X.5 Analysis of the Hydrogen Production and Delivery Infrastructure as a Complex Adaptive System

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Objectives

- Use agent-based modeling (ABM) to provide insights into likely infrastructure investment patterns.
- Deal with chicken-or-egg aspect of early transition.
- Provide answer to the question, "Will the private sector invest in hydrogen infrastructure?"

Technical Barriers

This project addresses the following technical barriers from the Systems Analysis section of the Hydrogen, Fuel Cells and Infrastructure Technologies Program Multi-Year Research, Development and Demonstration Plan:

(A) Future Market Behavior

(C) Inconsistent Data, Assumptions and Guidelines

Contribution to Achievement of DOE Systems Analysis Milestones

This project will contribute to achievement of the following DOE Systems Analysis milestones from the Systems Analysis section of the Hydrogen, Fuel Cells and Infrastructure Technologies Program Multi-Year Research, Development and Demonstration Plan:

- **Milestone 5:** Complete analysis and studies of resource/feedstock, production/delivery and existing infrastructure for various hydrogen scenarios. (4Q, 2009)
- **Milestone 25:** Complete the Agent Based Modeling System for infrastructure analysis of hydrogen fuel and vehicles. (4Q, 2008)

Accomplishments

- Introduced centralized hydrogen production to the ABM.
- Analyzed the influences on the date of entry of centralized hydrogen production.
- Discovered significant impacts of investor agent's satisficing behavior.
- Introduced into the ABM corporate-level investment decision making in addition to simple project evaluation as the full basis for investment choices.

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Introduction

The purpose of this project work is to analyze investment in hydrogen infrastructure during the early transition to a hydrogen economy using an agent-based modeling and simulation (ABMS) technique. ABMS is a micro-simulation technique that facilitates representation of heterogeneity in terms of many characteristics of the actors (agents) involved in the transition to a hydrogen infrastructure. These characteristics can include size, beliefs and preferences, expectations, goals, and location, among the most important. ABMS simplifies the modeling of learning by agents. In distinction from conventional modeling approaches currently applied to the hydrogen economy, ABMS relies on different objective functions (goals) for different agents; it also allows for different reactions to unmet expectations, different learning from the emerging economic environment, and different responses based on agent characteristics. It is easy to specify putty-clay capital (an investment in an earlier period of a simulation cannot change into another technology in a subsequent period), which is both realistic and facilitates analysis of quasi-rent changes (stranded investments). Altogether, ABMS is a well-suited vehicle to apply sophisticated economic models in an environment involving actors with widely differing characteristics and goals.

Early transition is expected to be a time of considerable uncertainty, when reasonable investors might hold widely differing expectations and could have different goals. An additional feature of early transition is the existence of a chicken-or-egg problem, in which potential investors in infrastructure want to wait for hydrogen vehicles to emerge on the market, but potential vehicle buyers want to wait until fuel is widely available. ABMS is a convenient tool for exploring these interactions via simulation, since analytical expressions for solutions to models with only modest complications are intractable.

Approach

The revised 1st-year goal of the project was to provide an answer to the question, "Will the private sector invest in hydrogen infrastructure?" and to focus on California as a likely region of early transition. To accomplish the revised 1st–year goal, the project developed a framework that focused on investments as business decisions and used that framework as a basis for preliminary assessment of profitability. In a parallel effort, efforts were begun to prepare the ABM for detailed simulations in the project's second year.

Results

Background Review of the Model Structure. The model is composed of two major modules, a driver module which simulates behavior of driver agents, and an investor module which simulates the decisions of the investor agent who supplies hydrogen to the Los Angeles market. The model uses a geographic information system platform of the Los Angeles metropolitan area based on one-mile grids. Driver agents are located at residential sites corresponding to Los Angeles residential densities. They decide whether to purchase a hydrogen vehicle on the basis of vehicle cost relative to a conventional vehicle, fuel availability, and taste for greenness. Hydrogen production is modeled with investor agents, who make investments in either 1,500 kg/d distributed steam methane reformer (SMR) stations or centralized production on the basis of their expectations of hydrogen vehicle adoption. They form their expectations from observing past growth in hydrogen vehicles and correct mistakes in expectations from period to period.

