Title

TECHNICAL AND ECONOMIC ASSESSMENT OF TRANSITION STRATEGIES TOWARD WIDESPREAD USE OF HYDROGEN AS AN ENERGY CARRIER

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Technical and Economic Assessment of Transition Strategies toward Widespread Use of Hydrogen as an Energy Carrier

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UCD-ITS-RR-05-06

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Report to the United States Department of Energy
Hydrogen, Fuel Cells and Infrastructure Technologies Program
For Phase I of NREL contract number XCM-4-44000-01

January 31, 2005

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EXECUTIVE SUMMARY

In this final report, we present results from research conducted under Phase I of NREL contract number XCM-4-44000-01, from May 2004-January 2005. The overall goal of this project is to better understand infrastructure development strategies for widespread implementation of hydrogen as an energy carrier. Under this contract, we continued earlier research on this topic (Ogden and Kaijuka 2004, Ogden 2004), improving simulation tools to study hydrogen transition strategies, and applying these methods to a geographically specific case study in the Midwest. We also worked as part of the USDOE's H2A group, developing models of hydrogen delivery systems.

Our technical approach is to attempt to capture the site-specific nature of the H_2 infrastructure design problem by use of Geographic Information System (GIS) data as a basis for understanding the spatial relationships between hydrogen demand and supply and existing infrastructure. In this study, we explored the use of mathematical programming techniques to find the lowest cost strategy for building a widespread hydrogen energy system. The goal of the study is to develop a better understanding of the entire system over time, and formulate "rules of thumb" for low-cost regional hydrogen infrastructure strategies.

Three tasks were completed.

Task 1: *Extending our earlier work, we improved simulation tools for modeling regional hydrogen energy infrastructure development based on geographic information system (GIS) input data and operations research optimization methods. The following milestones were achieved:*

- We developed an improved GIS-based method for estimating hydrogen demand spatially using census-derived population data (Ni, Johnson, Johnson, Yang and Ogden NHA 2005). This demand can be specified as a function of time and used for transition analyses of particular regions.

- In earlier work (Ogden and Kaijuka 2004), we developed a series of engineering/economic "component" models of hydrogen production, storage, distribution and refueling systems. During this contract, these estimates were updated, based on studies of refueling stations (Weinert 2005) and pipelines (Parker 2005) carried out within the UC Davis H_2 Pathways program. *In Phase II, these will be verified against forthcoming data from the USDOE H2A database*.

- Extending our earlier work, we developed and refined several methods for designing an optimized hydrogen infrastructure. These include:

    - Urban infrastructure design methods:
        - Idealized models of cities were formulated to estimate the spatial layout of hydrogen refueling stations and distribution infrastructure (Ogden 2004, Yang and Ogden 2004). This allows the direct comparison of hydrogen supply alternatives with respect to capital cost and delivered hydrogen cost. We find that the lowest cost alternative depends on assumptions about hydrogen production technologies, feedstock costs, city size, population density, market penetration of hydrogen vehicles and the number of refueling stations.
        - Methods were developed that use real-world GIS data about traffic flow and existing station sites to optimize hydrogen refueling station siting based on fuel accessibility. Case studies were conducted for Sacramento (Nicholas 2004) and Los Angeles (Nicholas, Weinert and Miller 2005). It appears that customer convenience equivalent to today's gasoline stations could be achieved if hydrogen were offered at 10-30% of existing gasoline stations.
        - *In Phase II, we plan to verify how well our idealized models represent real cities.*

    - Regional Infrastructure design methods: We developed GIS-based methods for designing regional hydrogen infrastructure including multiple hydrogen sources and demand centers.
        - Spatial optimization: Methods for Designing a spatially-optimized infrastructure for steady state hydrogen demand

    - We are developing methods to design a spatially optimized regional infrastructure to meet a steady-state demand. As a first case, we used a “spanning-tree” method to find the lowest cost pipeline network to connect multiple demand centers (cities) with a single hydrogen production facility.
    - *In future work we will extend spatial optimization methods to consider multiple hydrogen production facilities and multiple demand centers and other delivery modes such as trucks*

- Transition studies: Designing an optimized infrastructure for growing hydrogen demand
    - In preliminary work we studied the question of when a transition might occur from distributed on-site reformation to central plant reformation with pipeline delivery. The economics of the transition depend on several important parameters. These include the scale and timing of hydrogen demand growth, the size and density of the analysis area, and choices about incremental equipment capacity and underutilization. (Yang and Ogden NHA 2005)
    - *In future work, we will examine transitions in a GIS framework.*

Task 2: *We began a geographic specific case study of implementing a near-zero emission hydrogen energy system in regions of the US, using techniques described in Task 1. We examined how the optimum infrastructure design changes with input parameters, using geographic specific data on energy demand, resources for hydrogen production (and for fossil hydrogen, availability of CO_2 sequestration sites) and existing infrastructure.*

Several routes for hydrogen production were considered.

Centralized, large-scale production of hydrogen from:

- Coal gasification with and without CO_2 sequestration
- Natural gas with and without CO_2 sequestration
- Biomass gasification

Distributed production of hydrogen at refueling sites from:

- Natural gas reforming
- Electrolysis using off-peak power

Using the methods developed in Task 1, we explored the optimization of hydrogen infrastructure in Ohio based on two steady-state scenarios in which 10% and 50% of vehicles are powered by hydrogen. First, for both scenarios, we identified “demand centers”, which are the locations in which there might be adequate hydrogen demand to warrant potential investment in infrastructure. We then examined how one might design a hydrogen infrastructure to meet this demand by constraining the potential hydrogen infrastructure to the existing infrastructure (e.g., existing natural gas rights-of-way and coal plants). A minimal spanning tree algorithm was used to identify the most cost-effective pipeline network between coal plants (sources) and demand centers (sinks) based on the shortest distance between sites. This algorithm resulted in maps showing a potential hydrogen infrastructure for both scenarios given a central coal plant and delivery via pipeline (see Figure 10). The cost of the infrastructure was then calculated and compared with a scenario in which hydrogen is produced onsite using natural gas.

Given a scenario in which 10% of light-duty vehicles are fueled by hydrogen, our results indicate that a "coal-to-hydrogen" infrastructure would cost \$1.3 billion, or \$3,400/hydrogen vehicle. Furthermore, the levelized cost of hydrogen would be approximately \$3.65/kg. If 50% of the light duty vehicles used hydrogen, the hydrogen cost was about \$2.70/kg. Comparing these costs to estimates for onsite hydrogen production from natural gas, we see that onsite production is less costly at low market penetration (10%), but pipeline delivery is lower cost when 50% of vehicles use hydrogen.

In Phase I, we concentrated on hydrogen from natural gas and hydrogen from coal with CO_2 sequestration. *In Phase II, we plan to add biomass as a potential supply, and consider electrolysis from off-peak power. In addition, we plan to examine the impacts of multiple production facilities and more market penetration levels.*

Task 3: *Participation in the H2A delivery group.*

In 2003, the USDOE convened the H2A (Hydrogen Analysis) group, a team of experienced analysts studying hydrogen energy systems. H2A's goal is to produce a credible, well-documented set of information on hydrogen production, delivery and forecourt refueling technologies and options. Since H2A's inception, Joan Ogden has been a member of the H2A group, working in the area of hydrogen delivery infrastructure. Her activities during this contract included developing information on alternative pathways for delivering hydrogen to consumers, developing base case scenarios for hydrogen delivery, and working with other delivery team members and DOE researchers to document and present this information in a transparent format.

Relationship of this study to other ongoing hydrogen system studies

This project contributes to NREL's mission to understand how the development of hydrogen infrastructure might proceed, and complements other ongoing projects supported by NREL and the USDOE to study hydrogen transitions. We have interacted with other modeling groups including those at the National Renewable Energy Laboratory, Argonne National Laboratory, Oak Ridge National Laboratory, USEPA, Pacific Northwest National Laboratory and the National Energy Technology Laboratory. In table ES-1 below, we compare some attributes of our models to others now being developed.

Table ES-1. Comparison of Some Hydrogen Transition Models

	Model Type	Level of spatial detail	Regionally specific?	Engineering/econ. models of H2 system components	Optimized in space	Time dependent	H2 Demand
UC Davis	Engineering/ Economic/ Geographic Model of H2 system	GIS data used extensively. Population by census block; (option for higher levels of aggregation)natural gas system; electricity system; roads; traffic flows; rail; pipelines	Yes; Analysis can be done at city, state or regional level. Case studies in California, Ohio. Methods adaptable to other sites	Models for production, delivery and refueling stations. Cost as function of scale and cumulative production level (learning curve)	Yes. Idealized city model; Spatial optimization for regional pipelines	Yes Preliminary studies of transition from distributed to centralized H2 production	Exogenous, steady state or time dependent (demand is derived from data on population density, vehicle characteristics; assumed market penetration of hydrogen vehicles)
NREL H2 Infrastructure for commercial introduction (Melendez and Milbrandt)	H2 station location and cost model (estimate number of H2 stations needed in US for commercial introduction)	GIS data on roads, traffic flows, existing industrial H2 infra, alt fuel stations ,city populations used to select interstate routes for H2 station placement	Entire US	Station cost model. Does not consider H2 production or delivery costs explicitly	Yes. Best interstate corridors selected for H2 station placement. Considers interstate stations with spacing of 150 miles	Examines station mix that could handle assumed increase in vehicle use over time	Exogenous (demand is scaled to traffic flows on interstates)
NREL Wind H2 (Short)	Wind supply for electricity and H2 production	Regional electricity systems and wind resources by county	Regional	Considers wind power and wind hydrogen production and long distance transmission of energy to city-gate; does not include local H2 distribution and refueling	Yes	Yes Hourly electric demand data	Exogenous
HyTrans (ORNL)	Model impact of policies, vehicle and infrastructure attributes on H2 vehicle adoption and infrastructure build up	Aggregated, 3 levels of population density	Several US regions	Models for production, delivery. Cost as function of scale and cumulative production level (learning curve)	No	Yes	Endogenous; consumer choice model
Singh (ANL), Moore, Shadis	Model of regional hydrogen costs for use in EIA-NEMS model	11 separate US census regions; each with demand and resources	Each region produces its own H2 from "best" regional resource	Yes	No	Yes	Exogenous. Demand estimated from market penetration scenarios for each region
ANL CHAIN	Engineering Econ Model for H2 system		Ave. US	Yes. Includes some upstream costs for H2 feedstocks	No	No	Exogenous
PNNL	Integrated assessment; climate focus	14 global regions	14 global regions	Yes	No	Yes	Endogenous
EPA	MARKAL-type model of energy economy	Aggregated	Ave. US	Yes	No	Yes	Endogenous
TIAX H2 Now	Engineering Econ Model for H2 system	6 US regions	US regions	Yes	No	Yes. Scenarios	Exogenous

Like several other studies, UC Davis' work uses GIS databases to visualize hydrogen demand and supply, and employs optimization techniques to find low cost systems. UC Davis' modeling studies are distinguished by:

1) **High level of geographic detail; case study approach to regional H2 infrastructure analysis**. Our models incorporate high spatial resolution GIS-based census data (available at the block level) to estimate hydrogen demand spatially. GIS-based city or interstate traffic flow data are also used for station placement and sizing. We utilize detailed GIS information about existing infrastructure (natural gas system; electricity system; location of existing pipelines that could be used as rights of way) and resources for hydrogen production. This allows a case study approach rich in detail and insight. We have analyzed a variety of H2 systems from city scale to regional scale with these methods
2) **The development of simplified "idealized city" models to describe hydrogen delivery systems** in urban areas. We have developed simplified models for H2 delivery systems and plan to validate these (via comparison with detailed GIS models). This work contributes to the H2A delivery team effort.
3) Exploring the use of **spatial optimization methods to find low cost system spatial layouts** for hydrogen production and delivery systems.
4) Exploring the use of **dynamic programming and other optimization methods to find low cost transition paths** over time.
5) **Exploring methods for simultaneous spatial and time optimization**.
6) The **flexibility of the models to analyze different regional demand and supply scenarios** and estimate costs for hydrogen production, delivery and refueling (variables include: selection of a wide range of alternative hydrogen supply pathways; city size; city population density; urban versus rural; various levels of market penetration; hydrogen system component performance and cost assumptions; vehicle type, performance and cost)
7) The **leveraging benefit of the UC Davis Hydrogen Pathways Program**. (The Hydrogen Pathways Program is a four-year multi-disciplinary research program, begun in 2003, funded by a consortium funded by 20 industry and government sponsors to examine the implications of hydrogen for future transportation. The P.I. is co-director of this program.) This gives us access to ready industry feedback and comments on our research. We also have interactions with the California Fuel Cell Partnership (UC Davis is a member) and the California H2 Highway Network (where P.I. Joan Ogden served on the Advisory Panel).

Future Work

Task 1: We plan to continue the work begun under Phase I to refine simulation tools for modeling hydrogen energy infrastructure development based on geographic information system (GIS) input data and operations research optimization methods.

- We will improve and update the initial set of models created in earlier work. In particular, we will update hydrogen component models, consistent with ongoing work under the H2A project, as these data become finalized. In addition, we will include information developed under the Hydrogen Pathways program at UC Davis.
- We will continue exploring the use of mathematical programming and other optimization techniques to connect demand and supply in the lowest cost hydrogen energy system, and study how this changes in time. Additionally, we will combine the cost estimates from component models with the overall system optimization method. The goal is to compare various possible transition pathways to find the lowest overall costs for regional hydrogen infrastructure development. In this work, we will utilize simplified infrastructure design models developed under the H2A project and at UC Davis under the Hydrogen Pathways program.
- We have developed simplified spatial design and cost models for hydrogen distribution systems in cities. The design and cost of a truck delivery or pipeline system can be found as a function of the city size, population density, market fraction of hydrogen cars, and assumptions about the number and size of hydrogen stations. Using these idealized models greatly reduces the amount of computation time needed to cost infrastructure, but may not duplicate the characteristics of real cities. We will validate our idealized models of cities, by comparing these to real cities.

Task 2: We will complete a geographic specific case study of implementing a near-zero emission hydrogen energy system in a particular area (the Midwestern US), using techniques described in Task 1. This study continues work begun in Phase I and will examine how the optimum infrastructure design changes with input parameters, using geographic specific data on energy demand, resources for hydrogen production and existing infrastructure.

Under Phase I, we developed the GIS database required to do the cost study for natural gas and coal-based hydrogen supply alternatives. Under Phase II, we plan to expand the GIS database to include hydrogen from biomass and electrolytic hydrogen from off-peak power. We will apply tools developed under proposed Task 1 to estimate projected costs for different infrastructure alternatives over time, in response to alternative demand scenarios.

Task 3: Continued participation in the H2A delivery group. During Phase I of this contract, we worked with the H2A group in the area of hydrogen delivery infrastructure. Activities included developing information on alternative pathways for delivering hydrogen to consumers and developing base case scenarios for hydrogen delivery. In Phase II we will continue to work with other analysts and NREL/DOE researchers to document and present this information in a transparent format.

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Our technical approach is to attempt to capture the site-specific nature of the H_2 infrastructure design problem by use of Geographic Information System (GIS) data as a basis for understanding the spatial relationships between hydrogen demand and supply and existing infrastructure. In this study, we explored the use of mathematical programming techniques to find the lowest cost strategy for building a widespread hydrogen energy system. The goal of the study is to develop a better understanding of the entire system over time, and formulate "rules of thumb" for low-cost regional hydrogen infrastructure strategies.

BACKGROUND/MOTIVATION FOR STUDY

Hydrogen offers potential advantages as a future energy carrier, with respect to reduced environmental impacts and enhanced energy supply security. Use of hydrogen as a vehicle fuel would enable near-zero full fuel cycle emissions of greenhouse gases and greatly reduced emissions of air pollutants (Thomas et al. 1998, Wang 1999, Spath and Mann 1999, Weiss 2000, GM et al. 2001). Hydrogen can be produced from a variety of widely available primary energy sources, including natural gas, coal, biomass, wastes, wind, solar, hydropower and nuclear, encouraging use of a more diverse primary energy supply.

Despite hydrogen's potential benefits, the current lack of an extensive hydrogen infrastructure is a serious barrier to the introduction of hydrogen as an energy carrier. Technologies exist to produce, store and distribute hydrogen to industrial markets. Consequently, it would be technically feasible to build a hydrogen energy infrastructure today, although the costs would be high for early infrastructure development and issues remain in optimizing hydrogen infrastructure technologies for widespread energy use. In the long term, a fully developed hydrogen vehicle refueling infrastructure (defining infrastructure to include hydrogen production through dispensing to vehicles) has been estimated to cost several hundred to several thousand dollars per vehicle depending on the scale and source of hydrogen (Ogden et al. 1998, Thomas et al. 1998, Mintz et al. 2002, Williams 2002). This is roughly comparable in cost to estimates for other synthetic fuels (Ogden et al. 1998, Thomas et al. 1998, 2000, Mintz et al. 2004). In moving toward widespread use of hydrogen, the development of a viable transition strategy that can supply hydrogen at an acceptable cost is a larger issue than the technical feasibility of producing and delivering hydrogen.

Assuming that hydrogen becomes competitive in future energy markets, a host of unanswered questions surround the issue of implementing infrastructure during a transition to hydrogen. These include:

- How could a transition take place from current transportation fuels to hydrogen? How can the "chicken and egg" problem be overcome for hydrogen transportation fuel (what is the optimum hydrogen supply strategy to meet a growing demand)? How can hydrogen move from initial niche markets such as centrally refueled fleets (where a limited infrastructure is sufficient) into general transportation markets (where widespread infrastructure is required)?
- When is centralized hydrogen production preferred over distributed production?
- When is hydrogen pipeline delivery preferred to truck delivery?
- What is the role of co-production of electricity and/or heat in the economics of hydrogen (for example, in hydrogen power parks or in central fossil energy complexes)?
- For fossil-derived hydrogen, what are the cost and feasibility of CO_2 sequestration? At what scale could this be implemented?
- What are potential effects of technological changes on transition strategies, for example, a breakthrough in storage technologies?

