kg H_2/day]	Transport Distance [km] 25	50	75	100	125	150	175	200	225	250	275	300	325	350	375	400	425	450	475	500
2000	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	L	L	L	L	L
4000	G	G	G	G	G	G	G	G	G	G	G	L	L	L	L	L	L	L	L	L
6000	G	G	G	G	G	G	G	G	G	L	L	L	L	L	L	L	L	L	L	L
8000	P	G	G	G	G	G	G	G	L	L	L	L	L	L	L	L	L	L	L	L
10000	P	G	G	G	G	G	G	L	L	L	L	L	L	L	L	L	L	L	L	L
14000	P	P	P	G	G	G	L	L	L	L	L	L	L	L	L	L	L	L	L	L
18000	P	P	P	P	P	P	L	L	L	L	L	L	L	L	L	L	L	L	L	L
22000	P	P	P	P	P	P	P	L	L	L	L	L	L	L	L	L	L	L	L	L
24000	P	P	P	P	P	P	P	L	L	L	L	L	L	L	L	L	L	L	L	L
28000	P	P	P	P	P	P	P	P	L	L	L	L	L	L	L	L	L	L	L	L
32000	P	P	P	P	P	P	P	P	P	L	L	L	L	L	L	L	L	L	L	L
36000	P	P	P	P	P	P	P	P	P	P	P	L	L	L	L	L	L	L	L	L
40000	P	P	P	P	P	P	P	P	P	P	P	P	L	L	L	L	L	L	L	L
44000	P	P	P	P	P	P	P	P	P	P	P	P	P	L	L	L	L	L	L	L
48000	P	P	P	P	P	P	P	P	P	P	P	P	P	P	L	L	L	L	L	L
52000	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	L	L	L	L	L
56000	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	L	L	L	L
60000	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	L	L	L
64000	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	L	L
68000	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P
72000	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P
76000	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P
80000	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P
84000	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P
88000	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P
92000	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P
96000	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P
100000	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P

Figure 2 Map of the lowest cost distribution mode for the range of transport distances (25-500 km) and flowrates (2000-100000 kg/day). "G" indicates compressed gas trucks, "L" indicates liquid hydrogen trucks and "P" indicates compressed gas pipelines.

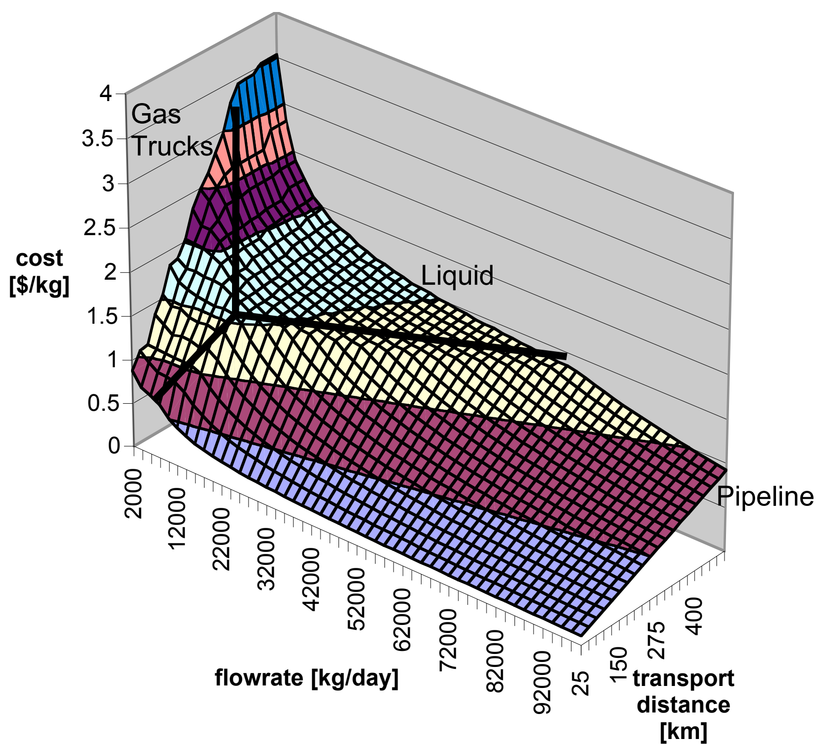

Figure 3 The distribution cost of hydrogen ($/kg) for different conditions of transport distance and flowrate.

For each combination of these two variables, the lowest cost is determined from the costs of the three distribution modes and these minimum costs are plotted on Figure 3. The colors are contour lines and indicate \$0.50 increments in the delivery cost of hydrogen (z-axis) while the two horizontal axes correspond to transport distance (0-500 km) and flow rate (0-100,000 kg/day). It is clear that the lowest cost (per kg H_2) occurs at a very high flowrate and small distribution distance, as would be expected, where pipeline capital costs would be significant but could be averaged over a very large amount of hydrogen. While this analysis using distance and flowrate does not completely capture the complexity of a distribution problem, it allows us to identify general set of conditions in which a mode is likely to be the lowest cost method of distribution. This work expands upon that of Amos and Simbeck by quantifying the specific conditions of distance and flow under which particular modes become the least cost.

