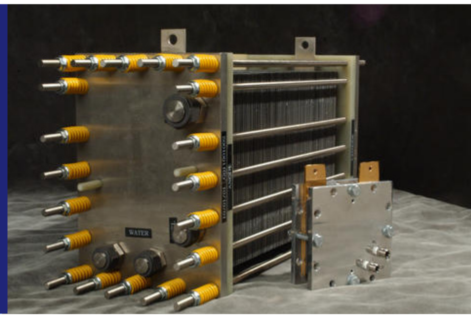
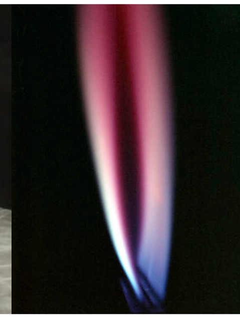
Building a Hydrogen Economy in Virginia

Suggested Strategies

2006


Produced by:

Virginia Hydrogen Economy Roundtable

This Virginia hydrogen plan and hydrogen vision were developed by the Virginia Hydrogen Economy Roundtable, a forum created in 2002 comprised of representatives from more than thirty energy- and transportation-related industries, federal and Virginia government agencies, Virginia academic institutions, and non-governmental organizations. The creation of Virginia's hydrogen vision and the recommendations made in the hydrogen plan are the result of input gathered from in-depth Roundtable discussions held from late 2005 through the first half of 2006.

Table of Contents

Executive Summary

As concern for energy security grows, so does the level of interest at the national and state levels. Fuel cells and hydrogen-sourced energy are regarded as viable long-range technologies that one day could alleviate the United States' dependence on foreign oil, reduce harmful emissions, and create thousands of new jobs. Forty-seven states and the District of Columbia have fuel cell or hydrogen legislation, technology demonstrations or other hydrogen initiatives in place or under consideration today. Many are laying the groundwork for adoption of these technologies in regulations and energy standards. With a commitment of resources, Virginia has the potential to play a significant role in the building of a hydrogen economy in the United States.

This plan recommends actions to foster the development of a hydrogen economy in Virginia. A range of three levels of effort and commitment is offered: 1. Commit significant resources 2. Leverage existing efforts and 3. Stay informed and maintain current level of effort. The recommendations have been developed by the Virginia Hydrogen Economy Roundtable (the Roundtable), a forum created in 2002 comprised of representatives from more than thirty energy and transportation related industries, federal and Virginia government agencies, Virginia academic institutions, and non-governmental organizations.

The following five actions are recommended as priorities to help focus Virginia's continuing efforts to build a hydrogen economy:

- Educate our future workforce, focusing on K-12 education
- Leverage the research and development (R&D) potential of Virginia's academic institutions
- Invest in hydrogen demonstration projects with high visibility
- Foster partnership building
- Coordinate policies and incentives to drive the building of a hydrogen economy in Virginia

A range of options is offered for each of the first four action items and several possible approaches to coordinate policy setting and an incentives strategy are discussed:

Educating Virginia's K-12 Students

- Option 1: Commit Resources for the Education of K-12 Students
- Option 2: Implement Pilot Hydrogen Curriculum and Teacher Training Program for Middle Schools
- Option 3: Implement the Green Box Program in 6th Grade Classrooms

University Research &Development

- Option 1: Create a Statewide Hydrogen R&D Consortium
- Option 2: Universities Form Voluntary Partnerships
- Option 3: Universities Continue Independent R&D Efforts

Demonstration Projects

- Option 1: Develop a Hydrogen Highway Corridor
- Option 2: Consider Discrete Demonstration Project Grants
- Option 3: Pursue external funding opportunities with existing resources

Partnership Opportunities

- Option 1: Create a Formalized Virginia Hydrogen Network
- Option 2: Join Forces with Existing Regional Partnerships
- Option 3: Support Partnerships upon Request

Policy Setting and Funding

- Create a Hydrogen Policy Commission to coordinate policy setting, review hydrogen-related initiatives and establish a Hydrogen Demonstration Incentive Fund.

Creating an environment in Virginia in which hydrogen-focused economic development can thrive will require a commitment to pursuing these measures.

PART 1.0
Introduction

Virginia Hydrogen Economy Roundtable Member Organizations:

Air Products | Avalence | Ballard Power Systems | BP | City of Chesapeake | City of Richmond - Public Utilities | Dominion Resources, Inc. | Ecron | Gas Technology Institute | GM | H2Gen Innovations | Hampton Roads Clean Cities Coalition | Hampton Roads Economic Development Alliance | Hampton Roads Hydrogen | Honorable William Haskins | James Madison University | MidAtlantic Hydrogen Consortium | NASA | National Hydrogen Association | North Carolina Advanced Vehicle Research Center | North Carolina Solar Center | Northrop Grumman Newport News | Ohio Department of Development | Old Dominion University | Plug Power | Princeron Group, Inc. | Propane Vehicle Council | Proton Energy Systems | Science Museum of Virginia | SENTECH, Inc. | Shell Hydrogen | U.S. Army | U.S. Department of Energy | U.S. Navy | University of Maryland | University of Virginia | Virginia Advanced Shipbuilding and Carrier Integration Center | Virginia Clean Cities | Virginia Commonwealth University | Virginia Department of Education | Virginia Department of Environmental Quality | Virginia Department of General Services | Virginia Department of Mines, Minerals, and Energy | Virginia Department of Transportation | Virginia Economic Development Partnership | Virginia Senate Staff | Virginia Tech | Virginia's Center for Innovative Technology

As concern for energy security grows, so does the level of interest at the national and state levels. Fuel cells and hydrogen-sourced energy are regarded as viable long-range technologies that one day could alleviate the United States' dependence on foreign oil, reduce harmful emissions, and create thousands of new jobs. Forty-seven states and the District of Columbia have fuel cell or hydrogen legislation, technology demonstrations or other hydrogen initiatives in place or under consideration today. Many are laying the groundwork for adoption of these technologies in regulations and energy standards. With a commitment of resources, Virginia has the potential to play a significant role in the building of a hydrogen economy in the United States.

Here are some examples of policies and funding levels in a selected group of states with aggressive hydrogen initiatives:

- ***South Carolina*** has committed $3.6 million annually to pursue hydrogen development. The governor's budget earmarks $2 million per year for the International Center for Automotive Research (ICAR) in Greenville. Another $1 million would be funneled to the University of South Carolina's hydrogen fuel cell research program based in Columbia. And the state's newly formed Hydrogen and Fuel Cell Alliance would get nearly $368,000 annually.[1]
- ***Ohio*** has committed $103 million over three years, including $75 million in financing to make strategic capital investments, $25 million for research and development (R&D) and demonstration, and $3 million for worker training.
- ***California*** plans to invest at least $40 million in state and private funds to build hydrogen refueling stations during the next five years.
- ***Michigan*** has committed $56 million for its NextEnergy program, which focuses on alternative energy technologies – especially for the automotive sector.
- ***Florida*** is among the states that have introduced legislation to provide extensive incentives for research, economic development, and market stimulation.
- ***Numerous other states, including New York and Massachusetts,*** are spending tens of millions of dollars per year on incentives to stimulate the adoption of hydrogen-related technologies.[2]

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The following five actions are recommended as priorities to help focus Virginia's continuing efforts to build a hydrogen economy:

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- Foster partnership building
- Coordinate policies and incentives to drive the building of a hydrogen economy in Virginia

FOOTNOTES

[1] www.swampfox.ws/hydrogen-economy-south-carolina-receive-more-than-36-million-annually/

[2] The South Carolina Hydrogen Economy: Capitalizing on the State's R&D Assets, Prepared for the South Carolina Hydrogen Coalition and South Carolina Energy Office by Concurrent Technologies Corporation, July 2005.