- What is the potential role of various policies (for example, zero emission vehicle mandates, feebates, energy or carbon taxes) in encouraging a transition to hydrogen?

In recent years, a number of detailed technical and economic assessments have examined the design and cost of hydrogen infrastructure (Audus 1996, DTI et al. 1997, Amos 1998, Ogden 1998, Thomas et al. 1998, Ogden 1999a,b,c, Padro and Putsche 2000, Simbeck and Chang 2002, Wang et al. 1999, Thomas et al. 2000, Weiss et al. 2000, Mintz et al. 2002, Ogden 2002, NAS 2004). In most of these studies, hydrogen system costs were estimated in a general way, rather than concentrating on particular sites. The few site-specific case studies that have appeared, used local energy prices and construction costs as input, but did not make extensive use of geographic data to study infrastructure (Ogden 1999a, Bevilacqua/Knight 2001). Over the past year several groups have begun to address how hydrogen costs might vary regionally within the US (Singh 2004; Unnasch 2004; Meyers, Ariff, James and Kuhn 2003). Also, several case studies have appeared of hydrogen infrastructure in particular regions (Nicholas 2004; Ogden and Kaijuka 2003, Yang and Ogden 2004, Hart 2004). Site specific factors are widely recognized to have a large impact on the actual design and cost of a hydrogen infrastructure. Yet modeling tools to conduct regional case studies are still needed. This is particularly important given regional efforts such as the California Hydrogen Highway Network.

Transition strategies, including time dependence of hydrogen demand, have been discussed in a number of papers (Berry 1996, DTI 1998, Ogden 1999, Ohi 2000, Melaina 2002, DOE Hydrogen Roadmap 2002, Edmonds et al., Farrell, Keith and Corbett 2002, NAS 2004, Greene and Leiby 2004) on a national or global scale. While regional issues are likely to be very important in understanding transitions, these have not been incorporated in most studies of hydrogen transition strategies.

In this final report, we describe research completed under Phase I, to develop new simulation tools to assess alternative transition strategies from today’s energy system toward widespread use of hydrogen as an energy carrier. This continues our earlier research on this topic (Ogden and Kaijuka 2004, Ogden 2004). Our focus is on understanding how a hydrogen infrastructure might evolve over time to meet a growing demand under different regional conditions. Our goal is to develop new techniques for studying hydrogen infrastructure development and transition strategies, based on use of Geographic Information System (GIS) data and mathematical programming techniques from operations research. Clearly, designing transition strategies for hydrogen infrastructure development is a complex problem that depends on many factors with large uncertainties. We seek to understand which factors are most important in finding viable transition strategies and to develop “rules of thumb” for future hydrogen infrastructure development.

TECHNICAL APPROACH

Our technical approach has been discussed in earlier reports (Ogden and Kaijuka 2004, Ogden 2004). To better understanding regional transition issues we develop engineering/economic models for the evolution of hydrogen infrastructure over time in response to a specified demand. The design and economics of a hydrogen energy infrastructure depend on a host of factors, many of which can change over time and vary with geographic location. These include:

- *Size and location of hydrogen demand/ hydrogen demand profile.* The scale of hydrogen demand, the geographic density of the demand, and the distance of the demand from the hydrogen production plant strongly impact the design of the hydrogen infrastructure and the cost of hydrogen distribution. The growth rate of hydrogen demand can determine how quickly and when large scale hydrogen supply systems are put in place. There can be a time varying demand for hydrogen on an hourly, daily, or seasonal basis, which requires storage in the system to match the hydrogen plant output to the end-use demand.

- *End-user requirements for hydrogen*. Depending on the end-use, different hydrogen fuel characteristics are needed. For example, for hydrogen used in proton exchange membrane (PEM) fuel cell vehicles, only very low concentrations of CO (<10-50 ppm) are allowed. For hydrogen used in vehicles with compressed gas storage, pressures in the range 5000-10,000 psi are being considered.

- *Cost and performance of technologies making up a* H_2 *energy system*. These include hydrogen production technologies for small (distributed) and large (centralized) hydrogen production plants, technologies for onsite co-production of electricity and hydrogen (energy stations), hydrogen storage technologies, hydrogen delivery (via hydrogen pipeline or truck), and hydrogen end-use technologies such as vehicles and combined heat and power systems for buildings, and, for fossil H_2 plants, CO_2 capture, transmission and storage technologies.

- *Cost and availability of primary resources for hydrogen production.* Hydrogen can be produced from a range of primary energy resources. The cost and availability of primary sources, at a given site helps determine the best mix of hydrogen supply options. For example, in areas where low cost natural gas is available, steam methane reforming might be the preferred method of hydrogen production, while in other regions electrolysis using off-peak hydropower might give the lowest hydrogen production cost. (For fossil derived H_2, location, availability and cost of sites for sequestering CO_2 is also an issue.)

- *The capacity and location of existing energy infrastructure and rights of way*. Siting H_2 transmission and distribution pipelines will be easier along existing rights of way. These corridors might have a large influence on where hydrogen pipelines are built. In cases where hydrogen is produced from existing energy carriers such as natural gas or electricity, the location and capacity of these systems could influence how a hydrogen system develops. Current gasoline refueling stations might be sites for future hydrogen stations.

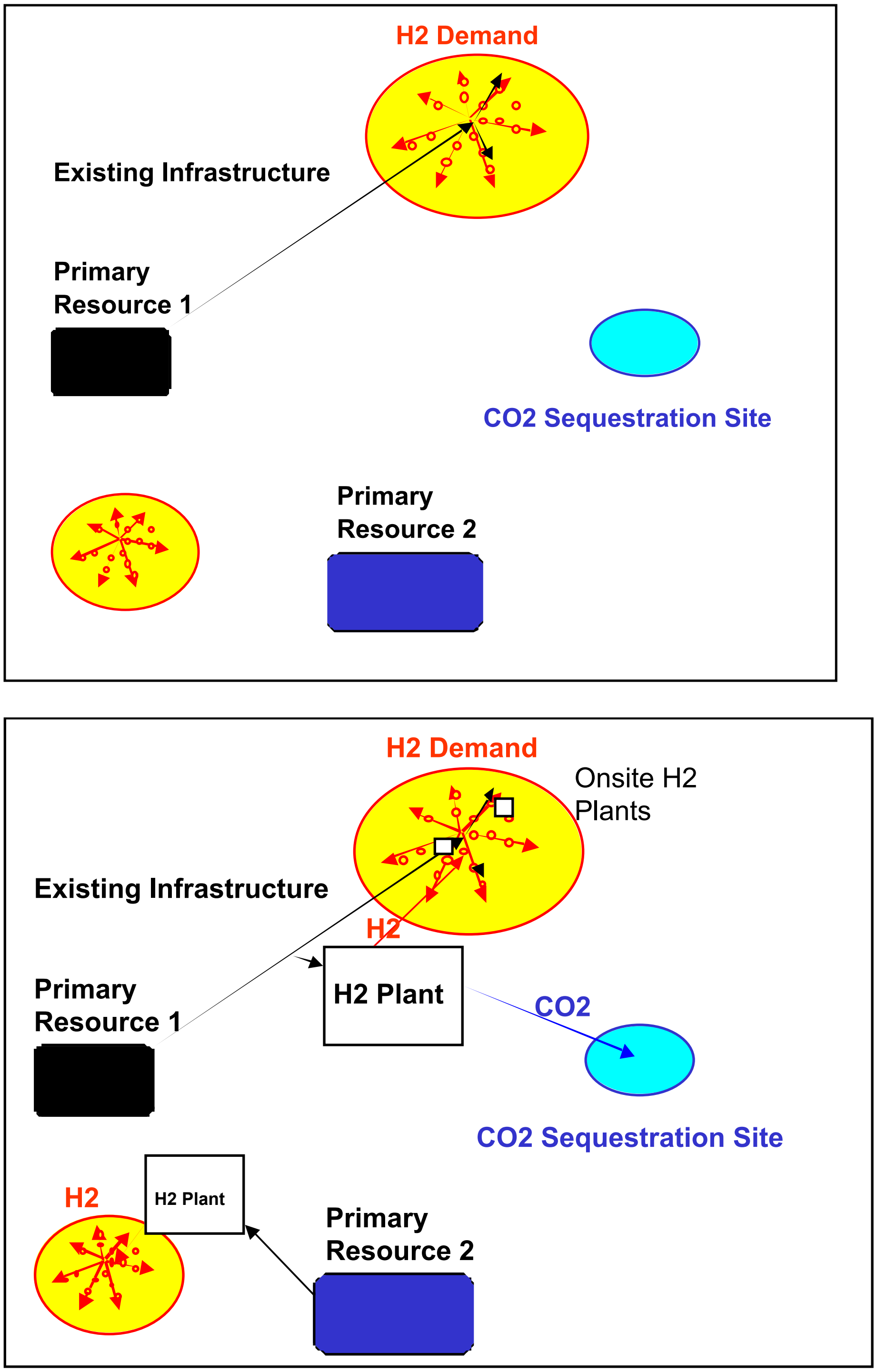
Because most of these factors depend on the location and vary over time, the best hydrogen infrastructure design is site specific and time dependent. More than one type of hydrogen supply might be used. The mix of hydrogen supply options might change over time, as demand grows, depending on technological progress and the cost and availability of various sources for hydrogen production. Different transition strategies will be favored depending on the regional conditions, and for different assumptions about the growth of hydrogen demand.

In Figure 1, we illustrate our approach to the problem of designing a hydrogen infrastructure over time for a particular region. We assume that hydrogen use is growing over time, and that several hydrogen demand centers (cities) are located within the region. Hydrogen demand sites (e.g. refueling stations) are shown as small circles. Hydrogen could be produced from existing energy carriers like natural gas or electricity, or produced in central plants and distributed to stations by truck or pipelines. Various primary resources could be used to make hydrogen, including renewables such as biomass, wind or solar, fossil sources, such as natural gas or coal, and nuclear power. For fossil primary sources, CO_2 might be captured and sequestered. Potential sites for CO_2 sequestration are shown.

Assuming that hydrogen demand is known over time, designing a hydrogen energy system to meet the specified demand can be posed as a problem in optimization. Given a GIS database showing hydrogen demand, existing infrastructure and primary resources (Figure 1, top), we attempt to design the lowest cost production and delivery infrastructure to provide hydrogen to users (Figure 1, bottom). The optimal infrastructure design changes as the demand grows, resulting in an evolving strategy for infrastructure development. The overall transition cost is found by summing costs over a multi-decade time frame.

In earlier work, we have applied this approach to studying the design and cost of hydrogen systems for steady state demands (Ogden 2004, Ogden and Kaijuka 2004), and for transitions (Yang and Ogden NHA 2004). In this contract, we further develop and apply these methods.

Figure 1. Modeling hydrogen infrastructure development. Top: Energy system with growing hydrogen demand. Bottom: A possible infrastructure configuration to serve this demand. The goal is to find the lowest cost design.



RESULTS

During Phase I of the project, three tasks were completed.

Task 1: *Extending our earlier work, we improved simulation tools for modeling regional hydrogen energy infrastructure development based on geographic information system (GIS) input data and operations research optimization methods.*

Task 2: *We conducted a geographic specific case study of implementing a near-zero emission hydrogen energy system in the Midwestern US, using techniques described in Task 1. We examined how the optimum infrastructure design changes with input parameters, using geographic specific data on energy demand, resources for hydrogen production (and for fossil hydrogen, availability of* CO_2 *sequestration sites) and existing infrastructure.Several routes for hydrogen production were considered.*

Centralized, large-scale production of hydrogen from:

- *Coal gasification with and without* CO_2 *sequestration*
- *Natural gas with and without* CO_2 *sequestration*
- *Biomass gasification*

Distributed production of hydrogen at refueling sites from:

- *Natural gas reforming*
- *Electrolysis using off-peak power*

Task 3: *Participation in the H2A delivery group.*

TASK 1: *Extending our earlier work, we improved simulation tools for modeling regional hydrogen energy infrastructure development based on geographic information system (GIS) input data and operations research optimization methods.*

The following milestones were achieved:

An improved GIS-based method for estimating regional hydrogen demand

Understanding the evolution of a hydrogen fuel delivery infrastructure depends on the spatial and time characteristics of the hydrogen demand. We have developed a preliminary method to model the magnitude, spatial distribution, and time dependence of hydrogen demand based on exogenously-derived market penetration rates and GIS data (Ni et al. 2005). Currently, we have used this model to examine steady-state (i.e., non-transition) market penetration scenarios in which we derive demand based on fixed percentages of hydrogen vehicle penetration (e.g., 10%). However, in the near future, we plan to incorporate transitional market penetration profiles.

Our current methodology employs census-derived population density, which is mapped at the census-block level, to calculate hydrogen demand density based on per-capita vehicle ownership, projections for daily hydrogen use per vehicle, and market penetration levels. Depending on the analysis year, current or projected population density can be used.

$$\frac{kgH_2/day}{km^2}=\left(\frac{persons}{km^2}\right)\left(\frac{total\ vehicles}{person}\right)\left(\frac{H_2vehicles}{total\ vehicles}\right)\left(\frac{kgH_2/day}{vehicle}\right)$$

Given hydrogen demand density, a threshold is then specified that selects only census blocks with sufficient demand to warrant consideration for infrastructure. Buffers are then applied to the high demand census blocks in order to aggregate them into demand clusters. The aggregate hydrogen demand within each cluster is then calculated and a threshold is applied to retain only the clusters with sufficient hydrogen demand to warrant investment in infrastructure. These remaining clusters are considered the viable hydrogen “demand centers” to which hydrogen should be supplied at a given hydrogen vehicle penetration. Figure 2 illustrates the preliminary hydrogen demand methodology.

In order to automate the processing of this methodology, a customized application was developed in ArcGIS that can quickly calculate hydrogen demand centers for any region with census data. Using this application, we conducted several sensitivity analyses to examine the impact on hydrogen demand of different market penetration levels, thresholds, and buffer sizes. The results allow one to examine the tradeoff between expanding hydrogen infrastructure and the associated projected costs of building it. Although this demand modeling method contains many simplifying assumptions, it provides a means for identifying potentially viable locations for hydrogen infrastructure investment at various market penetration levels.

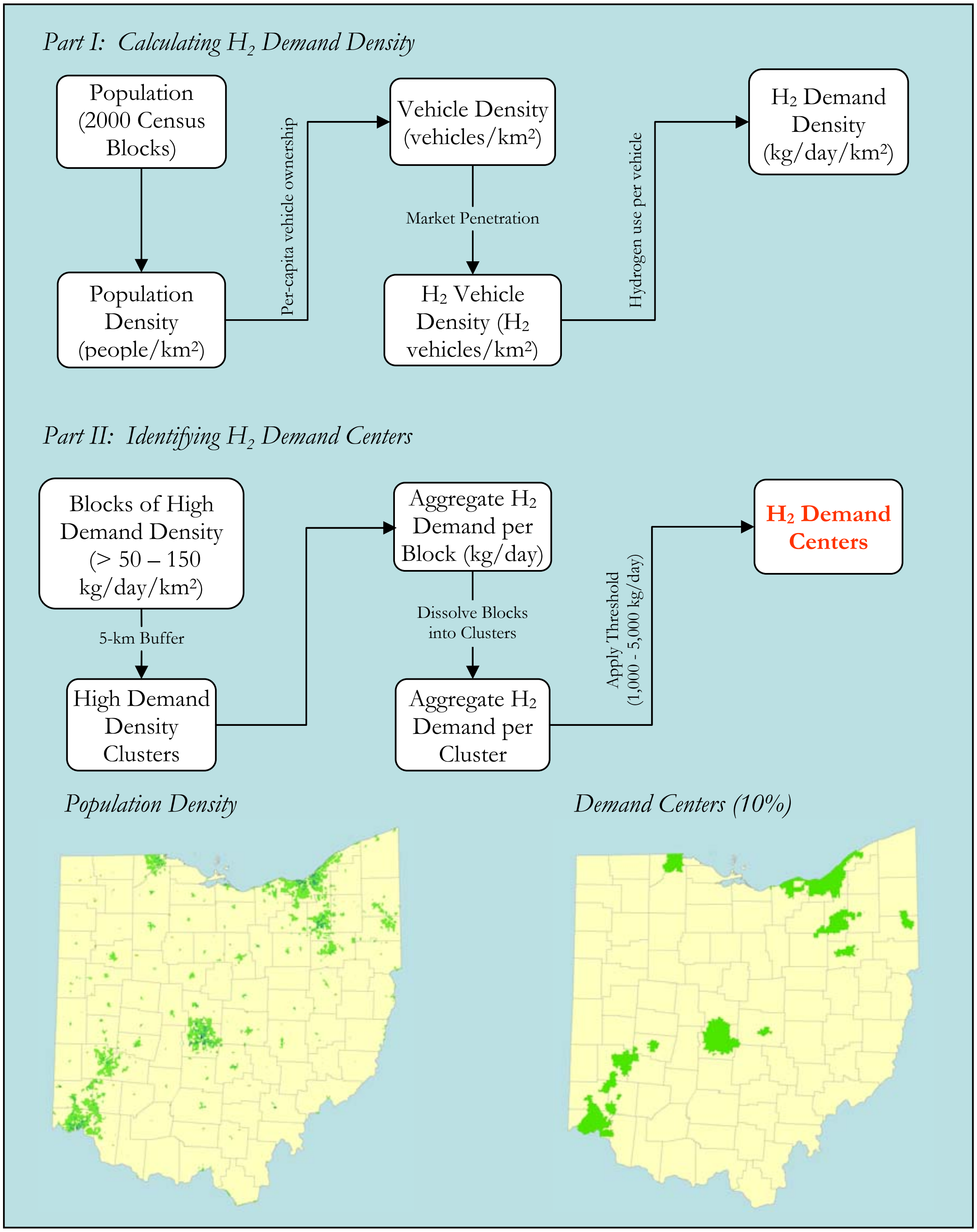


Figure 2. Improved GIS-based method for estimating demand in space and time.