2.4 Idealized Distribution network model

After hydrogen is brought to the city gate, it must be distributed to refueling stations. In order to get a reasonable estimate of the cost of the hydrogen pipeline distribution network for a city, it is necessary to determine what that distribution network looks like. Others have looked at possible configurations for a network of refueling stations [4, 17]. Even for the same number of refueling stations distributed throughout a city, the length and subsequent cost of the distribution network can be very different depending upon how those stations are arranged. The goal of this model is to develop some generalizations and abstractions with which to characterize a generic city in terms of its size, hydrogen demand and the resulting hydrogen infrastructure required to support this demand. This model city is circular, the population size and density are not specified absolutely but rather characterized as a percentage and distributed as a function of distance from the center. The city has a defined radius of "1" (in arbitrary units), and distance is calculated in this city as the straight-line distance between two points rather than following a road network.

The lack of detailed specification of physical size and population allows for application of the results to different sized cities. A detailed geographic study of a specific city/region using GIS (as has been done for the city of Sacramento by Nicholas [11]) is necessary to provide accurate estimates of the number of stations required, the travel time for consumers to refuel, and the exact configuration of stations and pipelines required to optimize infrastructure investment. However, while the simplified city discussed here may not lead to results with the same level of detail, it permits the development of "rules-of-thumb" which are generically useful and can be quickly applied to a new location in the way that a detailed analysis cannot.

In this model, a number of specific items were investigated: (1) the number of refueling stations within the city and the effect on the distance that consumers must travel to refuel, (2) The length of the distribution network (pipes) to supply the refueling stations from the city gate, and (3) the distribution of demand amongst the stations within the city. Several configurations of 5, 10, 25 and 40 stations distributed throughout the city are investigated and the model results depend upon these specific station configurations.

Given a specified distribution of population within the area of the city, it is possible to vary the station distribution throughout the city in order to minimize the average distance

(D_{avg}) for all consumers to the nearest station. The equation for the weighted average distance between consumers and the nearest station is:

$$D_{avg} = \sum_{x=1}^{n} d_{m,x,\min} f_x$$

where $d_{m,x,min}$ is the distance between the closest station and each population segment in the city, where there are m stations, n population segments, and f_x is the fraction of the total city population at each population segment. In this model, there are 1322 population segments evenly distributed at 0.05 unit intervals throughout the circular city. For the "homogenous" case, the population is equally distributed among these segments (i.e. f_x is identical for all x) while in another case, "center-weighted", there is a higher population density at the center as compared to the periphery of the city.

$f_a > f_b$ where radius a < radius b

The refueling stations are configured into rings that are concentric around the city center. Each city configuration consisted of one to four rings of stations with varying numbers of stations in each ring. For a given station configuration, the radii of the rings of stations were altered in order to minimize the overall weighted average distance traveled for users. This analysis does not find an optimal configuration of stations, because the average distance between users and stations is only one criteria among several that will be used to optimally site refueling stations. Reducing the length and cost of the pipeline network to supply these stations is another important criteria. As a result, the model also calculates the distribution network length (i.e. the length of pipe required to connect each of the stations together and to the edge of the city (city gate)).

To improve the accuracy of the analysis, a correction factor should be included in order to account for the difference (percentage increase) between a straight-line distance and the travel distance necessary on a road network. This correction will depend upon the density of the road network. In urban areas where there are more roads this number could be somewhere between 20 and 40% whereas in rural areas with fewer roads this number could be between 30 and 80%. The length of the distribution network is also calculated using the straight-line method as the minimum length of pipe required to connect each of the stations to the other stations and to the edge of the city. Rights-of-way will determine the actual length of the pipe and these will also vary in response to the density of a city and specific geographic features. These correction factors for travel distance or pipeline length are *not* included in this analysis and the distances provided here are merely straight-line distances. The model results are presented for different "cities" with homogeneous and heterogeneous (center-weighted) population distributions and different configurations of 5, 10, 25 and 40 station distribution networks. Distribution network lengths and travel distances are given as a function of the city radius.

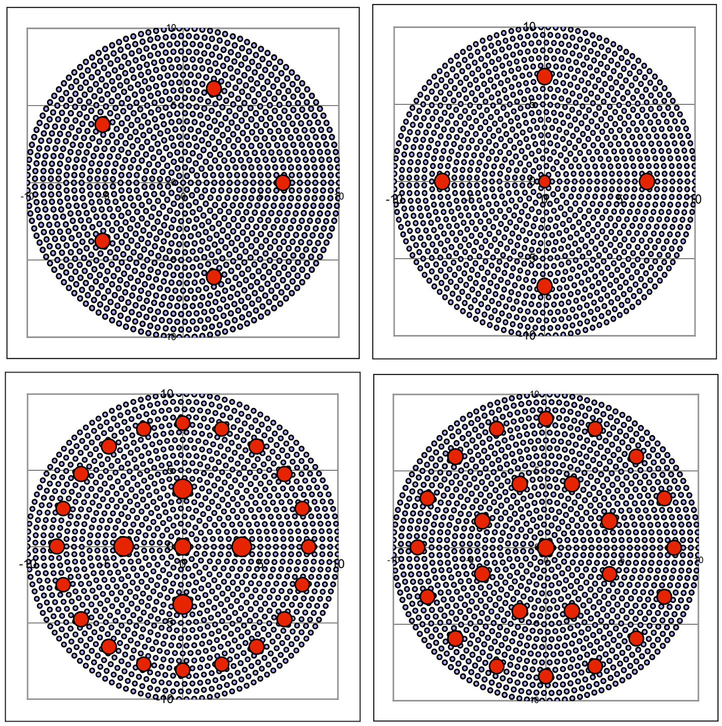

Figure 4 Sample station configurations (red) for model city with 1322 homogeneously distributed population centers (blue) and 5 and 25 stations respectively.

