

# A System-of-Systems Framework for the Future Hydrogen-Based Transportation Economy

## Preprint

Michael Duffy and Debra Sandor

*To be presented at the 2008 INCOSE International Symposium  
The Netherlands  
June 15–19, 2008*

**Conference Paper**  
**NREL/CP-150-42989**  
**June 2008**

NREL is operated by Midwest Research Institute • Battelle Contract No. DE-AC36-99-GO10337



## NOTICE

The submitted manuscript has been offered by an employee of the Midwest Research Institute (MRI), a contractor of the US Government under Contract No. DE-AC36-99GO10337. Accordingly, the US Government and MRI retain a nonexclusive royalty-free license to publish or reproduce the published form of this contribution, or allow others to do so, for US Government purposes.

This report was prepared as an account of work sponsored by an agency of the United States government. Neither the United States government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States government or any agency thereof.

Available electronically at <http://www.osti.gov/bridge>

Available for a processing fee to U.S. Department of Energy and its contractors, in paper, from:

U.S. Department of Energy  
Office of Scientific and Technical Information  
P.O. Box 62  
Oak Ridge, TN 37831-0062  
phone: 865.576.8401  
fax: 865.576.5728  
email: <mailto:reports@adonis.osti.gov>

Available for sale to the public, in paper, from:

U.S. Department of Commerce  
National Technical Information Service  
5285 Port Royal Road  
Springfield, VA 22161  
phone: 800.553.6847  
fax: 703.605.6900  
email: [orders@ntis.fedworld.gov](mailto:orders@ntis.fedworld.gov)  
online ordering: <http://www.ntis.gov/ordering.htm>



# A System-of-Systems Framework for the Future Hydrogen-Based Transportation Economy

Michael Duffy, PhD  
National Renewable Energy Laboratory  
1617 Cole Boulevard, MS-1722  
Golden, CO 80401-3393  
303-275-3022  
michael\_duffy@nrel.gov

Debra Sandor, PMP  
National Renewable Energy Laboratory  
1617 Cole Boulevard, MS-1722  
Golden, CO 80401-3393  
303-275-3029  
debra\_sandor@nrel.gov

Copyright © 2008 by Midwest Research Institute. All Rights Reserved. This work is subject to Government rights. Used by INCOSE with permission for the 2008 INCOSE International Symposium, International Council on Systems Engineering.

**Abstract.** Today, almost 60% of the petroleum consumed in the United States is imported. The nation's current transportation system of systems (SoS) relies almost exclusively on refined petroleum products, accounting for over two-thirds of the oil used in the U.S. each day. As a nation, we must work to reduce our dependence on foreign sources of oil in a manner that is affordable, ensures national energy security and preserves environmental quality. In the long-term, a potential solution to the nation's transportation energy problems is an operational hydrogen-based transportation economy. Transitioning to any alternative transportation fuel on a national scale will require the creation of a robust and cost-effective system of systems that operates in concert with the dynamics of today's mature and highly-networked transportation infrastructure. Using a supply chain point-of-view to trace the flow of transportation fuels through the necessary SoS, this paper addresses the current petroleum-based economy for transportation, the U.S. Department of Energy's (DOE's) vision for a future hydrogen-based transportation economy and the significant challenges associated with such a massive market and infrastructure transformation.

## Introduction

Ready access to affordable oil is the cornerstone of the U.S. economy. In 2004, the U.S. consumed almost 21 million barrels of crude oil and refined products per day [AEO, 2006]. Approximately 60 percent of the U.S. demand was supplied by imports.[AEO, 2006] The transportation sector, which receives nearly all of its energy from petroleum products, accounts for two-thirds of U.S. petroleum use. As President Bush aptly noted in his 2006 State of the Union Address, "America is addicted to oil."; but U.S. demand continues to grow, with petroleum imports expected to top 26 million barrels per day by 2025. [AEO, 2006] In light of increasing worldwide oil demand, our increased reliance on imported sources of energy threatens our national security, economy and future competitiveness.

How this growing demand for energy is met poses one of the most complex and challenging systems engineering problems of our time. The current national energy dialogue reflects the challenge in simultaneously considering the social, political, economic, and environmental issues as the future desired transportation SoS is defined, necessary interim technological capabilities are established, and programs and investments are implemented to meet those capabilities.

## U.S. Government Goals

In 2003, President Bush announced the Hydrogen Fuel Initiative to reverse America's growing dependence on foreign oil by developing the technology needed for commercially-viable, hydrogen-powered fuel cells—a way to power cars, trucks, homes, and businesses that produces no pollution and no greenhouse gases. Through partnerships with the private sector, the President's Hydrogen Fuel Initiative seeks to develop hydrogen, fuel cell, and infrastructure technologies needed to make it practical and cost-effective for large numbers of Americans to choose to use fuel cell vehicles by 2020 (Whitehouse 2003).

In 2006, the President unveiled the Advanced Energy Initiative, which outlined significant new investments and policies to (1) accelerate deployment of efficient hybrid and clean diesel vehicles in the near-term, (2) develop domestic renewable alternatives to gasoline and diesel fuels in the mid-term, and (3) invest in the advanced battery and hydrogen fuel-cell technologies needed for substantial reductions in future oil demand. Together, these efforts will help the U.S. reach the President's long-term goal of replacing more than 75 percent of our oil imports from the Middle East by 2025 (Bush 2006).

Transitioning from our current petroleum-based transportation fuel economy to a future hydrogen-based transportation fuel economy that incorporates significant amounts of renewable energy can be characterized and addressed as a classical SoS problem. This paper provides a working definition of SoS used to frame the discussion; describes the current petroleum-based transportation SoS; presents the DOE's vision for a future hydrogen-based transportation SoS, and describes the systems engineering approach that is being used to bring this long-term vision into being.

## System of Systems Overview

While SoS has its roots in the established systems engineering discipline, as outlined in Table 1, addressing SoS goes beyond traditional systems engineering in a number of ways.