1.1 Virginia's Transition to a Hydrogen Economy in the 21st Century

In 2005, both Houses of the Virginia General Assembly passed House Joint Resolution 711 and Senate Joint Resolution 406, expressing support for a Hydrogen Energy Plan. The resolutions called for a plan that would develop a strategy to address the hydrogen economy in Virginia. As a result, the Virginia Department of Mines, Minerals, and Energy (DMME) in Spring 2005 tasked Virginia Clean Cities to work on these elements of the resolutions, building on the hydrogen educational forum that had been established in 2002, the Virginia Hydrogen Economy Roundtable.

In late 2005, the Roundtable met to discuss the potential role for hydrogen systems in America's energy future. The intent of the meeting was to identify a common Virginia vision of the "hydrogen economy," and to lay out a process for determining how to get there. The result of those discussions was the creation of Virginia's Hydrogen Vision:

> *Hydrogen is one of America's and Virginia's clean energy choices. It is flexible, affordable, safe, domestically produced, used in many sectors of the economy, and throughout the Commonwealth. The Hydrogen Economy supports economic growth, environmental protection, and energy security.*

This vision guided the Roundtable in its development of the recommendations made in this Virginia hydrogen plan. In-depth discussions were held, and detailed input was gathered from Roundtable members over the course of the first half of 2006.

Virginia can play a significant role in the transition to hydrogen. Before hydrogen can achieve its promise, however, an array of technical, economic, and institutional challenges must be overcome. This plan recommends actions that the Commonwealth can take to expand the hydrogen economy in Virginia. The recommendations focus on opportunities that can be undertaken in the near-term (5 years) that provide a foundation for longer-term development.

1.2 Benefits of a Hydrogen Economy

The development of new hydrogen technologies will require the involvement of private industry working in partnership with academic research institutions. The opportunity for business development and job creation to support a hydrogen economy is tremendous. Many successful models have shown the significant impact that technology-based economic development (TBED) can have on a state and local economy. Silicon Valley in California and the Research Triangle in North Carolina demonstrate the economic growth potential that is possible with a technology development cluster. Similarly, Virginia has the opportunity to play a significant role or, with a large commitment of resources, a leadership role in the nation's quest to transition to a hydrogen economy

Use of hydrogen as an energy carrier in Virginia and the nation could help address concerns about energy security and supply reliability, global climate change, and air quality. Hydrogen can be derived from a variety of domestically available primary energy sources. It can provide distributed power, enhancing energy reliability. It could provide air quality benefits in Virginia's congested transportation corridors by eliminating vehicle tailpipe emissions through the use of fuel cells and could offer economic benefits to a Commonwealth rich in agricultural resources and coal.

1.3 Virginia's Status in the Hydrogen Economy

The opportunity for hydrogen-based economic development is great in Virginia. Many of the tools and other prerequisites are in place, including: abundant natural resources, highly skilled technical workforce, world-class research universities already engaged in hydrogen R&D, public-private partnership potential, major interstate thoroughfares, military presence, large population and tourist centers, proximity to the nation's capital, and hydrogen demonstration projects already on the ground. Virginia is in a position to be a hydrogen economy leader. Additionally, the high quality of life, along with its central location along the eastern seaboard can help to attract new business and investment to the state.

If the vision of a hydrogen economy is to come to fruition in Virginia, a concerted effort must be made to coordinate, focus, and guide hydrogen-related activities to take best advantage of Virginia's unique assets. This will help to ensure a cohesive strategy in making future decisions about hydrogen development, and will put Virginia in a position to realize the full potential that hydrogen-based economic development could offer.

Among Virginia's strongest assets are premier research universities, which have existing programs involved in R&D of hydrogen energy systems. Another unique advantage is a strong military presence in the Commonwealth, which includes the world's largest Navy base located in Norfolk, and a number of other military installations, including Langley Air Force Base, located throughout the state. The military often acts as a first adopter of new technologies. Military bases could serve as sites for early hydrogen fleet use and distributed power through stationary fuel cells. Military applications are very well suited to existing proton exchange membrane (PEM) fuel cell technology for use in generators, auxiliary power units, and ground support equipment. Military contractors with significant R&D capacity (such as Northrop Grumman), are actively involved in technology R&D and could be natural partners in Virginia's hydrogen development efforts.

Virginia is blessed with a strategic location central to major U.S. population centers and in close proximity to the nation's capital. This could be a significant factor in the effort to attract hydrogen-related industry. Furthermore, the Interstate Highway infrastructure of Virginia is highly developed, including four north-south Interstate segments (I-95, I-85, I-81, I-77) and two east-west segments (I-66, I-64). Virginia's location in the middle of the eastern seaboard greatly increases the number of travelers from the north and south traversing its interstates. The road transportation sector could provide a large end-user market for hydrogen fuel. The poor air quality that comes with traffic congestion could be significantly improved with the widespread introduction of hydrogen or fuel-cell powered vehicles.

Significant challenges related to hydrogen production, delivery, and storage, and the need for education and outreach need to be addressed if hydrogen is ever to play a role in the energy sector of Virginia and the nation. Recommended actions for addressing some of these issues are discussed throughout the remainder of this hydrogen energy plan.

One of the greatest barriers to the development of a hydrogen economy is the lack of public awareness about hydrogen – its potential benefits and uses, its R&D challenges, and safety and handling issues. If the vision of a hydrogen economy is to be realized, kindergarten to grade 12 (K-12) students will need to be educated on hydrogen as they are our future workforce and

PART 2.0

Educating Virginia's K-12 Students

potential end-users of hydrogen. Virginia has a strong, highly functional K-12 education system capable of incorporating a hydrogen education program. Educating the students of today builds the workforce of tomorrow.

2.1 *Option 1:* Commit Resources for the Education of K-12 Students

Student education is a key component to broadcasting the hydrogen message and developing a knowledgeable, involved hydrogen support network. Without a targeted technology- and applications-level education program for students and teachers, our past will continue to define our future. Long-term resources should be committed to educate K-12 students. Hydrogen curriculum has been developed at the federal level through efforts of the US Department of Energy (DOE). This curriculum could be adapted and integrated into Virginia's K-12 curriculum.

Develop and introduce a hydrogen middle school curriculum in Virginia schools in the near-term (8th grade statewide is recommended). The National Energy Education Development (NEED) Project, under a grant from DOE has developed and pilot tested in the State of New York a middle school hydrogen curriculum, H2 Educate. This hydrogen module correlates to Virginia's current standards of learning (SOL) for middle schools. Virginia could leverage the resources already invested in the development of this curriculum to tailor it to the needs of Virginia.

Conduct pilot teacher training workshops based on hydrogen curriculum. The curriculum would be introduced to students after teacher training. NEED's proven training model and nationwide teacher network could be used to introduce the hydrogen curriculum to teachers throughout the Commonwealth through regional workshops. The one-day teacher workshops are designed to meet state standards and provide educators with tools to return to their classrooms to integrate energy into their classroom plans and to make hydrogen a part of their curriculum. NEED recommends that the workshops be hosted for middle and secondary level educators as well as technology teachers. For a program to cover the entire state, a series of seven one-day workshops is recommended in the following areas: Abingdon, Chesapeake/ Virginia Beach, Lynchburg, Manassas, Richmond, Roanoke, and Winchester.

2.1.1 Funding Level

H2 Curriculum Workshops:
$6,000 each x 7 workshops = $42,000

Curriculum Materials:
$36,800 each x 7 workshops = $257,600

Total for Seven regions: $300,000 for seven teacher training workshops, which includes H2 Education kits with classroom materials for approximately 300 teachers. This budget includes substitute teacher reimbursement if needed at $100 per person plus meals.

2.1.2 Funding Sources

Commonwealth of Virginia (such as through the Virginia Department of Education), private industry sponsorship.

2.1.3 Key Responsible Parties

NEED Project, DMME, Virginia Department of Education, Science Museum of Virginia.

