Global Assessment of Hydrogen Technologies
DE-FC36-02GO12042

Executive Summary
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Fouad H. Fouad, Ph.D., P.E., Principal Investigator
Robert W. Peters, Ph.D., P.E.
Virginia P. Sisiopiku, Ph.D.
Andrew J. Sullivan, P.E.

University of Alabama at Birmingham
1075 13th Street South
Birmingham, Alabama 35294

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EXECUTIVE SUMMARY

This project was a collaborative effort involving researchers from the University of Alabama at Birmingham (UAB) and Argonne National Laboratory (ANL), drawing on the experience and expertise of both research organizations. The goal of this study was to assess selected hydrogen technologies for potential application to transportation and power generation. Specifically, this study evaluated scenarios for deploying hydrogen technologies and infrastructure in the Southeast.

One study objective was to identify the most promising near-term and long-term hydrogen vehicle technologies based on performance, efficiency, and emissions profiles and compare them to traditional vehicle technologies. Hydrogen vehicle propulsion may take many forms, ranging from hydrogen or hythane fueled internal combustion engines (ICEs) to fuel cells and fuel cell hybrid systems. This study attempted to developed performance and emissions profiles for each type (assuming a light duty truck platform) so that effective deployment strategies can be developed.

A second study objective was to perform similar cost, efficiency, and emissions analysis related to hydrogen infrastructure deployment in the Southeast. There will be many alternative approaches for the deployment of hydrogen fueling infrastructure, ranging from distributed hydrogen production to centralized production, with a similar range of delivery options. This study attempted to assess the costs and potential emissions associated with each scenario.

A third objective was to assess the feasibility of using hydrogen fuel cell technologies for stationary power generation and to identify the advantages and limits of different technologies. Specific attention was given to evaluating different fuel cell membrane types. A final objective was to promote the use and deployment of hydrogen technologies in the Southeast. This effort was to include establishing partnerships with industry as well promoting educational and outreach efforts to public service providers.

To accomplish these goals and objectives a work plan was developed comprising 6 primary tasks:

- **Task 1 - Technology Evaluation of Hydrogen Light-Duty Vehicles –** The PSAT powertrain simulation software was used to evaluate candidate hydrogen-fueled vehicle technologies for near-term and long-term deployment in the Southeastern U.S. Four types of hydrogen-fueled vehicles were assessed: 1) hythane-fueled internal combustion engines (ICEs), 2) hydrogen-fueled ICEs, 3) hydrogen-fueled hybrid electric propulsion vehicles, and 4) direct propulsion hydrogen fuel cell vehicles. Vehicles were evaluated for efficiency, performance, and emissions over a range of standard driving cycles. Emissions and efficiency profiles were developed for each.

- **Task 2 - Comparison of Performance and Emissions from Near-Term Hydrogen Fueled Light Duty Vehicles -** An investigation was conducted into the emissions and efficiency of light-duty internal combustion engines fueled with hydrogen and compressed natural gas (CNG) blends. The different fuel blends used in this investigation were 0%, 15%, 30%, 50%, 80%, 95%, and ~100% hydrogen, the remainder being compressed natural gas. The blends were tested using a Ford F-150 and a Chevrolet Silverado truck on the Argonne National Laboratory dynamometer. Tests on emissions were performed using four different driving cycles

- **Task 3 - Economic and Energy Analysis of Hydrogen Production and Delivery Options -** Expertise in engineering cost estimation, hydrogen production and delivery analysis, and transportation infrastructure systems was used to develop regional estimates of resource requirements and costs for the infrastructure needed to deliver hydrogen fuels to advanced-technology vehicles. Data on applicable resources, cost structures and infrastructure in the region was compiled and used to characterize the existing Southeastern US transportation energy infrastructure. These characterizations were input into DOE's H2A models to develop case studies of select Alabama metropolitan areas which estimated the delivered cost of hydrogen fuel to select markets under alternative assumptions about production and delivery technologies. Existing codes and standards for hydrogen fueling stations were also compiled as part of this effort.