	System Engineering Perspective	System of Systems Engineering Perspective
<b>Scope</b>	Product/Product	Enterprise/Capability
	Autonomous/Well-bounded	Interdependent
<b>Objective</b>	Enable fulfillment of requirements	Enable evolving capability
	Structured project process	Guide integrated portfolio
<b>Time Frame</b>	System lifecycle	Multiple, interacting system lifecycles
	Discrete beginning and end	Amorphous beginning Important history and precursors
<b>Organization</b>	Unified and authoritative	Collaborative network
<b>Development</b>	Design follows requirements	Design is likely legacy-constrained
<b>Verification</b>	System in network context	Ensemble as a whole
	One time, final event	Continuous, iterative

Table 1. Differences Between Traditional Systems Engineering and System of Systems Engineering [SOSECE, 2007]

The field of SoS engineering is still emerging and the SoS community has not yet come to agreement upon a single commonly-accepted definition of SoS. As a starting point, the International Council on Systems Engineering (INCOSE) defines SoS as follows:

“System of systems applies to a system of interest whose system elements are themselves systems; typically these entail large-scale inter-disciplinary problems with multiple, heterogeneous, distributed systems.” [INCOSE, 2006]

A key aspect of SoS that is not called out in this definition is the importance of context in developing a desired physical capability. According to the System of Systems Center of Excellence, “SoS engineering addresses a complex system in terms of relationships, politics, operations, logistics, stakeholders, patterns, policies, training and doctrine, context, environment, conceptual frame, geography and boundaries.” [SOSECE, 2007] This broader definition is needed to characterize and transform the petroleum-based transportation SoS.

## Petroleum-Based Transportation System of Systems

Conceptually, the petroleum-based transportation SoS can be represented as shown in Figure 1 and described in terms of capability and context.

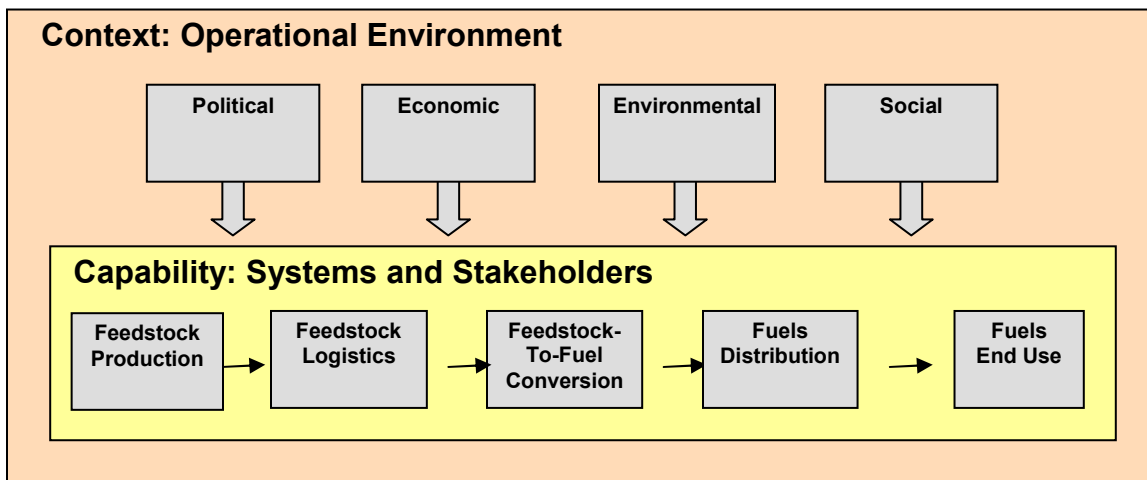


Figure 1. Transportation Fuel System of Systems

**Capability:** The physical systems and infrastructure included in the transportation SoS can be organized around five interdependent systems that comprise the feedstock-to-fuel supply chain. The primary objective of each system is described in the context of the existing transportation SoS, which moves crude oil from its source to the final processed fuel used by consumers, as illustrated in Figure 2.

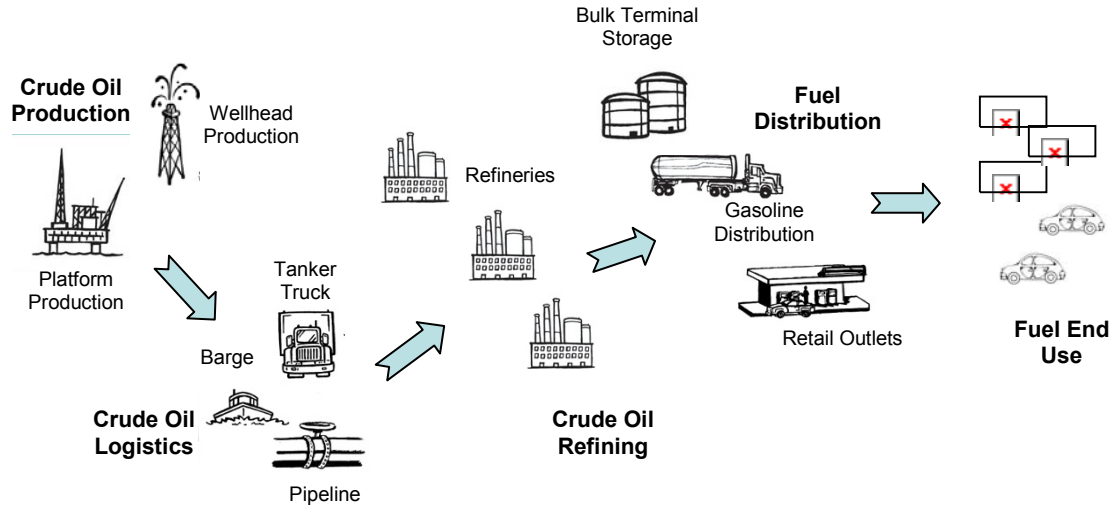


Figure 2. The Existing Petroleum-Based Transportation SoS

- **Feedstock Production System.** The objective of the feedstock production system is to produce large quantities of high-quality raw feedstock cost-effectively, efficiently and in compliance with applicable safety, environmental, etc. regulations. In the case of the current petroleum-based transportation SoS, this is all of the exploration and production infrastructure (e.g., drilling rigs, production platforms) required to extract crude oil from reserves around the globe.
- **Feedstock Logistics System.** The objective of the feedstock logistics system is to collect, store and transport raw feedstock from the production point to the fuel production facility. In the case of the current petroleum-based system, this includes all of the infrastructure required to move crude oil from the field to the refinery. The nation’s extensive network of petroleum transmission pipelines are the primary means of moving crude oil from oil fields on land and offshore to refineries where the oil is turned into fuels and other products. There are approximately 55,000 miles of crude oil trunk lines in the U.S. that connect regional markets.[Pipeline 101, 2007a] The crude oil logistics system also includes ports, storage tanks, barges and tankers depending on where the oil supply originates.
- **Feedstock-to-Fuel Conversion System.** The objective of the feedstock-to-fuel conversion system is to process raw feedstock into specification-compliant transportation fuel. In the case of the current petroleum-based system, this includes all of the infrastructure (e.g., reactors, distillation columns, etc.) required to operate a refinery. U.S. refining capacity stands at approximately 17 million barrels per day.[Petroleum Annual Supply, 2004] Refineries process the crude oil feedstock into gasoline, diesel fuel, heating oil, jet fuel, liquefied petroleum gases and other petroleum-based products. Gasoline, which represents nearly 45 percent of the domestic production of all refined products, is the petroleum product most demanded by U.S. consumers.[EIA, 2005]
- **Fuels Distribution System.** The objective of the fuels distribution system is to move transportation fuel from the refinery to the consumer point-of-use (i.e., the consumer’s

vehicle). In the case of the current petroleum-based system, this includes all of the infrastructure (e.g., pipelines, storage tanks, fuel dispensers) required to transport, store and dispense transportation fuel. There are approximately 95,000 miles nationwide of refined products pipelines, which move gasoline, diesel fuel and other petroleum products to consumer markets.[API, 2006]. The majority of gasoline is shipped by pipeline to bulk storage terminals near consuming areas. At these terminals the gasoline is loaded into tanker trucks and then delivered to one of the approximately 167,000 retail outlets in the U.S., where the gasoline is unloaded into the underground tanks at the gas station.[EIA, 2005]