2.4.1 Homogeneous population distribution results

The results of the generalized distribution model are shown in the following figures for a series of cities with different configurations of 5, 10, 25, and 40 stations. Figure 5 shows the results of the calculations for distribution network length and average distance from users to the nearest stations expressed as a function of the radius of the city for many different station configurations. In general, the trend is that as the number of stations increases and as the stations are more optimally sited, the average distance between the users and stations will fall, while the total length of the distribution network increases. As seen in Figure 4, as the number of stations increases and they are better distributed to meet the dispersed demand, the number and length of pipelines required to supply hydrogen to these stations increases. The size of the circles representing stations in Figure 4 indicates the percentage of total demand the station services. The distribution of demand among stations is important because uneven station utilization may not be economically optimal, although it may increase consumer convenience.

Figure 6 shows the various percentiles for the distance between H_2 consumers and their closest station. The spread between the 20th and 95th percentiles is greatest for the configurations with fewest stations and improved siting of stations can reduce the travel time for 95th percentile even while the median travel time stays approximately the same. The median travel distance drops from ~0.33 for 5 stations to ~0.23 for 10 stations, ~0.15 for 25 stations and ~0.12 for 40 stations. While median travel distance is important, the identification of the distribution of travel distances can be as useful to ensure that a large fraction of consumers are not greatly inconvenienced by a particular station siting configuration.

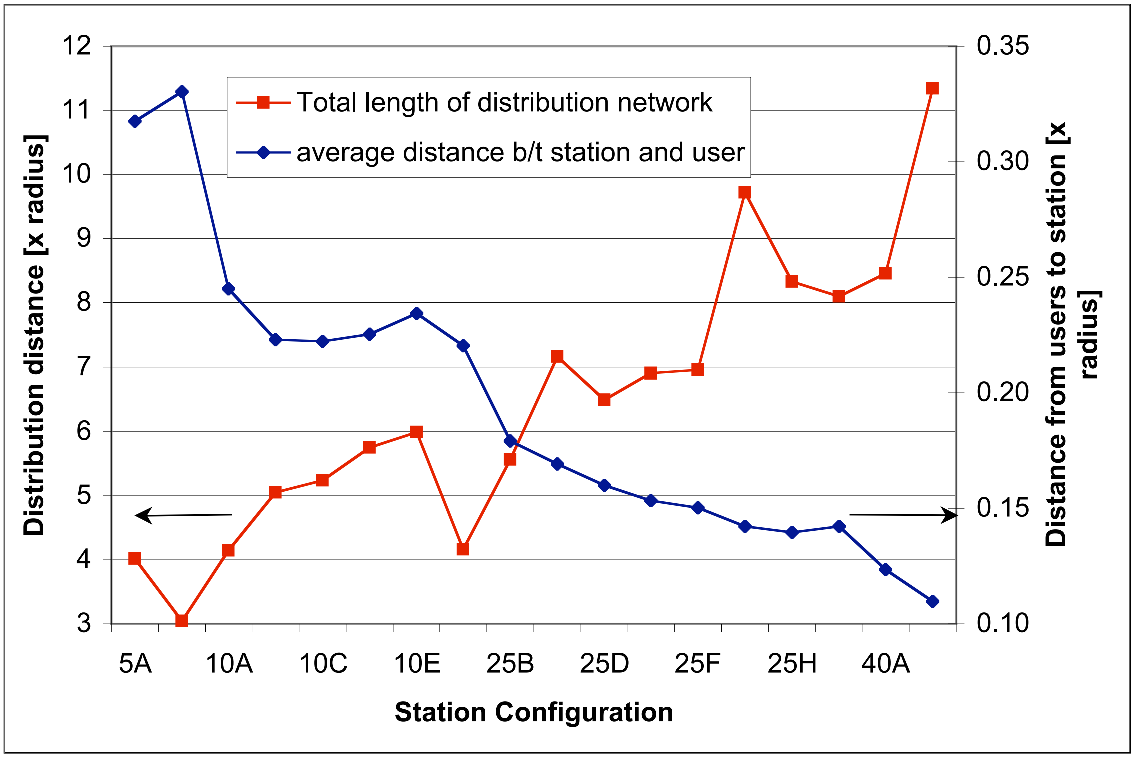

Figure 5 Length of distribution network and average distance between users and closest station for 5, 10, and 25 stations in a homogeneously distributed population. Length units are city radii.

