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Roadmap on Manufacturing R&D for the Hydrogen Economy

Based on the Results of the
Workshop on Manufacturing R&D for the
Hydrogen Economy
Washington, D.C.
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DEPARTMENT OF ENERGY
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JoAnn Milliken, Chief Engineer

DOE Hydrogen Program

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[1] The IWG operates within the President's National Science and Technology Council. Members of the IWG are identified in Appendix A.

Executive Summary

To meet critical national needs that involve energy security, environmental quality, and economic well-being, the President has established the Hydrogen Fuel Initiative (HFI)[2] and the Manufacturing Initiative.[3] The HFI will reverse America's growing dependence on foreign oil by developing the technology needed for commercially viable hydrogen-powered fuel cells. The Manufacturing Initiative, which addresses the entire manufacturing sector in the United States, will strengthen American manufacturing, create new jobs, and help U.S. manufacturers become more competitive in the global marketplace. This document on Manufacturing R&D for the Hydrogen Economy describes activities at the intersection of these two Presidential Initiatives.

In response to the Manufacturing Initiative, the President's National Science and Technology Council established the Interagency Working Group (IWG) on Manufacturing Research and Development.[4] The IWG is coordinating and leveraging the current federal efforts focused on manufacturability issues such as low-cost, high-volume manufacturing systems, advanced manufacturing technologies, manufacturing infrastructure, and measurements and standards. The U.S. Department of Commerce is leading the IWG. Manufacturing R&D for the hydrogen economy, one of three technical priorities of the IWG, is being led by DOE. This multiagency effort, led by DOE, complements the technology development efforts now underway through the HFI.

> *"For fuel cells, durability and cost are the most difficult goals, and for hydrogen storage, the most difficult are size, weight, and cost. In most instances, solutions depend on yet-to-be-conceived or -proven component and manufacturing technology rather than incremental improvement."*
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> - Review of the Research Program of the FreedomCAR and Fuel Partnership, first report 2005, National Academies of Science, Washington, D.C. www.nap.edu/books/0309097304/html/

We must overcome significant challenges to realize the vision of the hydrogen energy economy. These include reducing the cost of hydrogen production and delivery; increasing the capacity and reducing the cost of onboard vehicle hydrogen storage systems; and reducing the cost and increasing the durability of automotive fuel cell systems. The goal of the HFI is to advance hydrogen technologies to the point that industry can make commercialization decisions on hydrogen fuel cell vehicles and fuel infrastructure by 2015 so these technologies can begin to penetrate consumer markets by 2020. Commercializing hydrogen technologies by 2020 requires that manufacturing issues be addressed now. Manufacturing research and development (R&D) is needed to put in place the manufacturing processes and supplier chains that will be necessary for market introduction and economic growth. This roadmap

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[2] *Hydrogen Fuel: A Clean and Secure Energy Future*, Office of the President, Press Release, January 30, 2003. Retrieved September 9, 2005, from www.whitehouse.gov/news/releases/2003/01/20030130-20.html.

[3] Manufacturing in America: A Comprehensive Strategy to Address Challenges to U.S. Manufacturers, www.manufacturing.gov/initiative/index.asp?dName=initiative.

[4] The National Science and Technology Council's Committee on Technology (www.ostp.gov/mfgiwg).

focuses on manufacturing R&D to transform America's manufacturing sector for the hydrogen economy.

Challenges to Manufacturing R&D

Several challenges confront the transformation of the U.S. manufacturing sector to support the hydrogen energy economy. We must:

- Develop innovative, low-cost manufacturing technologies for new materials and material applications.
- Adapt laboratory fabrication methods to low-cost, high-volume production.
- Establish and refine cost-effective manufacturing technologies while hydrogen products are still evolving.
- Meet customer requirements for hydrogen systems.
- Address the diversity and size of industries in both the manufacturing and energy sectors.
- Develop a supplier base for hydrogen system components.

Workshop on Manufacturing R&D for the Hydrogen Economy

DOE, with support from the Department of Commerce's National Institute for Standards and Technology (NIST), conducted a Workshop on Manufacturing R&D for the Hydrogen Economy to identify the path forward to address these challenges.[5] The workshop brought together industry, university, national laboratory, and government representatives to discuss the key issues facing manufacturing of:

- Fuel cells
- Hydrogen production and delivery systems
- Hydrogen storage systems.

Workshop participants identified key technical challenges that face the manufacture of hydrogen technologies and recommended priorities for manufacturing R&D to facilitate their commercialization. The roadmap, which has incorporated these recommendations, will be used to guide R&D of critical manufacturing processes that are required for high-volume production of hydrogen technologies.

Major Findings

This summary contains the workshop findings for hydrogen components and systems that will need to be manufactured during the initial transition to the hydrogen economy along with the major topics that need to be addressed through manufacturing R&D, focusing primarily on technologies that are near commercial. Longer-term technologies under

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[5] DOE Manufacturing Workshop Web site:
www.eere.energy.gov/hydrogenandfuelcells/wkshp_h2_manufacturing.html

development by the HFI will be addressed in later manufacturing R&D efforts. Paths forward to address each topic are identified within the body of the roadmap.

Polymer Electrolyte Membrane Fuel Cells

Polymer electrolyte membrane (PEM) fuel cells consist of the cell stack (membranes, catalysts layers, gas diffusion layers, seals, bipolar plates, coolers, gas manifolds), balance-of-plant (BOP) (water and thermal management modules, hydrogen and oxygen management modules), and power conditioning and system controls.

Fuel cell stacks and their respective components are in the early stages of manufacturing. Fuel cells are now manufactured with laboratory fabrication methods that have been typically scaled up in size, but do not incorporate high-volume manufacturing methods. Major subsystems such as the hydrogen and oxygen delivery subsystems and the water and thermal management subsystems, are individually assembled by joining components, for example, by connecting the heat exchangers to the coolant system or integrating the humidification system to the air blower. The entire power system is usually constructed by integrating subsystems; however, each subsystem is assembled separately by a labor-intensive process.

The transition to high-volume production of PEM fuel cells will require that quality control and measurement technologies are established to be consistent with high-volume manufacturing processes. Manufacturers will need process control strategies that are specific to producing fuel cell components to reduce or eliminate sampling and testing of components, modules, and subsystems.

As fuel cell manufacturing scales up, we must clearly understand the relationships between fuel cell system performance and manufacturing process parameters and variability. Such understanding will likely play a major role in fuel cell design, tolerances, and specifications, and is integral to implementing design for manufacturability. Modeling and simulation can play a significant role in developing this understanding. Establishing knowledge bases that contain information on generic, cross-cutting manufacturing process technologies, reliable measurements, and standards will advance PEM fuel cell manufacturing.

Manufacturing R&D is needed on the following technologies:

- Membrane electrode assembly (MEA)
- Bipolar plates and cell stack assembly
- Water and thermal management subsystems
- Hydrogen and oxygen management subsystems.

The highest priority manufacturing R&D needs for PEM fuel cells are summarized in Table ES-1 at the conclusion of this summary. (Manufacturing R&D needs were prioritized as high, medium, and low by the workshop participants. They are all described in the roadmap.)

Hydrogen Production and Delivery

Production and delivery of hydrogen during the first years of the transition to the hydrogen economy (when a large scale hydrogen delivery infrastructure is not in place) will likely be dominated by distributed reforming of natural gas- or renewable energy-based liquids such as ethanol or bio-oils, and by distributed electrolysis. Today, hydrogen production is capital intensive, and the capital contribution to its cost is larger for smaller hydrogen production facilities that are designed for distributed applications. The larger contribution of capital to the cost of distributed reforming of natural gas is the result of site-specific fabrication of fuel processing systems, which include reformers, shift catalyst beds, and pressure swing adsorption cleanup subsystems.

In addition, there is very limited manufacturing of electrolysis units of the size necessary for a distributed hydrogen network. The roadmap focuses on near ambient temperature alkaline and proton exchange membrane electrolyzers. High-temperature solid oxide electrolyzers are not covered because they are not as close to commercialization, and probably more suited to centralized, rather than distributed, production. Because the roadmap focuses on near-term distributed production of hydrogen, bulk storage is the only component of hydrogen delivery that is addressed for manufacturing R&D.

Manufacturing R&D is needed on the following processes:

- Joining methods for system components
- Coatings and thin film deposition
- Pressurized systems and components
- Continuous manufacturing methods

Table ES-2 summarizes the highest priority manufacturing R&D needs for systems to produce and store hydrogen off-board the vehicle.

Hydrogen Storage

One of two storage technologies is currently employed on virtually every hydrogen-fueled vehicle: high-pressure compressed gas storage (on more than 90% of the vehicles) or liquid hydrogen storage at near ambient pressure. These two options require very different manufacturing methods because there are significant differences in terms of materials, fabrication processes, and performance requirements. Furthermore, several storage materials and technologies are undergoing intense development efforts, one or two of which may emerge in the near future with significantly improved performance over the current options. Hence, manufacturing requirements related to these systems were considered by the workshop. These other technologies fall into two very broad categories: chemical and solid-state systems, and high-pressure cryogenic systems.

Manufacturing viable onboard storage systems will require dramatic reductions in unit costs and fabrication times. It will also require significant investment in manufacturing equipment and the development of new approaches to fabrication, particularly in the case of composite tanks, but also for chemical storage system components and for cryogenic system components. The biggest challenges lie in the high-volume manufacture of composite tanks.

Components that are common to all storage systems include many of the BOP components, such as pressure regulators, solenoid valves, pressure relief devices, tubing, and mounting brackets. These parts can generally be manufactured by current metal production practices and seem to pose no challenges to the manufacture of storage systems.

Manufacturing R&D is needed in the following areas:

- Fabrication processes for composite tanks
- Assembly techniques for chemical storage systems
- Modeling and simulation of manufacturing processes
- Certification methods for storage systems and subassemblies that are compatible with high-volume manufacturing

The highest priority manufacturing R&D needs for systems to store hydrogen onboard vehicles are listed in Table ES-3 at the conclusion of this summary.

Cross-Cutting Manufacturing R&D

Manufacturing for the hydrogen economy covers a wide variety of components and systems that fit into the broad categories discussed in this roadmap. Manufacturing these components and systems requires a spectrum of technologies, from continuous chemical processes to discrete mechanical fabrication processes.

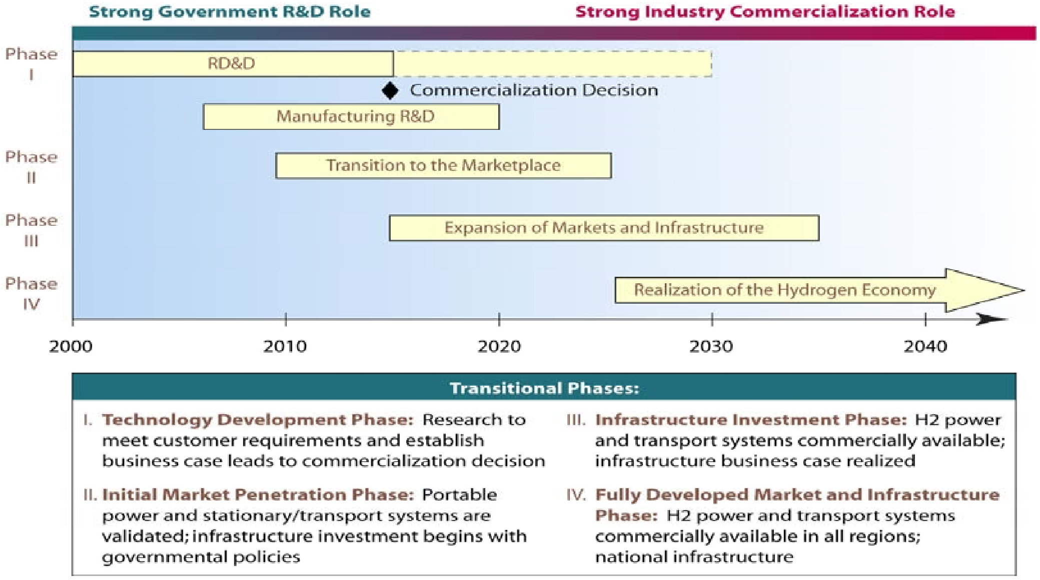
Manufacturing R&D is needed on the following cross-cutting topics:

- Metrology and standards
- Modeling and simulation
- Development of knowledge bases (including documents, databases, and models)
- Design for manufacturing and assembly
- Sensing and process control.

Interdisciplinary teams that include high-volume manufacturers, materials suppliers, technology developers, and system integrators will most effectively conduct manufacturing R&D on these topics. Manufacturing R&D results will provide important input for safety practices and codes and standards, and they should be incorporated into codes and standards on an ongoing basis.

Timeline, Major Activities, and Metrics

Manufacturing R&D needs to commence as soon as possible and be conducted synergistically with technology development. It needs to be an integral part of the HFI to help transform the U.S. manufacturing sector for the hydrogen economy, as illustrated in Figure ES-1.



Transitional Phases:

I. **Technology Development Phase:** Research to meet customer requirements and establish business case leads to commercialization decision

II. **Initial Market Penetration Phase:** Portable power and stationary/transport systems are validated; infrastructure investment begins with governmental policies

III. **Infrastructure Investment Phase:** H2 power and transport systems commercially available; infrastructure business case realized

IV. **Fully Developed Market and Infrastructure Phase:** H2 power and transport systems commercially available in all regions; national infrastructure

Figure ES-1: Hydrogen economy timeline with manufacturing R&D shown

Key activities under manufacturing R&D include:

- Develop a manufacturing R&D roadmap (this document).
- Develop detailed program plans for public-private manufacturing R&D.
- Conduct generic, precompetitive manufacturing R&D by national laboratory and university-led teams.
- Develop competitively awarded, scalable, manufacturing processes by industry-led teams.

DOE will establish metrics against which to evaluate the progress and benefits of manufacturing R&D for the hydrogen economy. These metrics will be developed along with more detailed R&D planning as DOE consults with the U.S. hydrogen and fuel cell R&D community and relevant portions of the U.S. manufacturing community. Metrics will focus on the cost of manufacturing specific hardware systems for producing, delivering, storing, and using hydrogen. This roadmap will be updated as hydrogen technologies are further developed.

Table ES-1: Summary of High-Priority Manufacturing R&D Needs: PEM Fuel Cells

Identify relationships between physical and manufacturing properties of MEAs and performance properties of MEAs

Manufacturing R&D that correlates physical properties of the MEA with performance properties is a high-priority need. The relationship between the *ex-situ* manufacturing properties and the *in-situ* properties that pertain to performance and durability needs to be established. The relationship could be an empirical-, mathematical-, or physical-based transfer function. Supporting this approach is a strong need for sensor technology that permits in-line inspection and would provide the database for statistical quality control.

Identify cost of PEM fuel cells, especially MEAs, at several levels of manufacturing

Industry considers a continuum in the development of fuel cells, especially the MEA, to be an important issue. A broad range of cost analyses that embrace the transition from low production levels to the high production levels is needed to establish progress goals in the development of manufacturing processes.

Develop agile, flexible manufacturing

Changes in manufacturing in response to changes in the materials and designs of MEAs result in high costs. More flexible (agile) and integrated manufacturing approaches are a high priority for the manufacture and assembly of MEAs. Industry will need agile manufacturing processes that can be adapted to the developing membrane, catalyst, and gas diffusion layers without incurring major capital expenditures.

Develop understanding of how manufacturing parameters affect catalyst layers

The relationship between catalyst layer manufacture and the performance and durability of the catalyst layer needs to be delineated to implement high-speed manufacturing processes. New methods of manufacturing will be important to fabricate new catalyst layers that meet the low precious metal cost targets.

Develop strategies for high-speed seal applications

High-speed processes need to be developed to integrate MEA components that include incorporating edge and interfacial seals and gaskets. Merging the MEA sealing assembly process with the bipolar plate sealing in a continuous process could lead to cost reductions in the assembly of the cell stack.

Apply and develop modeling tools for MEA manufacture

Integration of computer aided design tools with technology development and manufacturing R&D will advance performance and cost reduction opportunities.

Characterize membrane defects and develop fabrication techniques

Characterize defects in membranes and their causes to permit in-line control of membrane and MEA manufacture.

Develop high-speed forming, stamping, and molding of bipolar plates

Current processes individually form or machine the bipolar plates. Manufacturing bipolar plates requires the development of new high-speed forming, stamping, and molding processes that will maintain the high tolerance requirement of the PEM fuel cell. Rapid prototyping and flexible tooling specifically for the manufacture of bipolar plates is on the critical development path.

Develop automated processes to assemble cell stacks

Automated processes are needed to rapidly assemble cell stacks. Design for manufacturability and assembly should be applied to cell stack development to enable processes that lead to identical cells and eliminate the need to measure each cell component during cell stack assembly.

Develop high-speed welding/joining

Present laser welding methods are either too slow or too expensive for metallic bipolar plate manufacturing. Fiber lasers for microwelding bipolar plates need to be developed to achieve linear welding speeds greater than 50 meters per minute.

Develop materials for low cost and high performance heat exchangers (materials issue)

PEM fuel cells have at least four heat exchangers within the balance-of-plant (BOP). Composite or plastic heat exchangers that can be fabricated at high volume and low cost could provide a low-cost path for the manufacture of PEM power systems. Manufacturing processes will need to be developed for these new materials.

Establish protocols for qualifying new materials and processes (materials issue)

Materials that are compatible with PEM fuel cells need to be identified for all manufacturers. Presently individual fuel cell manufacturers specify acceptable materials. A compilation of materials acceptable to all fuel cell manufacturers will enhance the establishment of a supply chain network. Protocols need to be developed for qualifying new materials to be used in the manufacture of PEM fuel cells.

Develop frameless fuel cell systems (design issue)

PEM power systems are currently built by fitting components and subsystems in the power system box. Designs for assembly of the unit would address the interaction of subsystems and develop concepts for production and assembly of power systems. Design for manufacturing and assembly should be applied to the BOP to reduce the part count of integrated systems.

Develop manufacturing and assembly processes for interim production volumes

Manufacturing approaches suitable for an interim production volume of 5,000−50,000 power systems per year are a pathway to the large scale transportation production processes. Rapid prototyping and agile manufacturing are pathways to be developed for the construction of PEM BOP and PEM power system.

Establish flexible automated manufacturing technology facility

A national facility is needed to test flexible, automated manufacturing technology for BOP and power system assembly and component manufacture. It could provide a test bed for developing manufacturing processes, could be available to component and fuel cell manufacturers, and could serve as a clearinghouse for PEM fuel cell manufacturing R&D.

Develop production hardware for rapid leak detection

Leak testing of the BOP and power system is time-consuming and costly for today's PEM power system production. Rapid leak testing that can be accomplished in the production line and at production line rates is needed.

Table ES-2: Summary of High-Priority Manufacturing R&D Needs: Hydrogen Production and Delivery

Develop joining methods to facilitate component integration

Component integration requires labor-intensive welding. Manufacturers need high-reliability, low-variability joining processes that can be rapidly, robotically processed, that are applicable to dissimilar material combinations, and that enable leak-free hydrogen systems.

Develop metal joining methods that do not require high temperatures

Catalysts are being applied to reformer and electrolyzer components before the components are joined. High-temperature joining processes can damage the catalysts or make them inactive. Manufacturers will need low-temperature joining processes (e.g., laser or friction welding) that do not damage the catalyst coatings on the parts that are being joined.