2.1.4 Likely Results

If funding is provided to conduct 7 teacher training workshops throughout the Commonwealth, over 300 Virginia teachers could be trained to implement a hydrogen curriculum unit in their classrooms. Middle school students educated in the basic elements of a hydrogen economy will have an increased level of understanding, which is critical to ensuring a capable future workforce and informed end-users of hydrogen applications.

2.1.5 Timeline

Teachers trained within one year of funding. Students introduced to curriculum beginning year 2.

2.2 *Option 2:* Implement a Hydrogen Curriculum Teacher Training Pilot Project for Virginia Middle Schools

Conduct a pilot of the hydrogen curriculum and teacher training workshop for middle schools discussed under *Option 1* (section 2.1) above. Rather than seven regional teacher training workshops, this option would require funds only for one reduced-scope teacher training workshop.

2.2.1 Funding Level

Total for Pilot: $30,000 for initial training session for 40 participants including 40 Hydrogen Education kits with classroom materials. This budget includes substitute teacher reimbursement if needed at $100 per person plus meals.

2.2.2 Funding Sources

DMME.

2.2.3 Key Responsible Parties

NEED Project, DMME, Virginia Department of Education, Science Museum of Virginia.

2.2.4 Likely Results

A single pilot teacher training workshop could not implement hydrogen education on a widespread basis. Only 40 Virginia teachers would be trained and provided with materials to implement the hydrogen curriculum unit in their classrooms. A successful pilot may provide justification to expand the training workshops and offer them in regions throughout the Commonwealth, as described in *Option 1* (section 2.1) above.

2.2.5 Timeline

Year 1 (2007).

2.3 *Option 3:* Implement the Green Box Program in 6th Grade

Implement the Green Box program in Virginia's 6th grade classrooms. The Green Box project is a partnership for production of new educational materials to support Virginia teachers in meeting the new 6th grade standards on environmental science and environmental policy decisions. It is administered by the Virginia Department of Environmental Quality (DEQ). A hydrogen component will examine and investigate the concept of environmental resource management and facilitate understanding the role of hydrogen resources in the world, how living systems operate and how people can use resources in a sustainable way using various Virginia case studies.

PART 2.0 *cont.*
Educating Virginia's K-12 Students

2.3.1 Funding Level

$2,000 for the expense of development and publication of educational materials introducing the science and technology of the hydrogen economy to be incorporated into the Green Box project. The Green Box project is currently in final development for 6th grade classrooms in Virginia.

2.3.2 Funding Sources

DMME.

2.3.3 Key Responsible Parties

Virginia DEQ.

2.3.4 Likely Results

The Green Box program will enhance teachers' ability to deliver the requirements called for in the Standards of Learning. It will teach students about the public policy decision-making process, management of renewable resources and nonrenewable resources, and the cost-benefit tradeoffs in conservation policies. This project will reinforce student understanding of the importance of the Earth's natural resources and the need to manage resources. Students will explore a variety of ways in which people use and interact with the environment and will apply their knowledge to interpret how human interactions can affect ecosystem dynamics.

2.3.5 Timeline

First round of the Green Box program is expected to be in schools by Spring 2007.

PART 3.0
University Research & Development

Energy R&D and the role that could be played by state universities will be explored as part of the Virginia Energy Plan (VEP). Some of the recommendations of the Hydrogen Economy Roundtable will be considered within the broader context of the 10-year Virginia Energy Plan. The VEP work, which began in August of 2006, will inventory existing energy R&D resources, investigate R&D policies of other states and explore a possible energy-focused R&D approach that would include university-based initiatives. Research universities are Virginia's strongest existing resource for hydrogen energy development. A number of universities throughout the Commonwealth are involved in hydrogen activities, ranging from research, development and demonstration, to hydrogen-specific curricula that have been introduced into academic programs. While a number of universities are involved in such activities, most of them are not working in a coordinated fashion. Partnership and coordination among these universities could be the single-most influential force in laying the groundwork for hydrogen development in Virginia.

Examples of efforts at the university level include:

- ***The University of Virginia (UVA)*** - Offers energy and hydrogen related courses, undergraduate engineering projects related to fuel cells and the hydrogen economy, and research programs.
- ***James Madison University (JMU)*** - Development of K-12 curriculum and standards of learning (SOL), developing a small-scale demonstration hydrogen fueling station, hydrogen fuel cell demonstration, and research on fuel cell auxiliary power units for truck idle reduction.
- ***Virginia Polytechnic Institute and State University (Virginia Tech)*** - Hydrogen learning center with the University of Maryland; courses on hydrogen; research on fuel cell design, fuel supply, and system design and integration; and developing a hydrogen power park on campus.
- ***Virginia Commonwealth University (VCU)*** - Research on batteries and fuel cell systems and a fuel cell demonstration.
- ***Hampton University*** - Work on synthetic fuels.

3.1 *Option 1:* Create a Statewide Hydrogen R&D Consortium

Create a Statewide Hydrogen Research and Development Consortium, a formalized coalition of Virginia academic institutions conducting hydrogen-related research, development, and demonstration activities. Private industry should also participate to create additional partnership and leveraging opportunities. This Consortium could coordinate high-level hydrogen-related activities at higher education institutions throughout the Commonwealth. It could serve as an interdisciplinary study, research, and information resource for the Commonwealth on hydrogen energy issues. The Research Consortium could (i) consult with the General Assembly, Federal, state, and local agencies, nonprofit organizations, private industry and other potential users of hydrogen energy research; (ii) establish and administer agreements with other universities of the Commonwealth to carry out research projects relating to the feasibility of producing, storing, transporting, handling, and using hydrogen in Virginia; (iii) disseminate new information and research results; (iv) apply for grants made available pursuant to Federal legislation and from other sources; (v) facilitate the application and transfer of new hydrogen energy technologies; and (vi) coordinate areas of expertise among members in order for activities to complement instead of compete with each other.

3.1.1 Funding Level

$250,000 in Year 1 growing to $1 million by Year 5.

3.1.2 Funding Sources

Commonwealth of Virginia, membership contributions/dues, grants and endowments, U.S. Department of Energy, fee for service, State match of private investment, federal matching funds, could use a funding model of the National Science Foundation Engineering Research Center.

3.1.3 Key Responsible Parties

The Consortium could be governed by a board representing Virginia universities and colleges involved in hydrogen-related research; the General Assembly; Center for Innovative Technology; members of the hydrogen and related energy industries; and non-profits and other organizations engaged in hydrogen-based energy activities (such as the Hampton Roads Clean Cities Coalition).

3.1.4 Likely Results

A coordinated effort would leverage resources and maximize the impact of R&D efforts of Virginia academic institutions and private industry. Furthermore, a consortium of this sort would enhance the visibility of the prestigious R&D base in Virginia which could serve to attract significant investment and interest. The Consortium would be in a position to compete for high level funding opportunities associated with hydrogen development.

3.1.5 Timeline

As guided by the Virginia Energy Plan.

3.2 *Option 2:* Universities Form Voluntary Partnerships

Two or more universities create a voluntary network formalized by a memorandum of understanding. One challenge with this approach is that universities may be unwilling to commit resources without a reasonable expectation of a return on investment (ROI).

3.2.1 Funding Level

Dependent on the level of university participation.

3.2.2 Funding Sources

Universities, U.S. Department of Energy, National Science Foundation, and others.

3.3.3. Key Responsible Parties

Virginia academic institutions.

3.3.4 Likely Results

While universities seeking partnership opportunities with one another could indeed leverage resources, their full potential will not be realized without a mandated and coordinated statewide effort. As a result, universities may end up utilizing their own R&D budgets for more administrative functions, while a funded consortium could minimize that financial burden on the individual universities.

3.3.5 Timeline

Ongoing (as opportunities arise).

3.3 *Option 3:* Universities Continue Independent R&D Efforts

Universities seek R&D funding opportunities independently. This could lead to Virginia universities competing with one another for limited funding.

3.3.1 Funding Level

Dependent on availability. Universities seek funding on an individual basis, which could lead to competition for limited funding or missing out on some of the larger scale opportunities due to lack of competitiveness.