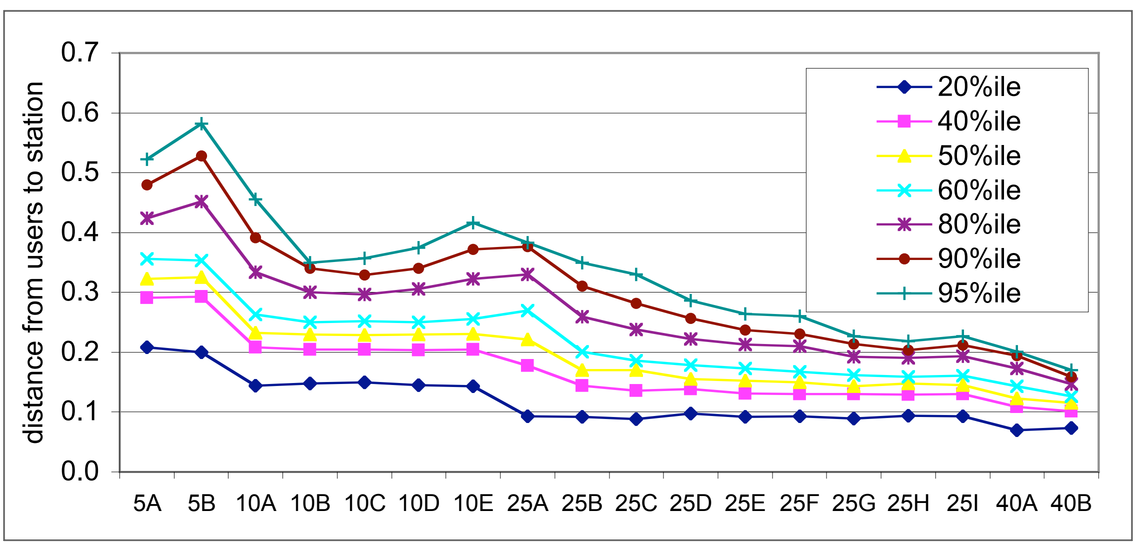

Figure 6 Percentiles for user distance (as multiple of city radii) to closest station for different configurations (5, 10, 25, and 40 stations) in a homogeneously distributed population

2.4.2 Center-weighted population distribution results

Results for the center-weighted population distribution show the same general trend as for the homogeneously distributed population results in Figure 6. Because of the uneven population distribution and very high density in the center of the city, the largest stations in these configurations have a much higher demand than in the homogenous population cases. The greater population density in the center of the city leads to a larger average distance between the stations and the users. In these scenarios, stations are generally sited closer to the center of the city to accommodate the greater population density there and minimize the average travel distance but this leads to a larger average distance and greater distances for users in the highest percentiles of travel distance when compared with the homogeneous population distribution. The length of the distribution network to supply the stations varies a great deal on the siting of stations within the city and the proximity to the higher population density areas. The distribution length is decreased for the center-weighted cities as compared to the homogeneous cities because more stations can be placed closer to one another in the denser city center.

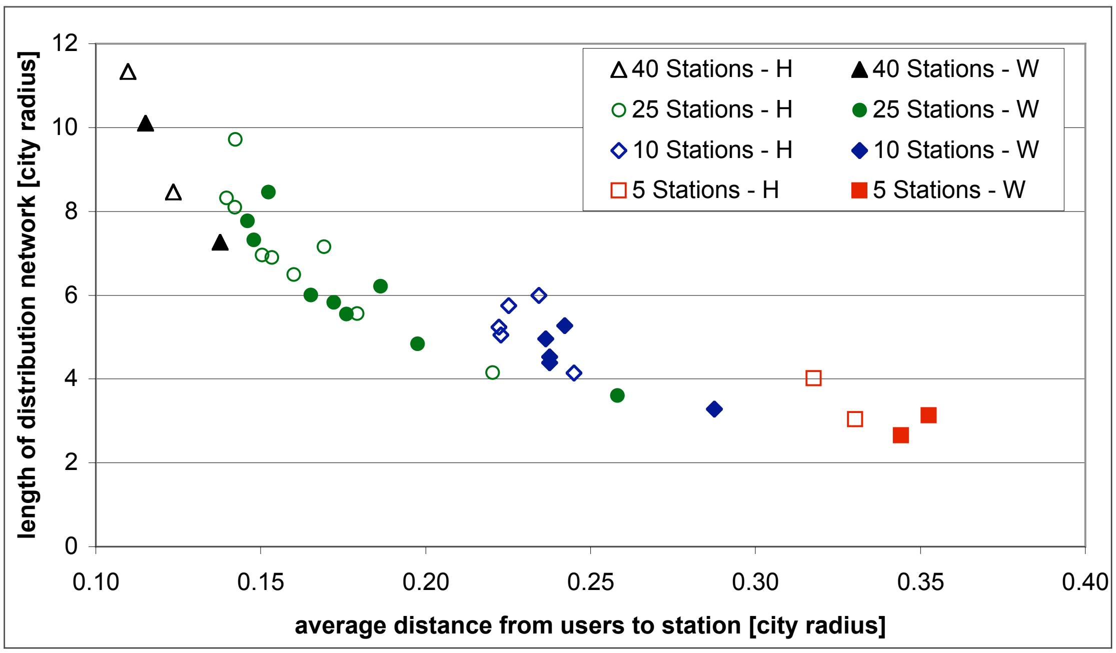

Figure 7 The length of the distribution network to supply refueling stations within a city as a function of average distance between consumers and the closest station for different configurations of 5, 10, 25 and 40 stations. "H" indicates homogeneous and "W" indicates center-weighted population distribution.

Figure 7 shows the tradeoff between siting a larger number of stations in configurations in order to reduce the average distance between the station and the users and the total length of the distribution network. In general, the figure shows that the homogeneous population distribution leads to a longer distribution network length but lower average station distance for users. This model is useful for determining the number of stations required from a convenience standpoint and helps determine the cost of the distribution network that is specified. In general, the pipeline network distances range from about 3 to 12 times the radius of the city, though these numbers will generally be higher when considering real road and pipe networks rather than ideal straight line distances.