- **Task 4 –Emissions Analysis for Hydrogen Production and Delivery Options -** The hydrogen production and delivery scenarios developed in Task 3 were expanded to include analysis of energy and greenhouse gas emissions associated with each specific case studies. Energy estimates were broken down into fossil and non-fossil fuels. Emissions estimates included CO_2, N_2O and CH_4. Because of the interrelated nature of the task scopes, Tasks 3 and 4 were combined into a single final report.

- **Task 5 – Use of Fuel Cell Technology in Power Generation -** The purpose of this task was to assess the performance of different fuel cell types (specifically low-temperature and high temperature membranes) for use in stationary power generation. Operating characteristics for each type were evaluated and strengths and weaknesses of each type identified. Also evaluated were the impacts of different parameters on fuel cell performance, such as water-to-carbon ratio, carbon formation, hydrogen formation, efficiencies, methane formation, fuel and oxidant utilization, sulfur reduction, and the thermal efficiency/electrical efficiency relationship. Finally, this task reviewed associated green house gas emissions and life cycle properties of fuel cells.

- **Task 6 – Establishment of a Southeastern Hydrogen Consortium -** The goal of this task was to establish a Southeastern Hydrogen Technology Consortium (SHTC) whose purpose would be to promote the deployment of hydrogen technologies and infrastructure in the Southeast. To achieve this goal UAB partnered with the Center for Transportation and the Environment (CTE) and the Southern Fuel Cell Coalition (SFCC), two existing organizations whose missions are to promote hydrogen technologies in the Southeast. Through this partnership UAB was able to assist in the promotion of hydrogen technologies and create opportunities to disseminate the research performed under this study.

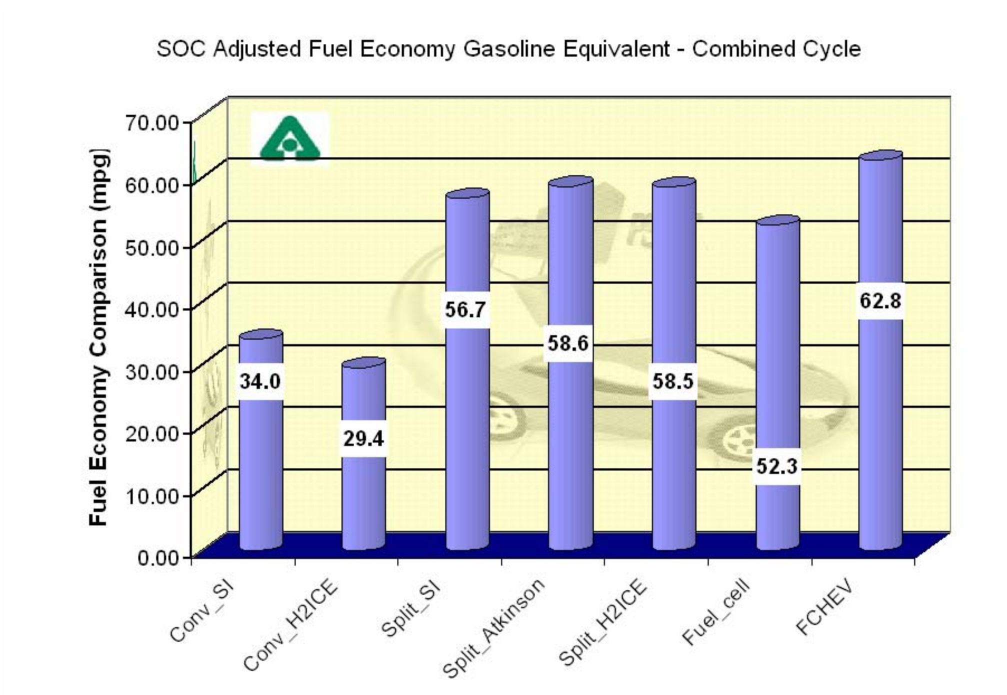
This research program concluded in November 2007. Final Reports have been prepared for each of the project tasks. Following is a brief summary of key findings for each project task.