Deposit catalyst coating onto nonconformal surfaces

A standardized, automated method for applying catalyst coatings to nonconformal surfaces (applying catalysts directly to heat exchange surfaces) will accelerate our ability to produce reformers and shift catalysts on a large scale. This approach will also benefit the deposition of catalysts onto electrode substrates for electrolysis. In-line quality control methods need to be developed.

Manufacture reaction vessels with protective coatings

Manufacturers will need an improved method for applying nickel cladding to lower cost metal substrates to reduce material costs. Developing alloys for brazing that enables a corrosion resistant reactor will be important.

Fabricate and heat-treat large-scale pressurized hydrogen vessels (for off-board storage)

The necessary retention of mechanical strength for pressure vessels is complicated by the thick walls needed for hydrogen containment. Advances in heat treatment of thick-walled vessels will lead to lower cost production processes. Laser heat treatment offers the opportunity for in-line processing of vessels.

Perform R&D for the manufacture of large composite pressure vessels from filaments (for off-board storage)

Filament-wound, composite pressure tanks are presently produced using “hand lay-up” techniques. Improved manufacturing methods for metallic, composite, and polymeric tanks are needed to resolve the issues of large-scale pressurized hydrogen storage (e.g., improved annealing methods, localized winding of carbon filaments).

Develop accelerated test methodologies to validate materials and processes

Accelerated test methods are needed to rapidly characterize performance in manufacturing processes and in end-use (product) applications.

Table ES-3: Summary of High-Priority Manufacturing R&D Needs: Hydrogen Storage

Develop process technologies for reducing the cost of carbon fiber

Currently, composite tanks require high-strength fiber made from carbon-fiber grade polyacrylonitrile precursor. The price of the carbon fiber is typically about $20/kg. Reducing the cost of the fiber by about 60%, or about $6/kg, would yield significant savings in the unit cost of composite tanks. Manufacturing R&D is needed to develop lower cost, lower energy decomposition process for carbon fibers, such as microwave or plasma processing.

Develop new manufacturing methods for high-pressure composite tanks

New manufacturing methods are needed that can speed up the cycle time, that is, the per unit fabrication time. Potential advances in manufacturing technologies include faster filament winding (e.g., multiple heads), new filament winding strategies and equipment, continuous versus batch processing (e.g., pultrusion process). New manufacturing processes for applying the resin matrix, including tow-pregs for room temperature curing, wet winding processes, and fiber imbedded thermoplastics for hot wet winding, should also be investigated.

Develop manufacturing technologies for conformable high-pressure storage systems

Although this is a design issue (improved energy density), new manufacturing methods for carbon fiber winding and fiber placement manufacturing could also be applied to improve conformability of tanks by allowing modified cylindrical tank shapes to be manufactured.

Improve fiber placement processes

Fiber placement technologies can reduce unit costs by reducing the amount of carbon fiber needed by as much as 20%-30%. This approach may also allow some improvement in conformability of high pressure tanks. However, the process is slow. New methods and equipment are needed to improve manufacturing cycle time.

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Introduction

America's future well-being is linked to the availability of clean, secure, sustainable energy. To reduce or eliminate our dependence on imported oil, and to ensure that the nation has access to domestic, clean energy supplies, the United States is actively engaged in research and development (R&D) of materials and enabling technologies for producing, delivering, storing, and using hydrogen as an energy carrier.

> *"Hydrogen is America's clean energy choice. Hydrogen is flexible, affordable, safe, domestically produced, used in all sectors of the economy and in all regions of the country."*
>
> -A National Vision of America's Transition to a Hydrogen Economy—to 2030 and Beyond

Many scientific, technical, and institutional challenges must be overcome to realize the vision of the hydrogen energy economy.[1,2] This Roadmap focuses on one major challenge—developing low-cost, high-volume manufacturing of hydrogen technologies—which has been identified by U.S. industry as a potential showstopper to a future hydrogen economy.

Manufacturing and the National Vision for the Hydrogen Economy

In his 2003 State of the Union address, President Bush proposed the Hydrogen Fuel Initiative (HFI) to reverse the United States' growing dependence on foreign oil by developing the technology needed for commercially viable hydrogen-powered fuel cells. Through the HFI, the President committed to request from Congress $1.2 billion for the first five years (fiscal years 2004−2008) of a long-term R&D effort for hydrogen infrastructure and fuel cell technologies.[3] The U.S. Department of Energy (DOE) is leading the HFI through an R&D program that is summarized in DOE's Hydrogen Posture Plan.[4] A major milestone of the HFI is to develop hydrogen technologies to the point that American industry can make a commercialization decision about hydrogen fuel cell cars and fueling systems by 2015 so these vehicles can begin to penetrate the consumer marketplace by 2020.

The HFI focuses on researching and developing critical hydrogen and fuel cell technologies. As these technologies become ready for commercialization, manufacturing processes must be developed concurrently to (1) reduce the costs of hydrogen systems to levels that are competitive with petroleum-based systems and (2) build the necessary manufacturing infrastructure to support the hydrogen economy. A sound understanding of projected costs for manufacturing hydrogen components and systems will be a key factor in industry's commercialization decision on hydrogen fuel cell vehicles and fueling systems in the 2015 timeframe.

The Congress, in passing the Energy Policy Act of 2005 (Public Law 109-58), authorized R&D on the manufacturability of hydrogen systems under Title VIII – Hydrogen, Section 805.[5] Manufacturing R&D is a new activity that DOE recommends for the HFI.

The National Research Council has recognized the need for both hydrogen and fuel cell technology development and the development of advanced manufacturing processes:

> The development of commercially viable fuel cells and onboard hydrogen storage is, without question, the most difficult vehicular aspect of this program. Multiple challenges are being addressed: performance, durability, efficiency, and cost, and they are being worked on at all levels: basic technology, the individual components, stacks, and systems.
>
> For fuel cells, durability and cost are the most difficult goals, and for hydrogen storage, the most difficult are size, weight, and cost. In most instances, solutions depend on yet-to-be-conceived or -proven component and manufacturing technology rather than incremental improvement.[6]

The President has also directed that a national initiative on manufacturing be undertaken.[7] This initiative will strengthen American manufacturing, create new jobs, and help U.S. manufacturers become more competitive in the global marketplace.

The Manufacturing Research and Development Interagency Working Group (IWG) of the President's National Science and Technology Council (NSTC) was established to coordinate and leverage the current federal efforts that focus on issues such as low-cost, high-volume manufacturing systems, advanced manufacturing technologies, manufacturing infrastructure, and measurements and standards (see Appendix A).[8] During fiscal year 2005, DOE and the Department of Commerce, through the IWG, laid the groundwork for coordinating and guiding R&D efforts on manufacturing processes critical to commercializing hydrogen and fuel cell technologies.

Manufacturing R&D

Reducing the cost of systems that produce, distribute, and use hydrogen is critical to commercializing hydrogen fuel cell vehicles. Although costs can be reduced significantly through R&D on hydrogen technologies, further cost reductions must be realized by advances in manufacturing processes. Manufacturing R&D of new processes for hydrogen systems is critical to driving down costs.

Costs can be reduced by improving the reliability and efficiency of manufacturing and by achieving economies of scale. Experience curves that relate unit cost reduction per doubling of cumulative production or production capacity are available for several industries and demonstrate the magnitude of possible cost reductions (see Figure 1).

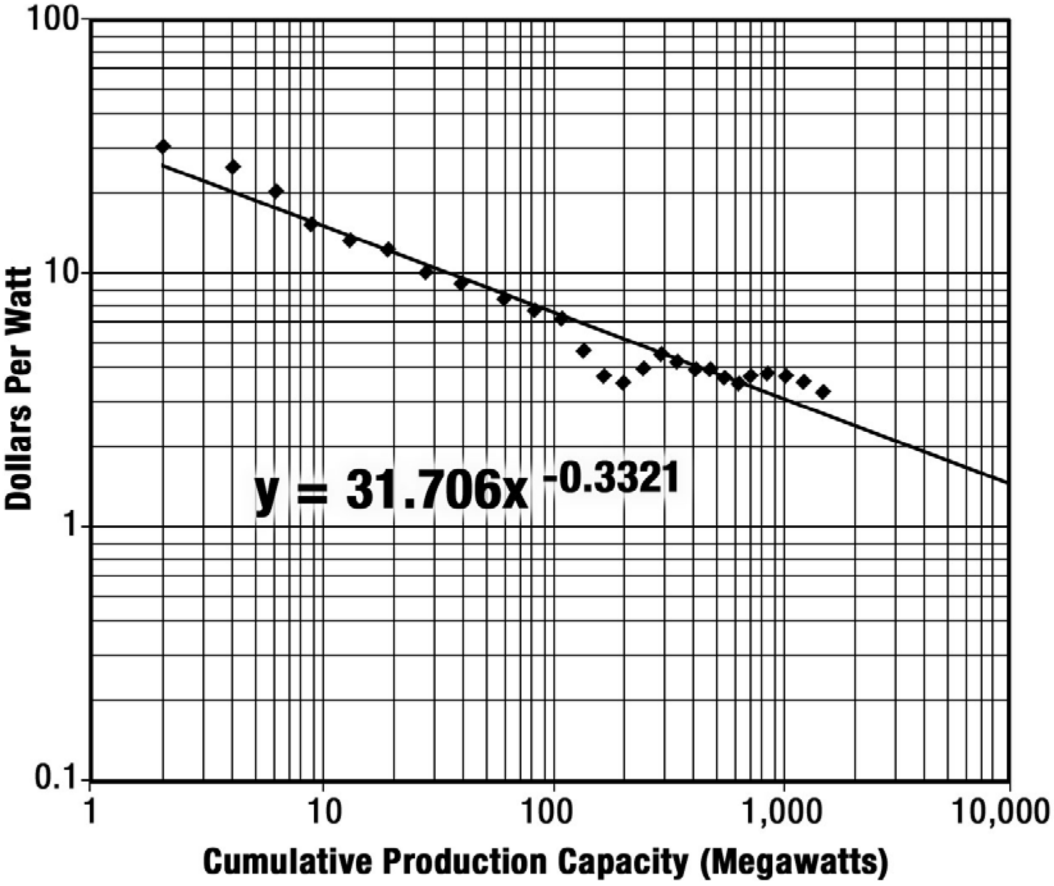


Figure 1: Manufacturing experience and economies of scale have led to decreases in the cost of photovoltaic modules as cumulative production capacity has increased.[9]

Manufacturing for the Hydrogen Economy, in the context of this roadmap, is the manufacture, in large-scale industrial operations, of components and their assembly into products that can be used to produce, deliver, store, and use hydrogen via polymer electrolyte membrane (PEM) fuel cells.[10] Cost of materials is an element of the manufacturing cost; however, manufacturing R&D focuses on processes and equipment. In addition, cross-cutting technologies and capabilities will undergird the manufacturers' processes: metrology and standards, modeling and simulation tools for manufacturing processes, knowledge bases for manufacturing, design for manufacturing, and sensors and process control. Of course, U.S. industry must build manufacturing capacity from thousands to millions of units per year as demand for products increases.

The key goals for Manufacturing R&D for the Hydrogen Economy are to:

- Reduce the cost of hydrogen components and systems to make them economically competitive.
- Transform laboratory processes to high-volume manufacturing.
- Develop a manufacturing infrastructure for hydrogen systems.
- Develop supplier base and networks.

Manufacturing R&D Drivers—Volume, Cost, and Quality

This manufacturing R&D roadmap emphasizes the expected demand for hydrogen production, hydrogen storage, and fuel cells within the transportation sector. Other applications for hydrogen and fuel cells such as portable and stationary uses will also play important roles in the hydrogen economy, and much of the manufacturing R&D that is recommended in this roadmap also applies to these markets. Manufacturing drivers from the automotive and energy industries of volume, cost, and quality can be understood in two contexts: providing vehicles and providing fuel for the vehicles.

With respect to the vehicles, automotive manufacturers today are under enormous competitive pressure to maintain production volume and to continually reduce costs and improve quality, reliability, performance, and safety. Many of these requirements are passed along to the well-established chain of automotive component suppliers. About 17 million light-duty vehicles are sold in the United States annually, about 12 million of which are produced in the United States.[11] (See Table 1.) Companies that manufacture fuel cell vehicle components and systems will be required to produce hundreds of thousands or even millions of units and meet stringent automotive quality assurance standards and drastically reduce costs.

With respect to providing fuel, manufactured systems for producing and delivering hydrogen will need to satisfy the mammoth U.S. energy sector. In 2000, energy expenditures accounted for 7.2% of the nation's $9.8 trillion gross domestic product, and the United States consumed almost 99 quadrillion British thermal units (Btu) of energy. The transportation sector accounted for 27% of the total energy consumed (26.5 quadrillion Btu).[12] The United States uses about 20 million barrels of oil per day, at a cost of about $6 billion per week (assuming a cost of $45 per barrel of oil). About two-thirds of this petroleum is used to power our vehicles, and about 22% is imported from the Middle East.[13]

No single company currently has the manufacturing capacity to produce more than a few hundred fuel cell power systems per year. Gradual conversion to fuel cell vehicles is anticipated, but a three to four orders of magnitude increase in production rate will be needed for the transition to a hydrogen-based fuel cell transportation system.

Table 1: U.S. Vehicle Production 2003[14]

Year	2003
Production, total	11,829,000
Passenger cars	4,510,000
Light trucks[a]	7,319,000

[a] Light trucks include gross vehicle weight rating classes 1−3, less than 14,001 lb, including pickups, vans, minivans, and sport utility vehicles.

The present cost of direct hydrogen fuel cell power systems is high and investment tax credits[15] of up to $1,000/kW (to 30% of the cost) are currently available to counterbalance the high cost of fuel cell power systems. However, TIAX LLC has forecast the cost of PEM cells with today's technologies at $108/kW for a net 80-kWe system based on a large-scale production of 500,000 units per year with the assumed benefits of large-scale production.[16] The major factor for the difference between today's cost and projected cost is the cost of manufacturing at today's production rates of hundreds of power plants per year compared to projected mature production process costs for 500,000 units per year.

As hydrogen and fuel cell production volumes increase, quality assurance will become a key manufacturing issue. In the automotive and other industries, the cost of poor quality can include scrapped and reworked parts, poor performance, manufacturer recalls, safety issues, liability, and lost customers. For new and emerging technologies, the cost of poor quality can also greatly influence customer acceptance. As suppliers to the automotive industry, hydrogen and fuel cell component manufacturers will be required by their customers to become certified to specific uniform quality assurance standards such as QS9000 and ISO/TS 16949.[17]

With respect to costs, manufacturing accounts for a significant portion of hydrogen and fuel cell component and system costs, and plays a crucial role in ensuring quality, safety, reliability, and performance. Thus the drivers for manufacturing will require no less than a transformation of the U.S. manufacturing sector to realize the benefits of the hydrogen economy.

Benefits

Benefits to be realized from manufacturing R&D for the hydrogen economy are:

- **Accelerated transition from a petroleum-based energy economy to the hydrogen economy**—Manufacturing R&D will enable industry to overcome manufacturing challenges and build manufacturing capacity. Public-private manufacturing R&D activity integrated with the HFI will spur these developments and accelerate the transition from petroleum to hydrogen in the United States. These activities will enable the United States to more rapidly realize the benefits of energy diversity, improved environmental quality, and economic well-being.
- **Enhanced economic competitiveness**—Our nation's increasing dependence on imported petroleum threatens America's economic well being as the price of oil increases. Hydrogen energy systems will offer an array of new opportunities for U.S. companies if American industry is positioned to take advantage of these opportunities. Enhanced economic competitiveness in providing products for the global hydrogen economy will enhance our economic well-being.
- **American jobs**—As the United States transitions to the hydrogen economy, the demand for products used in a petroleum-based economy will diminish and the manufacturing jobs will see the same type of shift. By establishing a manufacturing base for the transition to the hydrogen economy, we can create new jobs as the demand for current jobs decreases.[18]

R&D Roadmap—Manufacturing for the Hydrogen Economy

On July 13−14, 2005, DOE, supported by the National Institute of Standards and Technology (NIST) and coordinating with the IWG, brought together representatives from the hydrogen and fuel cell R&D and the manufacturing communities to create a roadmap for R&D on manufacturing for the hydrogen economy. Participants in the Workshop (see Appendix B) on Manufacturing R&D for the Hydrogen Economy discussed the issues that three major aspects of manufacturing for the hydrogen economy face. These aspects included (1) hydrogen production and delivery systems, (2) onboard vehicle storage, and (3) PEM fuel cells. Workshop participants identified key manufacturing challenges and recommended priorities for manufacturing R&D to facilitate commercialization of hydrogen technologies. The recommendations are incorporated into this *Roadmap on Manufacturing R&D for the Hydrogen Economy*.

Although the workshop focused on manufacturing R&D, participants also identified some needs for materials and technology development. Many of the technology R&D needs focus on materials. Materials and technology R&D is currently being addressed in the HFI; manufacturing R&D is recommended as a new DOE activity to be integrated with the HFI.

Workshop participants are reviewing this draft version of the roadmap; their comments will be reflected in the final version. DOE is also seeking input from experts in hydrogen and manufacturing who did not attend the workshop

Polymer Electrolyte Membrane Fuel Cells

Introduction

Polymer electrolyte membrane (PEM) fuel cells offer the United States the potential to power our vehicles with increased fuel efficiency and near zero emissions. DOE, under the HFI, is focusing its fuel cell R&D on PEM fuel cells for automotive and stationary applications. (DOE is also developing solid oxide fuel cells under the Office of Fossil Energy principally for stationary applications.)

PEM fuel cells have fast start capability, operate at low temperatures, and have specific energy densities that satisfy the requirements for a light-duty vehicle. Researchers who are involved in basic and applied research and technology development have made significant progress toward achieving DOE's performance, durability, and cost goals.[19] Specifically, DOE's goals are a 60% peak-efficient, durable, direct hydrogen fuel cell power system for transportation at a cost of $45/kW by 2010; and at a cost of $30/kW by 2015.[20]

The pathway to cost reduction of PEM fuel cells is illustrated in Figure 2. Today's estimate of the cost of fuel cells is based on advances already achieved in PEM fuel cell technologies coupled to assumptions of high-volume manufacturing. As depicted in the second arrow (to the right), further cost reduction will require technology R&D and development of new manufacturing processes.

> *"For viable fuel cell systems to reach the FreedomCar goal of ~$30/kW, low-cost materials, new, high-volume manufacturing technologies, and better performance and reliabiity must converge."*
>
> - Review of the Research Program of the FreedomCAR and Fuel Partnership, first report 2005, National Academies of Science, Washington, D.C. www.nap.edu/books/0309097304/html/

By 2010, an increase in the production volume of PEM fuel cell power systems to 10,000−20,000 per year (for all applicable applications) with a corresponding reduction in cost, is an important milestone identified by the industry participants at the workshop.[21] The DOE 2010 cost target for PEM fuel cell power systems is $\$45/kW_e$[22] and is based on production of 500,000 power systems per year. PEM fuel cell systems manufactured at a volume of 10,000 to 20,000 per year will most likely not achieve the target of $\$45/kW_e$. However the cost reduction associated with these lower production levels will provide a pathway for industry to identify and overcome subsystem and component manufacturing cost hurdles for the continuous transition to 500,000 power systems or greater per year for the transportation industry.