For example, a moderate city of 1 million people with an average population density of 2000 people per square mile will have a city radius of approximately 12.6 miles. Using the results for one of the 40 station configurations for a homogenous population distribution, we obtain an average user-to-station distance of 1.6 miles (0.125 x radius) and a pipeline network distribution length of 107 miles (8.5 x radius). These lengths are not adjusted for the location of roads or other geographic features, but still provide guidance for estimating pipeline infrastructure costs and the required number of stations for support user convenience. The number of refueling stations within a city is dependent upon multiple factors. In the case of stations for a fuel with low market penetration, obtaining adequate coverage with the minimum number of stations is highly desirable. Market research suggests that a minimum of 10-20% of gasoline stations is needed to supply hydrogen in order to satisfy consumers. (For a city with 1 million people or about 800,000 light duty vehicles, and assuming that each gasoline station serves 2000 light duty vehicles today, 40 stations would be about 10% of the total.) This approach looks at the distribution of distance between users and the nearest stations to identify the necessary number of stations. It also makes clear the tradeoffs between the costs of increasing numbers of stations and distribution network length and the increased convenience to drivers.

2.5 Transmission/pipeline cost – a time dependent analysis

In a scenario with continuous hydrogen demand growth, the capacity and utilization of the production and distribution infrastructure is important to the economics of hydrogen production and delivery. As demand increases, the production capacity of the plant and the distribution capacity of pipelines should increase to match or exceed demand. Questions need to be answered about the ideal timing and size of infrastructure investments: When should the system capacity be expanded and by how much? Which strategies give the lowest cost pathways over time? Instead of starting with the entire pathway from conversion to refueling, we begin with a simpler problem: how to expand a single segment of pipeline for different levels of demand growth. This example illustrates some of the issues in finding the lowest cost transition.

2.5.1 Model description

The costs associated with the pipeline transmission of hydrogen are segregated into pipeline capital, installation, right-of-way, compressor capital, operations and maintenance and energy costs. The capital cost of the pipeline is a function of the pipeline length and diameter. The pipeline flow is characterized by the following equation for turbulent pipeline flow [5, 16]:

$$P_{in,P} = \sqrt{\frac{64\dot{M}^2 fLR_{H_2}T}{\pi^2 D_{in}^5} + P_{out,P}^2}$$

The pipeline flow equation is used to determine to optimal pipeline diameter for a given flowrate. Increased pipeline diameter will reduce the frictional losses and consequently reduce the inlet pressure and energy costs required to supply a given outlet pressure. However, increased pipeline diameters lead to increased wall thickness for the same pressure, which will increase capital costs. Thus, there is an intermediate pipeline diameter that results in the minimum hydrogen delivery cost. The compressor energy and capital costs will be based upon the actual inlet pressure. This optimum pipeline size is used and the capital cost of the pipeline is proportional to the amount of pipeline material. Pipelines are assumed to have a lifetime of 30 years. The cost of pipeline installation and right-of-way is assumed to be a fixed cost per mile. The right-of-way cost is assessed when the first pipeline is installed and the installation costs are reduced for subsequent installations.

The hydrogen compressor cost is a function of the flowrate and the compression ratio with a cost sizing exponent of 0.9. O&M costs are a fixed percentage of the total capital (pipeline and compressor) costs. Finally, the energy requirements and cost are determined for underutilized pipelines. The flow is evenly split between the available pipelines and the pumping work is determined by determining the friction/pressure losses associated with specified utilization percentages for the pipelines.

Pipeline capital, right-of-way, and installation costs are financed with a 10% interest rate on borrowed capital and added to O&M and compression energy costs to determine the levelized present value cost (using a 10% discount rate) of this delivery component per unit of hydrogen delivered ($/kg). We consider a single 50 mile-long pipeline route connecting a hydrogen source to the city gate (for subsequent hydrogen distribution to refueling stations). In this problem, the pipeline capacity is assumed to be available in fixed increments (20,000, 40,000, and 80,000 kg/day). As demand increases (to a final demand of 80,000 kg/day), the pipeline infrastructure is expanded so that if supply is insufficient to meet demand, additional capacity is built. For each demand profile, the cost of supplying hydrogen via combinations of pipeline capacities is determined for different periods of time. The three supply infrastructure options are: 1) installing a single 80,000kg/day pipeline; 2) installing a 40,000 kg/day pipeline in year 1, and adding another 40,000 kg/day pipeline when the first pipeline is saturated and, 3) installing a 20,000 kg./day pipeline in year 1, followed by three other 20,000 kg/day increments over time when the capacity is needed.

The levelized costs for hydrogen transmission is determined for different time periods, 10, 20, 30 and 60 years. If the length of the time period does not coincide with the lifetime of the pipelines and compressors in question, the salvage value of the remaining capital equipment is subtracted from the total costs. The pipeline salvage value is modeled as a straight line depreciation to 20% of the initial value over 30 years. Table 1 shows some of the cost data that is used in this analysis.