3.3.2 Funding Sources

N/A.

3.3.3 Key Responsible Parties

Virginia academic institutions.

3.3.4 Likely Results

Virginia universities pursue funding opportunities independently, without the additional leverage potential that a consortium could offer. Lack of coordination could result in redundant efforts and lead to competition among Virginia universities for limited funding.

3.3.5 Timeline

Ongoing (as funding opportunities arise).

Highly visible hydrogen demonstrations will be critical in the near-term to foster broad-based awareness and acceptance of hydrogen technologies in Virginia. If coordinated and managed well, demonstration projects could encourage regional cooperation and partnerships, develop capacity to attract and leverage grant funds and lay the foundation for the potential future deployment of hydrogen technologies. A hydrogen demonstration fund could be created to help initiate the development of demonstration projects.

4.1 *Option 1:* Develop a Hydrogen Highway Corridor

Seek legislation to encourage and fund the development of a hydrogen transportation corridor along I-95 / I-64 in Virginia, connecting Northern Virginia, Richmond, and Hampton Roads, the largest population centers in the state. This would extend south the hydrogen transportation facilities that currently terminate at Fort Belvoir. Such a project would involve the development of hydrogen fueling stations spaced at intervals of 100 miles or less to allow a hydrogen or fuel cell-powered vehicle to travel the entire distance of the corridor in Virginia. Three hydrogen fueling stations could accommodate a demonstration project of this magnitude and would complement an existing hydrogen fueling station in Washington, DC (Benning Road Shell station) and a proposed station off of I-95 at the North Carolina Advanced Vehicle Research Center. Possible locations include Richmond, Newport News, and Virginia Beach. Fueling stations could be developed in conjunction with hydrogen/fuel cell vehicle demonstrations and hydrogen power park projects.

4.1.1 Funding Level

$5 million (for three hydrogen fueling stations, demonstration vehicle leases, and incorporation with hydrogen power park projects).

4.1.2 Funding Sources

Commonwealth of Virginia (such as DMME), private industry, U.S. Department of Energy, military (US Navy, US Army, especially commands located in Hampton Roads).

4.1.3 Key Responsible Parties

Universities; private industry; military; federal, state, and local government agencies.

4.1.4 Likely Results

Establish Virginia as a leader in hydrogen development. Attention could be drawn to the corridor for the extensive volume of out of state traffic that travels the I-95 corridor. Development of a hydrogen transportation corridor could result in a significant increase in partnership and funding activities within the Commonwealth. Furthermore, a Virginia hydrogen transportation corridor could expand the network of FuelCellSouth. FuelCellSouth is a 501 (c) 6 organization whose core mission is to foster awareness and create the marketplace for fuel cells in the southeastern United States. FuelCellSouth is actively working with State Energy and Transportation Offices and the Clean Cities Program to identify opportunities for Public Transportation and Fleet Vehicle Demonstrations. This could result in Virginia being the leader in a regionally developed Mid-Atlantic corridor that would serve as an East Coast equivalent to the California Hydrogen Highway.

Furthermore, Virginia's portion of a Mid-Atlantic Hydrogen Highway could link with the planned East Coast's Hydrogen Highway, a network of hydrogen fueling stations modeled after California's developing hydrogen highway. The stations would be built along I-95 between Boston, Massachusetts, and Washington, D.C., along I-95 in the north and linked through Richmond on the Mid-Atlantic Hydrogen Highway in Virginia, then south to the Southeastern Hydrogen Highway Program and the Florida Hydrogen Highway.

4.1.5 Timeline

Year 1: Identify number, frequency, and location of fueling stations and vehicle maintenance facilities; Identify potential hydrogen/fuel cell fleet purchasers/leasers.

Year 2: Issue Solicitation.

Years 3-5: Design and build hydrogen fueling stations and maintenance facilities; Acquire hydrogen/fuel cell vehicles.

4.2 *Option 2:* Consider Discrete Demonstration Project Grants

Under this option, grants could be made available to fund discrete hydrogen demonstration projects in Virginia. Examples of demonstration project opportunities include the following:

Create a hydrogen and/or fuel cell public demonstration site at a Commonwealth or public building. Perhaps the simplest way to make hydrogen and fuel cells visible to the public and to key decision-makers is to demonstrate hydrogen technology on the grounds of a public building (such as a Capitol Square building in Richmond or the Science Museum of Virginia). Opportunities include the siting of a stationary fuel cell to provide power for a building, and/or a hydrogen fuel cell-powered vehicle, or fleet of vehicles, alongside a hydrogen demonstration filling station. This demonstration project could complement and benefit from experience gained over more than a decade by a Fort Eustis fuel cell stationary power generation demonstration.

Invest in hydrogen/fuel cell bus projects that maximize public visibility of hydrogen technologies. Potential educational demonstration projects that have been identified include Norfolk buses that could run on hydrogen/hydrogen fuel blend or fuel cells. Colonial Williamsburg has a large fleet of compressed natural gas (CNG) buses, some of which could be converted to run on a hydrogen-CNG blend. Another great opportunity for public education is to power airport ground transportation, such as shuttle buses, with hydrogen or fuel cells. Dulles Airport, Norfolk International Airport, Newport News/Williamsburg International Airport, and Richmond International Airport see vast numbers of visitors and local residents annually and the opportunity to reach them is enormous. Vehicles could be outfitted with interpretive signage, brochures, and possibly a video loop, while the vehicles' exteriors could be clearly labeled to make them easily identifiable as clean energy vehicles.

Replicate Richmond's RFP for hydrogen production from a wastewater treatment plant in the Norfolk area. Richmond recently released (2006) an RFP to produce hydrogen from methane at its wastewater treatment plant (WWTP), which would provide enough hydrogen to produce 1MW electricity through stationary fuel cells. This can be coupled with efforts being considered by Hampton Roads Transit to convert its NET buses to hybrid-electric drivetrains. The converted buses could be hydrogen internal combustion engine (ICE)-electric hybrids, utilizing hydrogen produced at a local WWTP.

Develop a Hydrogen Power Park, a concept that involves generating hydrogen for a stationary power generating fuel cell, and to support fuel cell vehicles. This could be co-located with the hydrogen fueling stations for the hydrogen transportation corridor discussed under *Option 1* (section 4.1) above.

Develop a hydrogen vehicle and fueling station demonstration project in Poquoson. The City of Poquoson, a small city in the Hampton Roads area of Virginia, has indicated interest in installing a hydrogen demonstration project involving a hydrogen filling station to operate a small fleet of city vehicles. This might include replacing the police cars and/or school buses to run on hydrogen or fuel cells, and creating a hydrogen filling station. The city is already considering replacing its school bus fleet, and a local gas station owner has agreed to allow a hydrogen reformation unit at the station. Because of the relatively short distances traveled in Poquoson and the small fleet size, the percentage of clean energy from hydrogen that this city's fleet could operate on would be high.

In the near-term, pursue "low-hanging fruit" options for hydrogen production demonstrations. Demonstration projects to be considered include utilizing waste gas from landfills or wastewater treatment plants, obtaining hydrogen from chemical production plants, and utilizing biomass from food processing and agricultural operations, such as organic waste and animal waste (digester methane which could be reformed). Focus should be on applications that demonstrate least cost production ($/kg of hydrogen).

4.2.1 Funding Level

Dependent on the size and nature of the demonstration project. $5-10 million to fund multiple projects.

4.2.2 Funding Sources

Commonwealth of Virginia (such as DMME, U.S. Department of Energy, local governments).

4.2.3 Key Responsible Parties

Universities; DMME; private industry; federal, state and local government agencies.

4.2.4 Likely Results

Installing hydrogen demonstration projects in areas with high visibility will help to increase public awareness about hydrogen and fuel cell technologies and the issues associated with them. High profile demonstrations would display the Commonwealth's commitment and draw interest from industry outside the Commonwealth.