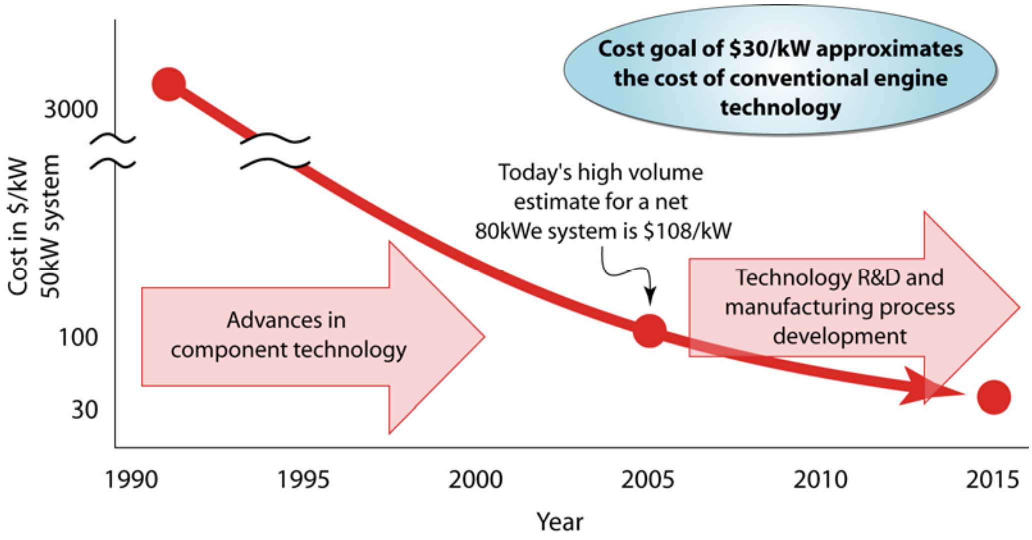


Figure 2: Cost reduction for PEM fuel cells will be realized through technology development coupled to manufacturing R&D.[23]

This section of the manufacturing R&D roadmap focuses on manufacturing R&D for PEM fuel cells. Table 2 summarizes the high-priority manufacturing needs for PEM fuel cells to provide context for the following discussion.

Table 2: Summary of High-Priority Manufacturing R&D Needs: PEM Fuel Cells

Identify relationships between physical and manufacturing properties of MEAs and performance properties of MEAs

Manufacturing R&D that correlates physical properties of the MEA with performance properties is a high-priority need. The relationship between the *ex-situ* manufacturing properties and the *in-situ* properties that pertain to performance and durability needs to be established. The relationship could be an empirical-, mathematical-, or physical-based transfer function. Supporting this approach is a strong need for sensor technology that permits in-line inspection and would provide the database for statistical quality control.

Identify cost of PEM fuel cells, especially MEAs, at several levels of manufacturing

Industry considers a continuum in the development of fuel cells, especially the MEA, to be an important issue. A broad range of cost analyses that embrace the transition from low production levels to the high production levels is needed to establish progress goals in the development of manufacturing processes.

Develop agile, flexible manufacturing

Changes in manufacturing in response to changes in the materials and designs of MEAs result in high costs. More flexible (agile) and integrated manufacturing approaches are a high priority for the manufacture and assembly of MEAs. Industry will need agile manufacturing processes that can be adapted to the developing membrane, catalyst, and gas diffusion layers without incurring major capital expenditures.

Develop understanding of how manufacturing parameters affect catalyst layers

The relationship between catalyst layer manufacture and the performance and durability of the catalyst layer needs to be delineated to implement high-speed manufacturing processes. New methods of manufacturing will be important to fabricate new catalyst layers that meet the low precious metal cost targets.

Develop strategies for high-speed seal applications

High-speed processes need to be developed to integrate MEA components that include incorporating edge and interfacial seals and gaskets. Merging the MEA sealing assembly process with the bipolar plate sealing in a continuous process could lead to cost reductions in the assembly of the cell stack.

Apply and develop modeling tools for MEA manufacture

Integration of computer aided design tools with technology development and manufacturing R&D will advance performance and cost reduction opportunities.

Characterize membrane defects and develop fabrication techniques

Characterize defects in membranes and their causes to permit in-line control of membrane and MEA manufacture.

Develop high-speed forming, stamping, and molding of bipolar plates

Current processes individually form or machine the bipolar plates. Manufacturing bipolar plates requires the development of new high-speed forming, stamping, and molding processes that will maintain the high tolerance requirement of the PEM fuel cell. Rapid prototyping and flexible tooling specifically for the manufacture of bipolar plates is on the critical development path.

Develop automated processes to assemble cell stacks

Automated processes are needed to rapidly assemble cell stacks. Design for manufacturability and assembly should be applied to cell stack development to enable processes that lead to identical cells and eliminate the need to measure each cell component during cell stack assembly.

Develop high-speed welding/joining

Present laser welding methods are either too slow or too expensive for metallic bipolar plate manufacturing. Fiber lasers for microwelding bipolar plates need to be developed to achieve linear welding speeds greater than 50 meters per minute.

Develop materials for low cost and high performance heat exchangers (materials issue)

PEM fuel cells have at least four heat exchangers within the balance-of-plant (BOP). Composite or plastic heat exchangers that can be fabricated at high volume and low cost could provide a low-cost path for the manufacture of PEM power systems. Manufacturing processes will need to be developed for these new materials.

Establish protocols for qualifying new materials and processes (materials issue)

Materials that are compatible with PEM fuel cells need to be identified for all manufacturers. Presently individual fuel cell manufacturers specify acceptable materials. A compilation of materials acceptable to all fuel cell manufacturers will enhance the establishment of a supply chain network. Protocols need to be developed for qualifying new materials to be used in the manufacture of PEM fuel cells.

Develop frameless fuel cell systems (design issue)

PEM power systems are currently built by fitting components and subsystems in the power system box. Designs for assembly of the unit would address the interaction of subsystems and develop concepts for production and assembly of power systems. Design for manufacturing and assembly should be applied to the BOP to reduce the part count of integrated systems.

Develop manufacturing and assembly processes for interim production volumes

Manufacturing approaches suitable for an interim production volume of 5,000−50,000 power systems per year are a pathway to the large scale transportation production processes. Rapid prototyping and agile manufacturing are pathways to be developed for the construction of PEM BOP and PEM power system.

Establish flexible automated manufacturing technology facility

A national facility is needed to test flexible, automated manufacturing technology for BOP and power system assembly and component manufacture. It could provide a test bed for developing manufacturing processes, could be available to component and fuel cell manufacturers, and could serve as a clearinghouse for PEM fuel cell manufacturing R&D.

Develop production hardware for rapid leak detection

Leak testing of the BOP and power system is time-consuming and costly for today’s PEM power system production. Rapid leak testing that can be accomplished in the production line and at production line rates is needed.

Table 3: PEM Fuel Cell Subsystems and Components

Cell Stack	
Major components to be manufactured	• Membrane • Catalyst layer • Gas diffusion layer • Seals • Bipolar plates • Coolers • Gas manifolds
Assembly of components into a cell stack subsystem	• Component assembly • Cell stack loading • Pressure testing • Stack conditioning
Balance-of-Plant	
Major components to be manufactured	Water and thermal management components and subsystems • Electric water pump • Electric valves • Controllers: temperature, pressure, and flow rate • Water and coolant reservoirs • Heat exchangers Reactant (H_2 and O_2) management subsystem • Electric air blowers and turbo-compressors • Hydrogen recycling pumps • Controllers: reactant flow, pressure, and humidity • Reactant pre- and post-conditioning heat exchangers
Assembly of components into a cell stack	• Subsystem assembly • Subsystem testing • Integration of modules into a subsystem • Subsystem testing
Power Conditioning and System Controls	
Major modules to be manufactured and assembled into a power conditioning subsystem	• DC/DC boost • Super/ultra capacitors • Power regulation: DC/DC converter or DC/AC converter

PEM Fuel Cell Systems to Be Manufactured

The PEM fuel cell power system for a light-duty vehicle is an 80 kW (net) device operating on direct hydrogen. There are three major subsystems within the PEM fuel cell power system: the cell stack, the BOP, and power conditioning/systems controls. Table 3 lists PEM fuel cell subsystems and components. The cell stack (see Figures 3 and 4), is the heart of the electrochemical device and generates unregulated direct current (DC) power. Power conditioning, while integrated with the light duty vehicle controls, converts the raw unregulated DC power from the stack to regulated power. The regulated power will be either DC or alternating current (AC) depending on the vehicle system requirement. Cost targets of the major subsystems and their respective components are given in Table 4.

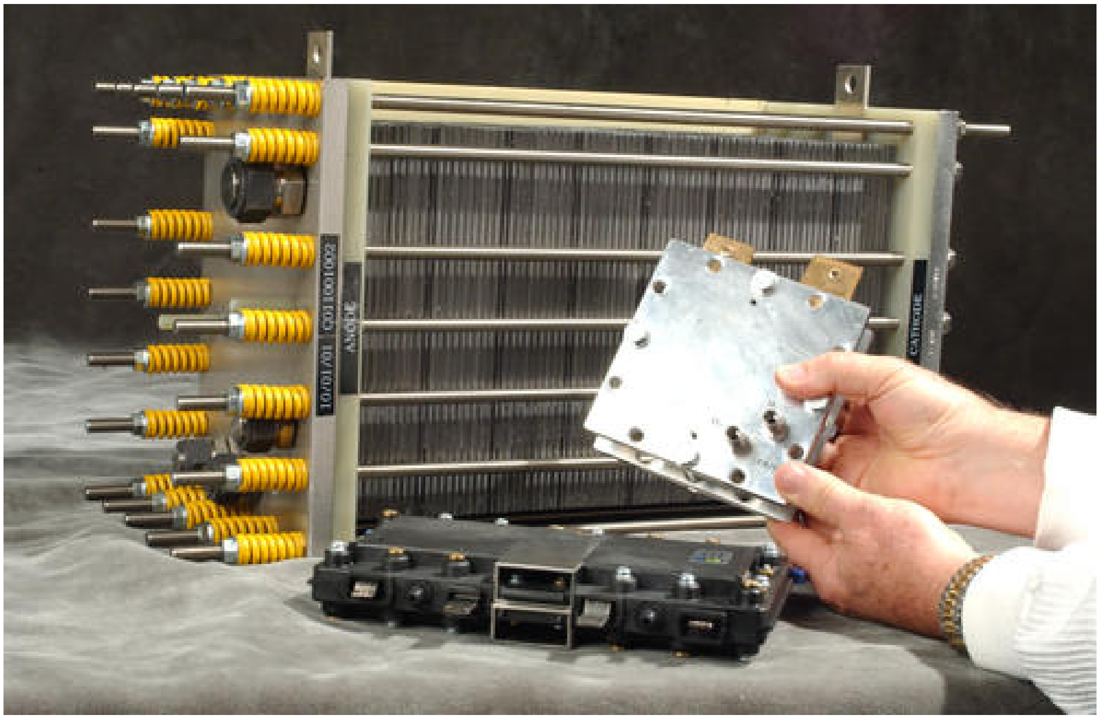


Figure 3: 5-kW fuel cell manufactured by PlugPower (large cell), 25-watt fuel cell (three cell stack) manufactured by H2ECOnomy (smaller silver cell), 30-watt fuel cell manufactured by Avista Labs.[24]

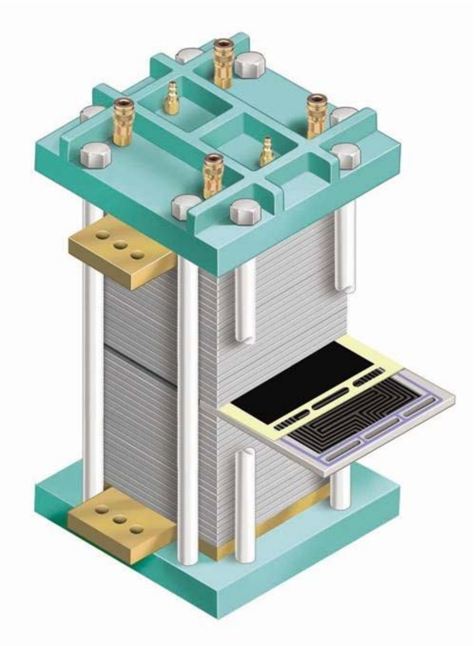


Figure 4: The fuel cell stack is the heart of the PEM fuel cell power system.[25]

Status of Manufacturing

U.S. production rates of fuel cell power systems are currently lower than 1,000 per year.[28] No one company produces more than a few hundred power systems per year. The National Research Council and the National Academy of Engineering proposed an “optimistic market scenario” of new hydrogen fuel cell and hybrid vehicles.[29] This suggests that fewer than 10% of new vehicle sales will be hydrogen fueled by 2020 and will increase 50%–60% in the following 15 years. Based on projections of a one-to-one relationship between the number of vehicles and PEM fuel cell power system requirements, millions of PEM fuel cells will be needed in the long term for light-duty vehicles. In 2005 only a few hundred direct hydrogen fuel cell vehicles will be produced worldwide, primarily for demonstration and validation programs. There is a large gap between 2005 fuel cell vehicle production and the “optimistic market scenario” production rates for the long term.

Table 4: Manufacturing Needs of Major Subsystems and Components[26]

Cell Stack	• Membrane	• $12/kW[27]
	• Catalyst	• $6/kW
	• Bipolar plates	• $4/kW
	• MEAs	• $10/kW
Balance-of-Plant	Air delivery system	$200/power system

Fuel cells are now manufactured with laboratory fabrication methods that have typically been scaled up in size, but do not incorporate high-volume manufacturing technology. The MEAS in fuel cells are multilayered structures. A five-layer structure, shown in Figure 5, is assembled in five separate stages, and then hot pressed to bond the layers together. The bonding is affected by the edge seal material, which typically has thermal set or thermal plastic properties. The final product is called, depending on manufacturer, a unified electrode assembly or unified cell device (UCD). All these manufacturing steps are conducted as discrete operations with most of the actual labor done by hand; indexing the anode and cathode layers is very time intensive.

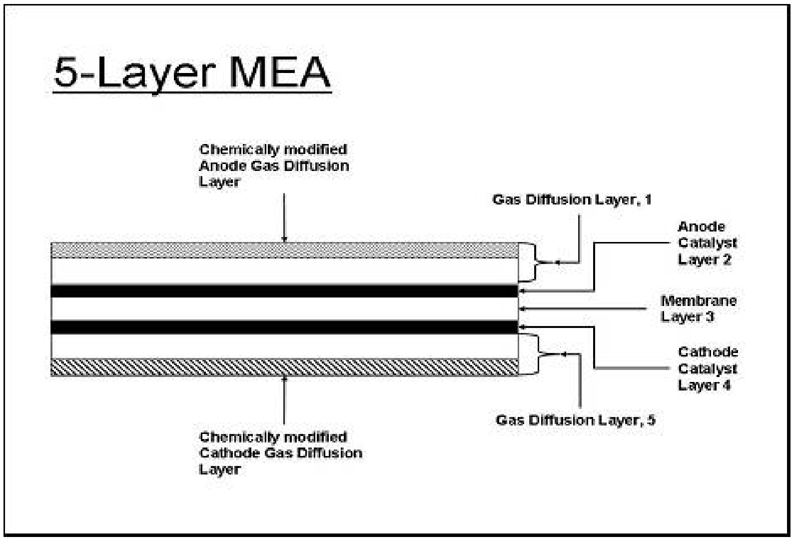


Figure 5: Components of a five-layer MEA (including the gas diffusion layer). It is assembled in five stages.

Precious metal catalysts represent a significant contribution to the overall cost of fuel cells. Recognized, reliable, and repeatable measurement technologies and methodologies that would allow catalyst application to be optimized within fuel cell stacks would greatly reduce fuel cell cost from both a materials and a process perspective. Figure 6 shows an example of a continuous catalyst coating method, one of the early improvements in moving toward high-volume manufacturing.

Assembling the fuel cell stack requires precise control of the layout of the individual UCDs to ensure direct alignment of the electrodes in adjacent cells. Between the UCDs is the bipolar plate whose flow fields are again carefully indexed. For cells with internal manifolds, sealing the bipolar plate to the UCDs is critical to avoid mixing reactant gases. An additional component for the stack is the cooling plate, which like the bipolar plate must maintain strict flatness and parallelism tolerances. Assembly today requires repetitive measurement of stack components and close tolerances for seals to ensure performance. Manufacturing ancillary equipment such as compressors, flow controllers, and converters must also be addressed.

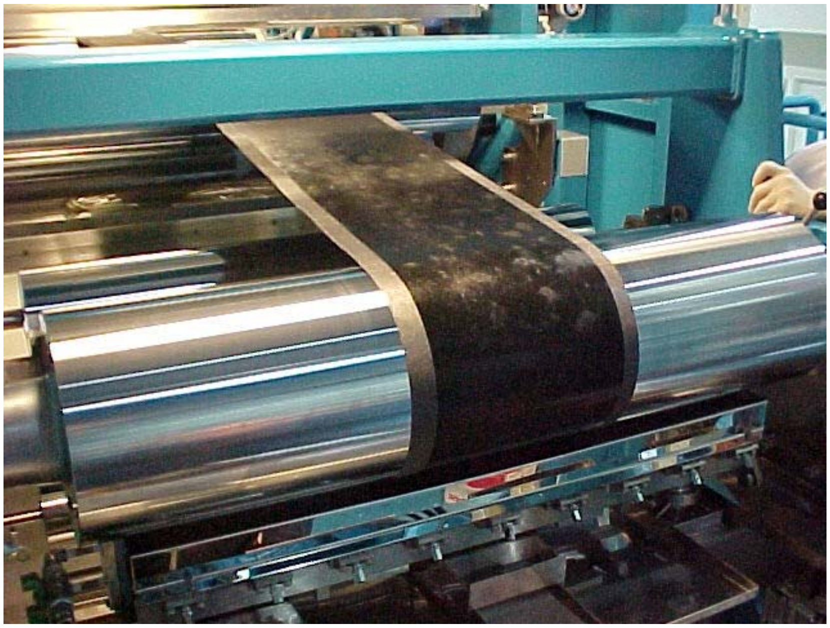


Figure 6: Semi-automated discrete/continuous fabrication of catalyst coating.[30]

The BOP has several major subsystems: the water and thermal management subsystem, reactant management subsystem, power conditioning subsystem, and power system controls subsystem. These major subsystems are individually assembled by joining components. Joining operations include connecting the heat exchangers to the coolant system and integrating the humidification system with the air blower. The power system is usually assembled by integrating subsystems; however, each subsystem is assembled separately by a labor-intensive process. Gas, water, and coolant manifolds may be constructed on site. To weld and join components, each connector must be separately cut, prepared, and joined to the subsystem. Prefabrication and molding of components are limited if used at all. A lack of standardized components is one reason for the limited manufacturing capability.

Manufacturing Challenges

The successes of the ongoing DOE PEM fuel cell technology development efforts are paving the way for high durability, high performance, and reduced cost. Developing manufacturing processes is now critical to further reduce cost and to ensure that PEM fuel cell development efforts do not constrain the manufacturing of the fuel cell components and subsystems.

The transition to high-volume PEM fuel cell production will require that quality control and measurement technologies be established early, consistent with the development of high-volume manufacturing processes. Process control strategies that are specific to producing fuel cell components are needed to reduce or eliminate sampling and testing of components, modules, and subsystems.