Task 1. Technology Evaluation of Hydrogen Light-Duty Vehicles

This task analyzed the efficiency and performance of several near-term and long-term hydrogen vehicle technologies. The analysis used the Powertrain System Analysis Toolkit (PSAT) software to compare the performance and efficiency of conventional hybrid electric vehicles (HEV) with gasoline and hydrogen-fueled internal combustion engines (ICEs) as well as fuel cell and fuel cell hybrid vehicles.

The hydrogen-fueled ICE, fuel cell hybrid, and fuel cell vehicles were modeled and simulated using Argonne's vehicle simulation model PSAT. Vehicle sizes and configurations consistent with the available component models/data were simulated to compare efficiency and emissions with baseline conventional vehicles. The simulations provided detailed results on the vehicle characteristics, performance, efficiency, and emissions profiles as functions of operating conditions over standard driving cycles.

The results of the fuel economy analysis are illustrated below for different vehicle configurations using the combined driving cycle (UDDS and FHDS). The analysis indicated that substantial gains can be achieved through hybridization both for conventional and fuel cell vehicles. The hybrid fuel cell configuration combines high fuel-cell-system efficiency and regenerative braking to achieve the highest fuel economy (62.8 mpg). However, it is important to note that, based on current technologies, ICE HEVs achieve higher fuel economy than fuel cell configurations.



In addition, the analysis found that current hydrogen ICE technology would require hybridization to be competitive with gasoline ICEs due to a lower power density. In fact, compared to conventional vehicles, hydrogen ICEs achieve not only lower fuel economy but also have slower acceleration. When hybridized, hydrogen ICE configurations achieve comparable fuel economies to their gasoline counterparts. Consequently, they can be viewed as a bridge to a future large-scale hydrogen vehicle deployment.

The parametric study also allowed the researchers to evaluate the fuel economy uncertainties related to various vehicle design characteristics, such as vehicle mass, wheel radius, final drive ratio, drag coefficient, and rolling resistance. Based on research under FreedomCAR initiatives, fuel cell hybrid vehicles are expected to provide even greater fuel economy than their internal combustion engine counterparts. However, because of lack of hydrogen infrastructure, the hydrogen ICE should be considered as an intermediate step toward creating a hydrogen economy.

Task 2. Comparison of Performance and Emissions from Near-Term Hydrogen Fueled Light Duty Vehicles

An investigation was conducted into the emissions and efficiencies of light duty ICE vehicles fueled with hydrogen and compressed natural gas (CNG) blends. The different blends used in this investigation were 0%, 15%, 30%, 50%, 80%, 95%, and ~100% hydrogen, with the remainder being compressed natural gas. The blends were tested using a Ford F-150 and a Chevrolet Silverado truck supplied by Arizona Public Services. Tests on emissions were performed using four different driving cycles.

Statistical analysis was performed on the test results to determine the extent to which hydrogen concentration in the H/CNG (hythane) affected vehicle emissions and fuel efficiency. It was found that emissions from hydrogen blended with compressed natural gas were a function of the driving cycle employed. Emissions were also found to be dependent on the concentration of hydrogen in the compressed natural gas fuel blend.

Results from the testing indicated the following:

- Hydrogen rich hydrogen-methane blends show combustion behavior similar to pure hydrogen.

- Due to the lower combustion speed of methane compared to hydrogen, the ignition spark timing has to be advanced with increased amounts of methane in the blend.
- Different gas properties of methane require adjustment of injection duration in order to achieve the same engine load. A curve that shows the necessary adjustments was developed.

- The NO_x emissions behavior of pure hydrogen compared to hydrogen rich hydrogen methane blends shows the same trends. Due to the lower combustion speed, the absolute level of emissions is slightly lower with increased amounts of methane.