- **Fuels End Use System (Vehicle).** The objective of the fuels end-use system is to provide high-performance, reliable, affordable and safe vehicles to consumers. In the case of the current petroleum-based transportation fuel system, this is all of the infrastructure (e.g., auto industry and supporting industries – rubber, computer chips, steel etc.) required to manufacture and distribute vehicles to consumers. In 2005, 12 million cars and commercial vehicles were produced in the U.S. [DOT, 2006a] In 2005, there were almost 250 million highway vehicles registered in the U.S. [DOT, 2006b]

**Context:** The transportation SoS must operate within the context of political, economic, social and environmental conditions that influence its physical domain. Together, these perspectives serve to define “the interrelated conditions which exemplify a system’s state of being and which describe its purpose, scope, and meaning for services it may offer.”[Polzer, et al., 2007] A brief description of each perspective with respect to the transportation SoS follows.

- **Political Context.** Government policies, incentives, laws and regulations have affected the transportation SoS for many decades. Global politics are, and will continue to be, a key consideration in the political operating environment, driven by the fact that over two-thirds of the world’s remaining global oil reserves lie in the Middle East.[Rifkin, 2002] Significant government incentives that directly support the U.S. petroleum based industry have been in place for years. For example, between 1968 and 2000, the petroleum industry received over \$150 billion dollars in tax breaks – for exploring for and producing petroleum within the U.S. through percentage depletion deductions, expensing of exploration and development costs and production of non-conventional fuels.[GAO, 2000] Since the 1970s, laws and regulations related to the transportation SoS have been primarily driven by increasing concerns for the environment, safety and energy efficiency (e.g., mandated vehicle emissions requirements and fleet average fuel economy standards).
- **Economic Context.** The transportation fuel SoS operates within a global marketplace. “Oil is the world economy’s most important source of energy and is, therefore, critical to economic growth.” With an estimated total value of between \$2 trillion and \$5 trillion, the petrochemical industry is the largest business in the world.[Rifkin, 2002] The automobile industry is also a major contributor to global and U.S. economies. In 2005, the total sales of automobiles were about 4% of the nation’s gross domestic product, equivalent to around \$500 billion dollars in sales. It is estimated that for every autoworker 7.5 jobs are created in other industries.[Ford Motor Company, 2007] On the down side, U.S. reliance on imported oil has significant negative impacts on the U.S. economy. The last three major oil price shocks, which were driven by political events in the Middle East, pushed the U.S. economy into economic recession. In addition, the U.S.

spends an estimated \$200,000 per minute on foreign oil, accounting for about one-fourth of the annual trade deficit. [UCS, 2002] In the future, petroleum prices are expected to rise as worldwide oil demand continues to increase and oil supplies begin to wane, further increasing cash flow out of the U.S. economy.

- **Environmental Context.** The current petroleum-based transportation SoS has had significant negative impacts on the environment. “Oil extraction, refining and transportation are responsible for land destruction and toxic contamination at the extraction point, oil spills in oceans around the world, and toxic air and water emissions from oil refining operations.”[CWAC, 2007] Millions of acres of farmland and wildlife habitat have been lost to roads and highways across the U.S. and vehicle emissions are major contributors to air and water pollution, as well as global climate change. Today, the transportation sector accounts for about a third of total U.S. emissions of carbon dioxide (an important greenhouse gas).[DOE Biomass Program, 2007] Not surprisingly, the transportation fuel SoS operates under a multitude of environmental protection laws and regulations regarding oil production, transport, and use. Pressure from environmental advocacy groups continues to motivate government action to mitigate and minimize the environmental impacts of our current transportation SoS through sustainable, energy-efficient and clean alternatives.
- **Social Context.** Affordable transportation fuel and personal mobility are virtual “rights” in the U.S. today. Even as traffic congestion and air pollution plague our cities, oil and the automobile are the foundation of our 21<sup>st</sup> century commercial and social lives. Today, the average American consumes about 25 barrels of oil per year; for perspective, the average person in China uses less than 2 barrels of oil per year.[Nationmaster, 2007] Modern food production and distribution are almost exclusively dependent on oil and natural gas – from producing the fertilizer used to grow crops to fueling harvesting equipment and refrigerated trucks that deliver food to consumers – and today, agriculture is one of the world’s most energy-intensive industries. .[Worldwatch Institute, 2007] Recognition that this oil-dependent lifestyle cannot be sustained into the future is slowly building – driven in part by the pinch consumers feel as the costs of food, gasoline and consumer products rise in response to higher oil prices, as well as increasing concern for the environment. For example, since 2004, the popularity of sport utility vehicles (SUVs) has waned and consumer demand for more fuel efficient vehicles has risen.[Worldwatch Institute, 2007] Nonetheless, consumers maintain their high expectations regarding performance, comfort, safety, reliability, cost, and size of the vehicles they purchase and drive. This illustrates the primary challenge from a social perspective – overcoming our natural resistance to change and managing expectations as alternative transportation fuels enter the market.

## Vision for a Future Hydrogen Economy

Hydrogen is the most abundant element in the universe but hydrogen does not exist alone in nature; it must be isolated from hydrogen-containing substances or feedstocks--water (H<sub>2</sub>O), natural gas (CH<sub>4</sub>), biomass (cellulose, hemicellulose or lignin), and hydrocarbons like coal. The U.S. has enough domestic energy resources—from wind, solar, biomass, hydroelectric, coal and nuclear---to meet all of the energy needs of the entire country, not just the transportation needs.



In DOE's 2040 vision of an operational hydrogen-based transportation economy, a robust hydrogen-based energy industry and supporting infrastructure will be in place, fully operational and capable of producing 64 million metric tons of hydrogen (quantity needed to fuel 300 million fuel cell vehicles annually). This vision, in terms of the elements of a hydrogen energy infrastructure illustrated in Figure 3, is outlined here.