Several demand scenarios for a city were used as an exogenous input into the model. Simple linear demand profiles were used for the model and the growth rates were varied to simulate slow, medium and fast growing demand and calculate the needed investment and infrastructure to meet this growing demand. Each of these demand scenarios eventually reach a "carrying capacity" of 80,000 kg/day, which is representative of a fully mature hydrogen demand for a small city of about a quarter of a million people. The linear demand profiles are broken into three profiles, slow, medium and fast, that increase at a steady rate of 1200, 2400 and 4800 kg/day annually. The logistic ("sshaped") demand profiles closely match the linear profiles with a decrease in hydrogen demand relative to the linear profiles in the early years and an increase in hydrogen demand in later years. The slow, medium and fast logistic profiles have logistic growth rates of 0.09, 0.18 and 0.4 respectively. The application of these demand scenarios to infrastructure problem of pipeline capacity in various pipeline capacity increments leads to a levelized cost of hydrogen transmission that will depend upon the extent of pipeline underutilization and the effects of economies of scale for pipeline and compressor capital costs.

Table 1. Pipeline Growth model assumptions and parameters

Flowrate/diameter independent factors		**20,000 kg/day pipeline and compressor**	
Installation cost:	$192,000/mile	Pipeline diameter:	4"
Right of way cost:	$128,000/mile	Pipeline material cost:	$36,000/mile
(charged when first pipeline increment is built, but not for subsequent increments)		Initial installed cost	$356,000/mile
		Compression:	600 kW
Pipeline length:	50 miles	Compressor cost:	$2500/kW
Compression:	20 to 70 atm		
Discount rate:	10%		
40,000 kg/day pipeline and compressor		**80,000 kg/day pipeline and compressor**	
Pipeline diameter:	5.5"	Pipeline diameter:	7"
Pipeline material cost:	$67,000/mile	Pipeline material cost:	$110,000/mile
Initial installed cost	$387,000/mile	Initial installed cost	$430,000/mile
Compression:	1200 kW	Compression:	2300 kW
Compressor cost:	$2300/kW	Compressor cost:	$2100/kW

2.5.2 Demand input

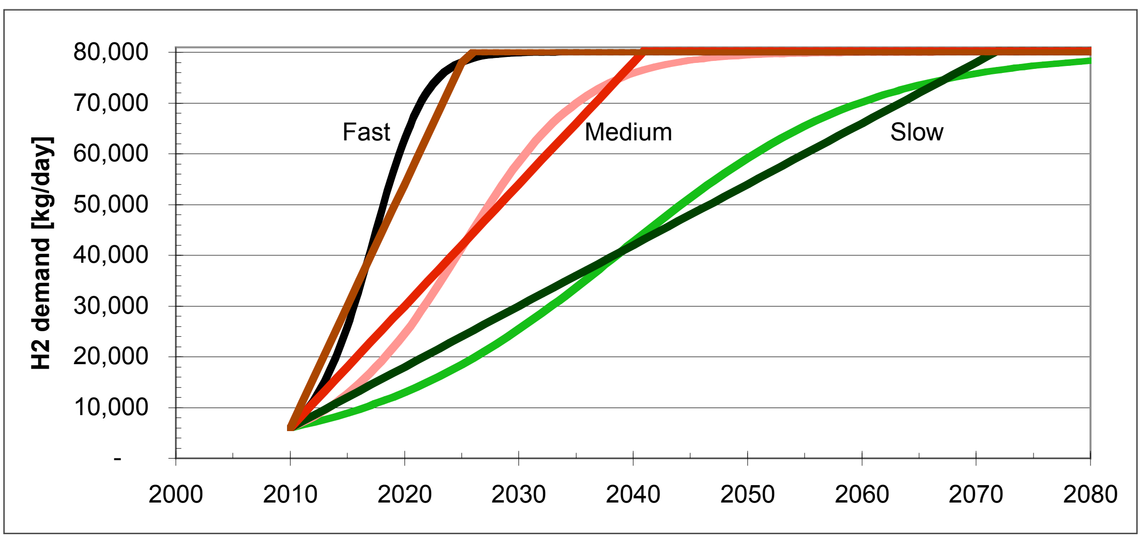

Figure 8 Linear and logistic demand scenarios inputs to pipeline growth model.

2.5.3 Transmission/pipeline model results

The model results are strongly influenced by the choice of discount rate. At a discount rate of 10%, a present value over 10 years will be only 39% of the future value, over 25 years, only 9% and after 40 years, only 2%. Thus, any delay in the infrastructure and capital expenditures will, from a present value perspective, be much cheaper than spending in earlier years. The timing of investment strongly influences the levelized costs and thus is affected by the demand profiles described above. The following set of figures shows the levelized cost of hydrogen for different demand profiles and pipeline increments.

Figure 9 and Figure 10 demonstrate several key trends when investigating infrastructure buildup and utilization. The first trend is that as you increase the time frame that the investments are considered, the delivery cost of hydrogen decreases from between 0.25 and 0.60 $/kg for 10 year levelized costs down to 0.02 to 0.03 $/kg for the 60 year costs. One reason is that each of the demand profiles specify demand growth over time so that increasing pipeline utilization and pipeline economies of scale lead to lower unit costs with higher flowrates. In addition, the present value of future expenditures on capital, installation, O&M, and energy costs decrease quickly as the analysis time period increases.