As fuel cell manufacturing scales up, the relationships between fuel cell system performance and manufacturing process parameters and variability must be well understood. Such understanding does not currently exist, but it can play a major role in fuel cell design, and it is integral to implementing design for manufacturability. Modeling and simulation can play significant roles in developing this understanding. Establishing the knowledge bases (including documents, databases, and models) for fundamental, precompetitive manufacturing process technologies, reliable measurements, and standards will advance PEM fuel cell manufacturing. Identifying correlations between properties measured during the fabrication of components and the performance properties of fuel cells will advance fuel cell manufacturing.

Paths Forward

Manufacturing R&D needs and approaches can be grouped into three categories: (1) membrane electrode assemblies; (2) bipolar plates and cell stack assembly; and (3) BOP, including integrating the subsystems for water and thermal management, reactant management, power conditioning, and system controls.

Membrane Electrode Assembly

The following recommendations focus on manufacturing R&D to enable high-volume manufacturing of MEAs.

Priority I (High)

- Identify relationships between physical properties of MEAs (from manufacturing) and performance properties of MEAs.

  Precompetitive manufacturing R&D to correlate the physical properties of the MEA with performance properties is a high-priority activity. The relationship between the *ex-situ* manufacturing properties and the *in-situ* properties that pertain to performance and durability needs to be established. The relationship could be an empirical-, mathematical-, or physical-based transfer function. Supporting this approach is a strong need for sensor technology that permits in-line inspection and will provide the database for statistical quality control.

- Identify the cost of PEM fuel cells, in particular MEAs, at several levels of manufacturing.

  Continuity in the development of fuel cells, especially the MEA, is an important issue for industry. A broad range of cost analyses that address the transition from low production levels to the high production levels need to establish targets for developing manufacturing processes.

- Develop agile, flexible manufacturing.

  Changes in manufacturing due to changes in the materials and designs of MEAs result in high manufacturing costs. More flexible (agile) and integrated manufacturing approaches are a high priority for MEAs. Industry will need manufacturing processes that can be adapted to new developments in membrane, catalyst, and gas diffusion layers without incurring major capital expenditures.

- Develop an understanding of how manufacturing parameters affect catalyst layers.

  The relationship between catalyst layer manufacture and its performance and durability needs to be delineated to implement high-speed manufacturing processes. New methods of manufacturing will need to be developed to fabricate the new catalyst layers that meet the low precious metal cost targets.

- Develop strategies for high-speed seal applications.

  High-speed processes need to be developed to integrate MEA components that include edge and interfacial seals and gaskets. Merging the MEA sealing process with the bipolar plate sealing in a continuous process could lead to cost reductions in the assembly of the cell stack.

- Develop and apply modeling tools for MEA manufacture.

  Integrate computer-aided design tools with manufacturing R&D to concurrently improve performance and reduce cost.

- Define characteristics of membrane defects and develop membrane fabrication techniques.

  Characterize defects in membranes to permit in-line control of membrane and MEA manufacture. There is an immediate need to develop in-line control strategies to detect defects in membranes during fabrication. Integrated high-speed sensor measurements and the control processes are needed to eliminate membrane defects during the manufacturing process. Statistical process control strategies are needed to optimize the manufacturing process.

- Develop methods for catalyst layer manufacture.

  The use of three dimensional catalyst layer structures requires precise control of the porosity and the distribution of catalyst and membrane. New high-speed manufacturing methods are needed to ensure the three-phase interface—catalyst layer/membrane/gas phase—is manufactured for optimal performance.

- Develop industry standard testing procedures.

  Presently, each MEA manufacturer and fuel cell developer develops and defines quality control procedures for performance and durability. Developing an industry standard would permit suppliers to better refine the manufacturing processes.

Priority II (Medium)

- Standardize the dimensions of MEAs.

  There is no single standard size for MEAs among fuel cell manufacturers. Industry must take the lead in standardizing MEAs. Cost reductions and efficiencies of scale could be achieved if standard width and length of the MEA were established.

- Develop methods to characterize catalyst layers in line.

  Catalyst layer properties are currently characterized through off-line sampling and quality control (QC) testing. In-line characterization procedures that monitor the performance properties of the catalyst layer could eliminate the need for QC testing at the conclusion of the manufacturing. The approach could greatly reduce costly scrap associated with the precious metal in the catalyst layer.

- Develop MEA packaging that facilitates assembly of cell stacks.

  MEAs are currently designed to meet performance and durability requirements. Design for manufacturability and assembly of MEAs that facilitates the construction and assembly of cells stacks could eliminate a high manufacturing cost.

Priority III (Low)

- Develop processes to seal MEAs using seals with high curing temperatures.

  High-speed and continuous processes that integrate seals and gaskets into MEAs will accelerate manufacturing.

- Develop catalyst collection and recycle techniques.

  The generation of scrap during manufacture is an issue because of the high cost of precious metal catalyst. Reclaiming the scrap from catalyst manufacturing and from used cell stacks could reduce cost.

Bipolar Plate and Cell Stack Assembly

Priority I (High)

- Develop processes for high-speed forming, stamping, and molding of bipolar plates.

  Current processes individually form or machine the bipolar plates. Manufacturing bipolar plates requires the development of new high-speed forming, stamping, and molding processes that will maintain the high tolerance requirement of the PEM fuel cells. Rapid prototyping and flexible tooling specifically for the manufacture of bipolar plates is on the critical development path to high-volume manufacturing.

- Develop automated processes for assembling cell stacks.

  Automated processes for rapid assembly of cell stacks need to be developed. Design for manufacturability and assembly should be applied to cell stack development to enable manufacturing processes leading to identical cells and eliminating the need for measuring each cell component during stack assembly.

- Develop high-speed welding and joining.

  Present laser welding methods are either too slow or too expensive for metallic bipolar plate manufacturing. Fiber lasers that microweld bipolar plates to achieve linear welding speeds greater than 50 meters per minute need to be developed.

- Establish modeling techniques to control manufacturing tolerances.

  Tight tolerances for the bipolar plates and cell stacks are important in the manufacture of PEM fuel cells. A detailed understanding of the manufacturing variability and its impact on the performance of the bipolar plate and fuel cell is necessary to establish tolerances. Models that can predict performance variances based on in-process measurements will need to be developed to establish a statistical process control of the fabrication of bipolar plates. Determining optimal rather than using "overtolerance" characteristics of PEM fuel cells could lead to optimized PEM manufacture.

- Develop high-speed sealing procedures for cell stack assembly.

  The placement of seals during the assembly of cell stacks is labor intensive. Developing automated high-speed installation of seals could reduce the labor-intensive and time-consuming alignment of seals.

- Develop rapid prototyping and flexible tooling for bipolar plate manufacture.

  Applying rapid prototyping methods will facilitate the development of high-speed bipolar plate molding and forming. Rapid prototype manufacturing will permit the design to be modified with a minimum of production line changes.

- Develop continuous line manufacturing.

  Continuous line manufacturing methods could greatly drive down the cost of the bipolar plate manufacture, and continuous line processing methods similar to those used for manufacture of paper need to be developed.

Priority II (Medium)

- Accelerate stack break-in. (*Note – materials R&D issue*)

  Cell stacks require break-in to achieve performance targets. Break-in periods of 24 hours are not uncommon with today's cell stack technology. Understanding the conditioning of cell stacks from a fundamental level and use of that understanding to establish manufacturing processes that permit accelerated break-in of the cell stack are needed.

- Develop in-line test and optical measurement methods.

  Individual component testing and evaluation is time-consuming and prevents the high-volume manufacturing of bipolar plates and rapid cell stack assembly. In-line testing methods and process technologies that eliminate dependencies on part and component inspection need to be developed.

- Develop procedures for implementing design for assembly of cell stacks.

  PEM cells are presently designed with performance and durability characteristics as the primary goal. Application of design for manufacturability methodologies should be included. Specifically, fabrication technologies that result in identical simplified cells that are easily assembled into cell stacks are needed.

- Develop in-process leak testing.

  Leak testing, in particular hydrogen leak testing, of the cell stack is time-consuming and costly. The development of rapid, in-line leak testing methods that will allow continuous measurement of the integrity of the seals could eliminate a costly testing operation.

Priority III (Low)

- Develop rapid surface treatment methods.

  Metallic bipolar plates are heat treated and have surfaces that are enriched with nitrides to prevent corrosion in the cell stack. Composite bipolar plates are surface treated to control their wettability. Present surface treatment processes are not compatible with high-volume production. Rapid surface treatments that use in-line processes need to be developed.

- Develop specialized tools for fuel cell manufacturing.

  Stack component machining requires tool replacement. This is time consuming and interrupts production. Long-life, low-cost tooling that is specifically designed for fuel cell applications will reduce the need to replace tools and will increase production rates.

- Develop nondestructive testing (NDT) methods.

  Quality control sampling of PEM stack components typically incorporates destructive testing of representative components. NDT methods will reduce scrap rates and permit thorough evaluation of cell components.

- Develop ultra-fast bonding methods.

  Bonding of plates is a tedious process that is typically controlled by the curing time of the adhesive. Alternative bonding methods that are consistent with high-volume manufacturing need to be developed to manufacture cell stacks.

- Develop low-stress clamping methods for cell stack assembly.

  The use of composite components and fragile MEAs in the assembly of cell stacks requires the development of clamping methods that rapidly align the cell stack components but do not introduce excessive strain into the components.

Balance-of-Plant and System Integration

Priority I (High)

- Develop manufacturing methods for low-cost, high-performance heat exchangers. (*Note - materials R&D issue*)

  PEM fuel cells have at least four heat exchangers within the BOP. Composite and plastic heat exchangers that can be fabricated at high volume and low cost could provide a low-cost path for the manufacture of PEM fuel cell power systems.

- Establish protocols for qualifying new materials and processes. (*Note - materials R&D issue*)

  Materials that are compatible with PEM fuel cells need to be identified for all manufacturers. Presently individual fuel cell manufacturers specify acceptable materials. A compilation of materials that are acceptable to all fuel cell manufacturers will enhance the establishment of a supply chain network. Protocols need to be developed for qualifying new materials to be used in the manufacture of PEM fuel cells.

- Develop frameless fuel cell systems.

  PEM power systems are currently built by fitting components and subsystems in the power system box. Designs for assembly of the unit would address the interaction of subsystems and simplify production and assembly of power systems. Design for manufacturing and assembly should be applied to the BOP to reduce the part count of integrated systems.

- Develop manufacturing and assembly processes for interim production volumes.

  Manufacturing approaches that are suitable for interim production volumes of 5,000−50,000 power systems per year are needed as a pathway to the large-scale transportation production processes. The economy of scale associated with the manufacture of millions of power systems may not be viable for lower volume manufacture.

- Establish a flexible automated manufacturing technology facility.

  A national facility is needed to test flexible, automated manufacturing technology for BOP and power system assembly and component manufacture. It will provide a test bed to aid development manufacturing processes, and could be available to component and fuel cell manufacturers, serving as a resource for PEM fuel cell manufacturing R&D.

- Develop production hardware for rapid leak detection.

  Leak testing of the BOP and power system is time-consuming and costly for today's PEM power system production. Rapid leak testing capability that can be accomplished in the production line and at production line rates is needed.

- Develop manufacturing processes for low-cost hydrogen sensors.

  Low cost hydrogen sensors need to be manufactured for future development. Present manufacturing methods and technologies are too costly to incorporate this key sensor into the fuel cell power system. Nanotechnology sensors and nanotechnology manufacturing methods need to be adapted to develop the low cost sensors.

- Produce simpler and faster sealing between modules and subsystems.

  Present assembly of the BOP is labor-intensive—components are joined with costly coupling and welding procedures. Design for assembly processes should be employed to develop rapid joining and sealing methods that would be compatible with automated assembly of the modules and subsystems.

- Design methods for assembly of cell stacks, BOP, and power systems.

  The present designs for PEM fuel cell power systems are typically based on prototype delivery, and the designs are only beginning to address large-scale production of cell stacks, BOP, and power systems. DFMA needs to be applied to all the subsystems and the power system to optimize production.

- Develop remanufacturing/recovery/requalification technology.

  Determining how a PEM power system will “age” and how to “restore” it successfully will include material salvage, finite element analysis, failure analysis, dimensional restoration, structural and material analysis. Applications of these techniques will provide a timeline for predicting how a product will function throughout its lifetime and provide guidelines to remanufacturers to successfully restore PEM fuel cell power systems.

Priority II (Medium)

- Design for life cycle.

  The manufacture of PEM fuel cell power systems and subsystems should include engineering design using sustainable products by concurrently addressing issues related to industrial ecology. The ability to recycle subsystems, modules, and components will help drive down power system costs. In particular, recycling of the catalyst offers an opportunity to reduce costs.

- Develop in-line test methods to eliminate off-line subsystem and power system testing.

  Present-day testing of 100% of subsystems and power system testing is costly, time consuming, and inconsistent with high-volume production of PEM fuel cells. R&D that will identify in-line testing procedures to eliminate the need for time-consuming testing could streamline the production of PEM fuel cells.

Priority III (Low)

- Develop manufacturing methods for low-cost forming of tubing to handle hydrogen.

  Tubing that carries hydrogen from the storage vessel to the cell stack needs to be defect and stress free. Low-cost forming methods need to be developed that will eliminate stresses in forming the tubing that may lead to defects.

A summary of high-priority needs and recommended approaches for fuel cell manufacturing follows in Table 5.

Table 5: Summary of Manufacturing High-Priority R&D Needs and Recommended Approaches for Fuel Cells

System	R&D Need	Approach
Membrane Electrode Assembly	Correlate MEA properties with performance metrics Cost models for scale-up of manufacturing processes More flexible (agile) and integrated manufacturing approaches In-line control strategies for membrane manufacture to detect defects Delineate the relationship between catalyst layer manufacture and the performance/durability of the catalyst layer New methods of manufacturing new catalyst layers that meet the low precious metal cost targets.	Conduct R&D to develop procedures for correlating manufacturing properties of MEAs with their performance. Develop sensors that permit in-line inspection and would provide the data for a knowledge base for statistical quality control Develop a cost analysis that incorporates the transition from low production levels to the high production levels Develop integrated high-speed sensor measurements and control processes to eliminate membrane defects during the manufacturing process. Create statistical process control strategies
Bipolar Plate and Cell Stack Assembly	High-speed forming, stamping, and molding processes A detailed understanding of manufacturing variability and its impact on the performance Automated processes for rapid assembly of cell stacks.	Create rapid prototyping and flexible tooling specifically for the manufacture of bipolar plates Develop continuous line manufacturing methods Develop models that can predict performance variances Apply design for manufacturability and assembly technology research
Materials and Design Issues	Protocols for qualifying new materials Processes for rapid sealing between BOP components and BOP modules.	Conduct precompetitive R&D on materials and processes to be used in manufacturing Apply design for manufacturing and assembly to the BOP to reduce part count of integrated systems.

Hydrogen Production and Delivery

Introduction

Today, approximately 9 million tons (~9 billion kg) of hydrogen are produced annually.[31] More than 95% of the merchant hydrogen is captive for industrial applications—chemical, metals, electronics, and space. Steam methane reforming accounts for 80% of the hydrogen produced. The remaining 20% is a by-product of chemical processes such as chlor-alkali production.[32] Water electrolysis represents only a niche segment of the merchant hydrogen market.

DOE's strategy for the near-term transition from today's production of hydrogen for industrial use to production for the emerging hydrogen economy is to focus R&D on production technologies that do not require a new hydrogen delivery infrastructure.[33] In the near-term, on-site distributed production of hydrogen via reforming of natural gas or renewable liquid fuels such as ethanol or methanol, and via small-scale water electrolysis, appear to be the most viable options for introducing hydrogen and beginning to build a hydrogen infrastructure. In the longer term, we will need large, centralized hydrogen production facilities (e.g., based on coal gasification with sequestration and biomass gasification) that can take advantage of economies of scale and meet increased hydrogen demand. Further down the road, successful R&D on photolytic technologies will lead to commercially viable systems that produce hydrogen directly from sunlight and water or other renewable sources. Each production process has its own set of manufacturing requirements and challenges.

Distributed production is the most viable option for introducing hydrogen and building hydrogen infrastructure.

The cost of hydrogen produced safely and efficiently from on-site hydrogen generators must be lowered enough to be competitive with gasoline on a cost per mile driven basis, without adverse environmental impacts. Today the cost of high-volume hydrogen production and delivery is two to three times the DOE target of \$2.00−\$3.00/gge untaxed (gge is gasoline gallon equivalent on an energy basis).[34,35] Figure 7 depicts the reductions in hydrogen production costs that need to be achieved for distributed steam methane reforming and electrolysis to be competitive with gasoline. These required reductions in the cost of producing hydrogen will require both technology and manufacturing R&D.

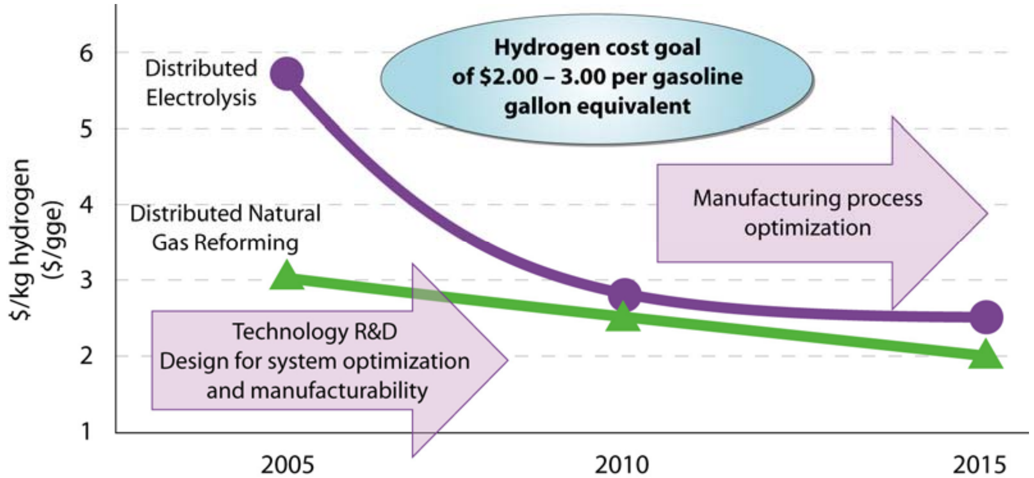


Figure 7: Cost goal for hydrogen will be realized through technology development coupled to manufacturing R&D.[36]

This section of the manufacturing roadmap focuses primarily on R&D needed to manufacture distributed hydrogen production and delivery systems—systems that will be needed in the nearer term transition to the hydrogen economy. Distributed hydrogen will be produced at the points of use and will not need to be transported over long distances. Table 6 summarizes the high-priority needs for manufacturing R&D to provide context for the discussion.

Table 6: Summary of High Priority Manufacturing R&D Needs: Hydrogen Production and Delivery

Develop joining methods to facilitate component integration

Component integration requires labor-intensive welding. Manufacturers need high-reliability, low-variability joining processes that can be rapidly, robotically processed, that are applicable to dissimilar material combinations, and that enable leak-free hydrogen systems.

Develop metal joining methods that do not require high temperatures

Catalysts are being applied to reformer and electrolyzer components before the components are joined. High-temperature joining processes can damage the catalysts or make them inactive. Manufacturers will need low-temperature joining processes (e.g., laser or friction welding) that do not damage the catalyst coatings on the parts that are being joined.