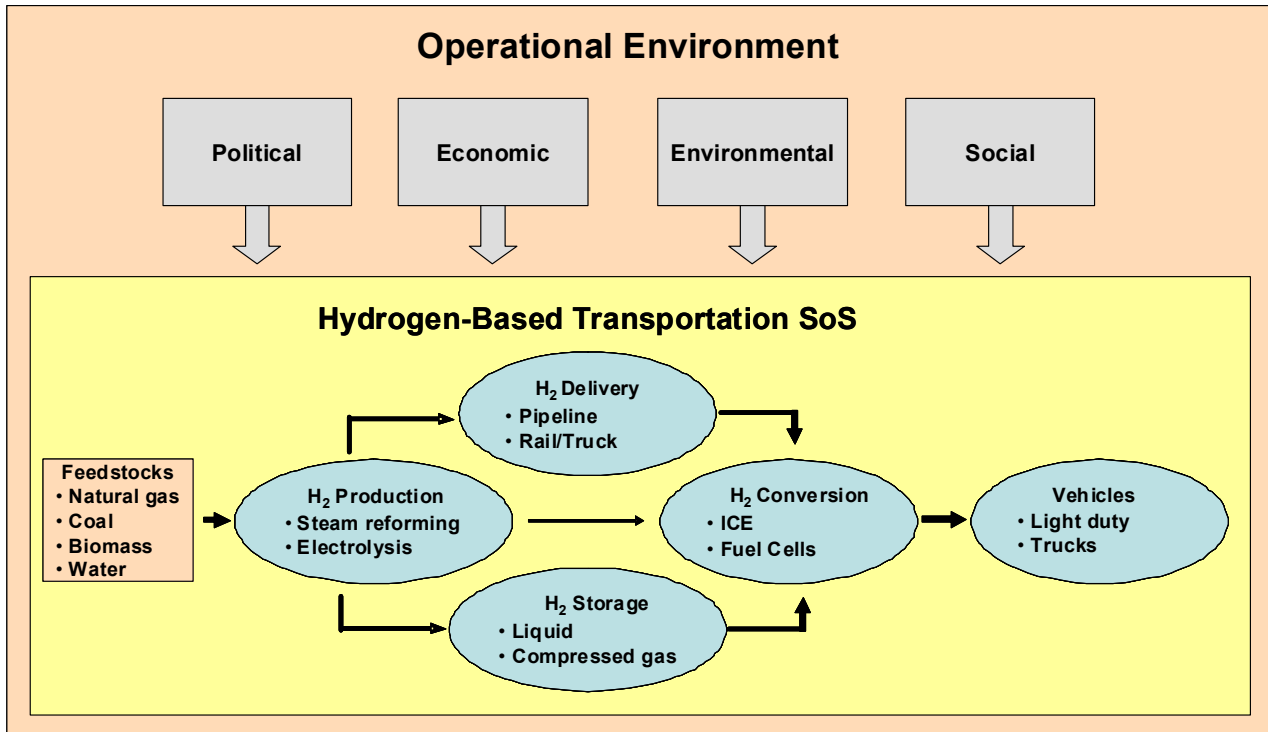


Figure 3: Elements of a Hydrogen Fuel Infrastructure

**Hydrogen Production.** In 2040, a variety of domestic feedstocks will be available for hydrogen production including biomass; coal (with carbon sequestration); and electricity-generating renewables such as wind and solar power as well as nuclear power (to drive water electrolysis). Feedstock selection will be based on the resources and processes that are most economical or specifically selected by particular states or regions. Hydrogen will be produced in centralized facilities in remote locations, in power parks and fueling stations in our communities, in distributed facilities in rural areas, and at customers' homes and businesses, using a variety of hydrogen production processes, as outlined in Figure 4. Thermal and electrochemical processes will use fossil fuels, biomass, or water as feedstocks and release little or no carbon dioxide into the atmosphere; water-splitting microorganisms and biomass fermentation will also become viable sources for renewable hydrogen. (Hydrogen Posture Plan 2006)

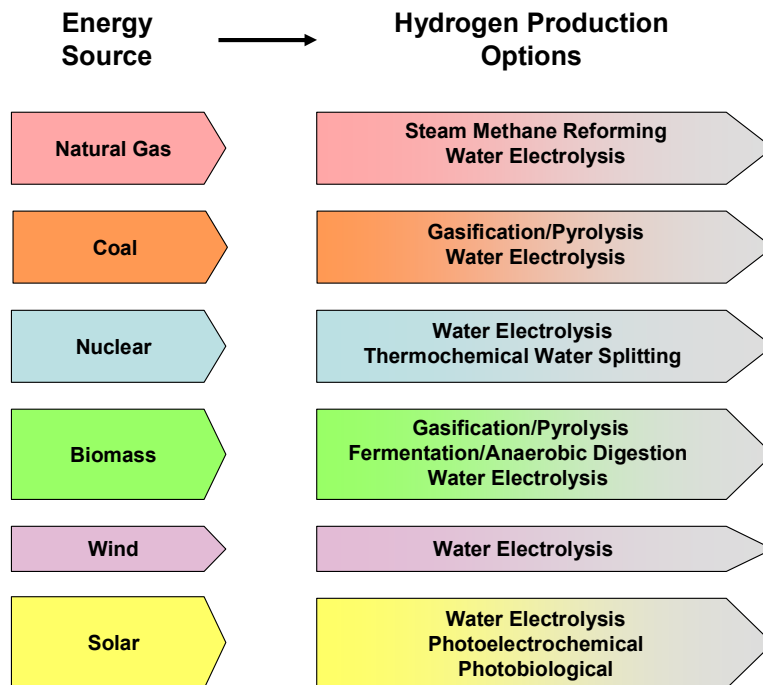


Figure 4: Hydrogen Production Options

**Hydrogen Delivery.** In 2040, a national supply network will evolve from the existing fossil fuel-based infrastructure to accommodate distribution of 64 million metric tons of hydrogen produced in both centralized and decentralized production facilities. Pipelines will distribute hydrogen to high-demand areas, and trucks and rail will distribute hydrogen to rural and lower demand areas.

**Hydrogen Storage.** In 2040, the hydrogen storage problem will be solved with lightweight, low-cost, and compact storage devices. One specific solution will be the use of high-tech solid materials, like metal hydrides and carbon nanotubes. These materials, along with chemical storage, may provide safe high-density storage options for both stationary and mobile applications.