Improved Engineering/Economic models of Hydrogen Components

In earlier work (Ogden and Kaijuka 2004), we developed a series of engineering/economic “component” models of hydrogen production, storage, distribution and refueling systems. During this contract, these estimates were updated, based on studies carried out within the UC Davis H_2 Pathways program. In Phase II, these will be verified against forthcoming data from the USDOE H2A database.

Refueling station Models

As part of the UC Davis Hydrogen Pathways program, graduate student researcher Jonathan Weinert developed an EXCEL-based database for hydrogen refueling station components and station costs (Weinert 2005). These models include capital costs, fixed and variable operating costs and installation, permitting, and construction costs as a function of station size and technological maturity. Various types of stations are modeled including stations with mobile refuelers, liquid hydrogen truck delivery, onsite production from natural gas, onsite electrolysis, and pipeline delivery. Costs for current stations are estimated based on studies of California demonstration projects (Weinert 2004). Progress ratio models for cost reductions by learning were also included. This model was used to produce economic estimates for the California Hydrogen Highways Network Blueprint Plan. Under this contract we incorporated Weinert’s hydrogen refueling station cost and performance estimates into our system models.

Pipeline Models

As part of the UC Davis Hydrogen Pathways program, graduate student researcher Nathan Parker reviewed 12 years of natural gas pipeline data from the Oil and Gas Journal. From this, he derived estimates for pipeline capital, labor, rights-of-way and “other” costs (see Table 1 from Parker 2005). He found that total costs for pipelines can be approximated in terms of pipeline diameter and length, as shown in figure 3. This is expressed as the following equation.

$$\text{Construction Cost (dia, length)} = [674(\text{dia})^2 + 11{,}754(\text{dia}) + 234{,}085](\text{length}) + 405{,}000$$

where (dia) is in inches, (length) is in miles, and Cost is in dollars.

There is considerable spread in the data, reflecting the strongly site specific nature of pipeline costs. (Figure 3). Under this contract, we incorporated Parker’s estimates into our hydrogen system models.

It is interesting to note that below about 8-10 inches pipeline diameter, there is relatively little cost dependence on diameter (Table 1), as other factors like labor dominate the costs (Figure 4). This suggests that there would be little economic penalty for installing “oversized” pipes up to about 10 inches in diameter that could handle future increases in demand (the flow rate of hydrogen in a pipeline scales as the diameter in the 2.5 power, so even small increases in diameter can yield significantly higher hydrogen handling capacity.)

Figure 3. Capital cost of pipelines $/mile of length as a function of pipeline diameter (inches) (Parker 2004)

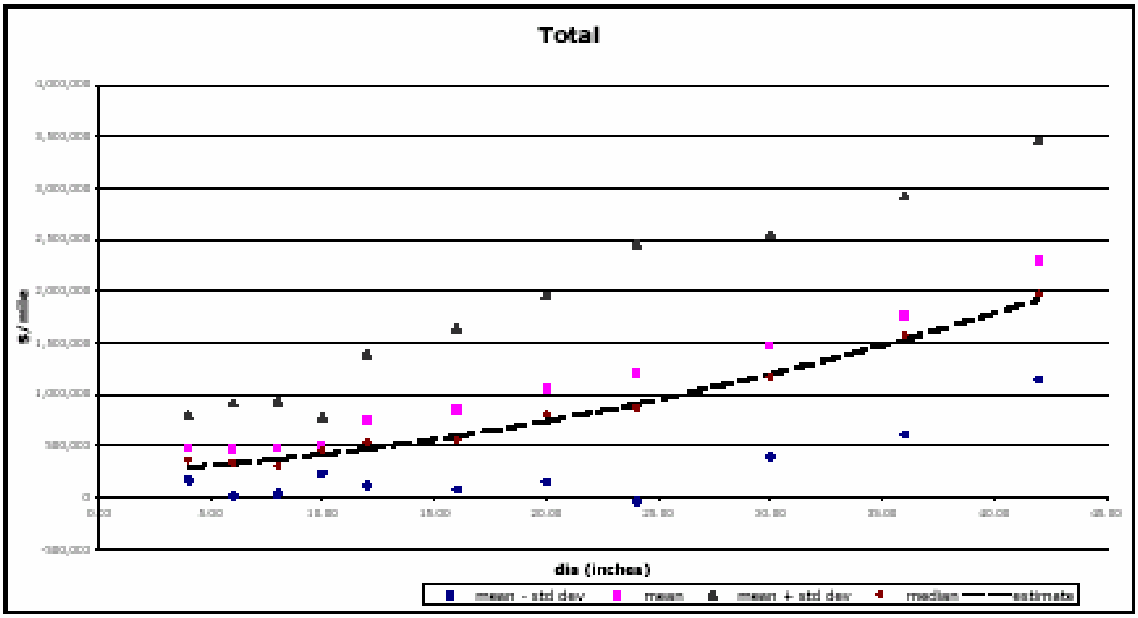


Figure 4. Fractional cost breakdown of installed pipeline cost as a function of pipeline diameter (Parker 2004)

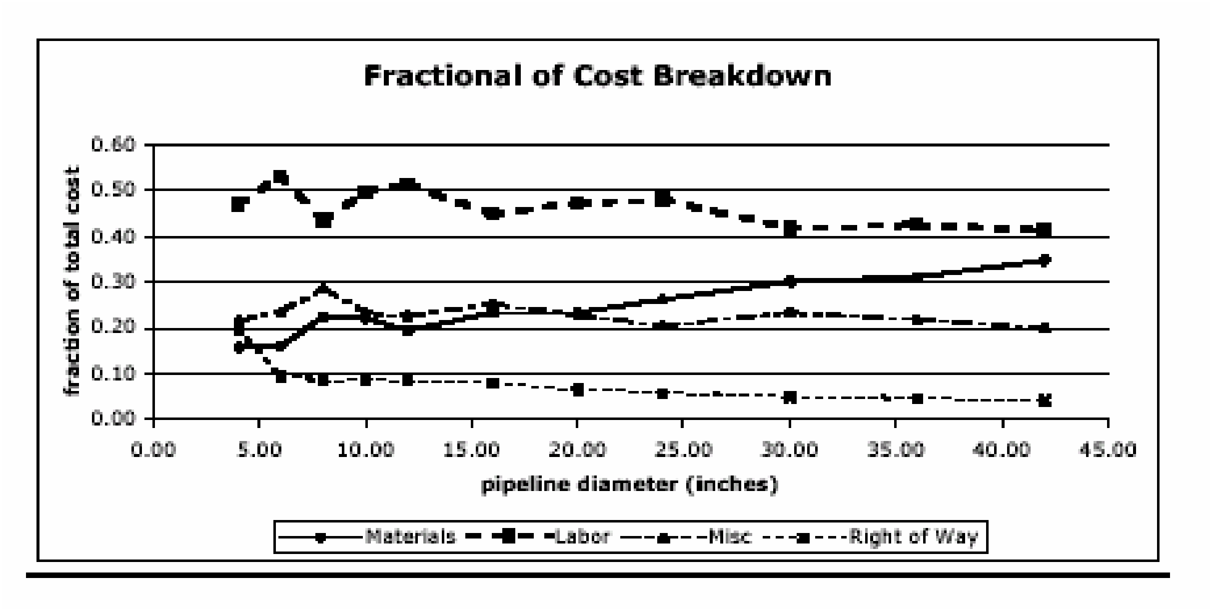
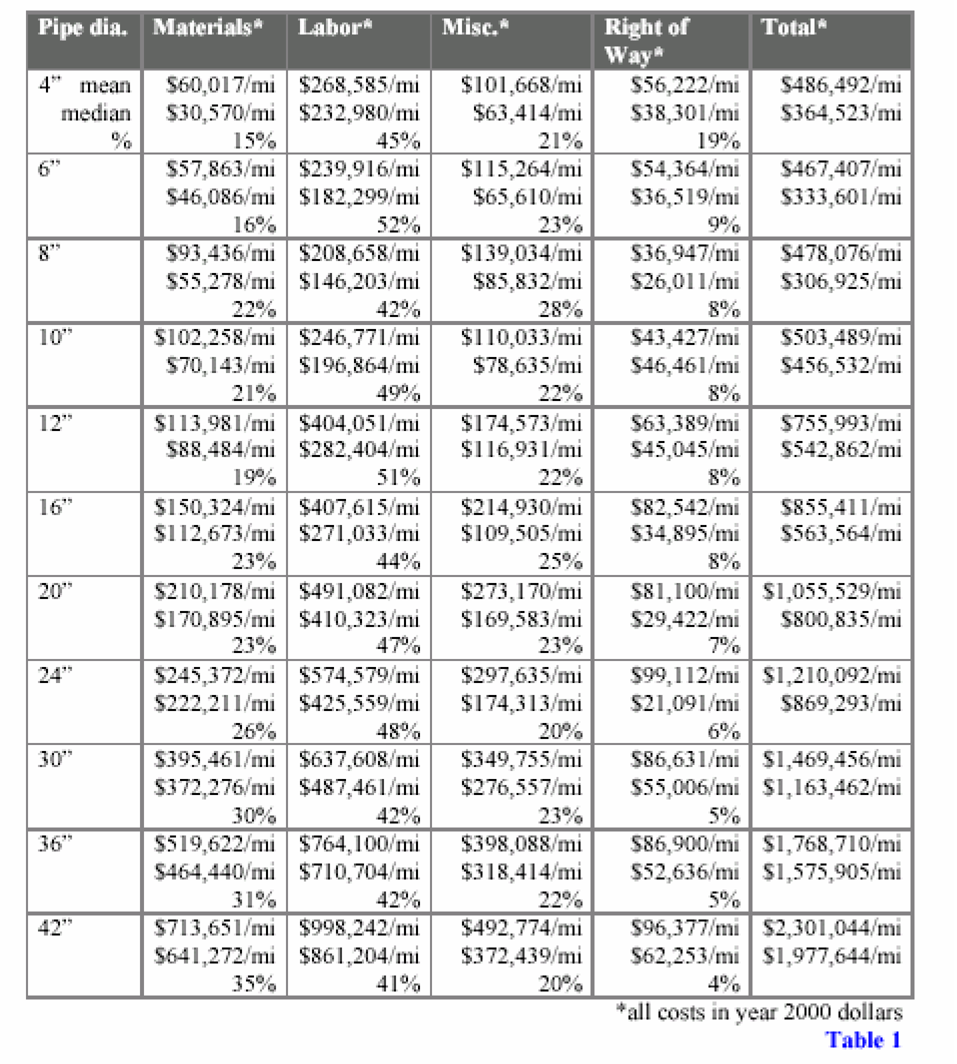


Table 1. Cost of Pipelines $/mile versus pipeline diameter (Parker 2004)



Pipe dia.	Materials*	Labor*	Misc.*	Right of Way*	Total*
4" mean	$60,017/mi	$268,585/mi	$101,668/mi	$56,222/mi	$486,492/mi
median	$30,570/mi	$232,980/mi	$63,414/mi	$38,301/mi	$364,523/mi
%	15%	45%	21%	19%	
6"	$57,863/mi	$239,916/mi	$115,264/mi	$54,364/mi	$467,407/mi
	$46,086/mi	$182,299/mi	$65,610/mi	$36,519/mi	$333,601/mi
	16%	52%	23%	9%	
8"	$93,436/mi	$208,658/mi	$139,034/mi	$36,947/mi	$478,076/mi
	$55,278/mi	$146,203/mi	$85,832/mi	$26,011/mi	$306,925/mi
	22%	42%	28%	8%	
10"	$102,258/mi	$246,771/mi	$110,033/mi	$43,427/mi	$503,489/mi
	$70,143/mi	$196,864/mi	$78,635/mi	$46,461/mi	$456,532/mi
	21%	49%	22%	8%	
12"	$113,981/mi	$404,051/mi	$174,573/mi	$63,389/mi	$755,993/mi
	$88,484/mi	$282,404/mi	$116,931/mi	$45,045/mi	$542,862/mi
	19%	51%	22%	8%	
16"	$150,324/mi	$407,615/mi	$214,930/mi	$82,542/mi	$855,411/mi
	$112,673/mi	$271,033/mi	$109,505/mi	$34,895/mi	$563,564/mi
	23%	44%	25%	8%	
20"	$210,178/mi	$491,082/mi	$273,170/mi	$81,100/mi	$1,055,529/mi
	$170,895/mi	$410,323/mi	$169,583/mi	$29,422/mi	$800,835/mi
	23%	47%	23%	7%	
24"	$245,372/mi	$574,579/mi	$297,635/mi	$99,112/mi	$1,210,092/mi
	$222,211/mi	$425,559/mi	$174,313/mi	$21,091/mi	$869,293/mi
	26%	48%	20%	6%	
30"	$395,461/mi	$637,608/mi	$349,755/mi	$86,631/mi	$1,469,456/mi
	$372,276/mi	$487,461/mi	$276,557/mi	$55,006/mi	$1,163,462/mi
	30%	42%	23%	5%	
36"	$519,622/mi	$764,100/mi	$398,088/mi	$86,900/mi	$1,768,710/mi
	$464,440/mi	$710,704/mi	$318,414/mi	$52,636/mi	$1,575,905/mi
	31%	42%	22%	5%	
42"	$713,651/mi	$998,242/mi	$492,774/mi	$96,377/mi	$2,301,044/mi
	$641,272/mi	$861,204/mi	$372,439/mi	$62,253/mi	$1,977,644/mi
	35%	41%	20%	4%	

*all costs in year 2000 dollars

Table 1

Improved Methods for Designing an Optimized Hydrogen Infrastructure

Extending our earlier work, we developed and refined several methods for designing an optimized hydrogen infrastructure. These include:

Urban infrastructure design methods

Idealized City Model

Idealized models of cities were formulated to estimate the spatial layout of hydrogen refueling stations and distribution infrastructure (Ogden 2004, Yang and Ogden 2004). This allows the direct comparison of hydrogen supply alternatives with respect to capital cost and delivered hydrogen cost. The lowest cost alternative depends on assumptions about hydrogen production technologies, feedstock costs, city size, population density, market penetration of hydrogen vehicles and the number of refueling stations.

In order to estimate the costs associated with hydrogen infrastructure, it is important to understand the location of refueling stations and the effects on hydrogen distribution. However, in a generic case, where detailed information is not available, or for reduced analytical time, the location of stations is not determined in a detailed manner. Instead, for a network of hydrogen stations within a demand area, hydrogen distribution is modeled using an idealized city model. This allows the details of the refueling station network, including the number of refueling stations and the length or distance of distributing hydrogen to those stations to be strictly a function of the physical size and hydrogen demand within the demand region. These areas are treated as an ideal city, which will have a distribution length that is a function of the city size (radius) and the number of refueling stations. Using general idealized city models speeds up the analysis and provides information about these distribution system characteristics for a wide range of cities. Several researchers have looked at possible configurations for a network of refueling stations (Ogden 1999 and Mintz 2002). The goal of this model component 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, which can then be used to determine costs for the distribution component of the infrastructure. Other future options include determining station numbers, locations, convenience and distribution system layout using a detailed geographic study of the distribution system of a specific city/region using GIS tools (such as in Nicholas 2004).

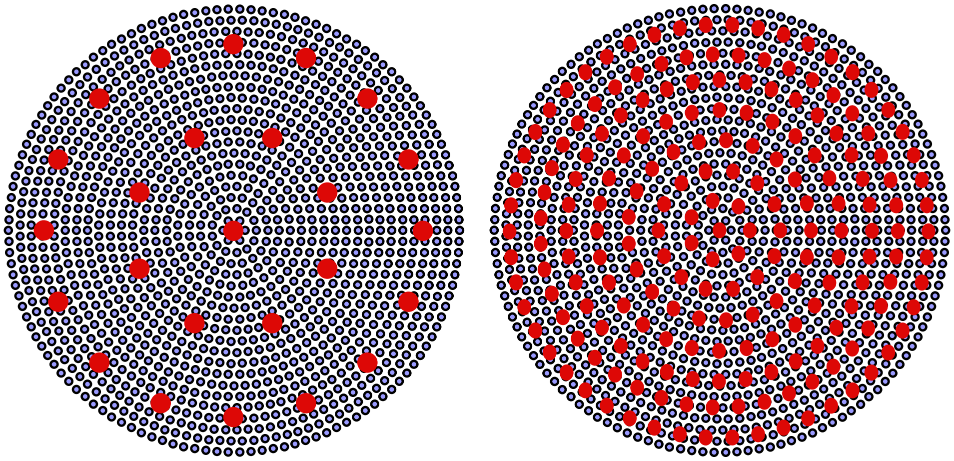


Figure 5. Idealized city model with 25 and 125 hydrogen stations distributed in rings throughout the city.

Model assumptions include a circular city and a radially distributed population (Figure 5). The city size is not specified explicitly but rather lengths are characterized as a function of the city radius, and distances are calculated in this city by following a grid (i.e. rectilinear) road network. The refueling stations are configured into rings that are concentric around the city center. Each city configuration consists of one or more rings of stations with varying numbers of stations in each ring. For a given station configuration, the radii of the rings of stations were varied 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 many 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, a comparison is made as to how convenience trades off against 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)) (Figure 6).