- The amount of unburned methane compared to hydrogen in the exhaust is higher relative to the composition of the feed fuel. This is due to the fact that hydrogen has a shorter quenching distance than methane and thus allows for a more complete combustion close to the combustion chamber walls.

- Overall, only minor adjustments should be necessary in order to run an engine calibrated and tuned for operation on pure hydrogen on hydrogen rich hydrogen methane blends.

- There is no consistent trend in emissions or efficiency with respect to either the hydrogen concentration or the driving cycles.

- The carbon dioxide emissions decreased with an increase in hydrogen concentration in the CNG. This trend was consistent across all the driving cycles. For example, for the CSFTP cycle, the CO_2 emissions from the 50% blend were about 15.65% less than for the 0% blend.

- The nitrogen oxide emissions increased by 51% when the hydrogen concentration in the CNG blend increased from 0% to 30%. However, the nitrogen oxide emissions for the HWFET and CSFTP cycles for 50% hydrogen blend showed some inconsistencies.

- The hydrogen concentration in the CNG blend did not have a substantial effect on the fuel efficiency (EQMPG) and the total hydrocarbon emissions for all the driving cycles.

- In summary, emissions and efficiency were a function of driving conditions and the concentration of hydrogen in the compressed natural gas.

- NO_x emissions were not zero, but were low for all the high hydrogen content fuel blends.

- As the percentage of natural gas increased to ~20%, the fuel economy decreased. This is due to the fact that methane has a lower heating value than hydrogen.
- Since there is no carbon in the pure hydrogen fuel, the carbon containing species are likely to come from the lubricating oil.

- One of the most important lessons learned from these tests on the Ford F-150 and the Chevrolet Silverado, is that to save fuel and minimize emissions, air conditioning should not be used.

Tasks 3 & 4. Economic, Energy, and Emissions Analysis of Hydrogen Production and Delivery Options

Argonne National Laboratory performed an analysis of likely scenarios for producing, storing, delivering, and dispensing hydrogen for use as a motor vehicle fuel in Alabama. This analysis assessed the costs and energy requirements associated with a large-scale deployment of hydrogen infrastructure in the state. UAB provided a summary of current codes and standards related to producing, delivering, and dispensing hydrogen as a motor vehicle fuel and a preliminary assessment of the requirements for a demonstration hydrogen fueling station in the Birmingham area.

The task report documents a set of case studies developed to estimate the cost of producing, storing, delivering, and dispensing hydrogen for several scenarios involving metropolitan areas in Alabama. While the majority of the scenarios focused on centralized hydrogen production and pipeline delivery, alternative delivery modes were also examined. Although Alabama was used as the case study for this analysis, the results provide insights into the unique requirements for deploying hydrogen infrastructure in smaller urban and rural environments that lie outside the DOE's high priority hydrogen deployment regions.

Hydrogen production costs were estimated for three technologies – steam-methane reforming (SMR), coal gasification, and thermochemical water-splitting using advanced nuclear reactors. In all cases examined, SMR has the lowest production cost for the demands associated with metropolitan areas in Alabama. Although other production options may be less costly for larger hydrogen markets, these were not examined within the context of the case studies.

Given the effect of economies of scale on capital-intensive production facilities, scenarios involving a single production facility supplying multiple metropolitan markets tend to produce the lowest production costs. However, such reductions should be examined on a case-by-case basis as increased transport distances (i.e. increased delivery costs) can result when production facilities serve combined markets.

In all cases considered in this analysis, hydrogen delivery via pipeline is less costly than delivery by either compressed gaseous tank truck or cryogenic liquid tank truck.

Hydrogen production at distributed locations (i.e. at refueling stations) has the potential to supply lower-cost hydrogen to relatively small markets like those associated with relatively low, early market penetration in Alabama metropolitan areas. However, distributed production is likely to have site-specific impacts on infrastructure costs (e.g., for additional pipelines to supply natural gas feedstock or for additional power lines to supply higher voltages at refueling stations). Those costs are not included in the generic models exercised for this analysis. Since infrastructure costs could significantly increase the final cost of hydrogen, they should be considered in any detailed comparison of central station versus distributed hydrogen production.

