VIII.3 Analysis of the Hydrogen Production and Delivery Infrastructure as a Complex Adaptive System

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- University of Michigan, Ann Arbor, MI
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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 an 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)

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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 project began as a 3-year project, with preliminary model results due in the second year, but the project was re-oriented before it began; its 1st-year budget was reduced by nearly 60 percent, and initial funding was delayed. 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 agent-based model (ABM) for detailed simulations in the project's second year. Work in the second year was delayed by a continuing resolution, which restricted staffing.

Results

Operational Prototype Model. A prototype model was made operational, using a geographical information system (GIS) 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. Distributed hydrogen production is modeled with investor agents, who make investments in 1,500 kg/d stations 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.

Driver Agents. Driver agents compare the utility of buying hydrogen vehicles with the alternative. Only driver agents whose vehicles are 10 years old buy a new vehicle, hydrogen or otherwise. The following factors influence the purchase decision of a driver agent:

1. *Fixed Benefits*: Vehicle price and other benefits of owning hydrogen vehicle over the alternative. These benefits do not vary with the intensity of use of vehicles (vehicle miles).
2. *Variable Benefits*: Fuel cost per mile and other benefits/costs that vary with travel.
3. *Fueling convenience:* Influenced by the density of fueling stations, especially, in the neighborhood of the driver.
4. *Imitation or bandwagon effects*: Buyers are influenced by what their neighbors do, but word of a new innovation and confidence in its reliability take some time to spread.

Investor Agent. The investor agent installs fueling capacity (fueling stations) in anticipation of demand. If the investor is risk neutral, he continues to add new capacity at each location until the expected revenue contribution of the last unit of capacity added falls to the cost of adding capacity. If the investor is risk averse, he continues to add capacity until the revenue contribution of the last unit of capacity falls to the utility-weighted cost of capacity, where utility weights decrease in the realization of demand but are always greater than one for a risk-averse investor.

To determine the desired number of new stations, the investor agent takes the following series of actions in each period:

1. First, observing the past growth in demand for hydrogen vehicles, the investor agent revises his expectations regarding future growth in demand. Using these revised expectations, he updates his prior estimates of the parameters that characterize the likely demand for hydrogen vehicles. This updating follows the principles of maximum likelihood estimation and Bayesian updating.
2. Based on the revised stochastic demand function for hydrogen vehicles and the existing stock of hydrogen vehicles, the investor agent infers the distribution of possible demand for hydrogen fuel.
3. Based on this expected distribution of demand for hydrogen fuel, and on economic parameters such as cost of installing fueling capacity, price of feedstock, and the price of fuel, the investor agent decides on his best choice of a target capacity for fueling at each location.
   – Determination of target capacity is only boundedly rational since the investor agent does not consider the entire solution space. Rather he makes his decisions heuristically, laying disproportionate emphasis on the immediate future.
   – If the investor agent is not risk neutral, the relationship between the target capacity and expected distribution of demand for fuel is mediated by his utility function and risk aversion.
4. The investor agent calculates the difference between the target capacity at each location, and the existing capacity. The number of *new* stations at

each location augments the total capacity to target capacity at that location.

Preliminary Simulation Results. The model was tested for sensitivity to key parameter values and several policies were simulated. Two parameters in the driver agent's utility function that affect adoption reflect (1) the speed of individuals' learning about the new technology, independently of what others do, and (2) the influence of what others do, called the bandwagon effect. Preliminary simulations suggest that the speed of individual learning affects the path of hydrogen vehicle adoption but does not greatly influence the level of adoption by 2038 (Figure 1). Other preliminary simulations (Figure 2) suggest that the bandwagon effect may be considerably more influential on ultimate adoption levels rather than just the path.

Two policies were investigated in preliminary simulations. First, adoption of hydrogen vehicles was found to take a steadier and more rapid path with more seed stations, while the provision of fewer seed stations led to adoption that begins very slowly but ultimately reaches the same levels. While the ultimate result is the same, the path differs immensely because more seed stations cause more adoption in the initial years, providing investors more information about the viability of the hydrogen economy early on. A preliminary simulation (Figure 3) shows that when there are five seed stations, hydrogen acquires 9% market share by 2027, while with 20 seed stations it gains 53% by that time, and 68% if there are 50 stations. By 2038 all these paths converge and five, 20, and 50 seed stations lead to 74%, 97% and 98% market share, respectively.

The second policy simulation investigates the impact of implementing, then discontinuing, a tax credit on hydrogen vehicle purchases. Figure 4 compares the effect on the share of hydrogen vehicles in the total light duty vehicle stock of a $6,000 tax credit which is discontinued in 2029 with a base case that offers no subsidy. The subsidy substantially increases the speed of adoption of hydrogen vehicles, and the elimination of the subsidy causes a distinct drop in their adoption, although the hydrogen share continues to rise beyond 2029.