Deposit catalyst coating onto nonconformal surfaces

A standardized, automated method for applying catalyst coatings to nonconformal surfaces (applying catalysts directly to heat exchange surfaces) will accelerate the ability to produce reformers and shift catalysts on a large scale. This approach will also benefit the deposition of catalysts onto electrode substrates for electrolysis. In-line quality control methods need to be developed.

Manufacture reaction vessels with protective coatings

Manufacturers will need an improved method for applying nickel cladding to lower cost metal substrates to reduce material costs. Developing alloys for brazing that enables a corrosion resistant reactor will be important.

Fabricate and heat-treat large-scale pressurized hydrogen vessels (for off-board storage)

The necessary retention of mechanical strength for pressure vessels is complicated by the thick walls needed for hydrogen containment. Advances in heat treatment of thick-walled vessels will lead to lower cost production processes. Laser heat treatment offers the opportunity for in-line processing of vessels.

Perform R&D for the manufacture of large composite pressure vessels from filaments (for off-board storage)

Filament-wound, composite pressure tanks are presently produced using “hand lay-up” techniques. Improved manufacturing methods for metallic, composite, and polymeric tanks are needed to resolve the issues of large-scale pressurized hydrogen storage (e.g., improved annealing methods, localized winding of carbon filaments).

Develop accelerated test methodologies to validate materials and processes

Accelerated test methods are needed to rapidly characterize performance in manufacturing processes and in end-use (product) applications.

Hydrogen Production Systems to Be Manufactured

The production of hydrogen by reforming is a well-established process with large-scale production (330,000 kg hydrogen/day) and large facilities that produce hydrogen at costs that approach the DOE target ($2.00−$3.00/gge).[37] However, hydrogen delivery is costly and can more than double the cost of the fuel. Distributed hydrogen generation, with small hydrogen gas stations generating 1,500 kg H_2/day, offers an alternative to centralized production.

Distributed Reforming

Hydrogen production from steam reforming can be divided into the following major subsystems: reforming, purification, compression, and delivery (offboard storage for this roadmap). The major reforming subsystems to be manufactured are shown in Table 7.

Reducing the size of today's central hydrocarbon reforming systems to the 1,500 kg hydrogen/day level eliminates many of the economic benefits associated with high-volume hydrogen production. Researchers need to develop new designs for reformers, shift converters, steam generators, and gas cleanup systems to facilitate smaller hydrogen production rates. The distributed hydrogen generation station will use thermally and mechanically integrated reformers with shift converters and the steam generators to maximize heat recovery, minimize heat loss, and minimize the number of BOP components. The design of a pressurized reformer to facilitate gas purification will be part of those integration needs. Balancing the heat load to achieve passive temperature control and reducing the number of control loops will be critical to optimizing performance. This is technology development, not manufacturing R&D. Manufacturing R&D will be critical to producing these new designs for the future integrated hydrogen generator.

Table 7: Major Reforming Subsystems to Be Manufactured

Reforming of Natural Gas

- Reformer
- Water gas shift reactor
- Partial oxidation reactor (option)
- Supported catalysts
- Thermal management
- Water management subsystem integration
- Desulfurization and reactant cleanup
- System controls

Hydrogen Purification
(pressure swing absorption)

- Compressors
- Adsorbents (liquid/solid)
- Pressure vessels
- Subsystem controls
- Subsystem integration

Hydrogen Purification Membrane Technology

- Compressors
- Pressure vessels
- Membrane

Hydrogen Storage and Delivery

- Pressurized hydrogen storage tanks (bulk)
- Compressors
- System monitors and controls

Distributed Electrolysis

Electrolysis systems are typically divided into two major subsystems: the cell stack and the BOP. The BOP can be subdivided into the hydrogen gas cleanup module, reactant management module, and the water and thermal management module. The major components for electrolysis are identified in Table 8. All these hydrogen production subsystems, for either reforming or electrolysis, use capital-intensive equipment.

There are two ambient temperature electrolysis processes for producing hydrogen: alkaline electrolysis, which uses concentrated potassium hydroxide (KOH) as the electrolyte, and PEM electrolysis, which uses the ionomer Nafion™ as the electrolyte. The membrane for PEM electrolysis is similar to that used in PEM fuel cell. Alkaline electrolysis stacks can be either monopolar or bipolar; PEM electrolysis stacks are bipolar.

The alkaline electrolysis cell stack uses titanium and nickel extensively, which adds to the cost. The development of manufacturing methods to clad or plate low cost substrates with these metals could reduce system cost. The design and construction of the alkaline cell would benefit from manufacturing advances in joining, forming, and stack assembly. Incorporation of design for manufacturability and assembly concepts could also reduce the cost of the cell stack.

The PEM-based electrolyzer has some similarities to PEM fuel cells. It is limited by the high cost of membrane, the need for a membrane with high ion exchange capacity and low resistance, and the need for a membrane that operates at temperatures higher than 80°C. There are also differences. The PEM electrolyzer requires higher catalyst loading than PEM fuel cells and the catalyst is unsupported; i.e., the precious metal is not supported on carbon/graphite substrates. Current collection substrates (either monopolar or bipolar design) are typically stainless steel, in contrast to the carbon-based or metallic bipolar plates used in PEM fuel cells. Like the alkaline electrolyzer, the PEM electrolyzer would benefit from manufacturing R&D on joining, forming, stack assembly, and application of DFMA concepts.

Table 8: Major Components for Electrolyzers

Major cell stack components to be manufactured	• Membrane • Catalyst • Bipolar plates and seals • MEA subsystem
Balance-of-plant	• Reactant delivery system • Water management system • Thermal management system • Gas (hydrogen) cleanup • System controls

The BOP for PEM and alkaline electrolysis (Figure 8) systems has some requirements that differ from those of the BOP for PEM fuel cells. These requirements include (1) power conditioning (specific for the electrolysis process) with load following capability, (2) hydrogen cleanup to dry the hydrogen or remove alkaline impurities, (3) cold weather operation, (3) water level sensing, (4) and hydrogen pressurization. These needs are being addressed by technology development activities. The capital costs associated with the compressors and cleanup system will need to be reduced for electrolysis systems. Manufacturing R&D is needed to reduce the cost of the joining and overall construction and assembly of hydrogen gas cleanup, reactant management, and water and thermal management modules. The application of DFMA could reduce the cost of the electrolyzer BOP.

Figure 8: The TELEDYNE TITAN™ HP Generator Series produces ultrapure, pressurized hydrogen without the need for additional purification.[38]

Status of Manufacturing

The infrastructure for hydrogen as a transportation fuel has not been established. Today, hydrogen production is capital intensive, and the contribution of capital to the cost of hydrogen is larger for smaller hydrogen production facilities that are designed for distributed applications. The capital contribution to the cost of hydrogen produced by reforming is 21% for a 330,000 kg/day plant, and increases to 54% for a distributed hydrogen generation facility.[39]

The larger contribution of capital to the cost of hydrogen for the smaller hydrogen production facility is the result of site-specific fabrication and assembly of fuel processing systems, which include reformers, shift catalyst beds, and pressure swing adsorption cleanup subsystems. Manufacturers have not established standardized designs for hydrogen production facilities. Consequently, design for manufacture has not been applied to standardizing the subsystems.

For electrolyzers, capital costs for the stack constitute a significant portion of the manufactured cost. Developers have not established standard designs for manufacturing large numbers of distributed electrolyzers.

Manufacturing Challenges

Manufacturing R&D is required to reduce the high capital cost associated with establishing a dispersed hydrogen generation network, e.g., 1,500 kg hydrogen/day facilities. Reducing the high capital cost by developing manufacturing facilities for pre-fabricating hydrogen generation systems and delivering the system modules to the generation sites will also be required. Constructing modules that can be readily integrated into a hydrogen generation/delivery station offers one approach to reducing cost by eliminating on-site construction and assembly of the individual components.

For distributed reforming, the hydrogen generation module presents one of the greatest opportunities for cost reduction because it integrates two reactors that operate at elevated temperatures - the reformer and the water-gas shift reactor. Manufacturing costs for reformers are typically high because the inherent high temperature reforming process requires advanced materials, machining, joining, and welding of these materials which are labor-intensive processes. Reformer pressure vessels are another source of high cost for hydrogen production. Forming and joining high-temperature reaction materials are currently costly and labor-intensive. Establishing an automated manufacturing facility for forming, heat treating, and assembling the catalyst supports, and welding and joining the reformer components offers one approach for capital reduction.

Capital cost is an issue for the purification of the reformate because of the high-pressure processing, up to 1,000 psig, associated with pressure swing adsorption or up to 2,000 psig for membrane purification. Both require pressure vessels and the associated compressors, valves, and piping. Constructing and assembling a purification module of a standard design at a specific production facility may reduce costs.

Capital equipment costs associated with reforming of hydrocarbon fuels include the hydrodesulfurizer with its catalyst to convert odorants, such as mercaptans, to hydrogen sulfide and subsequent adsorption of the hydrogen sulfide onto zinc and copper oxides. Major equipment costs are also incurred for the water management system which includes high-pressure steam generation for the reforming and water gas shift processes.

The cost of high-pressure storage vessels constructed from thick-walled alloys (see Figure 9) must be reduced. New methods for rapid heat treatment and forging of the storage vessels could help reduce manufacturing cost.

Manufacturing costs must also be reduced for electrolysis systems. The electrolytic production of hydrogen will require scaling up the manufacture of electrodes, current collectors, membranes, and bipolar plates. These are all costly components for hydrogen electrolysis systems. Standardized, automated methods for applying catalyst coatings to electrode substrates are needed. Replacing high-value metal substrates by cladding lower cost substrates offers another path to reducing both materials and manufacturing costs.

Cleanup of hydrogen produced by electrolysis will require equipment to dry the hydrogen, and, for alkaline electrolysis, to remove electrolyte impurities such as sodium and potassium. Storing the hydrogen will likely require compressors and storage vessels similar to those required for hydrogen produced by reforming. These operations are all part of the BOP for the electrolysis system.

In all these component systems and subsystems there is a need for economies of scale, which can only be accomplished by developing advanced and, in some cases, state-of-the-art manufacturing techniques.

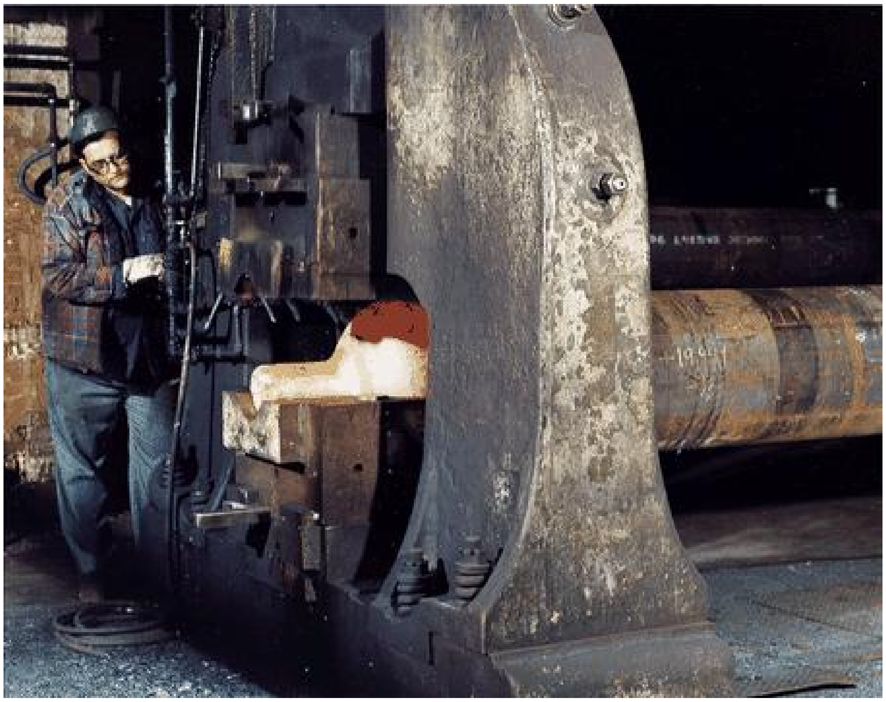


Figure 9: Improved methods for forging storage vessels offer opportunities for cost reductions.[40]

Paths Forward

Paths forward to address these challenges focus on meeting the near-term manufacturing requirements for hydrogen production and delivery. The manufacturing R&D needs for hydrogen production and delivery systems are grouped into the following topics:

- Joining methods
- Coatings and thin film deposition
- Pressurized systems and components
- Continuous manufacturing methods

Joining Methods for Production and Off-board Storage Components

Joining dissimilar materials or components is one of the single largest contributors to the overall manufacturing cost. The finished welds must be able to withstand high-temperature and high-pressure environments (for reformers), and must be impervious to hydrogen leakage and resistant to hydrogen embrittlement. Welds are currently evaluated using radiological methods that require off-line inspection, which is labor intensive and costly. The high temperatures used in current welding processes can also damage the catalyst coatings on components (of reformers and electrolyzers), which necessitates multistep manufacturing processes that minimize exposure of the coated components to high-temperature processes.

Priority I (High)

- Develop joining methods to facilitate component integration.

  Component integration requires labor-intensive welding. Manufacturers need high-reliability, low-variability joining methods that can be rapidly, robotically processed and that are applicable to dissimilar material combinations. They need methods for joining specialized materials that can be validated in an in-line manufacturing process.

- Develop metal joining methods that do not require high temperatures.

  Catalysts are being applied to reformer components before they are joined. Similarly, catalysts are applied to electrode substrates in electrolyzers before the substrates are joined to the current collectors and bipolar electrolyzer cells. High-temperature joining processes can damage the catalysts or make them inactive. Manufacturers will need low-temperature joining processes (laser or friction welding) that do not damage the catalyst coatings on the parts that are being joined.

Priority II (Medium)

- Reduce quality control testing of joints and welds for reaction vessels.

  Non-destructive testing is used to ensure the quality of the welds and joints for pressurized vessels and reactors. Advances in joining methods are needed that can reduce or eliminate the need for quality control testing. Laser machining and welding need to be improved, and incorporated to facilitate the development of fast production line processes for fabricating reformers and pressure vessels. The application of hybrid laser arc welding methods—a combination of laser welding and gas metal arc welding—offers the prospects of high rate, precision welding.

- Develop thin-sheet, bimetal cladding. (*Note − materials R&D issue*)

  The high cost of metal substrates such as nickel, niobium, and tantalum for electrolysis systems increases the cost of manufacturing electrolysis systems. Cladding the support materials provides a pathway to lower cost electrolysis units and offers a similar benefit for the support structures and reactors used in reforming and gas cleanup processes.

Coatings and Thin Film Deposition

Spray and flood coating processes are used in a number of manufacturing applications such as applying (1) catalyst layers to support materials used in reformers and gas cleanup systems, (2) nickel coatings as catalyst layers in electrolyzers, and (3) nickel powders to component parts for brazing. For larger, nonuniform surfaces, spray and flood coating are more of an “art” than a standardized technique. Reductions in capital costs for reformer and electrolyzer systems will require new designs and manufacturing techniques that integrate components and process steps. New, high-volume manufacturing methods for applying thin-film coatings to large, non-uniform surfaces will be needed. Because nickel is very costly, new manufacturing techniques to minimize its use in parts and coatings will lower the capital cost of process equipment. Finally, QC of coating layers is very important, and current inspection methods are both costly and time consuming.

Priority I (High)

- Deposit catalyst coating onto nonconformal surfaces.

  A standardized, automated method for applying catalyst coatings to nonconformal surfaces (e.g., applying catalysts directly to heat exchange surfaces) will facilitate high-volume manufacturing. This approach will also benefit the deposition of catalysts onto electrode substrates for electrolysis. In-line quality assurance methods need to be developed.

- Manufacture reaction vessels with protective coatings.

  Manufacturers will need an improved method for applying nickel cladding to lower cost metal substrates to reduce material costs. Alloys for brazing are needed that permit the use of coatings and enable corrosion resistant reactors.

Priority III (Low)

- Develop coating techniques for pipes.

  High-pressure, high-temperature hydrogen and reforming by-products react corrosively with pipes and connectors. New coating methods for manufacturing composite pipes used to transport high-temperature reactants and products will reduce the capital cost of the reactors.

- Develop new catalysts that are capable of multiple functions. (*Note − materials R&D issue*)

  Current practice is to have three separate catalysts in separate reaction vessels. Improved catalysts and simplified reforming systems are needed to enable a single primary system.

Systems and Components for Pressurized Operation

Pressure vessels are required for pressurized reforming and hydrogen storage. Thick-walled (approximately 6-inch) vessels are required to achieve the strength and reliability required at high pressure. Heat treating imparts material strength to the pressure vessel, and it is a critical and time consuming step in manufacturing pressure vessels.

Priority I (High)

- Fabricate and heat treat large-scale hydrogen storage pressure vessels for off-board use.

  The thickness of the walls of pressure vessels, which is required to maintain mechanical strength, makes heat treatment more difficult. Advances in heat treatment of thick-walled vessels will lead to lower cost production processes. Laser heat treatment offers the opportunity for in-line processing of pressure vessels.

Priority III (Low)

- Identify and develop methods for large-scale heat treating of reformers and shift reactors for pressurized systems.

Continuous Manufacturing Methods

Establishing production line capabilities for the continuous manufacturing of reformers, gas cleanup units, and electrolyzer and hydrogen delivery technologies is a high priority to successfully drive down the costs of hydrogen production systems. Developing testing and processing methods is important for continuous manufacturing.

Priority I (High)

- Develop accelerated test methodologies to validate materials and processes.
- Develop methods to manufacture large polymeric and composite pressure vessels for off-board hydrogen storage.

  Filament-wound, composite pressure tanks are presently produced using “hand lay-up” techniques. Improved manufacturing methods are needed for composite and polymeric tanks and localized winding of carbon filaments.
- Improved annealing methods are needed for metallic tanks.

Priority II (Medium)

- Improve stamping and extrusion methods for microchannel reactors and heat exchangers.

  Stamping and extrusion methods are needed to enable high-volume manufacturing of microchannel reactors and microchannel heat exchangers, which are machined and welded.
- Develop modular hydrogen reactors.

  Currently all hydrogen production systems are custom made; there are no modular (“snap together”) systems. Common, interchangeable components could permit assembly line production in the manufacture of hydrogen generators and, as economies of scale develop, could lead to significant cost reduction.
- Develop and adapt design for manufacturability tools.

  Manufacturers need analysis tools and design for manufacturability methods that are specific to hydrogen production and delivery systems. These tools can be employed by manufacturers to optimize high volume production.

Priority III (Low)

- Fabricate large-area catalyst and membrane supports for electrolyzers.

  The ability to fabricate large area (~1 m^2) catalyst layers, membranes, and bipolar plates is needed for PEM electrolyzers. The state-of the-art is typically smaller than 500 cm^2.

Table 9 summarizes the manufacturing R&D needs and recommended approaches for high-priority topics in hydrogen production and delivery.