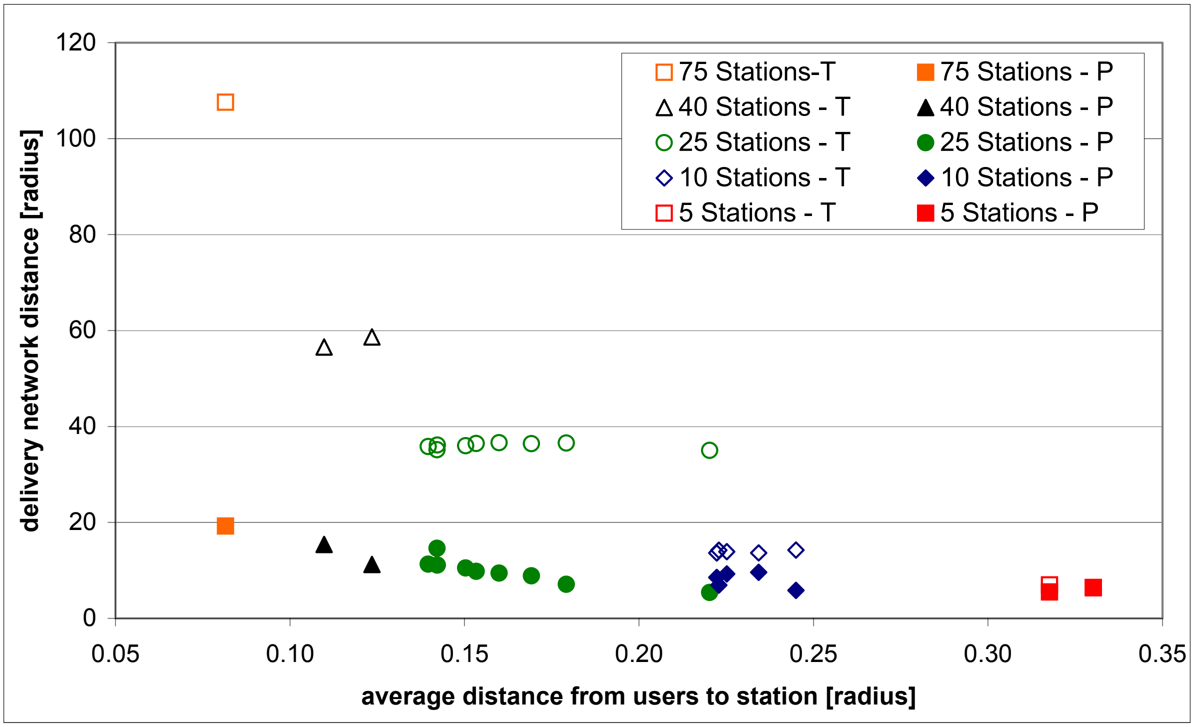


Figure 6. Tradeoff between convenience and delivery network distance for pipelines and trucks for different numbers and configurations of stations.

In figure 7, the pipeline length ($L_{pipeline}$) is shown to be a power law function of the number of stations, while the truck route distance scales linearly with the number of stations. Thus as the number of stations grows, the pipeline distribution modes become more efficient than trucks. The model results are plotted to compare length of the pipeline network or truck driving distance as a function of the number of stations. The data for pipeline length vs station number is fitted to a power function and for the homogeneous population density, the equation that describes this relationship is:

$$L_{pipeline} = \beta \cdot N_{stations}^{\gamma}$$

where $L_{pipeline}$ is the length of the pipeline (as a multiple of the city radius), $N_{stations}$ is the number of stations, β is 3.524 and γ is 0.4115. For the truck delivery scenario, it is assumed that trucks do not travel to multiple stations on a given trip so that a linear equation describes this distance:

$$D_{truck} = 1.44 \cdot N_{stations}$$

As demand increases along the demand profile, additional stations are added to the network of stations. Although this model is not designed to calculate the marginal increase in pipeline length resulting from adding new refueling stations, the curve fit can be used to estimate, on average, the length of pipeline needed to supply additional refueling stations.

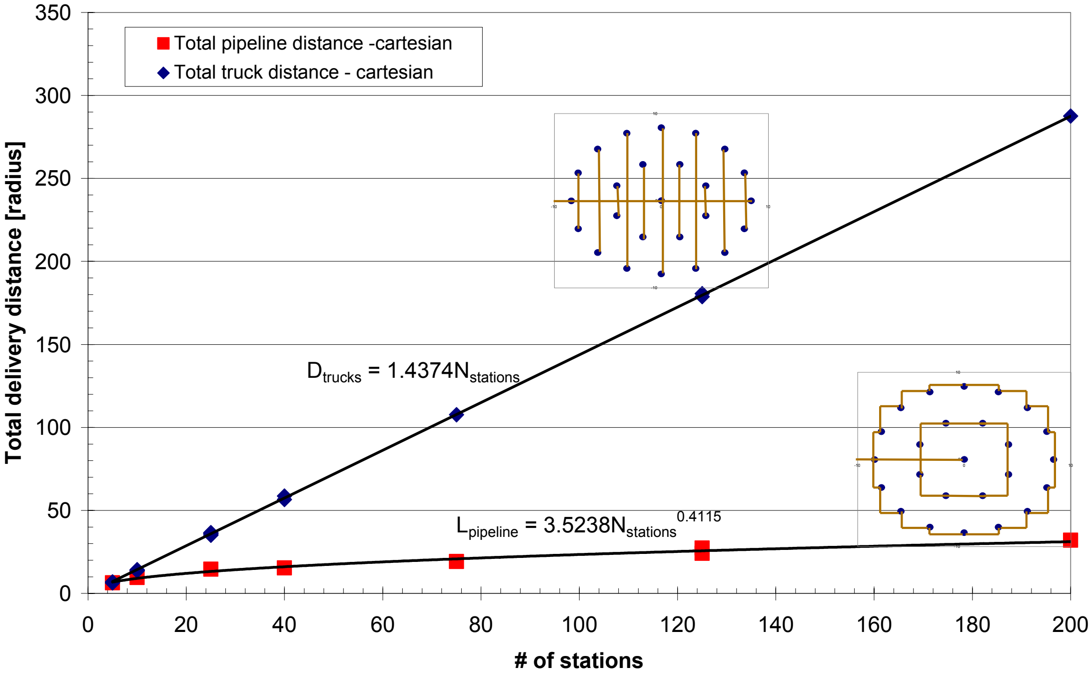


Figure 7. The relationship between the number of stations within the city and the total delivery distance for pipelines and trucks.

Given the hydrogen demand in a city of a certain physical size, an estimate can be made of the required number of refueling stations and using the equations above, the total length of pipeline or truck travel distance required to supply the network of refueling stations. The cost for the network can be calculated using cost models for truck or pipeline hydrogen delivery.

Siting Hydrogen Refueling Stations for Adequate Customer Access

Methods were developed as part of the H2 Pathways program that use real-world GIS data about traffic flow and existing station sites to optimize hydrogen refueling station siting within a city based on fuel accessibility. Case studies were conducted for the cities of Sacramento (Nicholas 2004) and Los Angeles (Nicholas, Weinert and Miller 2005). It appears that customer convenience similar to that for gasoline today could be achieved if hydrogen were offered at 10-30% of existing gasoline stations. We used this insight to help determine the minimum number of urban refueling stations needed for adequate coverage.

In Phase II, we plan to verify how well our idealized models represent real cities.

Regional Infrastructure design methods

We are expanding our use of GIS by developing spatial databases to study regional hydrogen infrastructure options. (For example, we have developed a preliminary GIS-based model for infrastructure in the state of Ohio using methods that can be readily applied elsewhere – see Task 2 below.)

Designing a spatially-optimized infrastructure for steady state hydrogen demand

We are developing methods to design a spatially optimized regional infrastructure to meet a steady-state demand. As a first case, we used a minimal spanning tree algorithm to find the lowest cost pipeline network to connect multiple steady-state demand centers (cities) with a single hydrogen production facility.

Transition studies: Designing an optimized infrastructure for growing hydrogen demand

In preliminary work we studied the transition from distributed on-site reformation to central plant reformation with pipeline delivery. The economics of the transition depend on several important parameters. These include the scale and timing of hydrogen demand growth, the size and density of the analysis area, and choices about incremental equipment capacity and underutilization. (Yang and Ogden 2005)

TASK 2: *We conducted a geographic specific case study of implementing a near-zero emission hydrogen energy system in regions of the US, using techniques described in Task 1. We examined how the optimum infrastructure design changes with input parameters, using geographic specific data on energy demand, resources for hydrogen production (and for fossil hydrogen, availability of CO_2 sequestration sites) and existing infrastructure.*

Several routes for hydrogen production were considered.

Centralized, large-scale production of hydrogen from:

- Coal gasification with and without CO_2 sequestration
- Natural gas with and without CO_2 sequestration
- Biomass gasification

Distributed production of hydrogen at refueling sites from:

- Natural gas reforming
- Electrolysis using off-peak power

Under Phase I, we made considerable progress on a case study examining potential hydrogen transition scenarios for the state of Ohio. Using the methods developed in Task 1, we optimized regional hydrogen infrastructure designs for two “steady-state” demand scenarios (10% and 50% hydrogen vehicle market penetration). First, we estimated hydrogen demand throughout the state and used this calculation to identify demand centers. The centers for the 10% market penetration scenario are illustrated in Figure 8.

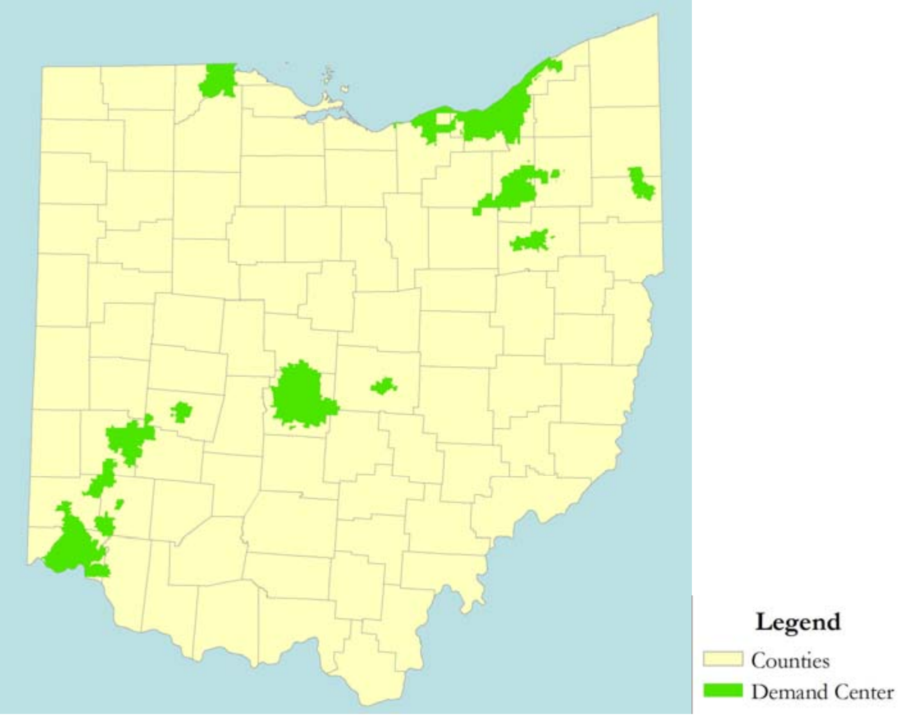


Figure 8. Demand centers with 10% market penetration

Given the demand centers, we then used GIS data of existing energy infrastructure (e.g., coal-fired power plants and electrical and natural gas rights-of-way) to identify the least cost design for delivering hydrogen from a centralized plant to the demand centers. Figure 9 shows the potential rights-of-way within Ohio that connect the existing production facilities to demand centers. Although coal-fired power plants were used in this study, the optimization can be applied to any type of plant.

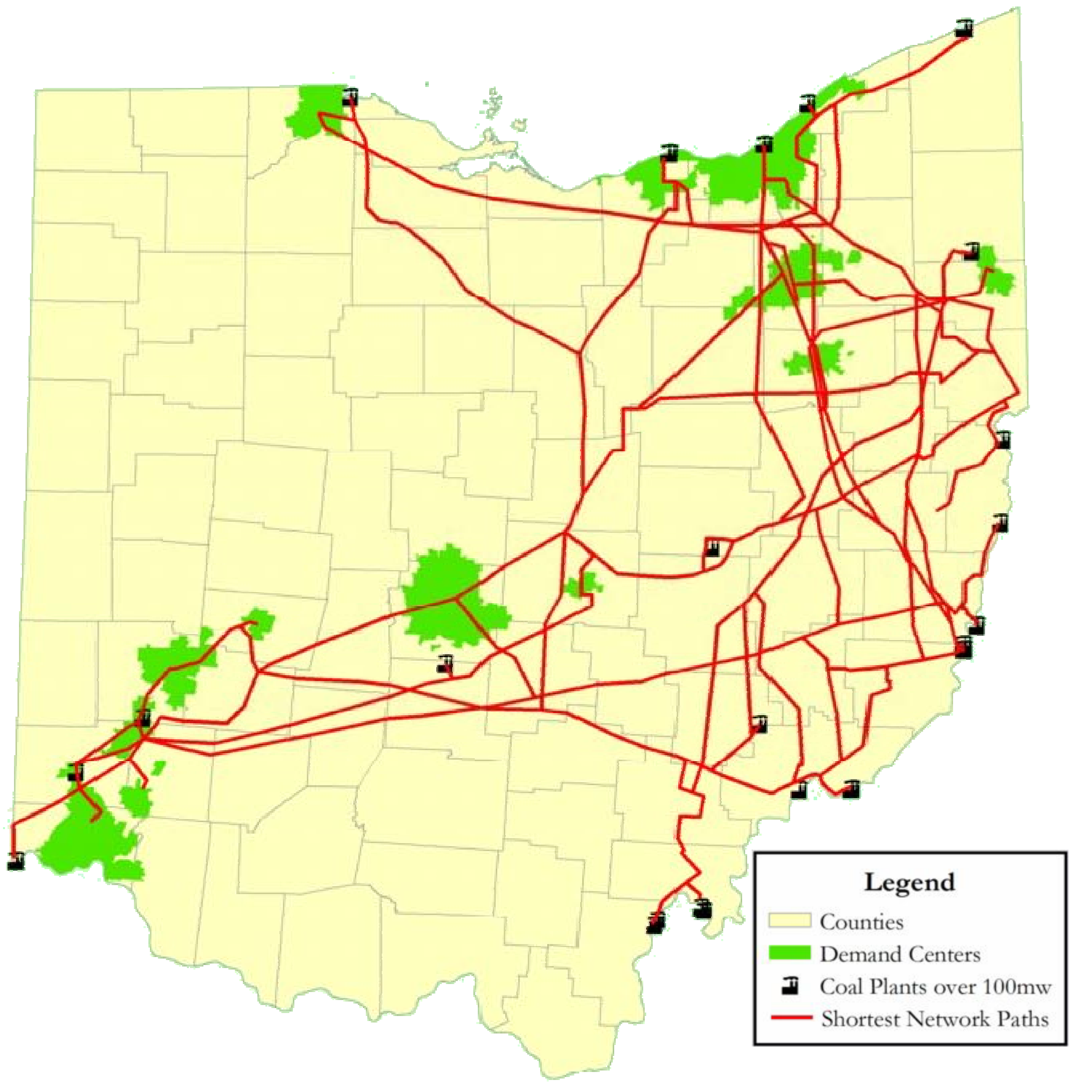


Figure 9. Nodes and paths for the hydrogen distribution infrastructure network including demand clusters, coal plants and potential hydrogen pipeline locations.

With this portfolio of potential power plants and rights-of-way, a GIS was used to identify the shortest distance between all demand centers and power plants as constrained by the rights-of-way. These distances were then fed to a network optimization algorithm, which is designed to identify the infrastructure that minimizes the total pipeline length required to connect all demand clusters to one or more H_2 production plants. This algorithm is similar to a minimal spanning tree algorithm. Figure 10 provides a snapshot of the optimized hydrogen infrastructure in the 10% scenario where one coal facility provides all the hydrogen to the demand centers via pipeline.