**Hydrogen Conversion and End Use Applications.** In 2040, fuel cells will be a mature, cost-competitive technology in commercial production. Advanced, hydrogen powered energy generation devices such as combustion turbines and reciprocating engines will enjoy widespread commercial use. Hydrogen will become the dominant fuel for vehicle fleets across the country (target of 300 million fuel cell vehicles on the road in 2040).

# Evolution to a Hydrogen-Based Transportation Fuel SoS

## ***Where Are We Now? Existing Hydrogen Industry***

Outside the space industry, hydrogen is not used as a fuel today except for a few automotive demonstration vehicles. Most hydrogen is used to convert heavy petroleum sources into lighter fractions suitable for use as fuels and to produce ammonia for fertilizer production. The existing hydrogen supply chain for these chemical applications is mature, but not sufficient to support significant transportation applications.

**Hydrogen Production.** Today, the primary feedstock for hydrogen production is natural gas. Coal is also used as a hydrogen feedstock, and ethane, propane, butane and naphtha are also occasionally used as feedstocks for hydrogen production in refineries. Grid electricity, produced primarily from coal and natural gas, in combination with water, is also used as hydrogen feedstock. Approximately 9 million tons of hydrogen are produced annually for the industrial sector, largely by steam methane reforming of natural gas as the hydrogen feedstock. To a lesser degree, hydrogen is produced via electrolysis by passing electricity through two electrodes in water. The water molecule is split and produces oxygen at the anode and hydrogen at the cathode. Electrolyzers are used primarily to produce small volumes of relatively high-purity hydrogen and oxygen for specialized applications.

**Hydrogen Delivery.** Today, the largest volumes of gaseous hydrogen are delivered by pipeline. The most extensive pipeline networks are located in the Gulf Coast, where large quantities of hydrogen are consumed at refineries located in the region. (Hydrogen CEH 2004) Hydrogen is also transported over the road in compressed hydrogen cylinders and cryogenic liquid tankers. Today, there are 70 hydrogen refueling stations in operation in the U.S. and Canada; of these, 15 are publicly accessible.

**Hydrogen Storage.** Hydrogen gas is difficult to store and transport because it is very light. To make it easier to handle, the energy density of hydrogen gas is increased in one of two ways. Hydrogen gas can be compressed to a high pressure (up to 7,000 psi) or cooled to a very low temperature (below -423 F) so that the hydrogen gas becomes a liquid. In either case, the hydrogen is stored in specially designed tanks.

**Hydrogen Conversion and End Use Applications.** Today hydrogen is primarily used as a chemical, rather than a fuel. It is used to make cleaner gasoline, fertilizer, and food products. Hydrogen's primary use as a fuel is in the U.S. Space Program for both the main engine of the Space Shuttle and the fuel cells that provide the Shuttle's electric power. In the race for the potential fuel cell vehicle market, GM is dispatching 100 fuel cell Chevy Equinox crossovers to drivers in New York, Los Angeles and Washington, D.C.; Ford has a handful of fuel cell Ford Focus vehicles being tested throughout the world; DaimlerChrysler has more than 100 fuel cell vehicles on the road, including 60 passenger cars and 30 buses; Toyota is testing 20 fuel cell Highlanders; and Honda recently unveiled its next-generation fuel cell vehicle, the FCX. (Detroit News 2007)

## ***How Do We Get There? Transition to a Hydrogen Future***

Dramatic advancements in the performance and cost-effectiveness of hydrogen and fuel cell technologies are necessary before they will be competitive with today's petroleum-based transportation infrastructure. In addition, transitioning to a hydrogen SoS will require initially

integrating with and ultimately transforming industries of the current transportation SoS, as well as the established chemical-based hydrogen production industry, the natural gas industry, and utilities that provide electricity for the grid. A phased approach will allow new energy systems to be integrated into the existing energy infrastructure as technologies and systems advance to the point of commercial readiness. The transition to a hydrogen-based transportation SoS will occur incrementally over many decades as technologies advance, market acceptance increases and large investments in infrastructure that can support the expanded production, delivery, storage and use of hydrogen are made. An overview of the step-wise transition is presented in Figure 5.

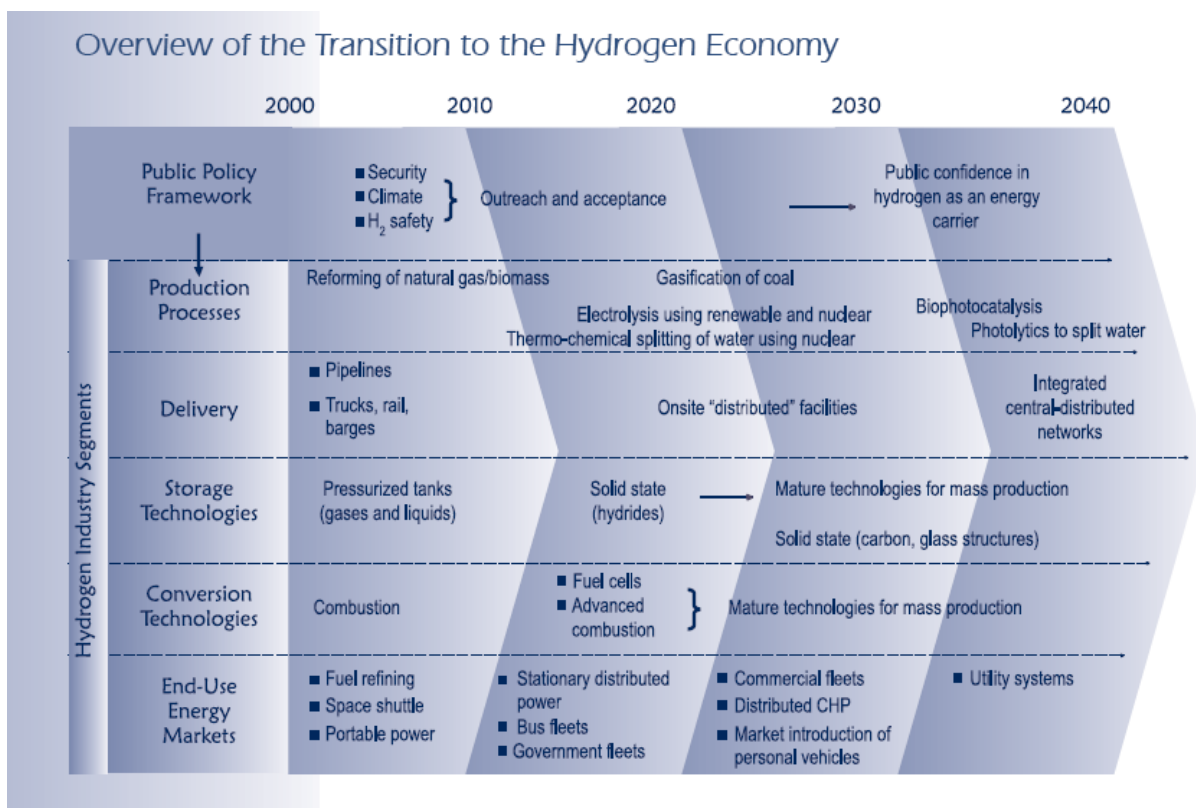


Figure 5: Overview of the Transition to a Hydrogen Economy (Hydrogen Posture Plan 2006)

The transition to a hydrogen-based transportation SoS is envisioned to occur in two phases.