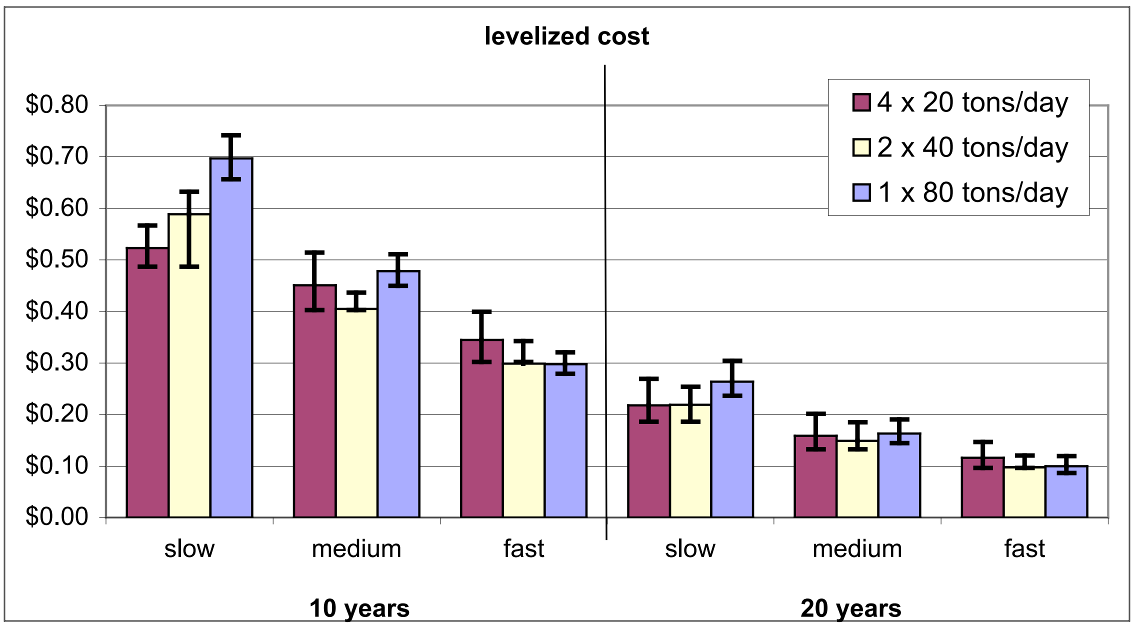

Figure 9 Levelized cost ($/kg) of hydrogen pipeline transmission for different economic analysis periods, 10 and 20 years using linear demand profiles. The black "error bars" indicate the effect of varying the discount rate from base case (10%) to 5% (higher bar) and 15% (lower bar).

Another trend is that for a specified year, as the growth rate of demand increases, the costs tend to decrease. The slow demand profile leads to longer periods of pipeline under-utilization which causes higher hydrogen delivery costs. The fast demand profile reaches the "carrying capacity" sooner and carries more hydrogen over the specified time period. The greater quantity of hydrogen is averaged over the same capital costs leading to a lower delivery cost.

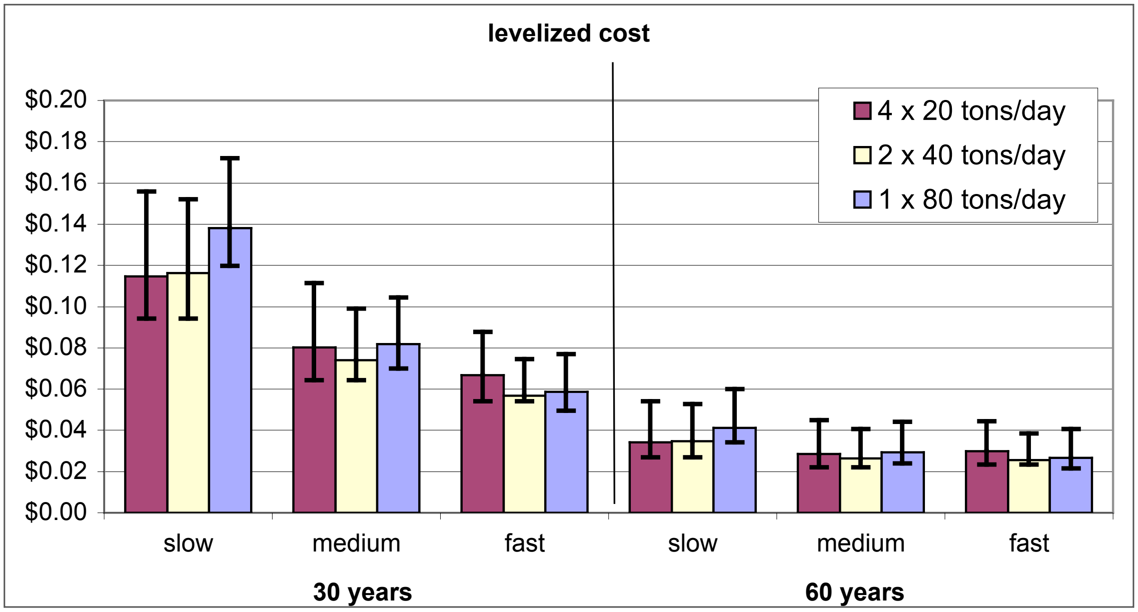

Figure 10 Levelized cost ($/kg) of hydrogen pipeline transmission for different economic analysis periods, 30 and 60 years using linear demand profiles.