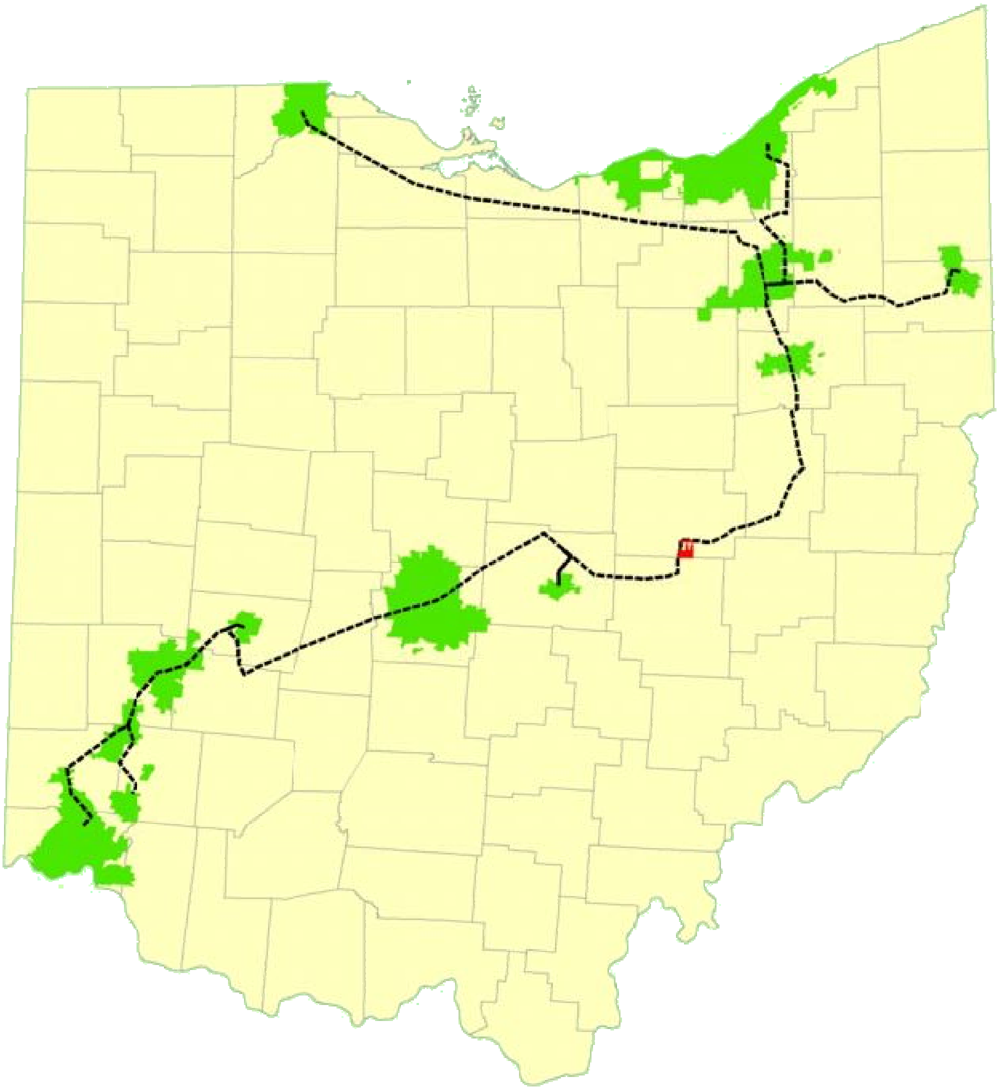


Figure 10. Layout of the minimum network length for one hydrogen production plant at the 10% hydrogen vehicle market penetration level.

Once the locations of the hydrogen production plants and pipelines are determined, the capacity of the hydrogen production plant and flow through the pipelines is determined and costs can be calculated for the production and delivery of hydrogen to each demand center. Within the demand centers, our model for an idealized city was used to estimate the cost for delivering hydrogen via intracity pipelines and fueling stations. In addition, we examined the cost of sequestering CO_2 from the coal-fired power plants. The costs of the centralized plant scenario were then compared with one in which the hydrogen is produced onsite from natural gas.

Given a scenario in which 10% of light-duty vehicles are fueled by hydrogen, our results indicate that a "coal-to-hydrogen" infrastructure would cost \$1.3 billion, or \$3,400/hydrogen vehicle. Furthermore, the levelized cost of hydrogen would be approximately \$3.65/kg. If 50% of the light duty vehicles used hydrogen, the hydrogen cost is reduced to about \$2.70/kg. Figure 11 compares the centralized cost estimates with those for onsite hydrogen production from natural gas. This figure predicts that onsite production is less costly at low market penetration (10%), but pipeline delivery is lower cost when 50% of vehicles use hydrogen.

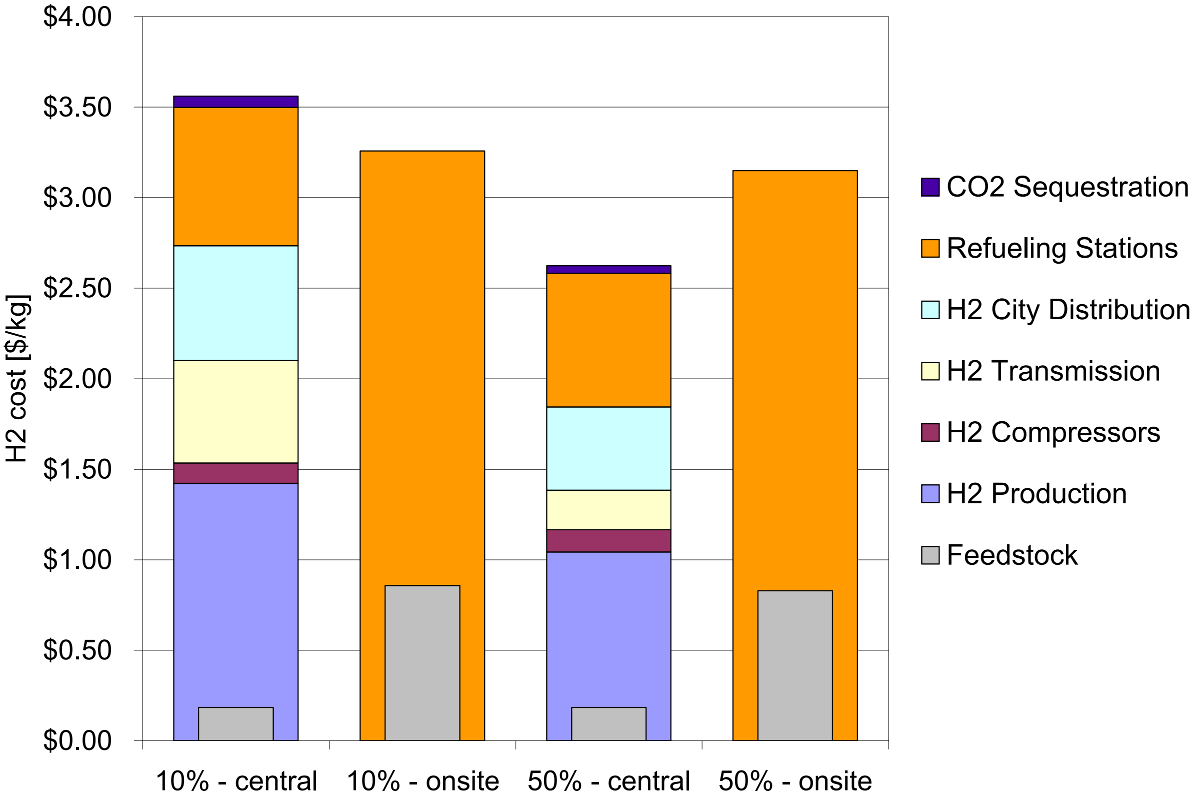


Figure 11. Cost comparison for central and distributed hydrogen production for the 10% and 50% market penetration levels.

In Phase I, we concentrated on hydrogen from natural gas and hydrogen from coal with CO_2 sequestration (Johnson et al. 2005). In future work under Phase II, we will add biomass as a potential supply. In addition, we hope to examine scenarios in which some demand centers are supplied via onsite production while others are supplied via pipeline from central plants. It is hoped that we will identify some rules-of-thumb that determine whether onsite or central production are more cost-effective. We also plan to analyze more market penetration scenarios as well as examine the tradeoff between the number of production plants and pipeline length. In other words, when is it cheaper to build another plant rather than extend the pipeline and vice versa?

TASK 3: *Participation in the H2A delivery group*

In 2003, the USDOE convened the H2A (Hydrogen Analysis) group, a team of experienced analysts studying hydrogen energy systems. H2A's goal is to produce a credible, well-documented set of information on hydrogen production, delivery and forecourt refueling technologies and options. Since H2A's inception, Joan Ogden has been a member of the H2A group, working in the area of hydrogen delivery infrastructure. Her activities during this contract included developing information on alternative pathways for delivering hydrogen to consumers, developing base case scenarios for hydrogen delivery (see results below), and working with other delivery team members and DOE researchers to document and present this information in a transparent format.

Throughout the contract period, Dr. Ogden, participated in meetings and conference calls with the H2A delivery group to develop spreadsheet models and associated documentation that outline various hydrogen delivery scenarios and associated component costs. During this process, she developed a spreadsheet for several delivery scenarios, incorporated comments from the group, integrated delivery component costs, participated in the revision and improvement of the spreadsheets on delivery components and scenarios, aided in the integration of the delivery spreadsheets with the master scenario spreadsheet, and reviewed, tested, and provided feedback on the master scenario spreadsheet.

In addition, Dr. Ogden presented the NREL-funded research at several meetings and conferences, including a poster at the Hydrogen, Fuel Cells, and Infrastructure Technologies Program Review Meeting (Philadelphia, May 2004), a presentation to the FreedomCAR hydrogen infrastructure technical team (Baltimore, July 2004), and a briefing to the FreedomCAR Delivery Tech Team (October 2004).

Results on H2 delivery cost for H2A Delivery Cases

The design and cost of a hydrogen delivery system depends on the total demand, the amount of hydrogen dispensed at each refueling station, the distance from the central hydrogen plant to the stations, and the amount of storage needed to handle variations in demand. In earlier work (Ogden 2004, Ogden, Mintz and Ringer 2004) we developed scenarios for several delivery "base cases", encompassing three types of markets that are likely to be important in a future hydrogen economy (metropolitan, interstate and rural) and four levels of market penetration (1%, 10%, 30%, and 70%). Our delivery base cases are summarized in Table 2.

Table 2. H2A Delivery Base Cases

Market Type	Early Fleet Market (1%)	General Light Duty Vehicles: Market Penetration		
		Small (10%)	Medium (30%)	Large (70%)
Metro	X	X	X	X
Rural			X	
Interstate			X	

Various delivery modes could be used to serve the demand for each base case. We consider three delivery modes:

- Compressed Gas Truck
- Liquid H2 Truck
- Gas Pipeline

The goal is to define a configuration for each base case and each delivery mode, as a basis for calculating the delivered hydrogen cost.

In this work, we will analyze costs for "pure" delivery modes (e.g., all the hydrogen is delivered via one mode), recognizing that this is a simplification, and it is possible that several delivery modes plus forecourt production might be used simultaneously.

Defining the metro base cases

In our analysis of hydrogen use in metropolitan areas, we make the following assumptions:

- **Consider 2 city sizes (100,000, 1 million).**
  - Average population density over entire city = 700-1200 people/km^2 (the city center has a higher density, suburbs have a lower density)
  - Average # light duty vehicles person =0.5-1.2 (#LDV/person is lower in the city center).

- **Consider two hydrogen refueling station sizes : 100 kg/d and 1500 kg/d**
  - Refueling stations are assumed to operate at 70% capacity factor, so the average amount dispensed per station is 70 kg./d, 1050 kg/d for the small (large) station

    - For a given case, it is assumed that all stations are the same size (e.g. either all the stations are 100 kg/d or all the stations are 1500 kg/d)

- **Customer convenience/station "coverage" and selecting a station size**
    - After market introduction into mass light duty vehicle (LDV) markets, H2 stations must be convenient enough so that # of H2 stations >10% x (# of current gasoline stations).
    - In selecting which size station to use, it is assumed that the number of hydrogen stations is somewhere between 10% and 100% of the number of gasoline stations today. It is assumed that each gasoline station today serves an average fleet of 2000 LDVs (each H2 station serves between 200 and 2000 H2 cars.

- **Siting refueling stations**
    - Refueling stations are sited within the city according to an idealized model of a city, (see Ogden 2004 and Task 1).

- **Consider a range of central H2 plant sizes from 50,000 – 500,000 kg/d (~20-200 million scf H2/d)**

- **Location of the central H2 plant relative to the refueling stations**
    - The central hydrogen plant is located 100 km from the city, if the city-wide demand is << 50 tonne/day (e.g. it is assumed that the central plant is shared among several cities).
    - If the demand > 50t/d, the hydrogen plant is located at the "city gate" (the city has its own "dedicated" hydrogen plant.

- **Hydrogen storage**
    - Hydrogen storage is needed to handle fluctuations in demand, and to assure reliability of supply.
    - The hydrogen storage terminal is located at the central hydrogen plant. It is assumed that 6 days of LH2 storage (for LH2 truck delivery) or 2 days of compressed hydrogen storage would be needed (for pipeline delivery).
    - The compressor (for compressed gas storage) or liquefier (for LH2 storage) are sized to match the hydrogen plant output.
    - Trucks are loaded at the hydrogen terminal at the central plant

- **Assumed hydrogen use in vehicles**
    - For mass light duty vehicle markets, average hydrogen consumption per vehicle = 0.72 kg/day (Based on a light duty hydrogen vehicle driven 14,950 miles/yr with an fuel economy of 57.5 mpg equivalent. This fuel economy was used in the 2050 study)

- For early fleet vehicles, average hydrogen consumption per vehicle = 0.96 kg/day (Based on a light duty hydrogen vehicle driven 20,000 miles/yr with an fuel economy of 57.5 mpg equivalent)

- We assume that there are 0.89 (large city) - 1.16 (small city) light duty vehicles per person, which is typical for the US.

In earlier work, we developed methods for sizing refueling stations, and truck delivery and pipeline delivery infrastructure (Ogden 2004). Under this contract, we extended this work to estimate levelized delivery costs for different scenarios and delivery modes. Results are shown below.

Hydrogen Delivery System Design and Cost

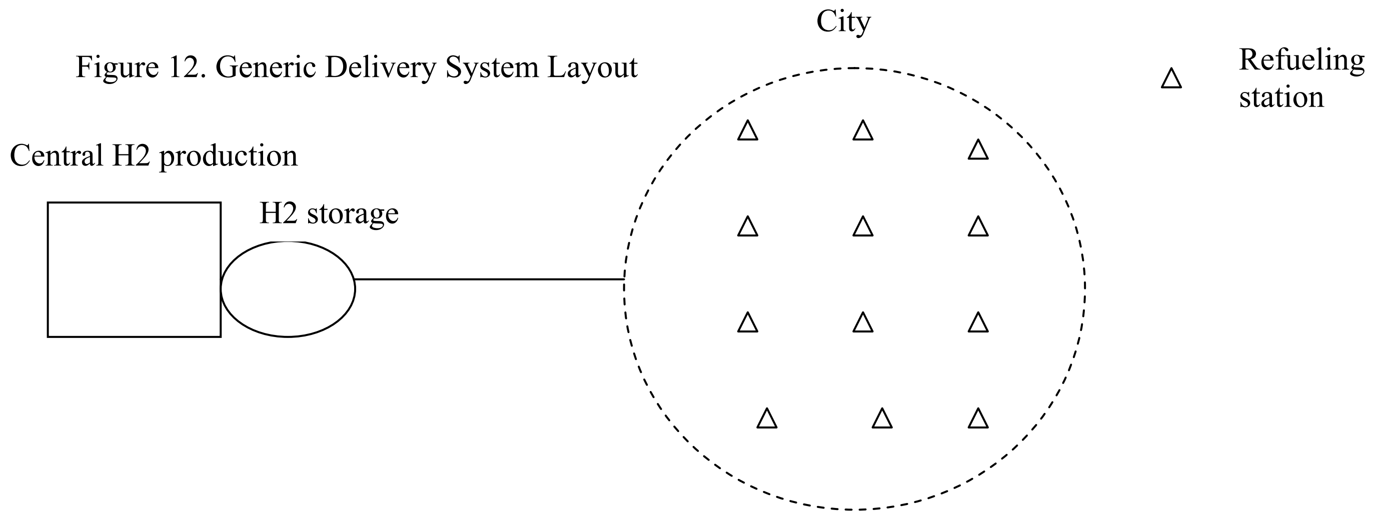
Table 3 summarizes the delivery system design for each case. Figures 12-21 illustrate the system layout for tube-trailer delivery, liquid hydrogen truck delivery and pipeline delivery. The capital cost of the system per vehicle served ($/LDV or light duty vehicle) and the levelized cost of hydrogen delivery ($/kg) are also shown for each delivery option for the large and small city cases. It is important to note that these are only delivery costs, and include everything **between** the central production plant and the refueling station: that is, centralized hydrogen storage (compression or liquefaction and storage vessels) and hydrogen delivery equipment (trucks or pipelines). To obtain a total delivered hydrogen cost to the vehicle, the costs of production and refueling must be added.