**Near- to Mid-Term (2007-2020).** The first steps toward a clean hydrogen future will build on the commercial processes and systems in use today. To build initial hydrogen fuel demand, hydrogen production capacity via steam reforming natural gas and water electrolysis using conventional electricity-generating sources (coal and natural gas) will be expanded. Distributed hydrogen generation will begin to play a role. Existing hydrogen distribution systems will be expanded dramatically. Fleets will transition to hydrogen fuel vehicles and the first hydrogen fuel cell vehicles will be introduced to consumer markets. Government-supported R&D will advance hydrogen production, storage and end-use technologies, and improve system performance and economics. Government policies and financial incentives will be implemented

to stimulate industry investment and encourage consumer adoption of hydrogen technologies and systems.

**Mid- to Long-Term (Beyond 2020).** As hydrogen markets grow, costs across the hydrogen transportation fuel supply chain will decrease through economies of scale and dramatic technological advances. Natural gas and coal will be replaced by biomass and water as primary hydrogen feedstocks. Distributed hydrogen generation capability will expand significantly to enable hydrogen to be used where it is produced. Hydrogen distribution systems will also be expanded to all regions of the U.S. as hydrogen-fueled vehicles become widely available to consumers. Government-supported R&D will continue to advance hydrogen production, storage and end-use technologies for next-generation applications. In this timeframe, government financial support for commercial ventures and consumer acceptance will no longer be needed as the hydrogen-based transportation SoS becomes firmly established.

## **Using Model-Based System Engineering to Bring the Future Hydrogen-Based Transportation Economy into Being**

The SoS challenge is how to design and implement a smooth transition from the legacy petroleum-based transportation SoS to a future hydrogen-based transportation SoS.

DOE is using a model-based systems engineering (MBSE) approach to document and track the progression from the existing “legacy” transportation SoS to a future hydrogen-based SoS. MBSE is a methodology for developing and analyzing system requirements using graphical representations of the underlying functions, requirements, architecture, relationships and interfaces that define the system. The MBSE approach helps to improve understanding and communication of complex system and system-of-systems designs. Beginning with the end in mind, i.e., the vision of a future hydrogen economy, MSBE can help to define and document what it will take, in terms of *capability*, to get from here to there.

The system engineering fundamentals underlying the MBSE approach can be readily expanded to SoS applications. Specifically, the capabilities required for a future hydrogen-based SoS can be defined and managed in terms of the functions, requirements, architecture and tests (FRAT) framework (Mar and Morais, 2002) as follows:

1. Describe each system within the SoS in terms of four views:
  - What the system does (functions)
  - How well the system performs its functions (requirements)
  - What the system actually is (architecture)
  - Verification and validation activities that provide the proof that the actual system satisfies the intended functions and requirements (test)
2. Define and understand the three interacting systems:
  - Physical system: the required infrastructure for an operational hydrogen economy
  - Program system: the RD&D program that brings the desired infrastructure into being
  - External system: everything else that interacts with the physical and program systems

The desired SoS infrastructure and the RD&D program for establishing the desired infrastructure are derived from the vision and mission, and captured in an integrated baseline, as illustrated in Figure 6. The purpose of the integrated baseline is to establish and control the documented, traceable relationships between requirements, functions, strategies, technologies, etc. of the SoS and the program for bringing it into being. The integrated baseline is comprised

of two components. The technical baseline, which focuses on defining the technological capabilities in terms of configuration, performance and characteristics of the SoS, ensures that we will be *doing the right things*. The technical baseline defines where the program is at any point in time and where it ultimately must be (from a technology development standpoint). The programmatic baseline, which focuses on the scope of work, schedule and costs of activities required to bring the technological capabilities into being, ensures that we will *do things right*. The goal is an integrated baseline for a requirements-driven, mission-oriented program and, hence, a firm foundation for designing and implementing the SoS necessary to transition to an operational hydrogen economy.