Table 9: Summary of Manufacturing R&D Needs and Recommended Approaches for High-Priority Topics in Hydrogen Production and Delivery

Topic	R&D Need	Approach
Joining Methods for Hydrogen Production and Off-Board Storage Components	Joining to facilitate component integration Metal joining methods that do not require high temperatures	Automated, high-speed, high-reliability, low-variability joining processes for dissimilar material combinations and specialized materials Low-temperature joining processes that do not damage catalyst coatings
Coatings and Thin Film Deposition	Deposition of catalyst coating onto nonconformal surfaces Manufacture of reaction vessels with protective coatings	Standardized, automated methods for applying catalyst coatings to non-conformal surfaces. Development of NDT methods Improved methods for applying nickel cladding to lower-cost metal substrates. Uniform process for spraying nickel or nickel alloy to parts for brazing
Pressurized Systems and Components	Fabrication and heat treatment of large-scale pressurized hydrogen storage vessels	Advances in heat treatment methods for thick-walled vessels to lower cost of production
Continuous Manufacturing	Accelerated test methodologies to validate materials and processes Manufacture of large composite pressure vessels from filaments Improved annealing methods for metallic tanks	Accelerated test methodologies for materials of construction that can be used to rapidly characterize their performance in manufacturing processes and in end-use applications Improved manufacturing methods for metallic, composite, and polymeric materials and tanks used for large-scale pressurized hydrogen storage

Hydrogen Storage

Introduction

One of two storage technologies is currently employed on virtually every hydrogen-fueled concept vehicle: (1) high-pressure compressed gas storage at 350 bar (5,000 psi) or 700 bar (10,000 psi) and ambient temperature or (2) liquid hydrogen storage at 20 K and near ambient pressure. These two options employ very different manufacturing methods because their materials and fabrication processes differ significantly.

Unfortunately, compressed gas and liquid hydrogen storage methods have fundamental limitations that may preclude their long-term application to onboard systems for all light-duty vehicle platforms. Specifically, compressed gas systems suffer from low volumetric density because of the inherent nonideal gas behavior of hydrogen. Even though liquid hydrogen has a much higher density, it is relatively energy inefficient and requires at least 30% of the energy content of the hydrogen for liquefaction. To overcome these limitations, DOE is funding a vigorous and extensive R&D effort to develop materials-based (solid state or liquid) or chemical technology that can store hydrogen at high density, but at low pressure. Some R&D efforts are also being pursued to improve the performance and lower the cost of compressed gas and liquid/cryogenic systems and components because of their importance for the initial transition to the hydrogen economy. It is these technologies that will be the primary focus of early manufacturing R&D efforts.

The pathway to cost reduction is summarized in Figure 10. Costs for storage systems for compressed gas stored at 5,000 and 10,000 psi can be reduced by lowering the cost of carbon fibers through materials development and moving to higher volume manufacturing processes through manufacturing R&D (left arrow).

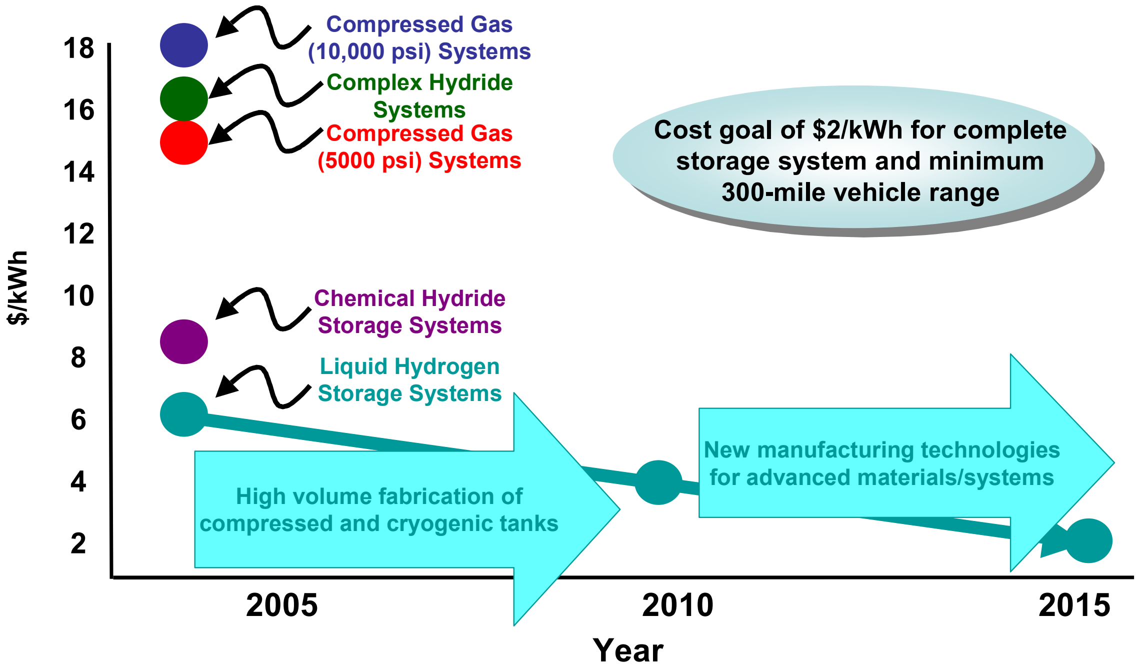


Figure 10: Hydrogen storage cost will be reduced by a combination of technology development and manufacturing R&D.[41]

This section of the roadmap focuses on the R&D needed to manufacture onboard storage systems that use compressed hydrogen, because this technology is most likely to be employed early in the transition to the hydrogen economy. As materials–based or chemical storage technologies are further developed, manufacturing R&D efforts will be expanded to address those systems. Improved high-volume manufacturing processes will play an important role in reducing the cost of hydrogen storage systems to meet the DOE 2015 target of $2/kWh (~$300 for a 5-kg hydrogen system). High-priority needs for manufacturing R&D are summarized in Table 10.

Table 10: Summary of High-Priority Manufacturing R&D Needs: Hydrogen Storage

Develop process technologies for reducing the cost of carbon fiber

Currently, composite tanks require high-strength fiber made from carbon-fiber grade polyacrylonitrile precursor. The price of the carbon fiber is typically about $20/kg. Reducing the cost of the fiber by about 60%, or about $6/kg, would yield significant savings in the unit cost of composite tanks. Manufacturing R&D is needed to develop lower cost, lower energy decomposition process for carbon fibers, such as microwave or plasma processing.

Develop new manufacturing methods for high-pressure composite tanks

New manufacturing methods are needed that can speed up the cycle time, that is, the per unit fabrication time. Potential advances in manufacturing technologies include faster filament winding (e.g., multiple heads), new filament winding strategies and equipment, continuous versus batch processing (e.g., pultrusion process). New manufacturing processes for applying the resin matrix, including tow-pregs for room temperature curing, wet winding processes, and fiber imbedded thermoplastics for hot wet winding, should also be investigated.

Develop manufacturing technologies for conformable high-pressure storage systems

Although this is a design issue (improved energy density), new manufacturing methods for carbon fiber winding and fiber placement manufacturing could also be applied to improve conformability of tanks by allowing modified cylindrical tank shapes to be manufactured.

Improve fiber placement processes

Fiber placement technologies can reduce unit costs by reducing the amount of carbon fiber needed by as much as 20%-30%. This approach may also allow some improvement in conformability of high pressure tanks. However, the process is slow. New methods and equipment are needed to improve manufacturing cycle time.

Hydrogen Storage Systems to Be Manufactured

An onboard hydrogen storage system is required for each hydrogen-fueled vehicle. The following types of storage systems are considered:

- High-pressure, compressed hydrogen gas systems (the focus of this roadmap)
- Low-pressure, liquid hydrogen systems
- High pressure, cryogenic hydrogen systems
- Chemical-based and solid-state hydrogen systems

Some components of storage systems are common to all these approaches. First, any storage method will require a container to hold the hydrogen as either a compressed gas or a liquid, or to enclose a material that has absorbed or adsorbed hydrogen. Typically, the material would also require an overpressure of gaseous hydrogen. Although the operational details such as pressure and temperature may differ between these alternatives, the container will always need to be manufactured at low cost and with minimal weight and volume. Additionally, cryogenic storage containers need effective thermal insulation barriers.

Many BOP components such as pressure regulators, solenoid valves, pressure relief devices, tubing, and mounting brackets are also common to all storage systems. These parts generally can be manufactured by current metal production practices, and they were not identified as posing challenges to the manufacture of storage systems. Heat exchangers and (for some chemical systems) reactors also will be widely used. Brief descriptions of the hydrogen storage technologies under development follow.

High-Pressure Compressed Hydrogen Gas Storage Systems

A high-pressure compressed gas system consists of a cylindrical tank that can withstand the internal pressure of the compressed hydrogen (the safety factor is currently set at 2.25), a pressure regulator that reduces the pressure to a lower value for delivery of the hydrogen to a fuel cell, a pressure relief device that releases gas if the temperature goes above a preset point, gas flow control valves, tubing, mounting brackets, and some environmental protection such as a stone shield. Typical high-pressure hydrogen storage systems are shown in Figures 11 and 12.

The tank is constructed of high-strength carbon fiber wrapped on a metal or polymer form, which also acts as an internal liner and permeation barrier to the hydrogen. The fiber is impregnated with a resin to form a continuous matrix. An outer layer of protective material completes the tank. A metal boss is embedded into the end cap for attaching metal components such as the pressure regulator and a high-pressure fill line. The additional components that are exposed to hydrogen gas are generally fabricated with hydrogen-compatible metal alloys.

Most onboard systems in use today operate at 350 bar (5,000 psi). However, composite tanks are available that can operate at 700 bar (10,000 psi). The higher pressure operation improves fuel capacity, but it also increases requirements for integrity, leak rates, and long-term compatibility for manufacturing the seals, valves, and regulators.

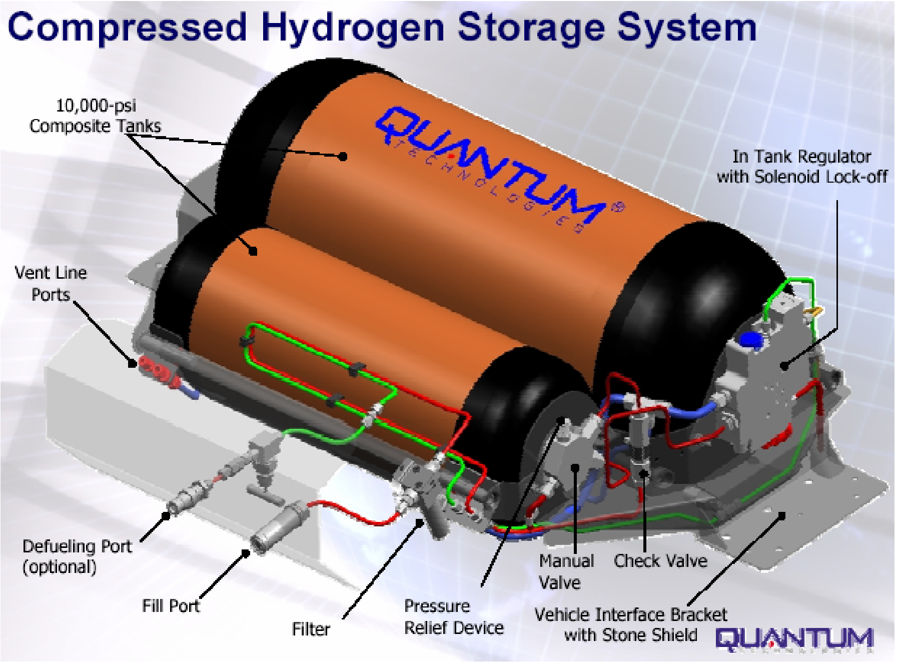


Figure 11: Compressed gas hydrogen storage system[42]

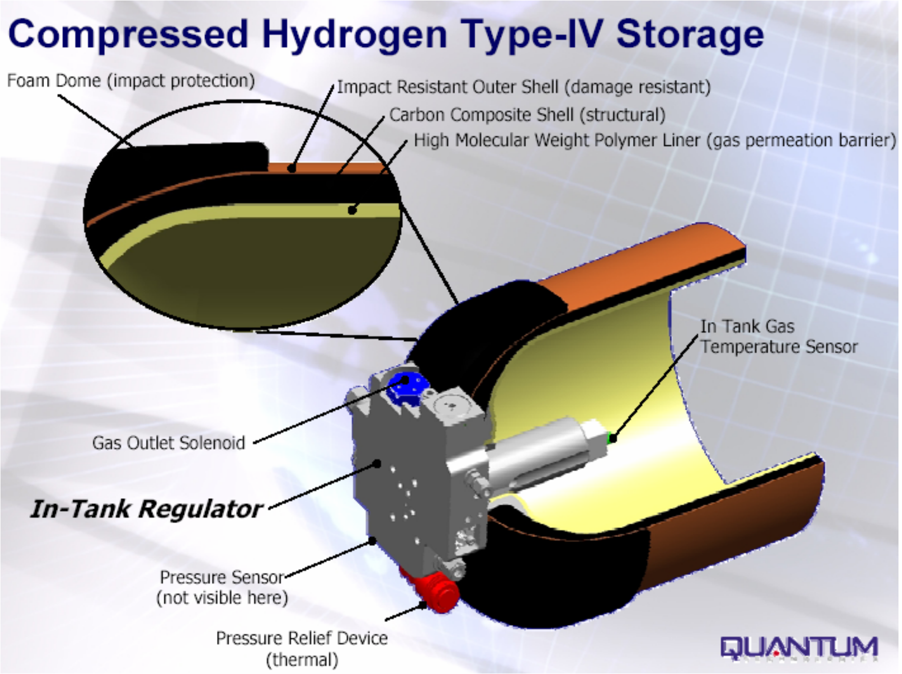


Figure 12: Filament wound composite type IV high pressure tank[43]

Low-Pressure, Liquid Hydrogen Storage Systems

Liquid hydrogen containers are generally cylindrical with relatively small aspect ratios (length to diameter) to minimize the surface-to-volume ratio for low heat transfer. Liquid hydrogen containers such as the one shown in Figure 13 are currently manufactured with relatively thin wall metal alloys to contain the liquid at 20 K (-253°C) and pressures of a few bars. The alloys must be readily formable and weldable to form a leak-tight container. The tanks are surrounded by a thermal insulation barrier to keep heat input from the external environment to the liquid as low as possible. Boil-off gas must be vented during periods when the vehicle is not being operated. Venting is predetermined by the maximum pressure allowed in the tank, and typical tanks are vented after about three days of system inoperation.

The thermal insulation barrier uses a larger diameter cylinder concentric with the liquid container, with high vacuum and thermal insulation layers between the cylinder walls. Achieving and maintaining the vacuum pose is important manufacturing issues, such as minimizing pumping times for evacuating the barrier and consistently fabricating leak-tight seals. A “getter,” that is, a reactive metal that scavenges gases released from the container materials, is typically used to maintain a vacuum in the thermal barrier assembly. Other components include a heater, liquefier, and BOP parts that are similar to high-pressure systems.

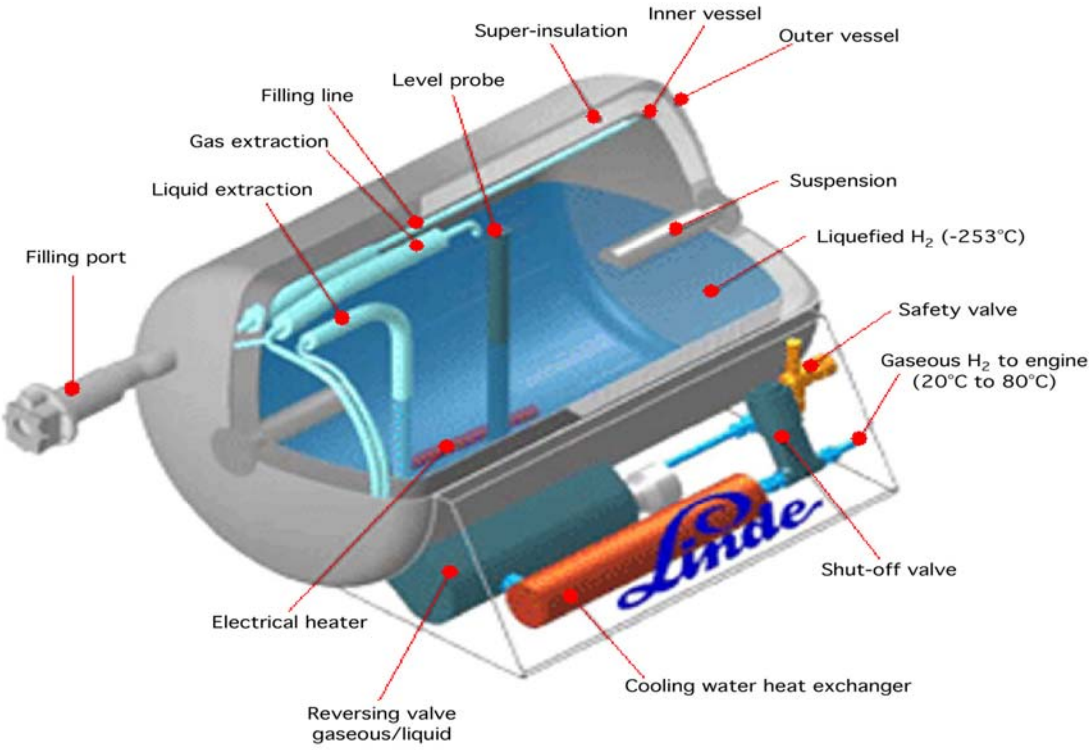


Figure 13: Liquid hydrogen storage system[44]

High-Pressure, Cryogenic Hydrogen Storage Systems

A high-pressure cryogenic system is essentially a combination of the first two methods. It offers a flexible approach to storing hydrogen, which can be tailored to the available infrastructure for supplying hydrogen. It consists of a high-pressure container with a surrounding thermal insulation barrier. The hydrogen can be stored either as a liquid or as a cold, compressed gas. The advantages of a cold, compressed gas system are (1) the energy density of the hydrogen, and hence the fuel capacity, at subambient temperatures can be significantly higher than room temperature, and (2) the storage temperature can be much higher (e.g., 77 K, or -196°C) than that of liquid hydrogen. On the other hand, if liquid hydrogen was available, it could also be stored in the same system. Because a cryogenic system container would be designed to withstand a much higher pressure than liquid hydrogen tanks, boil-off gas could be vented less frequently during inoperation than for low pressure systems.

Cryogenic systems currently use carbon fiber composite tanks for the hydrogen container and employ the same technologies as liquid hydrogen systems for the surrounding thermal barrier. Hence, manufacturing technologies employed for high pressure and for liquid systems would also be used for cryogenic systems. Since a lower operating pressure is used in the cryogenic approach compared to high-pressure compressed gas systems, the cost of the hydrogen container would be lower because of reduced fiber content and shorter fabrication time. However, these cost savings would likely be offset by the additional manufacturing costs of the thermal barrier.

This approach to onboard hydrogen storage has seen only limited evaluation on a vehicle and will need significant further development to assess its viability. Considerations of manufacturing issues specific to this storage technology may be premature; however, improvements in manufacturing technologies for high-pressure and liquid hydrogen systems would be applicable to cryogenic storage systems as well.

Chemical-Based and Solid-State Hydrogen Storage Systems

Chemical-based and solid-state hydrogen storage methods use materials that retain hydrogen, which can subsequently be released by heating or via a chemical reaction. These systems have the potential for greater onboard fuel capacity than compressed gas or liquid hydrogen systems. However, they are still at an early stage of development and a specific material or compound has not been identified with the desired hydrogen capacity, thermodynamic properties, and kinetic behavior. Clearly, a number of manufacturing issues will be associated with and unique to these systems, many of which will depend on the actual storage material, but specific considerations would be premature at this time. One possible exception is the liquid sodium borohydride solution that is discussed later.