4.2.5 Timeline

Projects would take approximately 2 years from time of funding.

4.3 *Option 3:* Pursue External Funding Opportunities with Existing Resources

Funding for demonstration projects would be sought on an ad hoc basis.

4.3.1 Funding Level

N/A.

4.3.2 Funding Sources

U.S. Department of Energy, military, private industry, others.

4.3.3 Key Responsible Parties

Universities; private industry; federal, state and local government agencies.

4.3.4 Likely Results

Committed stakeholders would continue to pursue existing external funding opportunities to demonstrate hydrogen technologies, but without the additional leverage that would be possible with state funding, high-level direction, improved coordination and partnering.

4.3.5 Timeline

Dependent on project interest and funding availability.

PART 5.0
Partnership Opportunities

If a significant hydrogen infrastructure is to be developed in Virginia, partnerships among universities, state and local governments, military, industry, and non-governmental organizations will be key. These partnerships, representing public and private sector interests, could be the driving force behind hydrogen-based economic development by leveraging resources and building the base of business opportunities throughout the Commonwealth.

The economic development benefits from pursuing a hydrogen economy in Virginia could be significant, even in the near-term. Opportunities for workforce development, job creation, and attracting and building new businesses are significant. A trained and coordinated workforce will need to be ready to handle each stage in the energy delivery process, from hydrogen production, delivery, and storage, to operating and managing on-the-ground projects. Virginia's K-12 and higher education institutions can play a key role in educating the future workforce. This workforce will include a collection of high paid jobs including engineers, technology manufacturers, code officials, technicians, policy makers, business managers, teachers, and marketing and outreach professionals.

A number of entities are already working on hydrogen activities in Virginia. These, in addition to others involved in similar or related technology and economic development efforts, have the potential to leverage each other's strengths and assets through partnerships. Potential partnering entities representing academic institutions, private industry, and public agencies in Virginia include, but are not limited to the following:

- Universities and research institutes working on hydrogen research, development, demonstration, and curriculum (detail provided below)
- National research centers and laboratories, including NASA Langley Research Center and the U.S. Department of Energy's Jefferson Laboratories
- Private industry, including fuel cell vehicle manufacturers (General Motors) and other advanced vehicle design companies (Siemens VDO); distributed, on-site hydrogen production technology manufacturers (H2Gen Innovations, Inc.); and technology and infrastructure development contractors (Northrop Grumman)
- Military installations (Norfolk Naval Base, Langley Air Force Base, and Ft. Belvoir among others)
- State and regional consortiums including the Mid-Atlantic Hydrogen Coalition, the Virginia Hydrogen Economy Roundtable, Hampton Roads Clean Cities, Virginia Clean Cities, and Hampton Roads Hydrogen
- State and local agencies, including the Virginia Economic Development Partnership; Virginia Department of Mines, Minerals, and Energy; Virginia Department of Environmental Quality; Virginia Department of Transportation; Virginia Department of Education; Science Museum of Virginia; and numerous municipalities
- Virginia utilities, including Dominion, and primary energy source providers, such as the coal, biomass, and nuclear industries
- NEED Project, a non-profit organization that develops energy curriculum and materials for K-12 schools around the country

Several Virginia universities are working on hydrogen research, development, demonstration, and curriculum. The University of Virginia (UVA) offered a new elective course on "Energy Outlook and Technology Options" to graduate and senior-level undergraduate students in the Department of Chemical Engineering in Jan-May, 2006. Energy topics have been offered in the undergraduate "Introduction to Engineering" course for incoming engineering students. Some undergraduate engineering senior theses have involved projects related to fuel cells and the hydrogen economy. The senior-level undergraduate design course in chemical engineering has dealt with reforming of fuels to produce hydrogen for automobiles. A new experiment is planned for the senior-level undergraduate chemical engineering laboratory course that includes reforming of a hydrocarbon fuel to produce hydrogen, which is then fed to a fuel cell to generate electricity. Finally, some of the research programs at UVA relevant to the hydrogen economy involve fuel cells (chemical engineering), thermochemical hydrogen production (chemical engineering), activation of hydrocarbons and hydrogen (chemistry) and hydrogen embrittlement of metals (materials science).

One of the top priorities within James Madison University's (JMU) hydrogen efforts is the development of K-12 curriculum, and the inclusion of hydrogen into the state's standards of learning (SOL). Additionally, it is developing a small-scale demonstration hydrogen fueling station on its campus, and is deploying a hydrogen fuel cell back-up unit for Shenandoah National Park. Another related area of research at JMU focuses on fuel cell auxiliary power units for truck idle reduction. This research team recently won the Society of Automotive Engineers Bendix Automotive Electronics Paper of the Year for its hydrogen fuel cell auxiliary power reduction work.

Virginia Polytechnic Institute and State University (Virginia Tech), through a grant from the State Technologies Advancement Collaborative, led a hydrogen learning center with the University of Maryland called the Hydrogen Technology Education Center (H2TEC). H2TEC helped to educate K-12 students as well as undergraduate and graduate students about hydrogen production, storage, and delivery. Additionally, Virginia Tech offers numerous courses on hydrogen to its students, and has a research group involved with fuel cell design, fuel supply, and system design and integration. Virginia Tech is also working to develop a hydrogen power park on campus using stationary fuel cell power systems.

Virginia Commonwealth University believes that education is essential to promoting the hydrogen economy and has been conducting research on batteries and fuel cell systems with NASA funding. New platinum catalysts are being developed that promise better fuel cell durability. A fuel cell demonstration experiment has been acquired and will be incorporated into a revised curriculum in Chemical and Life Science Engineering.

Hampton University has been doing work on synthetic fuels.

5.1 *Option 1:* Create a Formalized Virginia Hydrogen Network

Create a formalized Virginia hydrogen network or alliance that encourages hydrogen technology partnerships. Membership could include academic institutions, private businesses, government agencies, and military representation. This could be a more structured and formal version of the voluntary Hydrogen Roundtable. Membership should strive for a balance of elements required to demonstrate hydrogen technologies, including hydrogen producers and entities that can transport and distribute the hydrogen, manufacturers of hydrogen technology, and end-users. This network could also serve as a clearinghouse of hydrogen information, and could provide education, outreach, and networking opportunities through sponsorship of conferences and other events.

5.1.1 Funding Level

Membership dues, $250K seed money, $100K/year thereafter.

5.1.2 Funding Sources

Membership dues, Commonwealth of Virginia.

5.1.3 Key Responsible Parties

Universities, state and local government agencies, private business.

5.1.4 Likely Results

A formalized statewide hydrogen network could bring together private businesses, academic institutions, and government agencies to foster public-private partnerships.

5.1.5 Timeline

Immediately / upon funding.

5.2 *Option 2:* Join Forces with Existing Regional Partnerships

Leverage hydrogen economy opportunities by joining existing regional partnerships. Leverage partnership opportunities by joining forces with existing regional partnerships, such as the Mid Atlantic Hydrogen Coalition, Fuel Cell South (http://www.fuelcellsouth.com/), the Southern Governors Association (http://www.southerngovernors.org/), the Southeastern Hydrogen Highway Initiative, and the Southern Fuel Cell Coalition (http://www.sfcc.tv/).

5.2.1 Funding Level

Partnership driven.

5.2.2 Funding Sources

Dependent on partnership participation.

5.2.3 Key Responsible Parties

In the absence of a formal network, this level of participation could be handled by DMME, the Virginia Hydrogen Roundtable and Virginia Clean Cities.

5.2.4 Likely Results

By tapping into activities and partnerships already underway in the region, Virginia could build momentum in its hydrogen development activities.

5.2.5 Timeline

Ongoing.

5.3 *Option 3:* Support Partnerships upon Request

This option would not be a coordinated effort to build partnerships, but rather would support partnerships brought together to respond to current opportunities.

5.3.1 Funding Level

Dependent on project and availability of funding.