Energy efficiencies and greenhouse gas (GHG) emissions were also estimated for the scenarios considered in this analysis. Generally, for a given production or delivery technology, energy use (per kg of hydrogen) is only a weak function of market size. The same is true for GHG emissions. An exception to these generalities occurs in scenarios involving hydrogen liquefaction. In these cases, overall system efficiency is a strong function of equipment size, and larger markets (e.g., Birmingham) have a lower energy requirement (per kg of hydrogen) and lower GHG emissions than smaller markets (e.g., Montgomery).

Pipeline and gaseous truck delivery options have comparable energy efficiencies and GHG emissions. These are significantly less than those for liquid truck delivery. The liquefier itself accounts for the increased energy and GHG emissions for that delivery option.

Among centralized production options, SMR and coal gasification have high energy demands (principally due to upstream activities associated with producing the fossil fuels) and GHG emissions, while the nuclear production pathway is the most favorable from both an energy use and a GHG emissions perspective. Note that this analysis did not consider carbon capture and sequestration which would lower GHG emissions but significantly increase energy requirements and the overall cost of hydrogen for fossil fuel-based production technologies.

Section II of this report presents a summary of current codes and standards related to the design, construction, and operation of hydrogen fueling stations. The codes and standards documented in this report summarize the current state of the practice, although many codes related to hydrogen fueling stations are still in development. This section also presents preliminary specifications for a demonstration hydrogen fueling station to be built in Birmingham, Alabama.

Finally, Appendix B presents an analysis prepared by Dr. Marc Melaina of data on gasoline station networks in five southeastern urban areas: Birmingham, AL (1999), Nashville, TN (1995 and 2003), Owensboro, KY (2003), Gulfport-Biloxi, MS (2003) and Hattiesburg, MS (2003). The study attempts to identify patterns within these station networks that can be generalized to urban areas in general, with the goal of providing useful inputs for models of future hydrogen fueling station networks.

Task 5. Use of Fuel Cell Technology in Power Generation

The purpose of this task was to assess the performance of different fuel cell types (specifically low-temperature and high temperature membrane fuel cells) for use in stationary power generation. Operating characteristics for each type were evaluated and strengths and weaknesses of each type identified. Also evaluated were the impacts of different parameters on fuel cell performance, such as water-to-carbon ratio, carbon formation, hydrogen formation, efficiencies, methane formation, fuel and oxidant utilization, sulfur reduction, and the thermal efficiency/electrical efficiency relationship.

A 250 KW PEM fuel cell model was simulated [in conjunction with Argonne National Laboratory (ANL) with the help of the fuel cell computer software model (GCtool)] which would be used to produce power of 250 kW and also produce steam at 120^{o}C that can be used for industrial applications. The performance of the system was examined by estimating the various electrical and thermal efficiencies achievable, and by assessing the effect of supply water temperature, process water temperature, and pressure on thermal performance. It was concluded that increasing the fuel utilization increases the electrical efficiency but decreases the thermal efficiency.

The research examined both low temperature and high temperature membrane fuel cells and assessed their suitability for use in stationary power generation. Polymer electrolyte membrane (PEM) fuel cells operate at relatively low temperatures, around 70^{o}C. Low temperature operation allows them to start quickly (less warm-up time) and results in less wear on system components, resulting in better durability. The PEM system also allows compact designs and achieves a high energy-to-weight ratio. The limitations of the PEM system are high manufacturing costs and complex water management issues.