Status of Manufacturing

At the present time, relatively few components for onboard hydrogen storage are commercially available and these components are only manufactured in very small quantities. Issues include a lack of market pull because of the small number of hydrogen-fueled vehicles and the limitations in energy density with current storage technologies. As mentioned, virtually all of the 500–600 hydrogen-fueled vehicles worldwide use either compressed hydrogen at high pressures (typically 350 bar [5,000 psi]) or liquid hydrogen to store the fuel onboard.

Significant improvements have been made in compressed gas and liquid hydrogen storage systems. The development of improved carbon fiber composite tanks has resulted in the availability of robust compressed hydrogen gas systems which are relatively light weight, but capable of sustaining much higher pressures, hence achieving greater energy densities than previous designs. Similarly, improvements in liquid hydrogen systems have resulted in improvements in overall volume and in extended dormancy times. These improvements in system design are applicable to chemical, solid-state, and cryogenic storage components as well.

The exceptional strength-to-weight ratio of carbon fiber composite cylinders makes them prime candidates for use in chemical, solid-state, or cryogenic storage systems as well as in compressed gas applications. Hence, improvements in manufacturing aimed toward reducing the unit cost and production cycle time of these components would have wide applicability to hydrogen storage systems in general. The major limitations on manufacturing composite tanks are fiber winding methods and the cost of high-strength carbon fibers (see Figure 14). Even with multiple fiber winding machines, production capacity is limited to a few units per day. In stark contrast, high-volume production would require a production rate of ~60 units per hour. Clearly, significant challenges must be overcome to manufacture cost-effective units at a rate equivalent to that of projected fuel cell production rates.

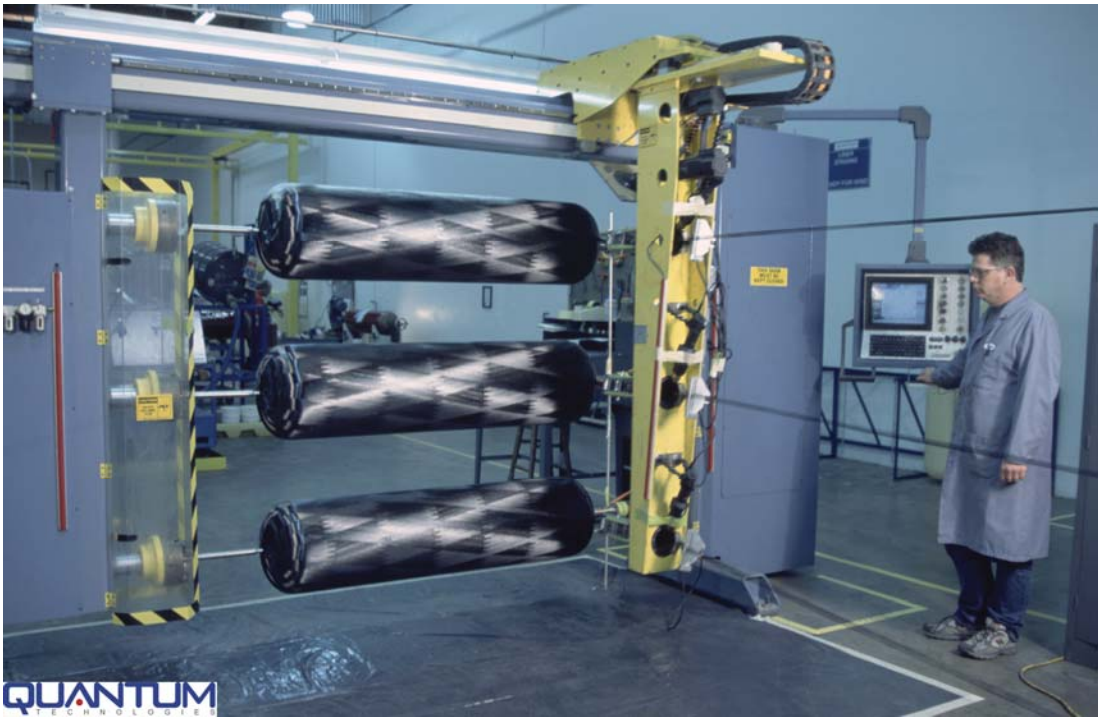


Figure 14: Carbon filament winding of carbon fiber composite cylinders[45]

Carbon fiber composite technology is widely used to manufacture various consumer products, most notably, perhaps, in sporting goods such as golf clubs, tennis rackets, and tanks for underwater breathing gear. It is also being used to a limited extent for specific automotive parts and components where the weight and strength properties outweigh cost considerations. The next generation of commercial airliners under development (by Boeing and AirBus) is expected to use carbon fiber composite construction extensively. Advancements in fabrication methods and cost reductions for carbon fiber composite-based hydrogen storage components, therefore, may have much wider implications for U.S. manufacturing in these other areas. Conversely, improvements developed for constructing composite components for airliners, for example, could also lead to improvements in storage component manufacturing.

Manufacturing Challenges

Manufacturing viable onboard storage systems will require dramatic reductions in unit costs and fabrication times. It will also require significant investment in manufacturing equipment and developing new approaches to fabrication, particularly for composite tanks, but also for chemical storage system components and for cryogenic system components.

Perhaps the biggest challenges lie in the high-volume manufacture of composite tanks. High volume production rates cannot be met simply by increased capitalization of current manufacturing equipment. Most importantly, the production time needs to be significantly reduced, which will require significant advances in filament winding processes or in the use of an alternative (yet to be identified) technology.

Cost is another issue with composite tanks. Current projections of the manufactured cost per unit for high production volumes are about a factor of five above storage system targets. Researchers estimate that about 40% of the unit cost is due to the carbon fiber. Hence, reducing the amount of fiber by, for example, fiber placement methods, and reducing the cost per kg of carbon fiber would go a long way toward lowering costs. Cost could also be reduced through faster cycle times and improvements in resin matrix technologies.

Other challenges affect the manufacture of components and systems for chemical, solid-state, and liquid/cryogenic systems. Liquid hydrogen and some cryogenic systems typically require nickel alloys for compatibility at low temperatures. These materials are relatively expensive and increase fabrication costs. To reduce material and manufacturing costs, alternative alloys (e.g., reduced nickel content) need to be developed and extrusion and forming processes used in their fabrication need to be improved. These systems also include a thermal insulation barrier using layered insulation within a vacuum layer surrounding the containment vessel. The cycle time for producing these units is currently about two days because of the long baking times required for the thermal barrier. Improvements are clearly needed to reduce the costs and increase production throughput for liquid and cryogenic storage subsystems.

As mentioned earlier, chemical and solid-state storage subsystems are too early in their development process to consider manufacturing issues. However, sodium borohydride solution is perhaps a unique case in that it has been demonstrated onboard concept vehicles and is being considered for portable power applications. As in most chemical storage systems, a reaction by-product is generated that must be stored onboard for later removal and reprocessing. A volume exchange subsystem must be used to minimize the containment volume of both the material and the byproduct. There is no method of manufacturing this subsystem at the present time.

Paths Forward

The consensus of the workshop was to place the greatest emphasis on manufacturing R&D for high-pressure composite tanks. Three distinct priority levels emerged from the workshop based on the relative importance attached to the issues. Some topics that were identified are likely technology development and design issues and not specifically manufacturing process concerns. This is most notable in some of the materials issues. However, they are included at the end of each prioritized list (and noted as being design or material issues) because they do influence the choice of manufacturing processes, manufacturing equipment, and unit costs.

Component Manufacturing and Manufacturing Processes for Composite Tanks

The following recommended R&D topics all focus on reducing the unit cost and increasing production throughput of composite tanks. They also address some performance issues that could be improved through manufacturing processes.

Priority I (High)

- Develop process technologies for reducing the cost of carbon fiber.

  Currently, the lightest weight composite tanks are fabricated with a high-strength fiber made from carbon-fiber grade polyacrylonitrile (PAN) precursor. The price of this fiber is about $170/kg. Lower strength carbon fibers generally cost less, as low as $20/kg, but more fiber is needed per unit to achieve the same operating pressure. Over this range of fiber cost, the material cost contributes about 40% (with the low-cost fiber) to 80% (with the PAN fiber) of the total unit cost. Clearly, reducing the cost of the fiber would yield significant savings in the unit cost of composite tanks. Two potential technical approaches to reduce the cost of fiber are (a) develop a lower cost precursor for high strength fibers, and (b) develop a lower cost, lower energy decomposition process, such as microwave or plasma processing.

- Develop new manufacturing methods for high-pressure composite tanks.

  New manufacturing methods are needed that can speed the cycle time, that is, the per unit fabrication time. Potential advances in manufacturing technologies include faster filament winding (e.g., multiple heads), new filament winding strategies and equipment, and continuous versus batch processing (e.g., pultrusion process). New manufacturing processes for applying the resin matrix, including tow-pregs for room temperature curing, wet winding processes, and fiber-imbedded thermoplastics for hot wet winding, should also be investigated.

- Develop fiber placement manufacturing.

  Fiber placement technologies can reduce unit costs by reducing the amount of carbon fiber needed by as much as 20%–30%. This approach may also allow some improvement in conformability of high-pressure tanks. However, the process is slow. New methods and equipment are needed to improve manufacturing cycle time.

- Design conformable high pressure storage systems (*Note – design issue)*.

  Although this is a design issue (improved energy density), new manufacturing methods for carbon fiber winding and fiber placement manufacturing could also be applied to improve the conformability of tanks by allowing modified cylindrical tank shapes to be manufactured.

Component Manufacturing and Manufacturing Processes for Chemical, Solid-State, and Cryogenic Systems

Priority (Medium) II

- Develop assembly techniques for bladder-type, volume exchange, storage subsystems.

  Many chemical systems produce a reactant by-product that must be stored onboard. Volumetric density is maximized by means of a volume exchange storage subsystem; however, no such unit is currently produced in volume. Implementing a manufacturing capability for these subsystems will require developing assembly techniques and optimizing materials. Because specific chemical storage systems are being considered by companies for portable power applications at this time, a viable manufacturing technology might be needed relatively soon.

  This subsystem assembly may involve significant design issues that must be addressed before a manufacturing process can be defined.

- Improve forming/extrusion processes for manufacturing metal tanks.

  These processes could improve manufacturing costs of liquid hydrogen and low-pressure cryogenic storage subsystems.

- Develop high-throughput solid storage material processing.

  High-volume production of chemical storage systems will require the synthesis and processing of large quantities of the storage media. These manufacturing issues may arise in the future when an effective storage material has been identified.

- Develop a lower cost substitute for high Ni alloys used in cryogenic tanks *(Note – materials R&D issue)*.

  Strictly speaking, this is a materials issue, but the choice of materials affects manufacturing processes. Metal cryogenic tanks currently require high Ni content alloys for low temperature hydrogen compatibility. This results in higher material and fabrication costs. Other alloys or nonmetals should be considered as substitutes to reduce overall costs. The DOE program currently has no experimental or modeling to examine this issue.

- Design compact, high-efficiency thermal management assemblies for storage systems *(Note – design issue)*.

  Microchannel reactors and heat exchangers offer potential advantages in weight, volume, and efficiency over conventional components. However, there are currently no manufacturing methods for these components.

Modeling and Analysis Tools

Priority II (Medium)

- Develop a model-based simulation and process design of containment vessel manufacturing.

  The availability of a process analysis tool would be of value in choosing and optimizing manufacturing processes and production throughput.

- Use DFMA techniques to enable high-volume manufacture of 700-bar (10,000 psi) components.

  The use of 700 bar (10,000 psi), compressed, hydrogen storage onboard vehicles pushes the limits on currently manufactured components such as valves, regulators, and seals. DFMA could potentially improve reliability and reduce manufacturing costs.

- Produce cost model for high pressure tank manufacture

  A cost model is needed to guide development of high-volume production processes for high-pressure composite tanks employing fiber placement technology.

Table 11 summarizes the manufacturing R&D high-priority needs and recommended approaches for storage.

Table 11: Summary of Manufacturing R&D High-Priority Needs and Recommended Approaches for On Board Storage

System	R&D Need	Approach
Component Manufacturing and Manufacturing Processes	Investigate process technologies for reducing the cost of carbon fiber. Develop new manufacturing methods for high-pressure composite tanks. Develop manufacturing technologies for conformable high pressure storage systems. Use fiber placement manufacturing.	Develop a lower cost precursor for high-strength fibers. Develop a lower cost, lower energy decomposition process such as microwave or plasma processing. Investigate new manufacturing processes for applying the resin matrix, including tow-pregs for room temperature curing, wet winding processes, fiber imbedded thermoplastics for hot wet winding. Apply new manufacturing methods for carbon fiber winding and fiber placement manufacturing to improve the conformability of tanks by allowing modified cylindrical tank shapes to be manufactured. Develop new methods and equipment to improve manufacturing cycle time.
Component Manufacturing and Manufacturing Processes for Chemical and Cryogenic Systems	No high-priority manufacturing R&D needs	
Modeling and Analysis Tools	No high-priority manufacturing R&D needs	

Cross-Cutting Issues

As outlined in the previous sections, manufacturing for the hydrogen economy covers a wide variety of components and systems that fit into the broad categories discussed in this report: hydrogen production and delivery; fuel cells; and hydrogen storage. Manufacturing these components and systems requires a spectrum of technologies, from continuous chemical processes to discrete mechanical fabrication processes. As such, diverse issues and challenges are associated with each of these manufacturing processes. However, significant cross-cutting manufacturing technologies span the three broad categories.

Common themes that were raised across the three technology categories are:

- Improved manufacturing processes are needed to achieve program cost targets.
- High-speed manufacturing processes need to be developed to meet the production volumes that are required to transition to and sustain the hydrogen economy.
- Accurate, reliable, and measurable manufacturing processes are needed to achieve the necessary quality levels, which affect performance, reliability, durability, and safety.

The following paragraphs describe specific manufacturing R&D needs that cut across hydrogen production, storage, and fuel cells.

Metrology and Standards

Rapid and accurate measurement systems and devices are needed across all three categories to apply statistical quality assurance techniques such as statistical process control. Metrology provides quantitative information about a manufacturing process and its output. The ability to measure reliably various process parameters such as leaks, microstructure defects, surface roughness, coating quality, dimensional accuracy, and other critical manufacturing process outputs enables cost-effective manufacturing. In process measurement, these parameters allow manufacturers to establish statistical process capabilities and make adjustments to control processes and component quality on the fly. Current inspection techniques often require off-line measurements, manual inspection techniques, and even destructive tests. These approaches slow the manufacturing process and add cost. NDE and NDT techniques that eliminate manual and time-consuming test and measurement processes are needed.

Specific metrology needs of manufacturing for the hydrogen economy include rapid, in-process measurement of dimension and form of components such as bipolar plate flatness, surface roughness, and channel dimensional accuracy; ability to rapidly detect defects and measure the quality of microstructures and surfaces; measurement and control of particle size and distribution; and the measurement of thin and thick film coatings. Industry will need rapid in-process measurements of hydrogen and fuel cell component and assembly performance parameters in the areas of pressure, temperature, vacuum, gas flow, water transport, resistance, conductivity, and electrical power.

Related issues include the need for standard measurement methods and protocols of the manufacturing process and component performance parameters. Such standards ensure quality in the supply chain, lower costs, enhance international trade, and improve the quality of the end products.

Modeling and Simulation

Modeling and simulation can significantly advance the development and optimization of manufacturing processes, and thus are key elements in developing viable manufacturing for the hydrogen economy. Mathematical models and modeling process integration are needed to evaluate the effects of various manufacturing techniques. Information on manufacturing process capabilities can be fed into component performance models to assess the impact of manufacturing variations. This will help to establish manufacturing process requirements (tolerances and quality assurance requirements), reduce manufacturing costs by relaxing noncritical tolerances, cut development times by generating more robust designs, and facilitate optimal solutions.

Knowledge Bases

To support modeling efforts, information and knowledge are needed about new materials and sealants, including their processibility, formability, machinability, and compatibility with other materials and gases. Information is also needed on new process technologies and on the fundamental correlations between manufacturing parameters and performance parameters. In many technology areas, the effect of variations caused by manufacturing is not understood well enough to establish appropriate tolerances and design practices. Creating precompetitive, easily accessible, user-friendly knowledge bases for the hydrogen industry will foster further innovation in this area. This knowledge base may take the form of technical publications on recent advances in manufacturing technologies, published manufacturing standards and guidelines, and a database of information on manufacturing properties of new materials for the hydrogen and fuel cell industry. This information could be collected, organized, and made available to the industry through a centralized source such as a DOE Web site.

Design for Manufacturing and Assembly

To move cost effectively from small-batch production to high-volume production, DFMA methodologies have to be used at the earliest stages of new technology development. Some DFMA principles that should be considered include component selection for reduced parts counts, designs that can be produced consistently at low and high volumes, material selections that enhance manufacturability, incorporation of manufacturing and assembly features into component designs, and realistic tolerance analysis and design specifications. Application of concurrent engineering principles is needed to ensure that manufacturing considerations are incorporated into the design process.

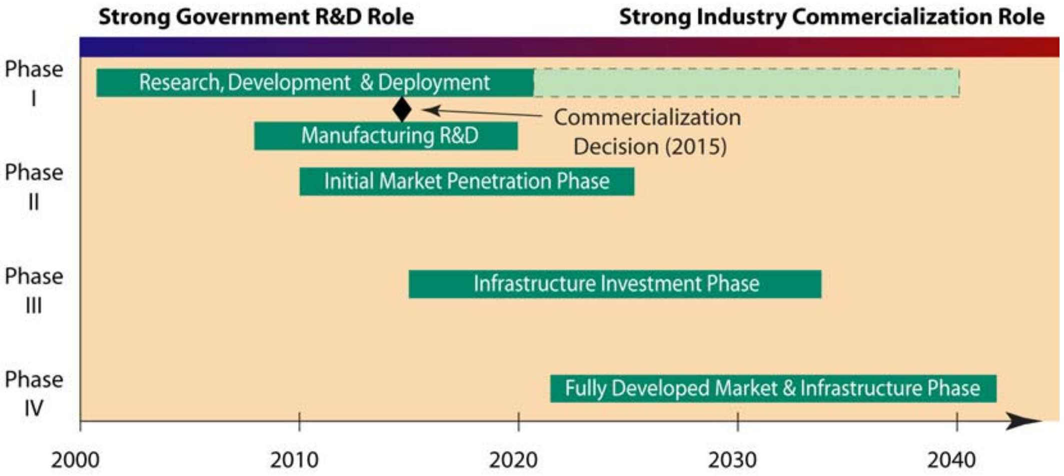
Sensing and Process Control

Sensors and process control technologies are key enablers for increasing the reliability and quality of manufacturing processes while reducing cost. Low-cost sensing and sensor fusion technologies with reliable sensor networks are therefore needed for in-process sensing of processes and in-operation sensing of product performance.

Conclusion

For the transportation sector, the HFI is advancing hydrogen technologies to enable U.S. industry to make a commercialization decision on hydrogen-powered fuel cell passenger vehicles and fueling stations by 2015. With a positive commercialization decision in 2015, market penetration is expected to begin between 2018 and 2020. Commercialization decisions and the subsequent market entry and expansion of hydrogen technologies will depend on the state of the manufacturing infrastructure for hydrogen systems. Enabling the development of manufacturing technologies that can provide profitability as the market scales up will lead to accelerated deployment of hydrogen systems into the marketplace.