5.3.2 Funding Sources

Commonwealth of Virginia, U.S. Department of Energy, private industry match.

5.3.3 Key Responsible Parties

Commonwealth of Virginia, academic institutions, private industry.

5.3.4 Likely Results

While this option would provide support to some partnerships, it would lack a coordinated effort to build partnerships throughout the Commonwealth.

5.3.5 Timeline

Ongoing.

PART 6.0

Policy Setting

6.1 Designate a Statewide Hydrogen Commission or Task Force

Designate a commission to serve as the Virginia hydrogen policy-setting entity. Many of the recommendations made in this hydrogen plan clearly need state government support. A commission or task force with a focus on hydrogen could serve as a driver for hydrogen policy for the Commonwealth. This commission could proactively set a hydrogen policy agenda for Virginia. This could be accomplished through existing commissions, such as the Joint Commission on Technology and Science. One of the issues that could be addressed by this commission could be the creation of a hydrogen demonstration fund.

6.1.1 Funding Level

N/A.

6.1.2 Funding Sources

N/A.

6.1.3 Key Responsible Parties

Various state government representatives or others as appointed.

6.1.4 Likely Results

A hydrogen policy-setting task force could ensure that state government has an agenda to support the advancement of hydrogen and that it is effectively coordinated with the agenda of the Virginia Energy Plan.

6.1.5 Timeline

Based on assignment or selection of members.

Appendix:

A Vision Of Virginia’s Transition to a Hydrogen Economy in the 21st Century

A Vision of Virginia's Transition to a Hydrogen Economy in the 21st Century

2006

Produced by:

Virginia Hydrogen Economy Roundtable

This Virginia hydrogen plan and hydrogen vision were developed by the Virginia Hydrogen Economy Roundtable, a forum created in 2002 comprised of representatives from more than thirty energy- and transportation-related industries, federal and Virginia government agencies, Virginia academic institutions, and non-governmental organizations. The creation of Virginia's hydrogen vision and the recommendations made in the hydrogen plan are the result of input gathered from in-depth Roundtable discussions held from late 2005 through the first half of 2006.

Table of Contents

Executive Summary

In late 2005, participants from over thirty organizations representing energy and transportation industries, universities, environmental organizations, and Federal and Virginia government agencies, met to discuss the potential role for hydrogen systems in America's energy future. (A list of the participants can be found in the appendix.) The intent of the meeting was to identify a common Virginia vision of the "hydrogen economy," and to lay out a process for determining on how to get there.

Virginia Clean Cities staff has reviewed the National Hydrogen Economy Vision that was published by the U.S. Department of Energy in 2002 (reference below), and has made modifications to that document based on the ideas and suggestions put forth by this group, known as the **Virginia Hydrogen Economy Roundtable**. This document presents the results of this editing, and is presented as a Virginia vision for hydrogen to become a premier energy carrier for Virginians. This vision serves as a guide to the Roundtable in developing a hydrogen plan for Virginia.

The proceedings of these meetings, which include the presentations and summaries of the meeting notes, are available at:
www.hrccc.org/hydrogen.html.

This vision was guided by the U.S. Department of Energy's **"A National Vision of America's Transition to a Hydrogen Economy – To 2030 and Beyond"** (February. 2002), available from www.hydrogen.energy.gov/pdfs/vision_doc.pdf

PART I
Introduction

In 2005, both Houses of the Virginia General Assembly passed House Joint Resolution 711, and Senate Joint Resolution 406, expressing support for a Hydrogen Energy Plan. This Plan included development of a strategy to address the Hydrogen Economy in Virginia. As a result, the Virginia Department of Mines, Minerals, and Energy (VA DMME) in Spring 2005 tasked Virginia Clean Cities to work on these elements of the resolutions, building on the hydrogen educational forum that had been established in 2002, the Virginia Hydrogen Economy Roundtable.

The Virginia Hydrogen Economy Roundtable now consists of over thirty representatives of energy-related and transportation industries, federal and Virginia government agencies, Virginia academic institutions, and non-governmental organizations. (A list of the participants can be found in the appendix).

The 2005 resolutions expressed the following objective for the future of Virginia's energy sector:

> *Virginia will take a leading position as a producer and user of hydrogen within a larger Hydrogen Economy, and Virginia will proactively support the growth of the Hydrogen Economy.*

The Virginia Hydrogen Economy Roundtable was established with the following charter:

> *Develop a plan that identifies actions, by state and local governmental agencies, individuals, and business entities, that are necessary or appropriate to achieve this vision of Virginia as a leading producer and user of hydrogen.*

Evaluation of specific elements for this plan include:

- Development of a comprehensive hydrogen economy blueprint for Virginia;
- Promotion of the Virginia Hydrogen Network;
- Evaluation, recommendation, and implementation of all necessary legislation and incentives;
- Strengthening the cooperative efforts between the private sector and government;
- Educating Virginians about the advantages and importance of a hydrogen economy;
- Promoting relationships with hydrogen industry;
- Development of additional courses at Virginia academic institutions;
- Further education of Virginians.

Each action that is identified by the Roundtable plan will require the following discussion:

- How the proposed action will contribute to the General Assembly's vision for Virginia;
- How the proposed action will be implemented:
  - Executor
  - Timeline
  - Cost
  - Proposed Funding Source

The Task Force will report its findings to the Virginia Department of Mines, Minerals, and Energy by October 15, 2006.

The Roundtable met twice in 2005 to define a Hydrogen Economy Roadmapping process for Virginia, with one step in this process consisting of developing a Vision for the Hydrogen Economy in Virginia. These meetings marked the first occasion that a broad cross-section of business leaders and energy and environmental officials from across Virginia have met to discuss hydrogen energy development and its future as an energy source for America. This document reflects the ideas and priorities put forth by the Roundtable participants. Subsequent meetings were held in the first half of 2006 in order to collect input to the plan.

PART II
The Hydrogen Industry Today

The current hydrogen industry is not focused on the production or use of hydrogen as an energy carrier or a fuel for energy generation. Rather, the nine million tons of hydrogen produced each year are used mainly for chemicals, petroleum refining, metals, and electronics. For example, the processes for making gasoline and diesel fuels, such as the breakdown of heavier crude oils and the removal of sulfur, are major users of hydrogen. The production of ammonia, used to make fertilizers, also consumes large amounts of hydrogen. The use of hydrogen as an energy carrier or major fuel requires development in several industry segments, including production, delivery, storage, conversion, and end-use. The table below provides a list of terms and explanations for hydrogen energy systems. Each industry segment is integral to building a hydrogen-based economy, and the development of one segment relies on corresponding development of all other segments.

Elements of Today's Hydrogen Energy System

Hydrogen Industry Segment	Explanation
Production	• The production of hydrogen from fossil fuels, biomass, or water • Involves thermal, electrolytic, and photolytic processes
Delivery	• The distribution of hydrogen from production and storage sites • Involves pipelines, trucks, barges, and fueling stations
Storage	• The confinement of hydrogen for delivery, conversion, and use • Involves tanks for both gases and liquids at ambient and high pressures • Includes reversible and irreversible solid-state systems
Conversion	• The making of electricity and/or thermal energy • Involves combustion turbines, reciprocating engines, and fuel cells
End-Use Energy Applications	• The use of hydrogen for portable power in devices such as mobile phones and computers, military field applications • The use of hydrogen for transportation systems such as fuel additives, fuel-cell vehicles, internal combustion engines, and in propulsion systems for the space shuttle, ships, and military vehicles with low noise and thermal signatures • The use of hydrogen for stationary energy generation systems, including mission critical, emergency, and combined heat and power applications

PART II *cont.*
The Hydrogen Industry Today

Overview

Hydrogen can be produced through many different thermal, electrolytic, or photolytic processes applied to coal or other fossil fuels, biomass, or water. Renewable and nuclear systems can produce hydrogen from water using thermal or electrolytic processes. The thermalchemical production process, which uses steam to produce hydrogen from natural gas or other light hydrocarbons, is most common. This hydrogen is either consumed on site ("captive" hydrogen) or distributed via pipelines or trucks ("merchant" hydrogen). Hydrogen can be stored in its elemental form as a liquid, gas, or as a chemical compound, and is converted into energy through fuel cells or by combustion in turbines and engines. Each of these components of the hydrogen industry is under development. The following sections explain the current status of these technological areas in greater detail.