Continued Model Development. The prototype model of 2006-07 was developed further during 2007-08.

Driver Module. Two improvements were made to the driver module. First, the empirical underpinnings of the taste distribution, which affects the propensity to purchase a hydrogen vehicle, was strengthened with information on membership in environmental organizations and voting patterns on environmental referenda in Los Angeles. Second, the variable benefit term in the driver-agent utility function was modified to react to fuel price changes.

Investor Module. Several major changes were made in the investor module. The most extensive change was the addition of centralized production of hydrogen to the choices the investor agent may make. To compare the profitability of distributed and centralized production, the investor agent must have estimates of the production cost of hydrogen at the pump. This is a simple calculation with distributed production but is considerably more complicated with centralized production because of the associated delivery infrastructure, which must be sized to handle the output of a number of production facilities. Consequently, the investor agent must make a long-term plan for the construction of multiple production facilities so as to eventually fully utilize the delivery infrastructure. The investor agent's expectation of hydrogen demand growth governs his construction plans, and the construction plan in turn is used to generate a levelized cost of hydrogen that can be compared with the cost of distributed hydrogen. Information from the H2A delivery and production models was used to create a section of the investor module that calculates levelized costs for any particular time path of infrastructure construction required by the investor agent's expectations of hydrogen demand growth.

The second addition to the investor module was to introduce upper-management decision making to the purely project-level decisions. Decision making by upper management takes a broader view of overall corporate goals and conditions and may thus make choices that differ from simple project profitability considerations, as shown in Figures 1 and 2. Modeling of the upper management decisions and linking them to the project evaluation was begun but not completed in 2007-08.

Simulation Results. Extensive simulations were conducted to study the entry date of centralized hydrogen production. Figure 3 summarizes those findings. The two most important influences on the entry of centralized production are the speed of adoption of hydrogen vehicles and the cost of distributed hydrogen production. The first panel of Figure 3 shows the high costs of unutilized capacity that are masked by levelized costs. These costs fall fairly rapidly, but with entry in year 3 of a transition are quite high in