This effort complements the phases that have been laid out for the development of the hydrogen economy, shown in Figure 15. These phases have been identified through a collaborative effort of the federal government (led by DOE), industry, and academia, to move our nation from our petroleum-based economy to the hydrogen economy.



Transitional Phases:

- I. Technology Development Phase: Research to meet customer requirements and establish business case leads to commercialization decision
- II. Initial Market Penetration Phase: Portable power and stationary/transport systems begin commercialization; infrastructure investment begins with governmental policies
- III. Infrastructure Investment Phase: H2 power and transport systems commercially available; infrastructure business case realized
- IV. Fully Developed Market and Infrastructure Phase: H2 power and transport systems commercially available in all regions; national infrastructure

Figure 15: The phases for development of the hydrogen economy showing manufacturing R&D

The timeframe of key activities for this manufacturing effort is shown in Figure 16.

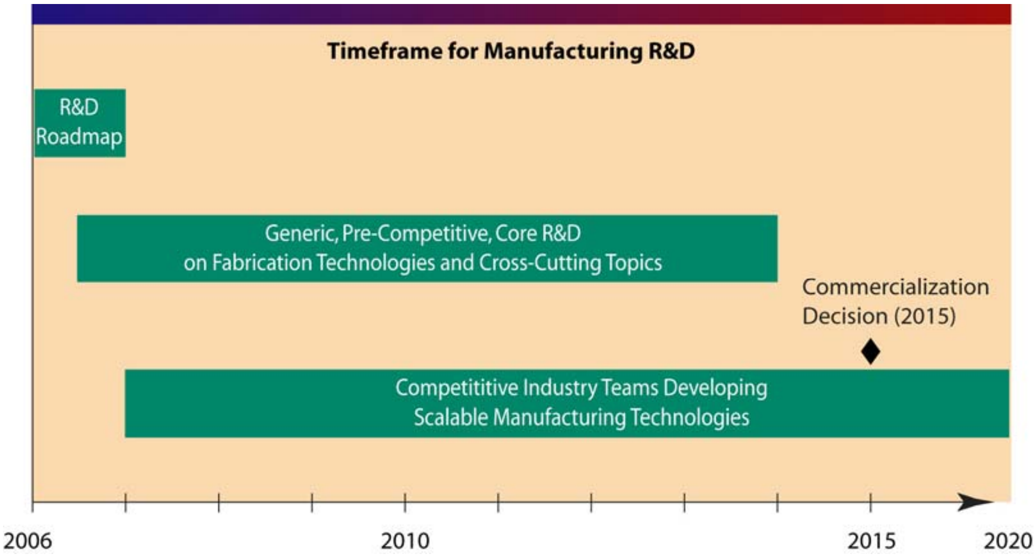


Figure 16: Hydrogen economy timeline

Metrics against which to evaluate the progress and benefits of manufacturing R&D for the hydrogen economy need to be established. Specific metrics will be developed along with more detailed R&D planning as DOE, the IWG, and the U.S. hydrogen and fuel cell community move forward.

Glossary and Acronyms

Glossary

Agile manufacturing, also referred to as *fast and flexible manufacturing*, aims to help manufacturers produce higher quality products more quickly and efficiently in a world of rapidly changing technology and customer requirements by improving communications between product designers, manufacturers, customers, and their web of suppliers.

Anode: The electrode at which oxidation (a loss of electrons) takes place. For fuel cells and other galvanic cells, the anode is the negative terminal; for electrolytic cells (where electrolysis occurs), the anode is the positive terminal.

Balance-of-plant: This term (sometimes referred to as balance of system) refers to equipment and components such as heat exchangers, pumps, compressors valves, tubing, and insulation materials that connect the major subsystems (fuel cell stack, fuel processor, power electronics) of a fuel cell system together.

Bipolar plate: Conductive plate in a fuel cell stack that acts as an anode for one cell and a cathode for the adjacent cell. The plate may be made of metal or a conductive polymer (which may be a carbon-filled composite). The plate usually incorporates flow channels for the fluid feeds and may also contain conduits for heat transfer.

Catalyst: A chemical substance that increases the rate of a reaction without being consumed; after the reaction it can potentially be recovered from the reaction mixture chemically unchanged. The catalyst lowers the activation energy required, allowing the reaction to proceed more quickly or at a lower temperature. In a fuel cell, the catalyst facilitates the reaction of oxygen and hydrogen. It is usually made of platinum powder very thinly coated onto carbon paper or cloth. The catalyst is rough and porous so that the maximum surface area of the platinum can be exposed to the hydrogen or oxygen. The platinum-coated side of the catalyst faces the membrane in the fuel cell.

Cathode: The electrode at which reduction (a gain of electrons) occurs. For fuel cells and other galvanic cells, the cathode is the positive terminal; for electrolytic cells (where electrolysis occurs), the cathode is the negative terminal.

Chemical-based hydrogen storage: A term used to describe storage technologies in which hydrogen is generated through a chemical reaction. Common reactions involve chemical hydrides with water or alcohols. Typically, these reactions are not easily reversible onboard a vehicle. Hence, the "spent fuel" and by-products must be removed from the vehicle and regenerated offboard. Reference: www.eere.energy.gov/hydrogenandfuelcells/storage/chem_storage.html

Cryogenic storage systems: Systems in which gases such as nitrogen, hydrogen, helium, and natural gas are stored at very low temperatures.

Design for manufacturability and assembly (DFMA): The process of designing products to (1) optimize all the manufacturing functions: fabrication, assembly, test, procurement, shipping, delivery, service, and repair, and (2) ensure the best cost, quality, reliability, regulatory compliance, safety, time-to-market, and customer satisfaction.

Design for six sigma (DFSS): A process used to develop new products or services to ensure they can be manufactured, or can operate, at six sigma quality levels. The process requires an understanding the customer requirements, performance measures, and possible sources and levels of input variations. Statistical tools, similar to those used in traditional six sigma processes, are used to ensure that the product is designed in a way that satisfies the customer's requirements independent of input variations.

Electrolysis: A process that uses electricity, passing through an electrolytic solution or other appropriate medium, to cause a reaction that breaks chemical bonds, e.g., electrolysis of water to produce hydrogen and oxygen.

Energy density: Amount of potential energy in a given measurement of fuel.

Fuel cell: A device that produces electricity through an electrochemical process, usually from hydrogen and oxygen.

Fuel Cell Poisoning: The lowering of a fuel cell's efficiency caused by impurities in the fuel binding to the catalyst.

Fuel Cell Power conditioning is the electronics hardware and software integrated with vehicle or system controls that converts the raw unregulated DC power from the fuel cell stack to regulated power. The regulated power will be either DC or alternating current (AC) depending on system requirement.

Fuel Cell Stack: Individual fuel cells connected in series. Fuel cells are stacked to increase voltage.

Lean manufacturing: A systematic process to reduce waste in manufactured products. The basic idea is to reduce the cost systematically, throughout the production process, by means of a series of process reviews.

Liquefied hydrogen: Hydrogen in liquid form. Hydrogen can exist in a liquid state, but only at extremely cold temperatures. Liquid hydrogen typically has to be stored at -253°C (-423°F). The temperature requirements for liquid hydrogen storage necessitate expending energy to compress and chill the hydrogen into its liquid state.

MEA: PEM fuel cells require catalyst and diffusion media applied to a membrane that is then layered between two conductive plates. This layered product is the membrane electrode assembly (MEA). The MEA system comprises 5 or 7 layers, including anode gas diffusion layer, anode catalyst, membrane, cathode catalyst, cathode gas diffusion layer. Reference: www.3m.com/about3m/technologies/fuelcells/our_prod.jhtml

Membrane: The separating layer in a fuel cell that acts as electrolyte (ion exchanger) as well as a barrier film that separates the gases in the anode and cathode compartments of the fuel cell.

Metrology: The ability to reliably measure various process parameters and process outputs.

PEM fuel cell: A type of acid-based fuel cell in which the transport of protons from the anode to the cathode is through a solid membrane contains an appropriate acid. The electrolyte is a called a polymer electrolyte membrane (PEM). The fuel cells typically run at low temperatures (<100°C).

Pressure swing adsorption: A commonly used technology for purifying gases. PSA is used extensively in the production and purification of oxygen, nitrogen, and hydrogen for industrial uses. In the hydrogen production process, PSA removes impurities such as CO, CO_2, CH_4, H_2O, and H_2S. A typical PSA system involves a cyclic process where a number of connected vessels that contain adsorbent material undergo successive pressurization and depressurization steps in order to produce a continuous stream of purified product gas.

Reforming: A chemical process in which hydrogen containing fuels react with steam, oxygen, or both to produce a hydrogen-rich gas stream.

Statistical process control (SPC): A standardized technique used to steer manufacturing processes in a desired direction, reducing variation, increasing knowledge about the process, assessing process capability and providing performance benchmarks.

Acronyms

AC	alternating current
BOP	balance of plant
DC	direct current
DFMA	design for manufacturability and assembly
DOE	U.S. Department of Energy
gge	gasoline gallon equivalent
IWG	Interagency Working Group
MEA	membrane electrode assembly
NDE/NDT	nondestructive evaluation/testing
PEM	polymer electrolyte membrane
PRD	pressure release device
QC	quality control
R&D	research and development
SPC	statistical process control
UCD	unified cell device

Appendix A: Interagency Working Group on Manufacturing R&D

Members of the Interagency Working Group on Manufacturing Research and Development are:

Department of Agriculture*

Department of Commerce/National Institute of Standards and Technology*#

Department of Defense*

Department of Education

Department of Energy*

Department of Health and Human Services/National Institutes of Health

Department of Homeland Security

Department of Labor

Department of Transportation*

National Aeronautics and Space Administration*

National Science Foundation*

Small Business Administration

White House Office of Management and Budget*

White House Office of Science and Technology Policy*

* Self-selected representatives on the IWG task team on Manufacturing for the Hydrogen Economy. DOE is the lead agency for this task team.

Mr. Dale Hall, Director of the Manufacturing Engineering Laboratory at NIST, is the Acting Chair of the IWG.

Appendix B: List of Workshop Participants

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Appendix C: Working Definition of Manufacturing Innovation and Manufacturing-Related R&D[46]

Manufacturing innovation is fostered by R&D of technologies that are aimed at increasing the competitive capability of manufacturing concerns. Broadly speaking, manufacturing-related R&D encompasses improvements in methods or processes, or wholly new processes, machines or systems. Four main areas include:

1. Unit process level technologies that create or improve manufacturing processes, including:
   a. Fundamental improvements in manufacturing processes that deliver substantial productivity, quality, or environmental benefits
   b. Development of new manufacturing processes, including new materials, coatings, methods, and practices associated with these processes.
2. Machine level technologies that create or improve manufacturing equipment, including:
   a. Improvements in capital equipment that create increased capability (such as accuracy or repeatability), increased capacity (through productivity improvements or cost reduction), or increased environmental efficiency (safety, energy efficiency, environmental impact)
   b. New apparatus and equipment for manufacturing, including additive and subtractive manufacturing, deformation and molding, assembly and test, semiconductor fabrication, and nanotechnology.
3. Systems level technologies for innovation in the manufacturing enterprise, including:
   a. Advances in controls, sensors, networks, and other information technologies that improve the quality and productivity of manufacturing cells, lines, systems, and facilities.
   b. Innovation in extended enterprise functions critical to manufacturing, such as quality systems, resource management, supply chain integration, and distribution, scheduling and tracking.
   c. Technologies that enable integrated and collaborative product and process development, including computer-aided and expert systems for design, tolerancing, process and materials selection, life-cycle cost estimation, rapid prototyping, and tooling.

4. Environment or societal level technologies that improve workforce abilities and manufacturing competitiveness, including:
    a. Technologies for improved workforce health and safety, such as human factors and ergonomics
    b. Technologies that aid and improve workforce manufacturing skills and technical excellence, such as educational systems incorporating improved manufacturing knowledge and instructional methods.

Endnotes

[1] *A National Vision of America's Transition to a Hydrogen Economy—to 2030 and Beyond*, U.S. Department of Energy, February 2002. www.eere.energy.gov/hydrogenandfuelcells/pdfs/vision_doc.pdf

[2] *National Hydrogen Energy Roadmap*, U.S. Department of Energy, November 2002. www.eere.energy.gov/hydrogenandfuelcells/pdfs/national_h2_roadmap.pdf

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[8] Public Forum on Nanomanufacturing, Manufacturing for the Hydrogen Economy, and Intelligent and Integrated Manufacturing Systems. Interagency Working Group on Manufacturing, Research, and Development. www.ostp.gov/mfgiwg.

[9] "An Experience Curve Based Model for the Projection of PV Module Costs and Its Policy Implications," Clayton Handleman, Heliotronics, Inc. www.heliotronics.com.

[10] See Appendix C for working definitions of manufacturing innovation and manufacturing-related R&D as developed by the IWG.

[11] *Transportation Energy Data Book*, Edition 23, Oak Ridge National Laboratory, ORNL-6970, October 2003

[12] Energy Consumption, Expenditures, and Emissions Indicators, Selected Years. www.eia.doe.gov/emeu/aer/pdf/pages/sec1_13.pdf.

[13] *Annual Energy Outlook with Projections to 2025.* www.eia.doe.gov/oiaf/aeo/economic.html.

[14] National Transportation Statistics 2004, January 2005. www.bts.gov/publications/national_transportation_statistics/2005/html/table_01_15.html.

[15] Energy Policy Act of 2005, Public Law 109-58, Section 1336.

[16] *Cost Analysis of PEM Fuel Cell Systems for Transportation*, TIAX LLC subcontractor report to NREL, September 30, 2005.

[17] QS9000 is the American Automobile Industry Quality System Standard that embraces ISO9000 with emphasis on customer satisfaction and the foundation for an exceptional line of products. TS16949 is the new technical standard that is gaining acceptance as the worldwide replacement for QS9000. The ISO/TS 16949 standard, published in March 2002 by the International Automotive Task Force, focuses on continuous improvement to reduce costs in automotive manufacturing.

[18] The Secretary of Energy will provide a report on the likely effects of a transition to a hydrogen economy on overall employment in the United States as required by the Energy Policy Act of 2005, Section 1820.

Public Law 109-58 can be accessed through the Thomas Web site at http://frwebgate.access.gpo.gov/cgi-bin/getdoc.cgi?dbname=109_cong_public_laws&docid=f:pub1058.109.pdf

[19] "Hydrogen, Fuel Cells & Infrastructure Technologies Program, Multi-Year Research, Development and Demonstration Plan," Multi-Year Research, Development and Demonstration Plan, U.S. Department of Energy: Energy Efficiency and Renewable Energy; Hydrogen, Fuel Cells, and Infrastructure Technology Program. February 2005. www.eere.energy.gov/hydrogenandfuelcells/mypp/

[20] Ibid.

[21] Discussion fuel cell group, Workshop on Manufacturing R&D for the Hydrogen Economy, July 13−14, 2005.

[22] "Hydrogen, Fuel Cells & Infrastructure Technologies Program, Multi-Year Research, Development and Demonstration Plan," Multi-Year Research, Development and Demonstration Plan, U.S. Department of Energy: Energy Efficiency and Renewable Energy; Hydrogen, Fuel Cells, and Infrastructure Technology Program. February 2005. www.eere.energy.gov/hydrogenandfuelcells/mypp/

[23] Today's high volume estimate for manufacturing cost is from *Cost of PEM Fuel Cell Systems for Transportation*, TIAX LLC subcontract to NREL, December 2005, NREL/SR-560-39104. www.nrel.gov/hydrogen/pdfs/29104.pdf. Cost goal of $30/kW is from "Hydrogen, Fuel Cells & Infrastructure Technologies Program, Multi-Year Research, Development and Demonstration Plan," Multi-Year Research, Development and Demonstration Plan, U.S. Department of Energy: Energy Efficiency and Renewable Energy; Hydrogen, Fuel Cells, and Infrastructure Technology Program. February 2005. www.eere.energy.gov/hydrogenandfuelcells/mypp/

[24] Source: Matt Stiveson, NREL PIX 12505

[25] Source: Parker Hannifin.

[26] "Hydrogen, Fuel Cells & Infrastructure Technologies Program, Multi-Year Research, Development and Demonstration Plan," Multi-Year Research, Development and Demonstration Plan, U.S. Department of Energy: Energy Efficiency and Renewable Energy; Hydrogen, Fuel Cells, and Infrastructure Technology Program. February 2005. www.eere.energy.gov/hydrogenandfuelcells/mypp/

[27] Calculated from information in reference 26, assuming cost goal of $\$40/m^2$ and membrane covers only the active area and does not go into the seal area.

[28] Estimate based on input from fuel cell manufacturers attending the Workshop on Manufacturing R&D for the Hydrogen Economy, Washington D.C., July 13−14, 2005.

[29] National Research Council and National Academy of Engineering of the National Academies, The Hydrogen Economy, Washington, D.C.: The National Academies Press, 2004, p. 29.

[30] Source: Ballard Power Systems, Inc.

[31] "Hydrogen, Fuel Cells & Infrastructure Technologies Program, Multi-Year Research, Development and Demonstration Plan," Multi-Year Research, Development and Demonstration Plan, U.S. Department of Energy: Energy Efficiency and Renewable Energy; Hydrogen, Fuel Cells, and Infrastructure Technology Program. February 2005. www.eere.energy.gov/hydrogenandfuelcells/mypp/

[32] Ibid.

[33] *Hydrogen Posture Plan*, U.S. Department of Energy, February 2004. www.eere.energy.gov/hydrogenandfuelcells/pdfs/hydrogen_posture_plan04.pdf

[34] Multi-Year Research, Development and Demonstration Plan: Planned program activities for 2003−2010. www.eere.energy.gov/hydrogenandfuelcells/mypp.

[35] Hydrogen Cost Goal. www.hydrogen.energy.gov/pdfs/h2_cost_goal.pdf.

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[36] Cost goal of $2.00−$3.00/gge can be found on the DOE Hydrogen Program Web site: www.hydrogen.energy.gov/pdfs/h2_cost_goal.pdf.

[37] Ibid.

[38] TELEDYNE Energy Systems.

[39] "Direct Hydrogen Fueled Proton Exchange Membrane Fuel Cell System for Transportation Applications," *Hydrogen Infrastructure Report*, Contract No DE-1C02-94CD50389.

[40] Source: CPI Industries Web site, www.cp-industries.com/tour2.htm.

[41] "Hydrogen, Fuel Cells & Infrastructure Technologies Program, Multi-Year Research, Development and Demonstration Plan," Multi-Year Research, Development and Demonstration Plan, U.S. Department of Energy: Energy Efficiency and Renewable Energy; Hydrogen, Fuel Cells, and Infrastructure Technology Program. February 2005.change www.eere.energy.gov/hydrogenandfuelcells/mypp/

[42] Source: K. Newell, Quantum Technologies, Inc.

[43] Source: K. Newell, Quantum Technologies, Inc.

[44] Source: Linde.

[45] Source: Quantum Technologies

[46] Working definition produced by the National Science and Technology Council Interagency Working Group on Manufacturing Research and Development, July 2004. This working definition is being used in conjunction with implementation of Executive Order (EO) 13329, Encouraging Manufacturing Innovation. Any official information with respect to EO 13329 should be obtained from the White House Office of Science and Technology Policy.