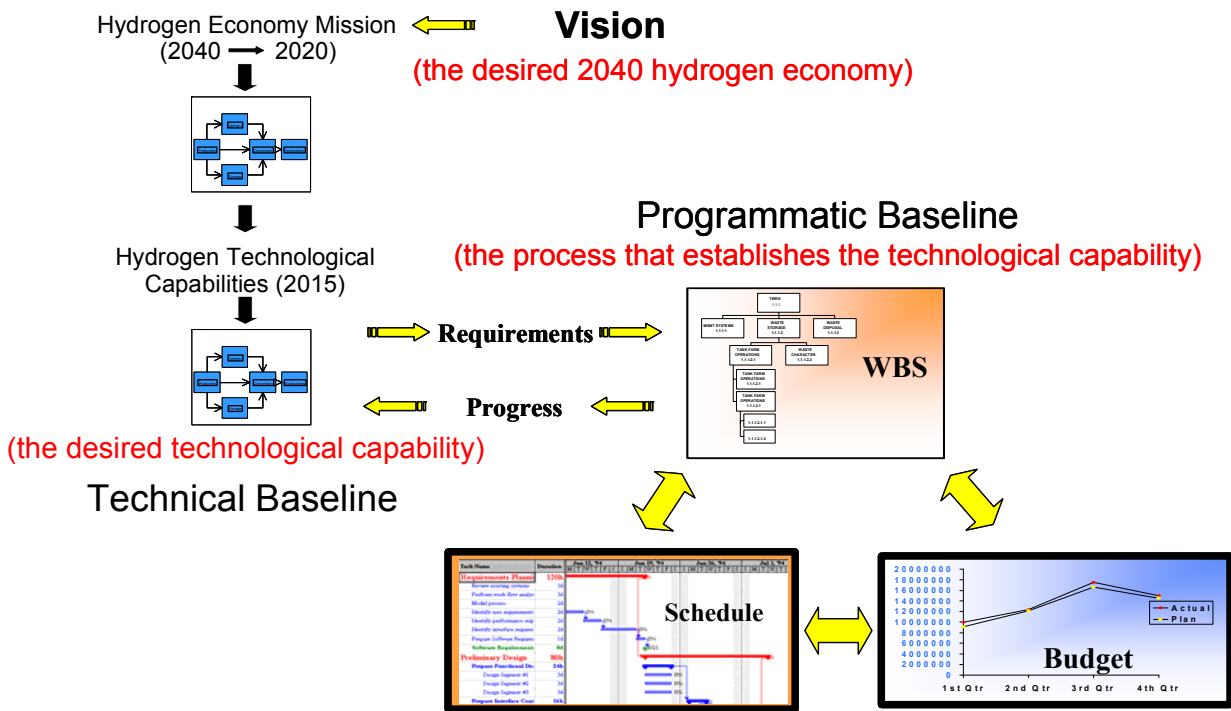


Figure 6: A Requirements-Driven, Mission-Oriented Transition Program

The hydrogen integrated baseline is built on the CORE MBSE software platform (Vitech Corporation 2007), a database-driven integrated systems engineering and program management support tool, designed to document and manage each step of the FRAT process in a centralized electronic repository. In addition to providing a graphical representation of the system, CORE allows program organization and efforts to be viewed from a variety of perspectives through automatic generation of standard reports, tables, and diagrams. Figure 7 illustrates how CORE can be used to organize, coordinate and document both the technical and programmatic baselines necessary to efficiently achieve the desired operational hydrogen economy. This diagram highlights the traceability of the information back to its source document and shows the key relationships between the model components (or “elements”).

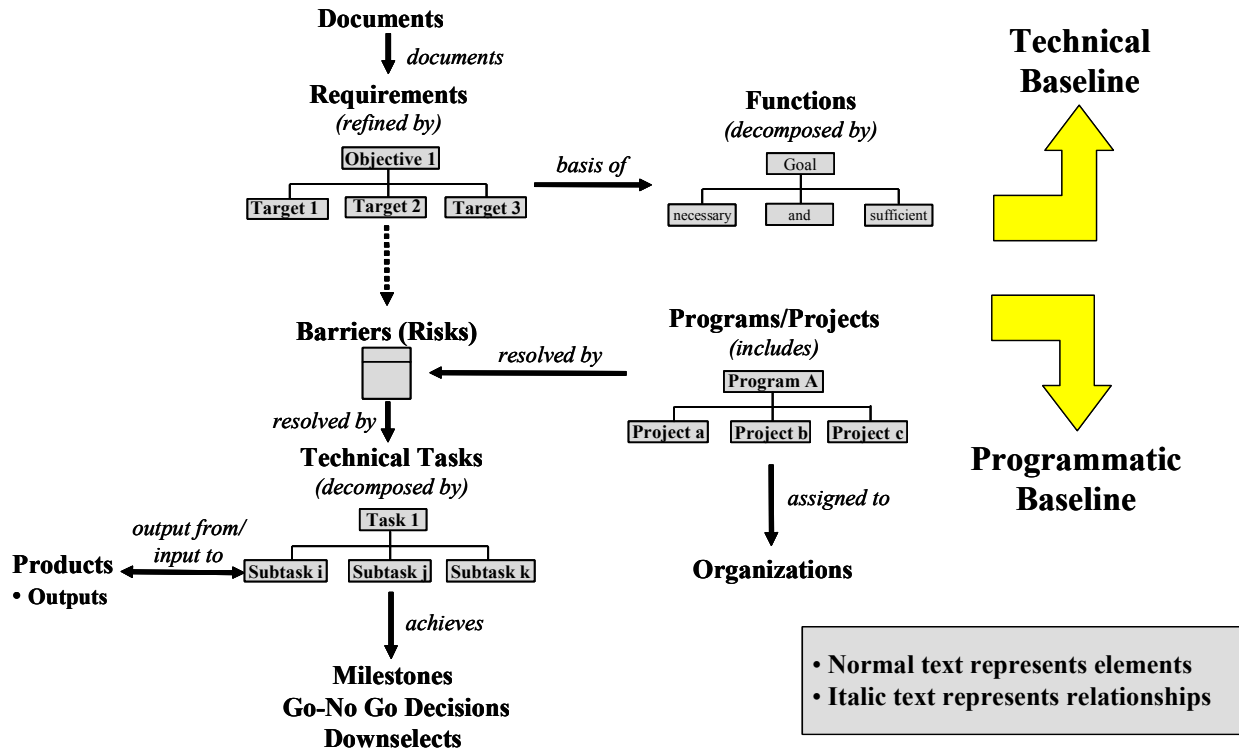


Figure 7: Implementing the SoS Engineering Process within CORE

The technical information for the baseline – requirements (in the form of performance and cost targets), barriers (risks), and technical tasks and milestones – is drawn from high-level guiding documents for the DOE Hydrogen Program (DOE Strategic Plans, DOE Hydrogen Program Posture Plan and Multi-Year Program Plans; available at <http://www.hydrogen.energy.gov/>). The programmatic information for the baseline – integrated portfolio of projects (which form the basis of the Program’s work breakdown structure), along with the associated budgets, schedules and resource requirements – is developed in conjunction with the DOE Hydrogen Program and Project management teams. The integrated baseline is updated regularly as technologies advance, requirements evolve, and budgets expand and contract.

The integrated baseline as implemented in the CORE MBSE software provides a robust tool to (1) document and track the current state and progress of the hydrogen SoS and (2) establish a defensible basis for budget estimates and technical decisions as the hydrogen fuel SoS moves from concept to commercial reality.

## Summary/Conclusions

Deploying significant volumes of hydrogen fuel will require major technology advancements along with consistent government policies to spur the transformation of the current petroleum-based market and infrastructure. Efforts to change energy infrastructure will require sustained public and private sector commitment and investment over a multi-decade period. A system-of-systems framework can effectively guide the complex evolutionary process, in which advanced transportation fuels and systems will be continually integrated into the existing petroleum-based transportation infrastructure as they become commercially available.