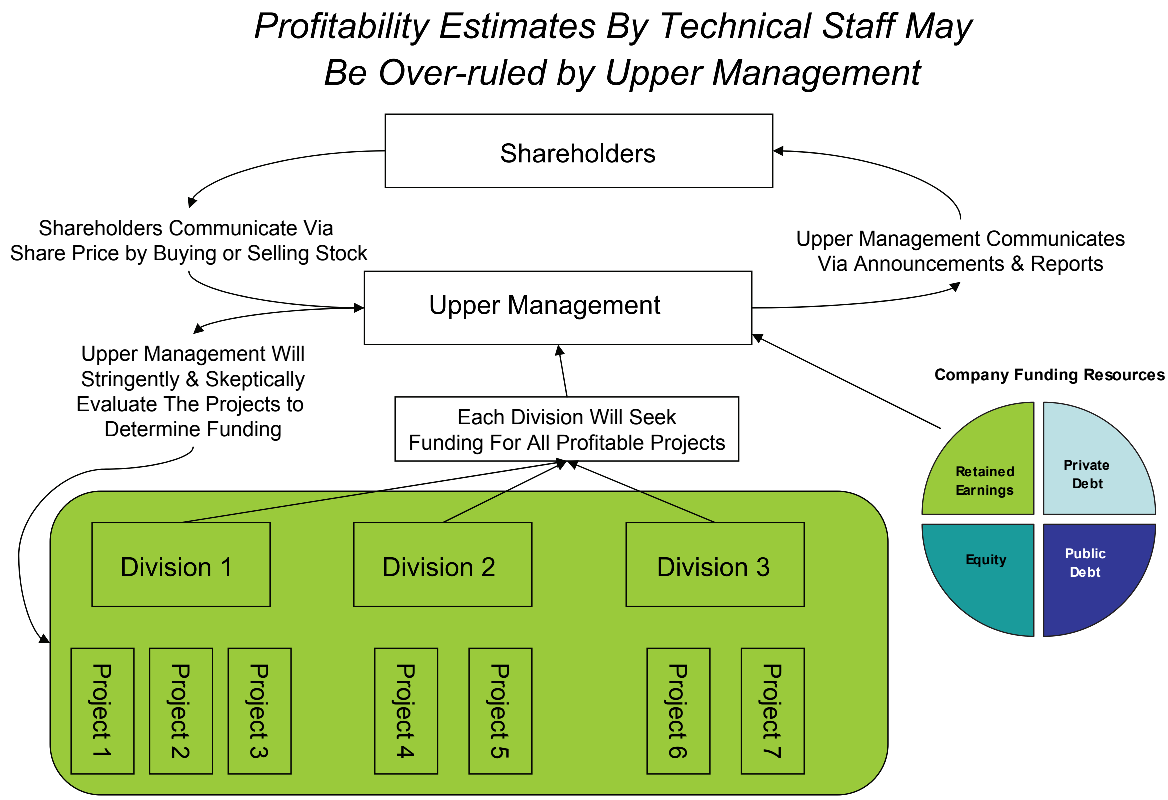


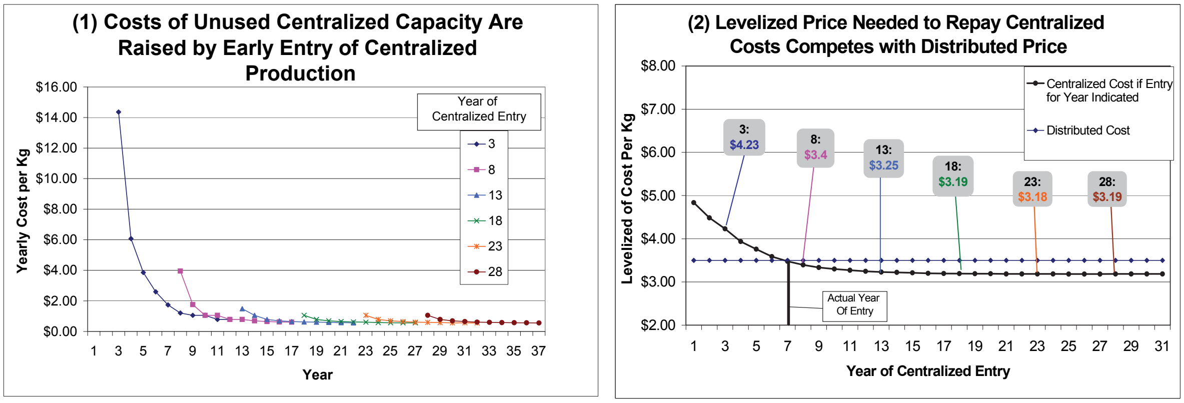
FIGURE 1. Role of Upper Management in Infrastructure Provision

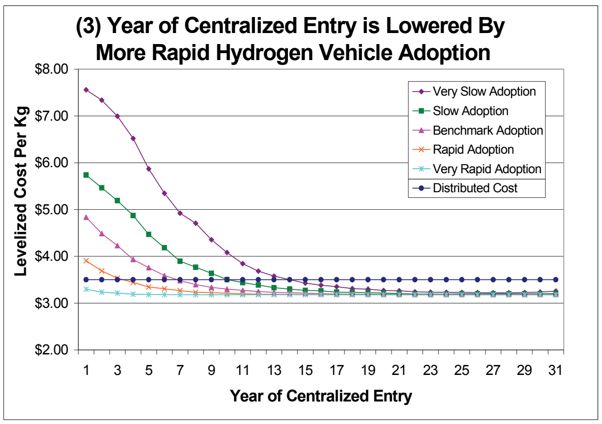
FIGURE 2. In Addition to Standard Project Evaluation, A Project Must Jump Hurdles Reflecting Broader Company Goals