Table 3. H2A Metro Base Cases

	Small City 100,000 people Area =155 km^2 City radius = 7 km				Large City 1 million people Area = 1258 km^2 City radius = 20 km			
	Fleet 1%	10%	30%	70%	Fleet 1%	10%	30%	70%
City H2 Demand tonne/d	1	8.3	25	58	9	63	191	446
H2 Station Capacity (kg/d)	100	1500	1500	1500	100	1500	1500	1500
Ave H2 dispensed/sta kg/d	70	1050	1050	1050	70	1050	1050	1050
# H2 Sta.	16	8	24	56	122	61	183	426
Coverage= #H2 sta/ # gasoline sta today	0.28	0.14	0.41	0.97	0.27	0.14	0.41	0.96
Central H2 plant	shared	shared	shared	dedicated	shared	dedicated	dedicated	dedicated
Distance from H2 plant -> city km	100	100	100	0	100	0	0	0
Ave. # km between H2 sta in city	3.1	4.4	2.5	1.7	3.2	4.5	2.6	1.7
Average roundtrip distance traveled by truck from plant to station (km)	216	219	219	19	239	53	53	53
Comp gas trucks/ trailers	2/22	-	-	-	13/ 165	-	-	-
LH2 Trucks	2	2	5	7	11	7	21	48
Pipeline length km	-	40	68	121	-	293	525	980

TRUCK DELIVERY

Figure 12. Generic Delivery System Layout



PIPELINE LAYOUT OPTIONS

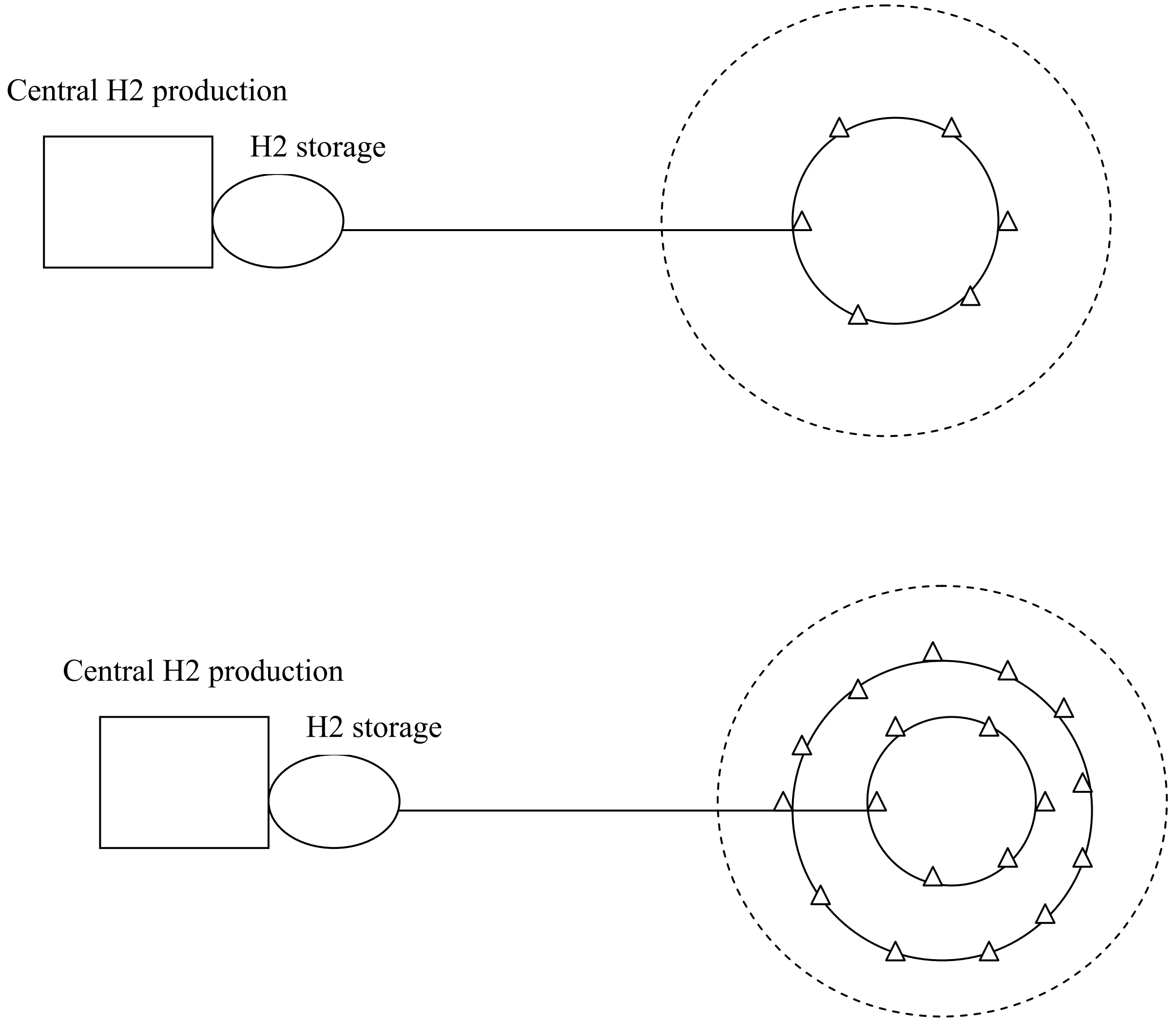


Figure 13

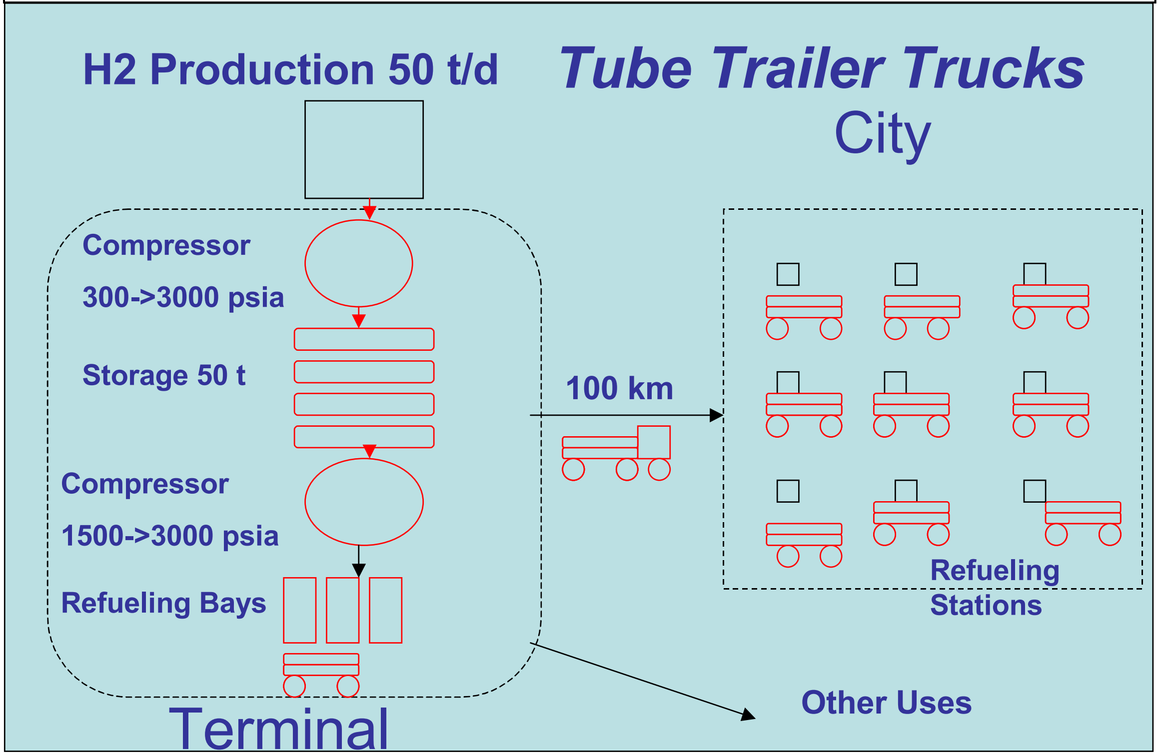


Figure 13. Layout for tube trailer delivery

Figure 14

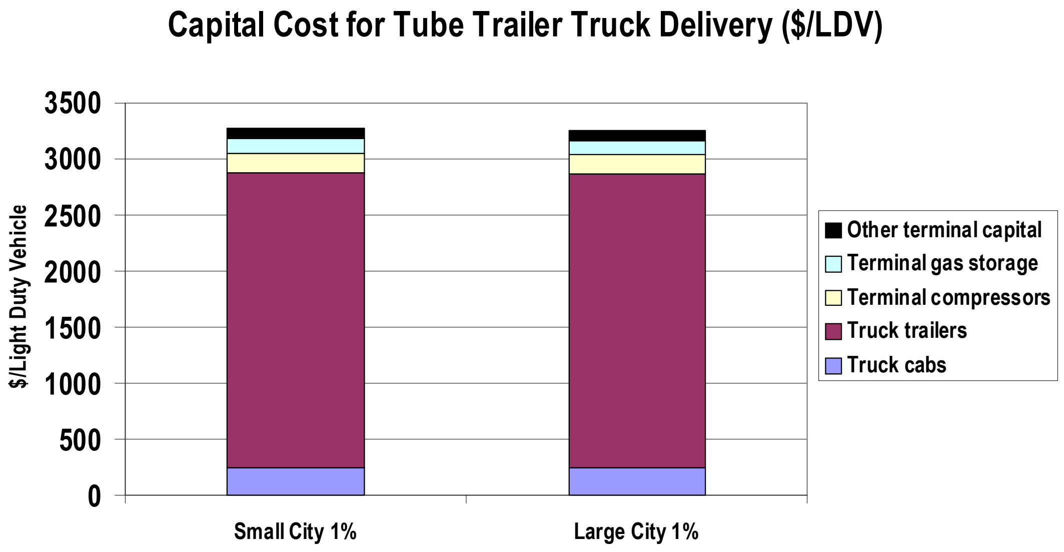


Figure 15

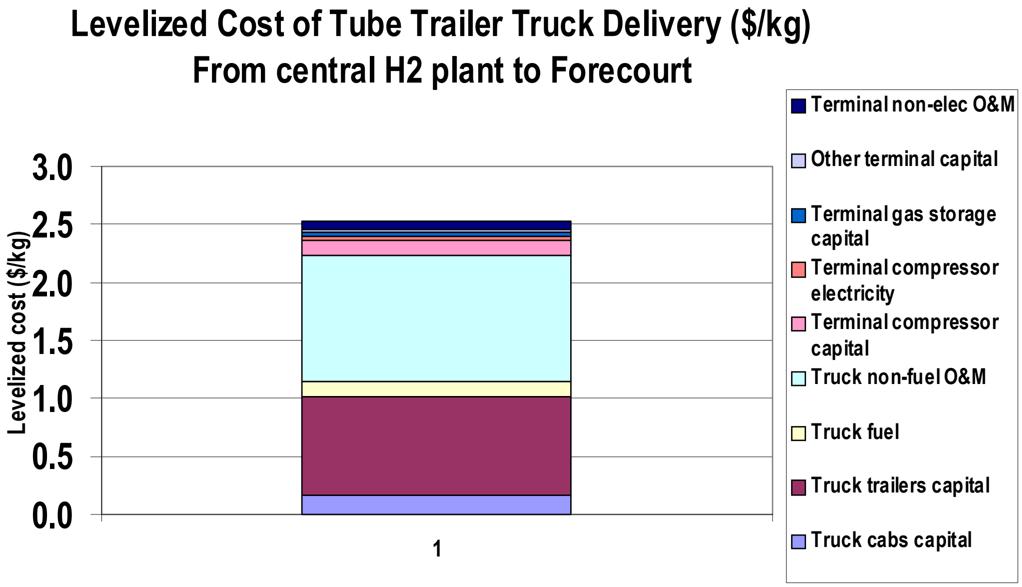

Levelized Cost of Tube Trailer Truck Delivery ($/kg)
From central H2 plant to Forecourt
Levelized cost ($/kg)
3.0
2.5
2.0
1.5
1.0
0.5
0.0
1
Terminal non-elec O&M
Other terminal capital
Terminal gas storage capital
Terminal compressor electricity
Terminal compressor capital
Truck non-fuel O&M
Truck fuel
Truck trailers capital
Truck cabs capital

Figure 16

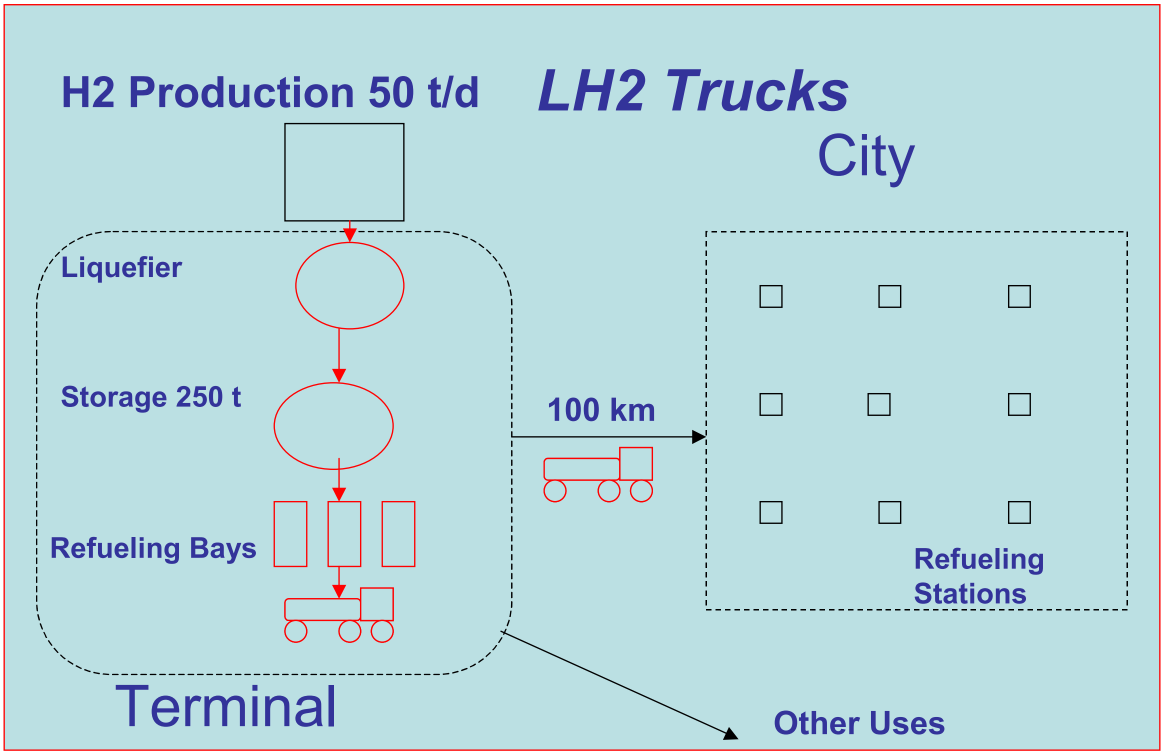


Figure 17

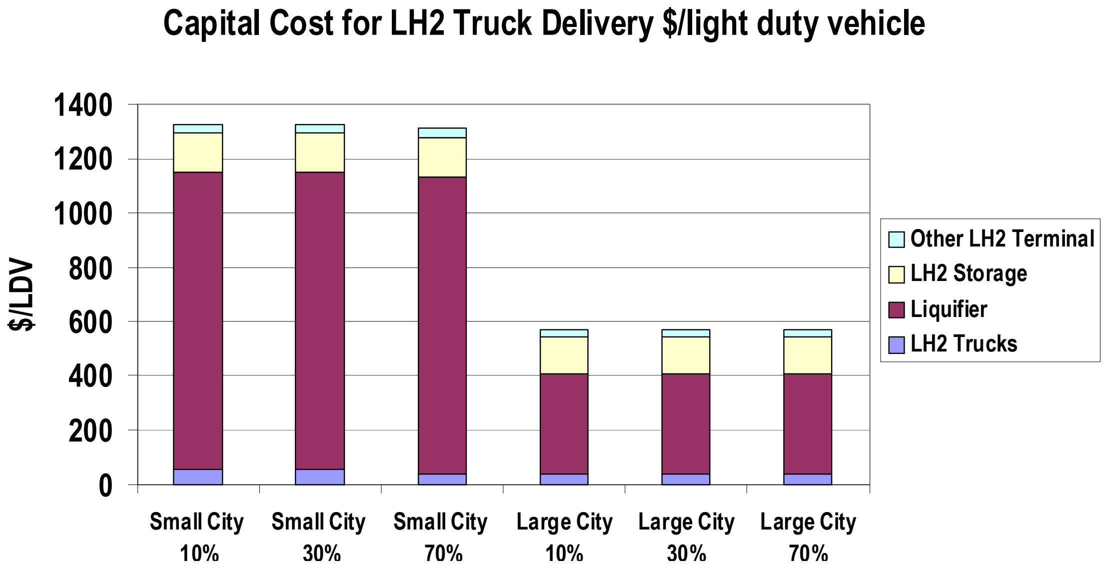


Figure 18

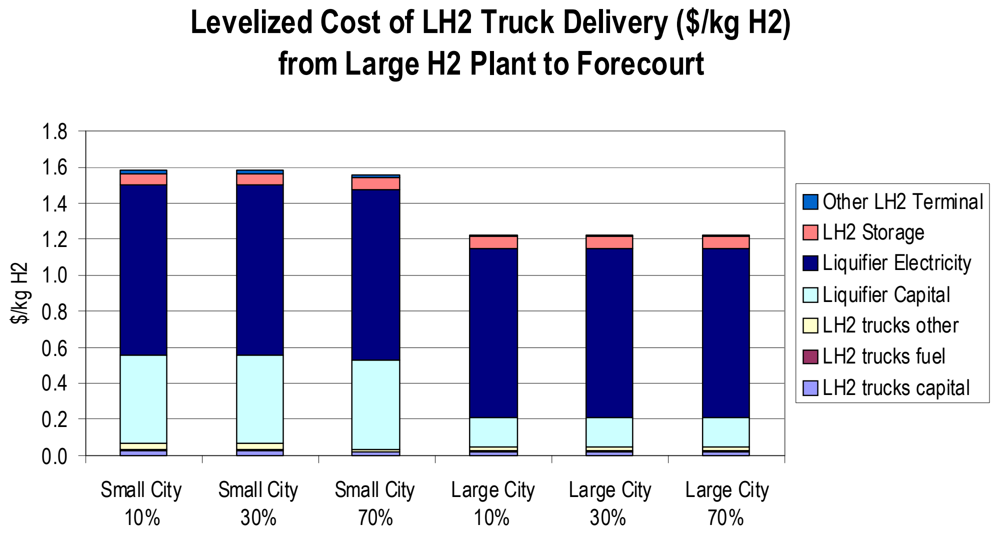

Levelized Cost of LH2 Truck Delivery ($/kg H2)
from Large H2 Plant to Forecourt
$/kg H2
1.8
1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
Small City 10%
Small City 30%
Small City 70%
Large City 10%
Large City 30%
Large City 70%
Other LH2 Terminal
LH2 Storage
Liquifier Electricity
Liquifier Capital
LH2 trucks other
LH2 trucks fuel
LH2 trucks capital