High-temperature solid-polymer electrolyte membranes capable of operating at 150-200°C are at an early stage of development. These are being encouraged as alternatives to Nafion-based solid-polymer electrolyte membranes that operate at less than 90°C. An advantage of operating at higher temperatures is the reduced sensitivity of the electrocatalyst to carbon monoxide in the anode stream. Reduced CO sensitivity and higher temperature operation may make it possible to lower the loading of anode and cathode catalysts. In addition, the reduction in overpotentials at higher temperatures can potentially lead to improvement in current density and a lighter, more compact stack. Specific weight and volume of PEFC stacks are of concern when dealing with Nafion-based membranes. On the whole, high temperature membranes offer the following advantages over low temperature ones: a higher resistance to carbon monoxide from reformed hydrogen gas, cost-effective water management within the cell, a higher operating temperature leads to more efficient use of heat for household and commercial use, and elimination of the PROX reactor reduces the cost and the weight of the fuel processor and the entire fuel cell system.

Additional conclusions from the analysis include:

- Fuel processor efficiencies are slightly affected by reducing the electrochemical fuel utilization below 85% in the fuel cell stack. However the total system efficiency is reduced significantly by lowering the fuel utilization.

- The total water to carbon that can be used in the fuel processing subsystem is strongly affected by the autothermal reforming temperature. Increasing the reforming temperature increases the amount of water that can be used in the fuel processor.

- Use of thermal energy from the fuel cell stack exhaust burner in the fuel processing subsystem permits the use of larger amounts of water in fuel processing. This is due to the increase of the total thermal energy available to heat the process water.

- The analyses indicate the potential for increased fuel processor and fuel cell system efficiencies if more active catalysts can be developed for lower temperature operation. With such catalysts it might be possible to suppress or reduce methane formation. This could lead to a higher content of hydrogen and a better fuel processor performance.

- The results for the overall system performance are also subject to several assumptions such as the average cell operating voltage in the fuel cell stack, fuel and oxidant utilizations, and the efficiencies of the compressors and expander and of the various pumps, blowers and fans, radiator and condenser that are used in the balance of plant in the fuel cell system. Changes in those assumptions would affect the actual system efficiencies attained.

The environmental impacts of fuel cell use depend upon the source of the hydrogen rich fuel used. This final task report presents an overview of the green house gas emissions, briefly looking in to the life cycle assessment of fuel cells. The report also looks into some of the newer emission-free reformers for fuel cells. Atmospheric impacts of hydrogen are summarized along with some of the methods adopted to remove contaminants from fuel cells.

Task 6. Establishment of a Southeastern Hydrogen Consortium

The purpose of this project task was to establish a technical consortium to promote the deployment of hydrogen technologies and infrastructure in the Southeast. The goal was to partner with fuel cell manufacturers, hydrogen fuel infrastructure providers, electric utilities, energy service companies, research institutions, and user groups to explore opportunities for research and deployment projects and to improve education and awareness of hydrogen technologies in an area that may be lagging behind other parts of the country in terms of vehicle and infrastructure demonstrations and deployments.

When the University of Alabama at Birmingham (UAB) began investigating opportunities to establish a Southeast Hydrogen Consortium it soon identified a similar effort underway in Atlanta. The Center for Transportation and the Environment (CTE) and its sister organization the Southern Fuel Cell Coalition (SFCC) have goals similar to those identified in the scope for this project. Rather than duplicate efforts and possibly fragment resources, UAB decided to join forces with CTE and the SFCC to promote hydrogen technologies in the Southeast.

Through this partnership with CTE, UAB was able to offer the following outreach activities:

- Co-sponsor the 2006 *Generation FC Conference* in Atlanta. This conference explored the status of hydrogen demonstrations in the Southeast and explored opportunities for future projects.

- Present findings of this research program to industry and key stakeholders in the Southeast.

- Present findings of this research program to various technical and non-technical audiences.

- Involve students in the program research. Three masters theses were developed through research on this program.

- Present or publish over 22 papers and presentations highlighting work by program researchers.

- Make presentations to high school students on the possibilities of a future hydrogen economy as well as technical roadblocks to success.

UAB's partnership with CTE and SFCC will continue after this project. A complete summary of outreach activities conducted under this program is presented in the task final report.