The final trend is that for a given demand profile, the size of the pipeline incremental capacity can play an important role in determining the delivery cost of hydrogen. For each of the analysis time periods, the same general trend is observed. For the slow demand profile, the small pipeline increments (20 tons/day) lead to the lowest cost, while the large pipeline increments (80 tons/day) leads to the highest cost. For the fast demand profile, this result is almost reversed so that the small pipeline increment leads to the highest cost and the larger pipeline increments are approximately the same cost. For the medium profile, the minimum delivery cost occurs for the medium pipeline increment (40 tons/day). This observed trend is due to several competing factors. The smaller pipeline cost more per unit capacity than larger pipelines because small differences in the pipeline diameters lead to large differences in flow rate (flow rate has a 2.5 power dependence on diameter). However, this effect is opposed by the fact that the smaller pipelines are utilized more fully than larger pipelines over a given time period so that the average unit cost of delivered hydrogen may be lower. The growth rate associated with the demand profile will affect the extent of pipeline utilization. Faster growth rates saturate the pipelines earlier and can lead to lower costs for larger pipeline increments.

The sensitivity of the results to the discount rate is indicated by the black 'error' bars in the figures. The upper limit bar is indicative of the lower discount rate (5%), which causes an increase in the present value levelized costs, while the lower limit bar indicates the higher discount rate (15%), which yields lower present value levelized costs. The discount rate makes a more significant difference in levelized cost for the longer analysis periods of 30 and 60 years. In the slow and medium demand scenarios, the higher discount rate of 15% makes the levelized costs for the small and medium pipeline increments approximately the same. This analysis shows that many issues, including the rate of demand growth, length of the analysis period, discount rate, and the size of incremental pipeline capacity can greatly affect the levelized cost of hydrogen delivery by pipeline. This result is expected to be true for the entire infrastructure system, including production plants, distribution systems, and refueling networks.

3. FUTURE WORK

These model component descriptions and preliminary results represent the first pieces of a larger, integrated model, which will contain engineering and economic descriptions of each of the links along the process chain to producing, distributing, storing and dispensing hydrogen to meet hydrogen demand scenarios. Initially, this model will be fairly simple in order to integrate each of the major components and to investigate the main effects of various demand scenarios. The choice to start simply will allow us to get a better sense of the overall costs and important factors while still allowing for transparency in its development. Geographic specific factors, heterogeneity and uncertainty will be included in the model. There is currently work being carried out at ITS-Davis on geographic information systems (GIS) on the siting of refueling stations. This will be expanded to include the entire process chain of hydrogen supply since the geographic distribution of hydrogen demand will affect the size of hydrogen production plants, the size and siting of distribution systems, and the location and size of refueling stations.

Other planned work includes incorporating uncertainty and probabilistic features into these detailed demand scenarios. This uncertainty can manifest itself in the demand growth rate (characterized by a probability distribution). With perfect future information, it is possible to determine the lowest cost infrastructure development to meet any particular demand profile. However, when future annual demand growth is characterized only by a probability distribution, the choices surrounding adding new incremental infrastructure capacity become more difficult and these trials can determine the flexibility and risks associated with particular pathway options. The use of simulations of many different scenarios for key inputs will help determine and quantify the flexibility and ability of specific pathways to deal with future risk and unknown conditions.

The next task under development is the integration of the distribution models described here with models of the central plant and refueling station. Initially, a smaller integrated model will be developed to address some of the issues related to model integration. One particularly interesting pathway combination is the comparison of on-site natural gas reforming and dispensing with centralized natural gas reforming, distribution and dispensing. This problem will encompass many of the same questions as the fully detailed problem: When does it make sense to switch pathways and replace existing useable equipment? What effect does the demand profile have on this timing? Will widespread distributed generation lead to large barriers to eventual centralized production?

4. SUMMARY

The goal of the integrated infrastructure model at UC Davis is to capture the major elements associated with building the infrastructure to produce, distribute and refuel hydrogen for a growing number of hydrogen vehicles. Modeling this transition process will yield insights into the potential pitfalls and optimal strategies for energy companies and governments to facilitate this process. The lessons to be learned from simulating the infrastructure buildup for different pathways, strategies, operating conditions and scenarios include understanding which infrastructure networks and pathways are more suitable for specific cities with different sizes and characteristics, for different demand profiles, and under specific government policies or economic conditions.

This paper discusses the preliminary development of the integrated infrastructure model and results from some of the early work on modeling distribution components:

- The optimal delivery mode analysis compares costs among three different point to point delivery modes (H_2 pipelines, compressed H_2 trucks and liquid H_2 trucks) to identify which makes sense under specific conditions (distance and flow rate). Hydrogen costs can vary over a wide range (~\$0.10/kg to over \$3/kg), but pipelines are the cheapest and least energy intensive delivery method when large H_2 flow rates are required.
- The idealized distribution network analysis describes the user-to-station distance and pipeline distribution network length for cities with different population distributions and arrangement of stations. This analysis provides a tool for estimating the number of stations required for a given type of city and the costs of the hydrogen supply infrastructure in order to optimize station siting.
- The transition pipeline growth model determines the levelized costs associated with the choices for adding incremental pipeline capacity in response to alternative demand growth profiles. The timing, location and size of infrastructure deployment greatly affect the costs and will depend strongly on the expected demand growth. These results are representative of those for other system aspects such as distributed hydrogen generation, centralized production plants, hydrogen storage and refueling station equipment which are also influenced by these same factors when installing incremental capacity.

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