Figure 19

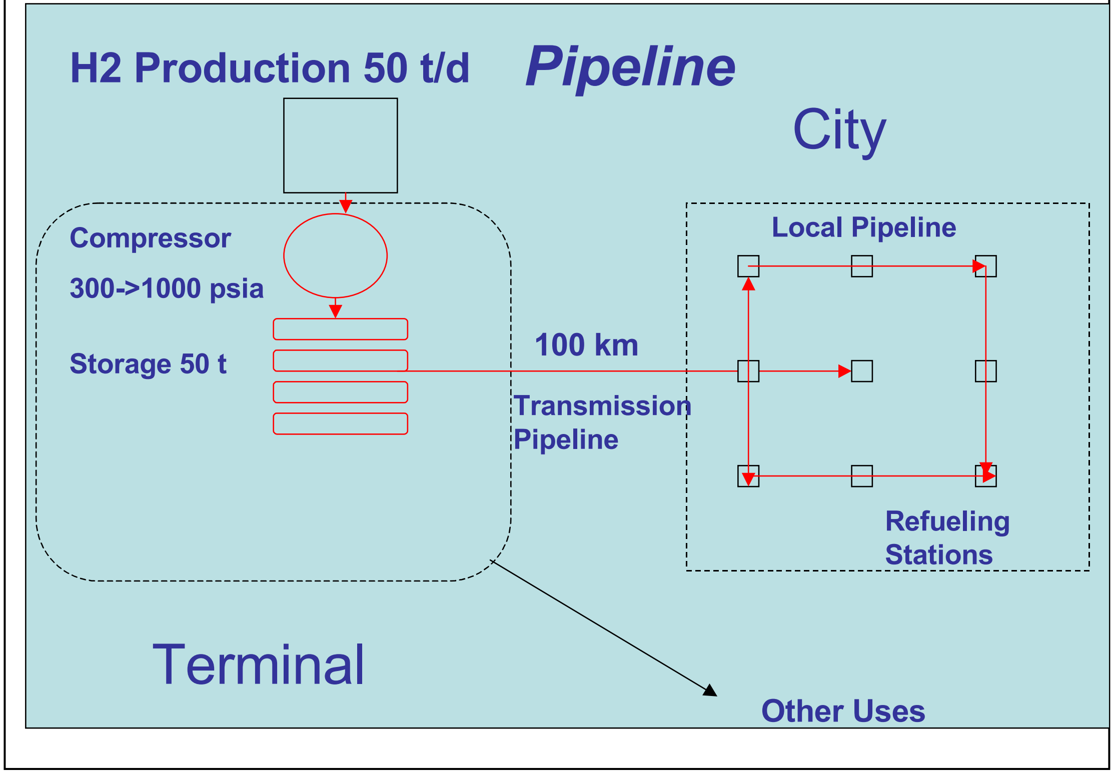


Figure 20

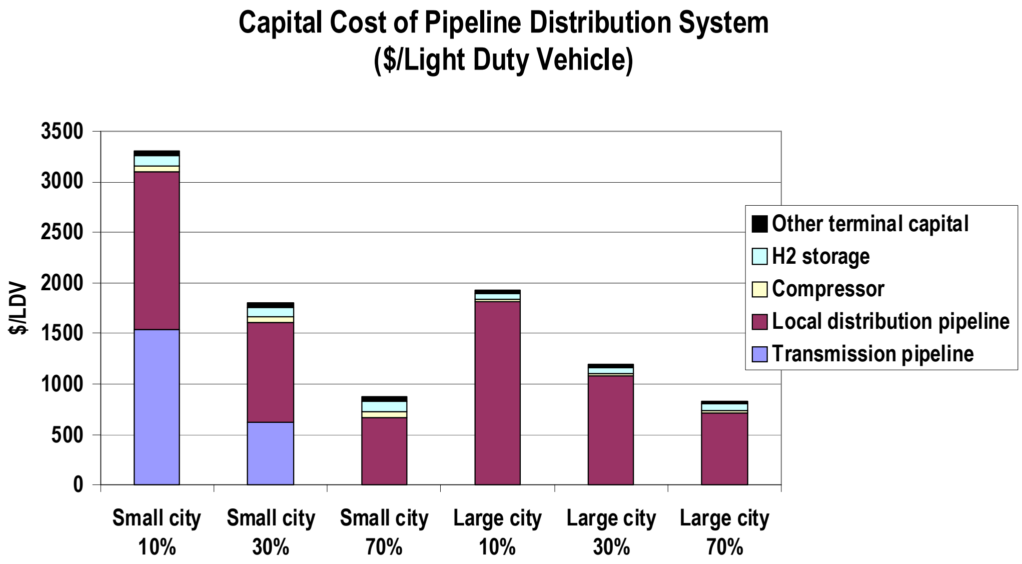
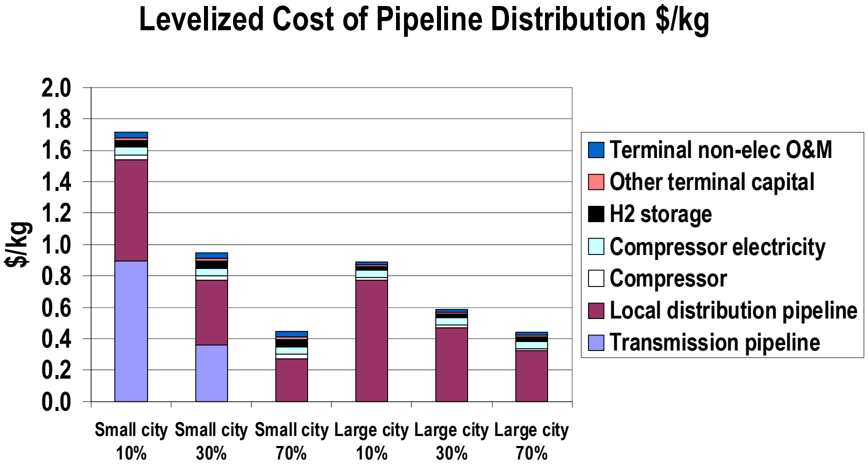


Figure 21


Levelized Cost of Pipeline Distribution $/kg
$/kg
2.0
1.8
1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
Small city 10%
Small city 30%
Small city 70%
Large city 10%
Large city 30%
Large city 70%
Terminal non-elec O&M
Other terminal capital
H2 storage
Compressor electricity
Compressor
Local distribution pipeline
Transmission pipeline

Several cost trends are evident from these results.

- Tube trailer truck delivery only makes logistical sense for small market fractions (1%) suggesting that this will be an early delivery mode (Ogden 2004). For tube trailer delivery, the capital cost of the trailers and non-fuel O&M (labor for drivers, other maintenance) are the largest contributors to the levelized ($/kg) cost. Central compression and storage do not add much to the cost, as it is assumed that the compressor and gas storage at the central plant are shared by other users, since the hydrogen demand for vehicles is much less than the 50 tonne per day central plant production capacity. The overall delivery cost is about $2.5/kg.
- For truck delivered liquid hydrogen, the liquefier and LH2 storage at the central plant are the largest costs, and trucks are a relatively minor contributor to the overall $/kg. (This is the reverse of the case for compressed gas trucks. This is true for several reasons: 1) the LH2 truck holds about 10 times as much hydrogen as the compressed gas truck so more energy is delivered in each trip; 2) for the compressed gas delivery system about 10 trailers are needed for each tractor, so the total cost in trucks plus trailers is higher per vehicle served; 3) liquefaction is about 4 times more energy intensive than compression, so electricity costs are more significant for LH2, 4) liquifiers are more costly than compressors.) Because of scale economies for liquefaction, the delivery cost for LH2 from a 500 t/d plant is about 25% less than for a 50 t/d plant. The overall delivery cost is about $1.2-1.6/kg. The delivery cost depends very little on market fraction, as it is assumed that the liquefier and LH2 storage are fully utilized by other users (so increasing the number of trucks going to serve vehicles makes no difference.)
- For pipeline delivery, the capital cost of the pipeline dominates the total cost. Unlike the case for trucks, there is a strong scale economy with market fraction, as the pipeline cost depends on the flow rate. The cost of pipeline delivery is $0.45-1.7/kg

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INTERSTATE DELIVERY CASES

In collaboration with the others in the H2A delivery team, we calculated the cost of various delivery options for stations located along an interstate highway.

Today, about 10% of light-duty vehicle miles traveled (VMT) occurs on 33,060 miles of rural interstates (FHWA, 2002). This can be expressed as 17,000 VMT per mile of interstate highway per day. For a hydrogen car assumed to have a fuel economy of 57.5 miles per gallon gasoline equivalent (mpgge), ~400 gge/mi/d would be needed for a peak demand day (July weekend day).

This allows us to estimate the amount of hydrogen fuel that must be supplied along interstates to support this travel.

$$\mathrm{KG/MI} = \Sigma\ \mathrm{VMT/MI}\ \times\ \mathrm{MPGE}\ /\ \mathrm{KG/GGE}$$

Where:

VMT= Miles traveled by light duty vehicles on rural interstates by state, extrapolated from yr 2000 at 1.5%/yr
MI = Road miles of rural interstates by state
MPGE = Miles per gasoline gal equivalent (57.5)
KG/GGE = Conversion from gals gasoline to kg hydrogen

Table 4 indicates the amount of hydrogen that would be needed along a 100 mile (160 km) length of interstate highway for different market penetration levels. The number of LH2 trucks needed to support this demand is also shown.

Table 4. Hydrogen Demand along 160 km length of interstate highway

	Market Penetration: H2 LDVs		
	10%	30%	70%
H2 Demand t/d	3.9	11.6	27.0
# H2 stations (1500 kg/d)	4	12	26
Ave. km between stations	40	13	6
# LH2 trucks`	1	2	3

In Figures 22-27, the system layout, capital cost ($) and the levelized delivery cost are shown for LH2 truck delivery and pipeline delivery to interstate stations. The cost of LH2 truck delivery is not very sensitive to the market fraction, as liquefaction costs dominate. The levelized delivery cost is about $1.5/kg. The cost of delivery via pipeline is about $1.0-3.5/kg and depends strongly on the market fraction (flow rate in the pipeline). The capital costs and levelized costs are lower for pipelines than for LH2 trucks, above a market fraction of about 30%.

Figure 22

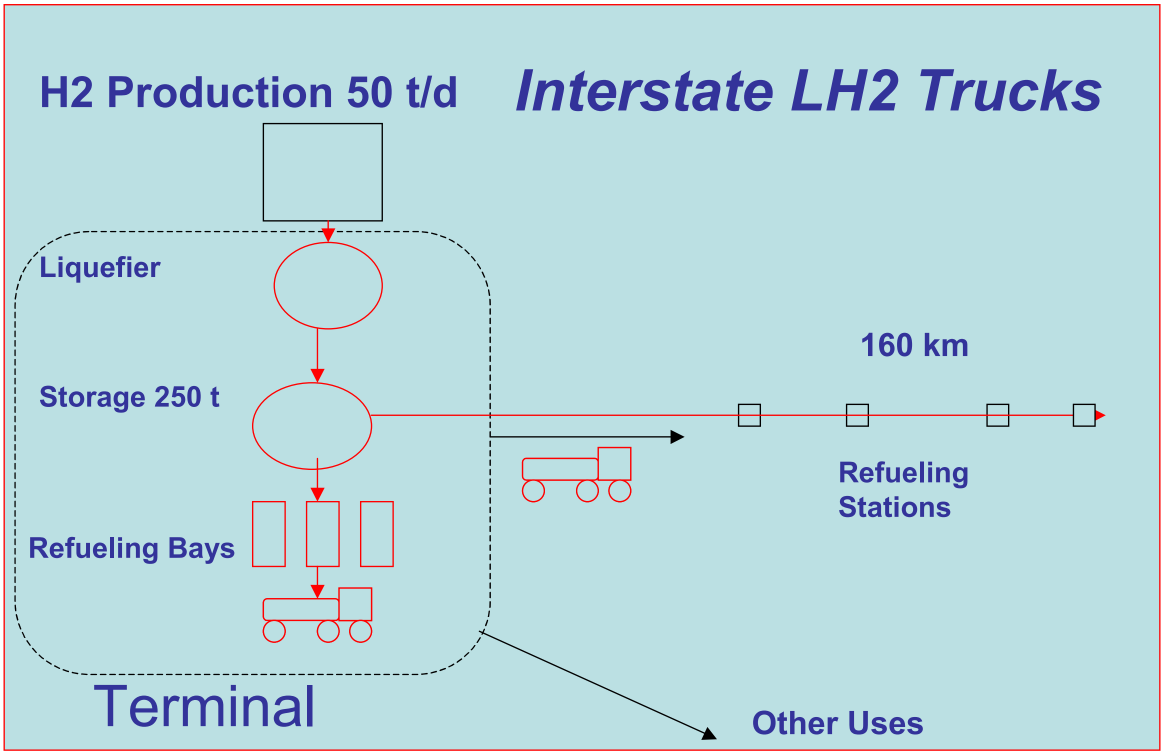


Figure 23

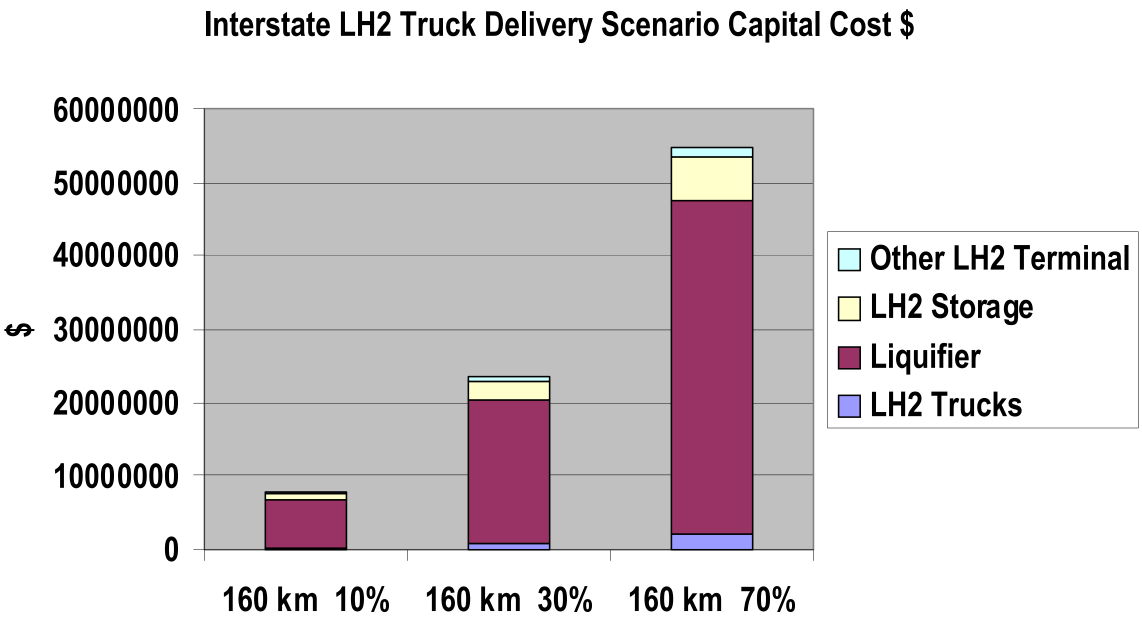


Figure 24

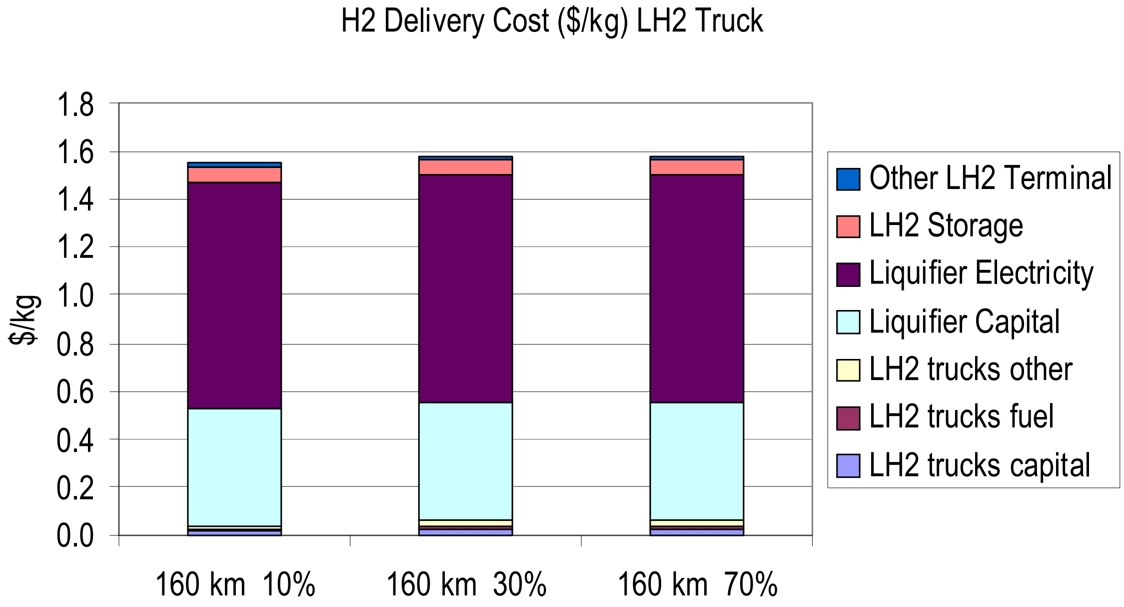

H2 Delivery Cost ($/kg) LH2 Truck
$/kg
1.8
1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
160 km 10%
160 km 30%
160 km 70%
Other LH2 Terminal
LH2 Storage
Liquifier Electricity
Liquifier Capital
LH2 trucks other
LH2 trucks fuel
LH2 trucks capital