## References

- Annual Energy Outlook 2006 (AEO 2006a). U.S. Energy Information Administration.  
<http://www.eia.doe.gov/oiaf/archive/aeo06/gas.html>
- AEO 2007 <http://www.eia.doe.gov/oiaf/aeo/overview.html>
- (API 2006) <http://www.api.org/aboutoilgas/sectors/pipeline/index.cfm>
- Bush, George W. State of the Union Address, January 31, 2006.  
<http://www.whitehouse.gov/stateoftheunion/2006/>
- (Detroit News 2007) GM Aims to Market Fuel Cell Vehicles. Detroit News Website (visited 10-02-07). The Detroit News. June 15, 2007.  
<http://www.detnews.com/apps/pbcs.dll/article?AID=/20070615/AUTO01/706150354/1001/biz>
- (DOE Alternative Fueling Station Locator 2007) DOE Alternative Fueling Station Locator. DOE Alternative Fuels Data Center Website (visited 10-17-07).  
<http://afdcmap2.nrel.gov/locator/findpane.asp>
- Fuel Cell Basics: Applications. Fuel Cells 2000 Website (visited 10-28-07)  
<http://www.fuelcells.org/basics/apps.html>
- (Hydrogen CEH 2004) CEH Marketing Research Report: Hydrogen. August 2004. Chemical Economics Handbook. SRI Consulting.
- (Hydrogen Posture Plan 2006) Hydrogen Posture Plan: An Integrated Research, Development and Demonstration Plan. (December 2006). U.S. Department of Energy and U.S. Department of Transportation. [http://www.hydrogen.energy.gov/pdfs/hydrogen\\_posture\\_plan\\_dec06.pdf](http://www.hydrogen.energy.gov/pdfs/hydrogen_posture_plan_dec06.pdf)
- Mar, Brian W. and Bernard G. Morais. FRAT-A Basic Framework for Systems Engineering. INCOSE 2002 International Symposium, July 28-August 1, 2002. Las Vegas, Nevada.  
[http://www.eskimo.com/~jjs-sbw/524\\_bmar.PDF](http://www.eskimo.com/~jjs-sbw/524_bmar.PDF)
- LLNL <https://eed.llnl.gov/flow/pdf/USEnFlow02-quads.pdf>
- (National Hydrogen Association 2007) Hydrogen Fueling Stations. National Hydrogen Association website. (visited 10/3/07).  
<http://www.hydrogenassociation.org/general/fuelingSearch.asp>
- Rifkin, Jeremy. The Hydrogen Economy. Penguin Group (USA) Inc. 2002. p.121-122.
- (Union of Concerned Scientists 2002) Energy Security: Solutions to Protect America's Power Supply and Reduce America's Oil Dependence. (January 2002). Union of Concerned Scientists. [www.ucsusa.org](http://www.ucsusa.org)
- U.S. Energy Information Administration, Petroleum Supply Annual 2004, Vol. I, Tables 36 and 40. (EIA 2004a)
- U.S. Energy Information Administration, Where Does My Gasoline Come From?, June 2005. (EIA 2005) <http://www.eia.doe.gov/neic/brochure/gas06/gasoline.htm>
- (Vitech Corporation 2007) Vitech Corporation. <http://www.vitechcorp.com/>
- Whitehouse (2003) Hydrogen Fuel: A Clean and Secure Energy Future (January 30, 2003)  
<http://www.whitehouse.gov/news/releases/2003/01/20030130-20.html>



## **Biography**

### ***Michael Duffy, PhD***

Michael Duffy is the Lead Systems Engineer for the National Renewable Energy Laboratory's Hydrogen Program. He has a Ph.D. from the Ohio State University in Systems Engineering, an M.S. from Northeastern University in Engineering Management, a second M.S. from the Massachusetts Institute of Technology in Mechanical Engineering, and a B.S. from Tufts University in Mechanical Engineering. His background includes over 30 years of systems engineering experience as a consultant and Chief Systems Engineer in energy, safeguards and security, nuclear waste management, national defense, transportation, and space programs. Dr. Duffy has been a member of the International Council on Systems Engineering since 1992.

### ***Debra Sandor, PMP***

Ms. Sandor has ten years of process engineering experience in manufacturing and R&D organizations. She has a range of hands-on and theoretical experience, including scaling up pilot operations to full-scale production processes, process evaluation and validation, modeling of conceptual processes, and program and personnel management. As the Lead Systems Engineer for the DOE Biomass Program, she is responsible for maintaining the program's integrated baseline and managing the development and implementation of the program's system dynamics model. She holds a BS in Chemical Engineering from the University of Florida and a ME in Engineering Management from the University of Colorado.

# REPORT DOCUMENTATION PAGE

Form Approved  
OMB No. 0704-0188

The public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing the burden, to Department of Defense, Executive Services and Communications Directorate (0704-0188). Respondents should be aware that notwithstanding any other provision of law, no person shall be subject to any penalty for failing to comply with a collection of information if it does not display a currently valid OMB control number.

**PLEASE DO NOT RETURN YOUR FORM TO THE ABOVE ORGANIZATION.**

<b>1. REPORT DATE (DD-MM-YYYY)</b> June 2008		<b>2. REPORT TYPE</b> Conference Paper		<b>3. DATES COVERED (From - To)</b>	
<b>4. TITLE AND SUBTITLE</b> A System-of-Systems Framework for the Future Hydrogen Economy: Preprint				<b>5a. CONTRACT NUMBER</b> DE-AC36-99-GO10337	
				<b>5b. GRANT NUMBER</b>	
				<b>5c. PROGRAM ELEMENT NUMBER</b>	
<b>6. AUTHOR(S)</b> M. Duffy and D. Sandor				<b>5d. PROJECT NUMBER</b> NREL/CP-150-42989	
				<b>5e. TASK NUMBER</b> HS074001	
				<b>5f. WORK UNIT NUMBER</b>	
<b>7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)</b> National Renewable Energy Laboratory 1617 Cole Blvd. Golden, CO 80401-3393				<b>8. PERFORMING ORGANIZATION REPORT NUMBER</b> NREL/CP-150-42989	
<b>9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)</b>				<b>10. SPONSOR/MONITOR'S ACRONYM(S)</b> NREL	
				<b>11. SPONSORING/MONITORING AGENCY REPORT NUMBER</b>	
<b>12. DISTRIBUTION AVAILABILITY STATEMENT</b> National Technical Information Service U.S. Department of Commerce 5285 Port Royal Road Springfield, VA 22161					
<b>13. SUPPLEMENTARY NOTES</b>					
<b>14. ABSTRACT (Maximum 200 Words)</b> From a supply chain view, this paper traces the flow of transportation fuels through required systems and addresses the current petroleum-based economy, DOE's vision for a future hydrogen-based transportation economy, and the challenges of a massive market and infrastructure transformation.					
<b>15. SUBJECT TERMS</b> hydrogen economy; system of systems; hydrogen transportation economy					
<b>16. SECURITY CLASSIFICATION OF:</b>			<b>17. LIMITATION OF ABSTRACT</b> UL	<b>18. NUMBER OF PAGES</b>	<b>19a. NAME OF RESPONSIBLE PERSON</b>
<b>a. REPORT</b> Unclassified	<b>b. ABSTRACT</b> Unclassified	<b>c. THIS PAGE</b> Unclassified			<b>19b. TELEPHONE NUMBER (Include area code)</b>

Standard Form 298 (Rev. 8/98)  
Prescribed by ANSI Std. Z39.18