the first several years. Panel 2 of Figure 3 reports the levelized costs associated with the entry years reported on Panel 1. Levelized costs exhibit much less variation, with a high of just under $5.00/kg for entry in the first year of transition to an asymptotic minimum of $3.18 for entry in year 18. With a distributed hydrogen cost of $3.50, centralized production would find it profitable to enter in year 7 but not sooner. Panel 3 of Figure 3 presents levelized costs associated with different years of entry for different rates of adoption of hydrogen vehicles. The same $3.50 cost of distributed production is shown on the graph, and it can be seen that the adoption rate underlying Panels 1 and 2 are the benchmark rate shown in Panel 3. With very rapid adoption, centrally produced hydrogen would always be cheaper than distributed. Panel 4 reports the first profitable entry year of centralized production for combinations of vehicle adoption rates and the distributed hydrogen cost. At distributed production costs below $3.19/kg, centralized production is never profitable, and at distributed costs above $7.56/kg, it is always profitable to enter in the first year of transition. These exact numbers remain preliminary and may change somewhat with further modifications to particular features of the model.

Figure 4 reports sensitivity analysis of hydrogen vehicle penetration to the capital cost of the distributed SMR facility. The most important conclusion emerging from this set of simulations is that the market penetration of hydrogen vehicles is not highly sensitive to a 3-fold variation in this cost.

Consequences of the satisficing behavior of the investor agent also appear in the market penetration curves of Figure 4. The share of hydrogen vehicles in new vehicle sales does not increase smoothly, but occasionally falls below its level in a previous year, only to recover in subsequent years. Experimentation indicates that this is a result of the investor agent using a rule of thumb in siting stations which assumes