Figure 25

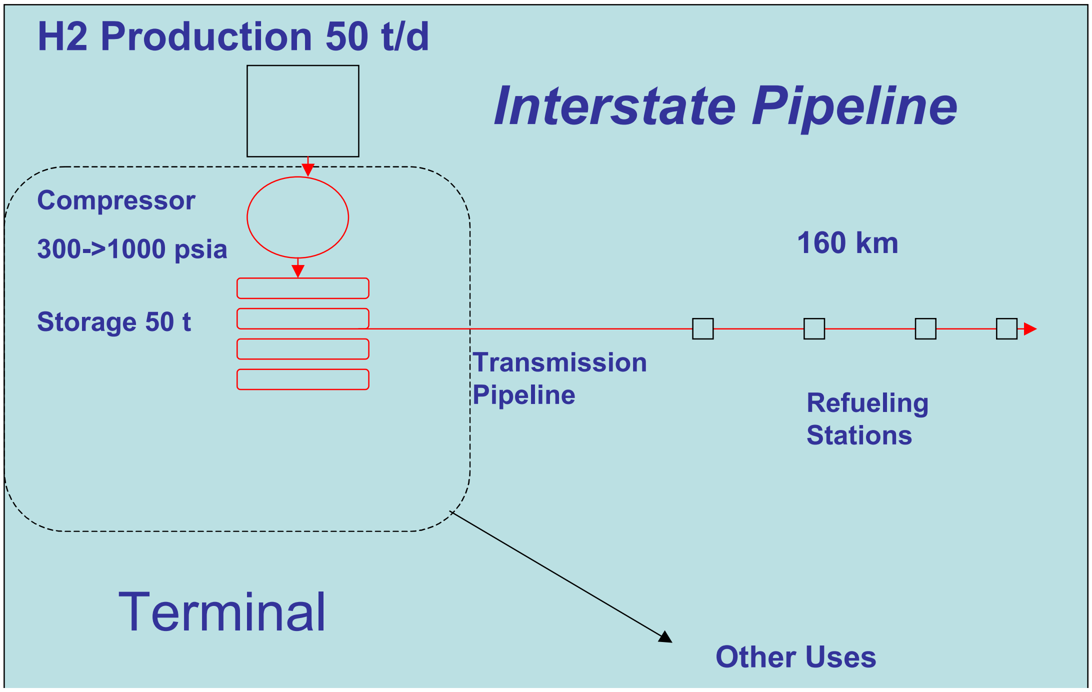


Figure 26

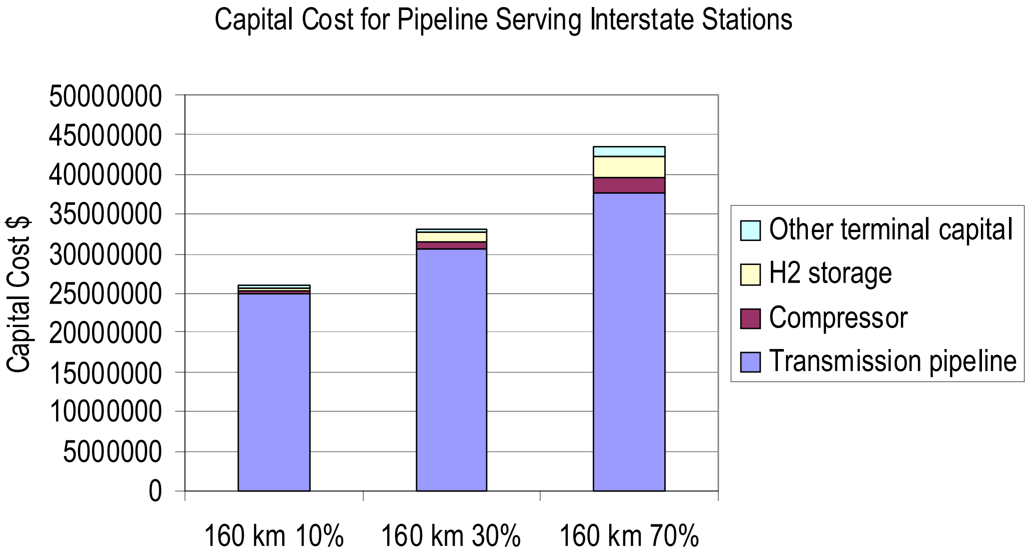
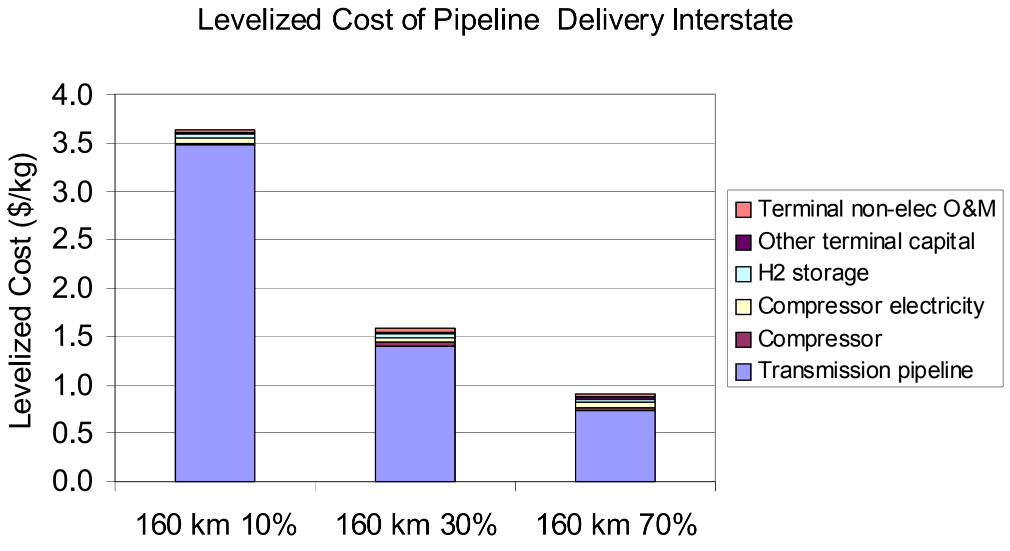


Figure 27


Levelized Cost of Pipeline Delivery Interstate
Levelized Cost ($/kg)
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
160 km 10%
160 km 30%
160 km 70%
Terminal non-elec O&M
Other terminal capital
H2 storage
Compressor electricity
Compressor
Transmission pipeline

CONCLUSIONS

During Phase I, we improved our models of regional hydrogen infrastructure development (Task 1), applied these models to geographically specific case studies (Task 2), and developed infrastructure models as part of the H2A delivery group (Task 3).

Task 1:

- We developed an improved GIS-based method for estimating hydrogen demand spatially using census-derived population data. This demand can be specified as a function of time and used for transition analyses of particular regions.
- We improved our engineering/economic "component" models of hydrogen systems based on estimates from focused studies of refueling stations and pipelines within the UC Davis H_2 Pathways program. In Phase II these models will be verified against forthcoming data from the USDOE H2A database.
- Extending our earlier work, we developed and refined several methods for designing an optimized hydrogen infrastructure. These include:

    - Urban infrastructure design methods:
        - Idealized models of cities were formulated to estimate the spatial layout of hydrogen refueling stations and distribution infrastructure (Ogden 2004, Yang and Ogden 2004). This allows the direct comparison of hydrogen supply alternatives with respect to capital cost and delivered hydrogen cost. We find that the lowest cost alternative depends on assumptions about hydrogen production technologies, feedstock costs, city size, population density, market penetration of hydrogen vehicles and the number of refueling stations.
        - Methods were developed that use real-world GIS data about traffic flow and existing station sites to optimize hydrogen refueling station siting based on fuel accessibility. Case studies were conducted for Sacramento (Nicholas 2004) and Los Angeles (Nicholas, Weinert and Miller 2005). It appears that customer convenience equivalent to today's gasoline stations could be achieved if hydrogen were offered at 10-30% of existing gasoline stations.
        - *In Phase II, we plan to verify how well our idealized models represent real cities.*

    - Regional Infrastructure design methods: We developed GIS-based methods for designing regional hydrogen infrastructure including multiple hydrogen sources and demand centers.
        - Spatial optimization: Methods for Designing a spatially-optimized infrastructure for steady state hydrogen demand
            - We are developing methods to design a spatially optimized regional infrastructure to meet a steady-state demand. As a first case, we used a minimal spanning tree algorithm to

        find the lowest cost pipeline network to connect multiple demand centers (cities) with a single hydrogen production facility.
        - *In future work we will extend spatial optimization methods to consider multiple hydrogen production facilities and multiple demand centers and other delivery modes such as trucks*

    - Transition studies: Designing an optimized infrastructure for growing hydrogen demand
        - In preliminary work we studied the question of when a transition might occur from distributed on-site reformation to central plant reformation with pipeline delivery. The economics of the transition depend on several important parameters. These include the scale and timing of hydrogen demand growth, the size and density of the analysis area, and choices about incremental equipment capacity and underutilization. (Yang and Ogden NHA 2005)
        - *In future work, we will examine transitions in a GIS framework.*

Task 2:

- We used GIS to develop spatial databases to study regional hydrogen infrastructure options.   We developed a preliminary GIS-based model for infrastructure development in the state of Ohio using methods that can be readily applied elsewhere. In this process, spatial optimization was used to minimize cost by finding the shortest path H_2 pipeline distribution network that connects steady-state demand centers with a single coal-to-hydrogen facility. Given a scenario in which 10% of light-duty vehicles are fueled by hydrogen, results indicate that the infrastructure would cost \$1.3 billion, or \$3,400/hydrogen vehicle. Furthermore, the levelized cost of hydrogen would be approximately \$3.65/kg.
- In preliminary work studying the transition from distributed on-site reformation to central plant reformation with pipeline delivery, the economics of the transition appear to be dependent on several important parameters. These include the scale and timing of hydrogen demand growth, the size and density of the analysis area, and choices about incremental equipment capacity and underutilization.

Task 3:

- As part of the H2A delivery team, we made preliminary estimates for the levelized cost of hydrogen delivery for a set of city and interstate demand scenarios.

RELATIONSHIP OF THIS STUDY TO OTHER ONGOING HYDROGEN SYSTEM STUDIES

This project contributes to NREL's mission to understand how the development of hydrogen infrastructure might proceed, and complements other ongoing projects supported by NREL and the USDOE to study hydrogen transitions. We have interacted with other modeling groups including those at the National Renewable Energy Laboratory, Argonne National Laboratory, Oak Ridge National Laboratory, USEPA, Pacific Northwest National Laboratory and the National Energy Technology Laboratory. In table 5 below, we compare some attributes of our models to others now being developed. Like several other studies, UC Davis' work uses GIS databases to visualize hydrogen demand and supply, and employs optimization techniques to find low cost systems. UC Davis' modeling studies are distinguished by:

1. **High level of geographic detail; case study approach to regional H2 infrastructure analysis**. Our models incorporate high spatial resolution GIS-based census data (available at the block level) to estimate hydrogen demand spatially. GIS-based city or interstate traffic flow data are also used for station placement and sizing. We utilize detailed GIS information about existing infrastructure (natural gas system; electricity system; location of existing pipelines that could be used as rights of way) and resources for hydrogen production. This allows a case study approach rich in detail and insight. We have analyzed a variety of H2 systems from city scale to regional scale with these methods
2. **The development of simplified "idealized city" models to describe hydrogen delivery systems** in urban areas. We have developed simplified models for H2 delivery systems and plan to validate these (via comparison with detailed GIS models). This work contributes to the H2A delivery team effort.
3. Exploring the use of **spatial optimization methods to find low cost system spatial layouts** for hydrogen production and delivery systems.
4. Exploring the use of **dynamic programming and other optimization methods to find low cost transition paths** over time.
5. **Exploring methods for simultaneous spatial and time optimization**.
6. The **flexibility of the models to analyze different regional demand and supply scenarios** and estimate costs for hydrogen production, delivery and refueling (variables include: selection of a wide range of alternative hydrogen supply pathways; city size; city population density; urban versus rural; various levels of market penetration; hydrogen system component performance and cost assumptions; vehicle type, performance and cost)
7. The **leveraging benefit of the UC Davis Hydrogen Pathways Program**. (The Hydrogen Pathways Program is a four-year multi-disciplinary research program, begun in 2003, funded by a consortium funded by 20 industry and government sponsors to examine the implications of hydrogen for future transportation. The P.I. is co-director of this program.) This gives us access to ready industry feedback and comments on our research. We also have interactions with the California Fuel Cell Partnership (UC Davis is a member) and the California H2 Highway Network (where P.I. Joan Ogden served on the Advisory Panel).

Table 5. Comparison of Some Hydrogen Transition Models

	Model Type	Level of spatial detail	Regionally specific?	Engineering/econ. models of H2 system components	Optimized in space	Time dependent	H2 Demand
UC Davis	Engineering/ Economic/ Geographic Model of H2 system	GIS data used extensively. Population by census block; (option for higher levels of aggregation)natural gas system; electricity system; roads; traffic flows; rail; pipelines	Yes; Analysis can be done at city, state or regional level. Case studies in California, Ohio. Methods adaptable to other sites	Models for production, delivery and refueling stations. Cost as function of scale and cumulative production level (learning curve)	Yes. Idealized city model; Spatial optimization for regional pipelines	Yes Preliminary studies of transition from distributed to centralized H2 production	Exogenous, steady state or time dependent (demand is derived from data on population density, vehicle characteristics; assumed market penetration of hydrogen vehicles)
NREL H2 Infrastructure for commercial introduction (Melendez and Milbrandt)	H2 station location and cost model (estimate number of H2 stations needed in US for commercial introduction)	GIS data on roads, traffic flows, existing industrial H2 infra, alt fuel stations ,city populations used to select interstate routes for H2 station placement	Entire US	Station cost model. Does not consider H2 production or delivery costs explicitly	Yes. Best interstate corridors selected for H2 station placement. Considers interstate stations with spacing of 150 miles	Examines station mix that could handle assumed increase in vehicle use over time	Exogenous (demand is scaled to traffic flows on interstates)
NREL Wind H2 (Short)	Wind supply for electricity and H2 production	Regional electricity systems and wind resources by county	Regional	Considers wind power and wind hydrogen production and long distance transmission of energy to city-gate; does not include local H2 distribution and refueling	Yes	Yes Hourly electric demand data	Exogenous
HyTrans (ORNL)	Model impact of policies, vehicle and infrastructure attributes on H2 vehicle adoption and infrastructure build up	Aggregated, 3 levels of population density	Several US regions	Models for production, delivery. Cost as function of scale and cumulative production level (learning curve)	No	Yes	Endogenous; consumer choice model
Singh (ANL), Moore, Shadis	Model of regional hydrogen costs for use in EIA-NEMS model	11 separate US census regions; each with demand and resources	Each region produces its own H2 from "best" regional resource	Yes	No	Yes	Exogenous. Demand estimated from market penetration scenarios for each region
ANL CHAIN	Engineering Econ Model for H2 system		Ave. US	Yes. Includes some upstream costs for H2 feedstocks	No	No	Exogenous
PNNL	Integrated assessment; climate focus	14 global regions	14 global regions	Yes	No	Yes	Endogenous
EPA	MARKAL-type model of US energy economy	Aggregated	Ave. US	Yes	No	Yes	Endogenous
TIAX H2 Now	Engineering Econ Model for H2 system	6 US regions	US regions	Yes	No	Yes. Scenarios	Exogenous

FUTURE WORK

Task 1: We plan to continue the work begun under Phase I to refine simulation tools for modeling hydrogen energy infrastructure development based on geographic information system (GIS) input data and operations research optimization methods.

- Continue to improve and update the initial set of models created in earlier work. In particular, we will update hydrogen component models, consistent with ongoing work under the H2A project, as these data become finalized. In addition, we will include information developed under the Hydrogen Pathways program at UC Davis.
- We will continue exploring the use of mathematical programming and other optimization techniques to connect demand and supply in the lowest cost hydrogen energy system, and study how this changes in time. Additionally, we will combine the cost estimates from component models with the overall system optimization method. The goal is to compare various possible transition pathways to find the lowest overall costs for regional hydrogen infrastructure development. In this work, we will utilize simplified infrastructure design models developed under the H2A project and at UC Davis under the Hydrogen Pathways program.
- We have developed simplified spatial design and cost models for hydrogen distribution systems in cities. The design and cost of a truck delivery or pipeline system can be found as a function of the city size, population density, market fraction of hydrogen cars, and assumptions about the number and size of hydrogen stations. Using these idealized models greatly reduces the amount of computation time needed to cost infrastructure, but may not duplicate the characteristics of real cities. We will validate our idealized models of cities, by comparing these to real cities.

Task 2: We will complete a geographic specific case study of implementing a near-zero emission hydrogen energy system in a particular area (the Midwestern US), using techniques described in Task 1. This study continues work begun in Phase I and will examine how the optimum infrastructure design changes with input parameters, using geographic specific data on energy demand, resources for hydrogen production and existing infrastructure.

Under Phase I, we developed the GIS database required to do the cost study for natural gas and coal-based hydrogen supply alternatives. Under Phase II, we plan to expand the GIS database to include hydrogen from biomass and electrolytic hydrogen from off-peak power. We will apply tools developed under proposed Task 1 to estimate projected costs for different infrastructure alternatives over time, in response to alternative demand scenarios.

Task 3: Continued participation in the H2A delivery group. During Phase I of this contract, we worked with the H2A group in the area of hydrogen delivery infrastructure. Activities included developing information on alternative pathways for delivering hydrogen to consumers and developing base case scenarios for hydrogen delivery. In

Phase II we will continue to work with other analysts and NREL/DOE researchers to document and present this information in a transparent format.

ACKNOWLEDGMENTS

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