Production

Although hydrogen is the most abundant element in the universe, it does not naturally exist in its elemental form on Earth. It must be produced from other compounds such as water, biomass, or fossil fuels. Each method of production from these constituents requires energy in some form, such as heat, light, or electricity, to initiate the process.

In the United States, approximately 95 percent of hydrogen is currently produced via steam reforming [1]. Steam reforming is a thermal-chemical process, typically carried out over a nickel-based catalyst that involves reacting natural gas or other light hydrocarbons with steam. This is a three-step process that results in a mixture of hydrogen and carbon dioxide, which is then separated by pressure swing adsorption, to produce high-purity hydrogen. Steam reforming is the most energy efficient commercialized technology currently available, and is most cost-effective when applied to large, constant loads. Research is being conducted on improving catalyst life and heat integration, which would lower the temperature needed for the reformer and make the process even more efficient and economical. In Virginia, H2Gen Innovations of Alexandria is a world leader in researching and developing medium-scale steam reformation technologies.

Coal gasification shows promise as a low cost production method for hydrogen. Projects like "Future Gen" are under development now where hydrogen is co-produced with electricity in a 50/50 split. Estimates indicate that a mature technology could produce hydrogen for under a dollar per kilogram (a kilogram of hydrogen has the same energy content as a gallon of gasoline, about 120,000 BTU). Virginia has more than a 200-year supply of known reserves of coal.

Partial oxidation and autothermal reforming of fossil fuels is another method of thermalchemical production. It involves the reaction of fuel with a limited supply of oxygen to produce a hydrogen mixture, which is then purified. Partial oxidation can be applied to a wide range of hydrocarbon feedstocks, including light hydrocarbons as well as heavy oils and coal. However, it has a higher capital cost because it requires pure oxygen to minimize the amount of gas that must later be treated. In order to make partial oxidation cost effective for the specialty chemicals market, lower cost fossil fuels must be used. Current research is aimed at improving membranes for better separation and conversion processes in order to increase efficiency, and thus decrease the consumption of fossil fuels.

Hydrogen can also be produced by using renewable and nuclear resources to extract hydrogen from water, but these methods are currently not as efficient or cost effective as using fossil fuels.

FOOTNOTES

[1] Air Products and Chemicals, Inc.

Biomass can be thermally processed through gasification, pyrolysis or partial oxidation to produce hydrogen. Research on nuclear-based hydrogen production is mostly conducted on thermochemical processes or high-temperature electrolysis. Both are continuing to be developed. Also wind and other renewably generated electricity can be used to produce hydrogen. Creation of more efficient, less expensive electrolyzers using renewables and nuclear power is also ongoing.

Delivery

A hydrogen energy infrastructure would include production and storage facilities, structures and methods for transporting hydrogen, fueling stations for hydrogen-powered applications, and technologies that convert the fuel into useful energy through end-use systems that power buildings, vehicles, and portable applications. This section focuses on existing infrastructure that moves the hydrogen from its point of production to an end-use device.

Today hydrogen is produced primarily in decentralized locations and is used on-site for making chemicals or upgrading fuels. Approximately 17 percent of hydrogen is centrally produced for sale and distribution, and is transported through pipelines or via cylinders and tube trailers [2]. Air Products and Chemicals Inc., Air Liquide Group, Praxair Inc., and the BOC Group are major producers of merchant hydrogen. Together these companies operate about 80 plants in the United States that are dedicated to the production of merchant hydrogen.

Similar to natural gas distribution, pipelines are used to supply hydrogen to customers. Currently hydrogen pipelines are used in only a few areas of the United States. Air Liquide Group, Air Products and Chemicals Inc., and Praxair Inc. operate hydrogen pipelines in Texas, Louisiana, California, and Indiana. Pipelines provide an efficient means for transporting hydrogen. Concerns regarding the weakening of carbon steel pipes in a process called hydrogen embrittlement are being addressed. Alternate delivery forms such as the transport of hydrogen in safe compounds or chemical forms, are being developed to get hydrogen to end-use sites on an as-needed and real time usage basis.

Hydrogen is also distributed via cylinders and tube trailers that are transported by trucks, railcars, and barges. For long-distance distribution of up to 1000 miles, hydrogen is usually transported as a liquid and then vaporized for use on-site. In 2001, eleven plants had the capacity to produce 283 tons of liquid hydrogen per day in North America.

Storage

Hydrogen can be stored as a gas or liquid or in a chemical compound using a variety of technologies.

Compact storage of hydrogen gas in tanks is the most mature storage technology, but is difficult because hydrogen is the lightest element and has very low density under normal conditions. This is addressed through compression to higher pressures or interaction with other compounds. In addition, storage tank materials are advancing—they are getting lighter and better able to provide containment. Some have a protective outside layer to improve impact resistance and safety. Currently, however, indications are that operating pressures would have to approach 10,000 psi (700 bar) in order to approach on-board storage design targets for the transportation sector. In 2003, the National Academies came to a determination that compressed hydrogen would most likely not be a viable option for a widespread mass-market hydrogen economy. [3]

Liquid hydrogen is stored in cryogenic containers, which requires less volume than gas storage.

FOOTNOTES

[2] Air Products and Chemicals, Inc.

[3] "The Hydrogen Economy, Opportunities, Costs, and Barriers", National Academies Press, February 2004: in particular, recommendation 4-2 expresses the committee's view that cryogenic and high pressure compressed hydrogen technologies "have little promise of long-term practicality for light-duty vehicles."

[4] *Ibid.*

However, the liquefaction of hydrogen consumes large quantities of electric power, equivalent to about one-third the energy value of the hydrogen. [4]

Hydrogen can be stored "reversibly" and "irreversibly" in hydrides. In reversible storage, metals are generally alloyed to optimize both the system weight and the temperature at which the hydrogen can be recovered. When the hydrogen needs to be used, it is released from the metal hydride under certain temperature and pressure conditions, and the alloy is restored to its previous state. In irreversible storage, the material undergoes a chemical reaction with another substance, such as water, that releases the hydrogen from the chemical hydride. The byproduct is not reconverted to a hydride, and so must be reprocessed into a hydride using external energy input.

Laboratory research continues in the development of carbon-based storage systems. Hydrogen storage in carbon structures is achieved chemically in fullerenes or by physical sorption in carbon nanotubes. These processes are controlled through temperature and pressure and are still a long way from development.

Conversion

Hydrogen is an energy carrier that requires production by an energy source (e.g., fossil, renewable, or nuclear) using a feedstock (e.g., fossil, biomass, or water) followed by consumption of the hydrogen by a particular end-use device to produce heat or electricity. Hydrogen can be converted to energy via traditional combustion methods and through electrochemical processes in fuel cells.

Combustion

Hydrogen can be combusted in the same manner as gasoline or natural gas. The benefit of using hydrogen combustion over fossil fuel combustion is that it releases fewer emissions. Also, no carbon dioxide is emitted, and nitrogen oxides, produced by a reaction with the nitrogen in the air, can be significantly lower than with the combustion of fossil fuels. Hydrogen internal combustion engine vehicles are being demonstrated—Ford and BMW have made significant progress in advanced Hydrogen Internal Combustion Engine (H2-ICE) vehicles. Also, the combustion of hydrogen blended with methane (natural gas) is being practiced, particularly in heavy-duty vehicle demonstrations (e.g. at Penn State University, City of Las Vegas, Sunline Transit). Some analysts see the H2-ICE as an important transition technology that could help develop the transportation refueling infrastructure as more advanced end-use conversion technologies such as fuel cells develop.