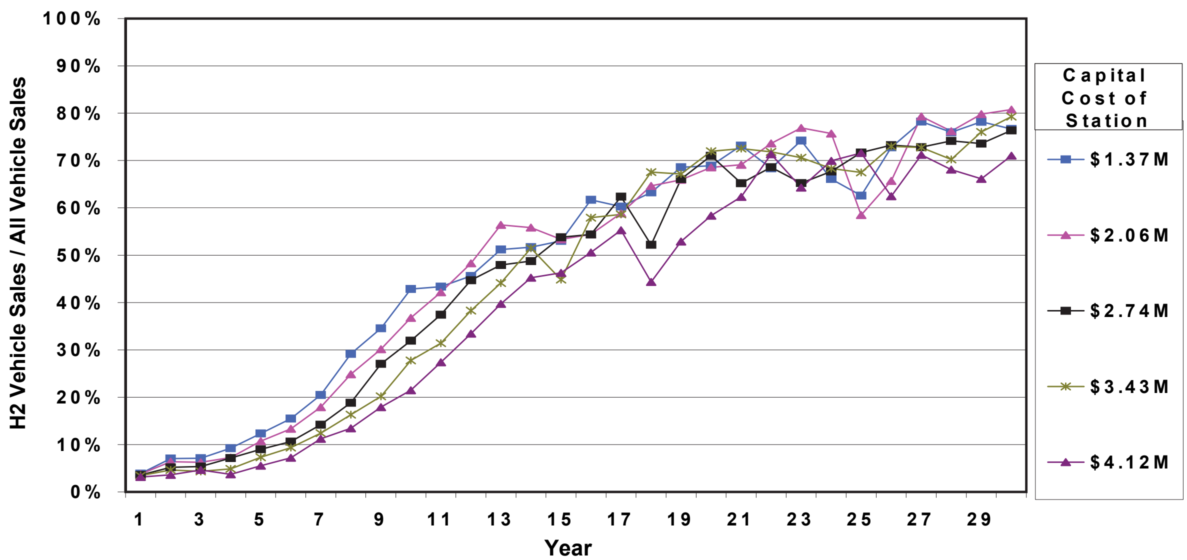




(4) Year of Centralized Entry is Lowered By Higher Distributed Price

Distributed Price	Vehicle Adoption Rate: Very Slow	Slow	Benchmark	Rapid	Very Rapid
>$7.56	1	1	1	1	1
$5.50	6	2	1	1	1
$3.50	**14**	**10**	**7**	**4**	**1**
<$3.19	-	-	-	-	-

FIGURE 3. Entry of Centralized Hydrogen Production



Scenario	Capital Cost of Station	Percent market share by 5th year	10th year	20th year	30th year
Highest Penetration	$1.37M	12.3%	42.9%	68.9	76.7%
Middle Penetration	$2.74M	9.0%	31.9%	71.0%	76.4%
Lowest Penetration	$4.12M	5.5%	21.5%	58.4%	71.0%

FIGURE 4. Sensitivity of Market Penetration to Capital Cost of Distributed Hydrogen SMR Station

that driver agents patronizing their stations in the current period will remain loyal to that station when new stations are located. Driver agents, however, are not loyal to stations, instead patronizing the most convenient, which may not be the same stations they patronized in previous periods. This rule of thumb results in non-optimal station location which in turn results in some periods of temporary retreat in the hydrogen share of new vehicle sales. Experimentation shows that this non-optimizing behavior on the part of the investor agent has substantial impacts on the rate of market penetration of hydrogen vehicles.

Conclusions and Future Directions

- Continued development of an ABM for understanding the dynamics between adoption of hydrogen vehicles and provision of fueling infrastructure with focus on spatial heterogeneity in the density of demand for hydrogen vehicles.
- Calibrated the model to the Los Angeles Metropolitan Area
  - Simulated the model to obtain results concerning
    - market share of hydrogen vehicles,
    - vehicle stock share of hydrogen vehicles,
    - rate of growth of hydrogen demand, and
    - date of entry of centralized production.
- Tested the sensitivity of the model results to the following model inputs:
  - Factors influencing demand for hydrogen vehicles such as
    - price of the vehicle,
    - vehicle subsidy,
    - strength of the imitation effect, and
    - strength of the innovation effect.
  - Supply side factors such as:
    - Risk aversion of the investor agent.
    - Learning behavior and updating of investor agent's expectations of hydrogen demand growth.
- Model the organization of the investor market (expand the number of investors) (Fiscal Year 2008).
- Experiment with additional business decision algorithms (FY 2009).
- Allow investor agents to have different technology (capital) access (FY 2009).
- Complete the modeling of upper management decisions for the investor agent (FY 2009).
- Assemble a peer review team (FY 2009).
- Complete the project final report (FY 2009).

FY 2008 Publications/Presentations

1. Stephan, C., M. Mahalik, T. Veselka, and G. Conzelmann, *Modeling the Transition to a Hydrogen-based Personal Transportation System*, Proceedings of the Conference. Frontiers in Transportation; Social Interactions, Amsterdam, Netherlands (October 14-16, 2007).

2. Mahalik, M., G. Conzelmann, C. Stephan, M. Mintz, T. Veselka, G. Tolley and D. Jones, *Modeling the Transition to Hydrogen-based Transportation*, Proceedings of the AGENT 2007 Conference on Complex Interaction and Social Emergence, Evanston, IL (November 15-17, 2007).

3. Mahalik, M., G. Conzelmann, C. Stephan, M. Mintz, T. Veselka, G. Tolley, and D. Jones, *Transition to Hydrogen Transportation Economy*, Poster presentation at the National Hydrogen Association Annual Conference: Ramping up Commercialization, Sacramento, CA (March 30 – April 3, 2008).