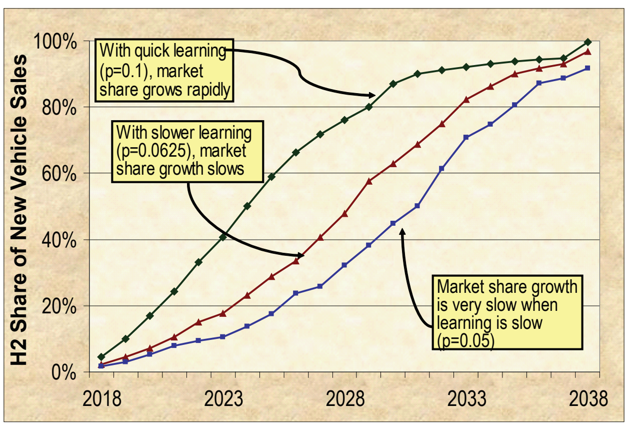

FIGURE 1. Parameter Sensitivity: Consumer Learning Behavior Affects Adoption

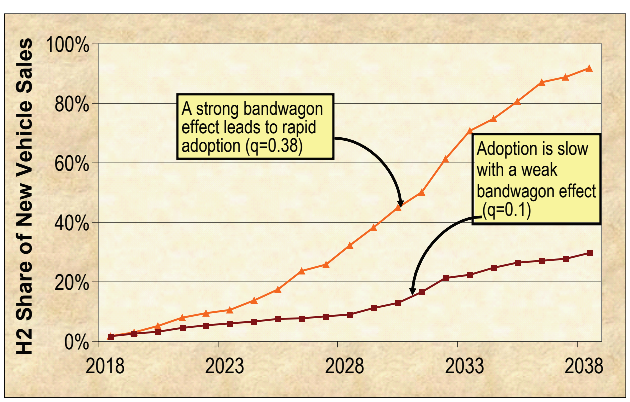

FIGURE 2. Parameter Sensitivity: Stronger Bandwagon Effect Speeds Up Adoption

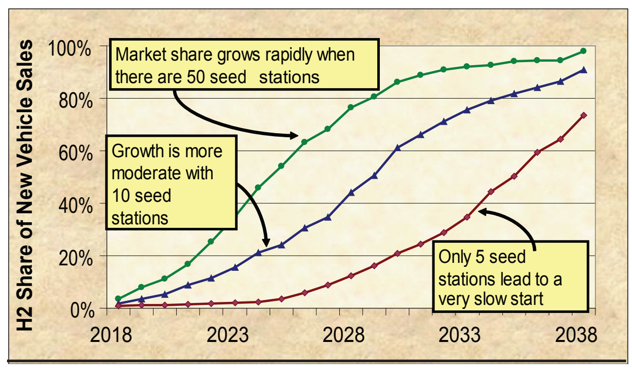

FIGURE 3. Policy Analysis: More Seed Stations Accelerate Adoption

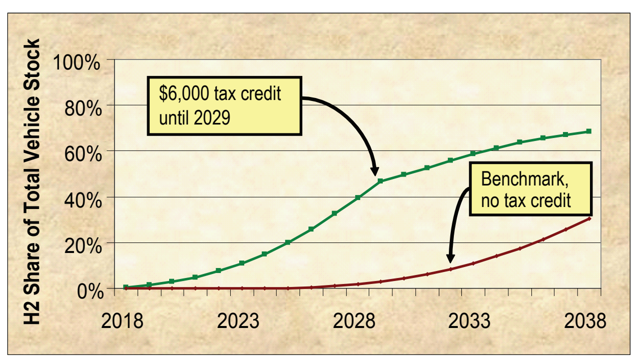

FIGURE 4. Policy Analysis: Tax Credit in Early Years Enables Take-off if Initial Market Conditions are Unfavorable

Conclusions and Future Directions

- Developed a prototype/preliminary model 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 Los Angeles Metropolitan Area
  - Simulated the model to obtain results concerning
    - market share of hydrogen vehicles,
    - vehicle stock share of hydrogen vehicles, and
    - number and location of hydrogen fueling stations in the LA area over the first twenty years of transition (2018-2038).
- 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
    - Pilot programs (number of exogenous filling stations)
- Based on preliminary results, spatial effects as well as imitation effects cause subsidies and seed stations in early years to have a large influence on the path of adoption if not the ultimate market share.
- Introduce the possibility of capital loss. (FY08)
- Introduce centralized production. (FY08)
- Model the organization of the investor market (expand the number of investors). (FY08)
- Develop a preliminary model of a vehicle manufacturing agent. (FY08)
- Experiment with additional business decision algorithms. (FY08)
- Internalize stranded asset analysis. (FY08)
- Allow investor agents to have different technology (capital) access. (FY08)

FY 2007 Publications/Presentations

1. A presentation on the full scope of the project, with results to date, was given at the FPITT meeting (November 2006).

2. A presentation on the full scope of the project, with results to date, was given at the DOE Annual Merit Review Meeting (May 2007).

3. A presentation on the full scope of the project, with results to date, was given at an FPITT meeting at BP's Naperville campus (June 14, 2007).