Fuel Cells

Fuel cells utilize the chemical energy of hydrogen to produce electricity and thermal energy. A fuel cell is a quiet, clean source of energy. Water is the only by-product it emits if it uses hydrogen directly. Since electrochemical reactions can generate energy more efficiently than combustion, fuel cells can achieve higher efficiencies than internal combustion engines. Current steady-state fuel cell system efficiencies are in the 40 to 50 percent range, with up to 80 percent efficiency reported when used in combined heat and power applications.

Fuel cells are similar to batteries in that they are composed of positive and negative electrodes with an electrolyte or membrane. The difference between fuel cells and batteries is that energy is not recharged and stored in fuel cells as it is in batteries. Fuel cells receive their energy from hydrogen or a similar fuel that is supplied to them. No recharge is thereby necessary.

FOOTNOTES

[4] "The Hydrogen Economy, Opportunities, Costs, and Barriers", National Academies Press, February 2004: in particular, recommendation 4-2 expresses the committee's view that cryogenic and high pressure compressed hydrogen technologies "have little promise of long-term practicality for light-duty vehicles."

Fuel cells are characterized by their electrolyte, operating temperature, and level of hydrogen purity required. Phosphoric acid fuel cells are the most developed fuel cells for commercial use. Many of the installed units are used in stationary applications to provide grid support and reliable back-up power, and in transportation applications to power large vehicles such as buses. Proton exchange membrane (PEM) fuel cells are being developed and tested for use in transportation, stationary, and portable applications. There has been a tremendous upsurge in interest in PEM fuel cells over the past few years, and most major automotive manufacturers are developing fuel cell concept cars with PEM technology for propulsion. Alkaline fuel cells have been used in military applications, for NASA space missions to provide electricity and drinking water for astronauts, and are being tested for transportation auxiliary power applications. Solid oxide and molten carbonate fuel cells are best for use in generating electricity in stationary combined cycle applications and cogeneration applications in which waste heat is used for cogeneration. They also fit well for portable power and transportation applications, especially large trucks with long duration steady state auxiliary power loads.

Fuel cells have operating advantages for both stationary and mobile applications in that they are quiet and typically have high efficiencies at partial loads. They also have environmental advantages. For example, when pure hydrogen is used as the fuel, there are no emissions of sulfur or nitrogen oxides, or particulates. And if the hydrogen comes from a net-carbon-free renewable or nuclear energy source, the system will also be free of carbon dioxide emissions. Hydrogen derived from fossil fuel sources can mitigate carbon dioxide emissions when combined with effective and environmentally sensitive carbon sequestration. The direct conversion of the energy stored in the hydrogen fuel to electricity in a fuel cell can be achieved at high efficiencies, avoiding limitations of standard heat-to-power cycles used in combustion engines and turbines. Fuel cells are also deployable in combined heat and power applications, further raising fuel energy utilization.

End Use Energy Applications

Hydrogen energy end-use applications include stationary, transportation, and portable devices. As mentioned, the most common current use for hydrogen is in industrial processes such as refineries. It is also used as a fuel at NASA, where the combustion of hydrogen has fueled its space shuttle main engines and propulsion systems for years. Other energy uses are generally limited to research and demonstrations.

One application of hydrogen fuel cells is for distributed generation. A number of UTC Fuel Cell's phosphoric acid fuel cells and Fuel Cell Energy's molten carbonate fuel cells are operating in locations around the world, providing heat and power for buildings and industrial applications.

In the transportation sector, a number of fuel cell vehicles are being tested and developed. Vehicular use of hydrogen energy requires a compact power system and refueling stations. Given the current state of hydrogen technologies, city-owned buses are a promising application because they are capable of carrying large tanks of hydrogen and typically refuel at a single location. In March 1998, for example, Chicago became the first city in the United States to use hydrogen fuel cells to power buses in their public transit system. Subsequent demonstrations have continued at transit systems in Palm Springs, California (Sunline Transit), and also at a number of European cities under the Clean Urban Transport for Europe program (CUTE).

Several car manufacturers, including Hyundai, Ford, General Motors, Toyota, Honda, and DaimlerChrysler are developing fuel cell vehicles for personal use. Ford and BMW are demonstrating hydrogen-powered internal combustion engine vehicles. Ford and GM have both demonstrated their fuel cell vehicles in Virginia for the Roundtable, and GM currently operates a fleet of several vehicles based in Northern Virginia at Fort Belvoir, including vehicles being used by the US Postal Service and the Virginia Department of Environmental Quality Northern Virginia Regional Office.

Portable fuel cells can also be used to power small devices such as mobile telephones or personal computers. These small fuel cell stacks could compete with batteries for market share in the near-term and are more environmentally benign. Larger power generators for recreation and other off-grid applications are under development. For example, Ballard Power Systems has developed the Nexa™ power module, a PEM fuel cell system that generates up to 1200 watts of unregulated direct current electrical power that can be used for industrial and consumer end-product applications.

Today's emerging hydrogen energy industry is eager to develop hydrogen fuel infrastructure technology that can be used to generate power for stationary, transportation, and portable power applications. Much work needs to be done to reach this goal, but a foundation for future efforts has been established by these various technology sectors.

PART III
Key Drivers Affecting the Future of Hydrogen Energy Development

The United States' energy sector is experiencing a confluence of events. New technologies are being developed and opportunities for entrepreneurial ideas and innovative approaches are ripening at a time when our capital-intensive, aging energy infrastructure is in need of improvement. Despite this window of opportunity, the overall business environment for energy investments in America today is not conducive to the massive introduction of new technologies.

The Nation faces uncertainties in our energy future and inertia in our infrastructure system. America's energy future will include unpredictable ups and downs, price volatility, regional gluts and shortages, and market instabilities. The natural pace of turnover of existing capital in our infrastructure is relatively slow, there is reluctance to alter traditional systems, and the framework of changing policies and regulations tends to favor incumbent suppliers and technologies.

These factors introduce uncertainties and risk and interfere with making changes. For example, existing inertia in our energy system has made it difficult for policy makers and business executives to make strategic decisions about long-term energy requirements, which has led to delays in decision-making, and has made it hard for businesses to commit to large financial resources to energy investments.

The factors affecting hydrogen's potential are rooted in these issues. Our infrastructure has been designed to provide users with reliable supplies of fossil fuels at an affordable cost while protecting the environment. Other forms of energy, including nuclear and renewable sources, may play important roles but face their own hurdles in the global competition for market share.

In developing a vision for the hydrogen economy, certain questions about market and policy forces arise. Are there technological, economic, or policy-related factors, issues, or trends that can encourage a dynamic of change in our current market? If so, how might they affect hydrogen energy development over the next several decades, in terms of supporting or hindering it? Many of these "drivers" will affect not only hydrogen, but also the future of the energy system as a whole.

National Security

The need to supplement the supply of domestically produced transportation fuels is great. The United States depends on a global petroleum market where many of the major suppliers are countries that are politically unstable or, in some cases, hostile to U.S. interests. Even domestic production and distribution is vulnerable to disruption from natural disaster (for instance, Hurricane Katrina), accidents, and terrorism. America's transportation sector relies almost exclusively on refined petroleum products; more than one-half of the petroleum consumed in the United States is imported, and that percentage is expected to rise steadily for the foreseeable future, unless we change our energy use. Hydrogen (along with biofuels) is a versatile energy carrier that could be produced entirely from domestic sources of fossil fuel (e.g., natural gas and coal with capture and sequestration of carbon dioxide), renewable (e.g., solar, wind, and biomass), and nuclear energy, in large quantities. Its use as a major energy carrier would provide the United States with a more diversified energy infrastructure.

Climate Change

The combustion of fossil fuels accounts for the majority of anthropogenic greenhouse gas emissions released into the atmosphere. Although international efforts to address global climate change have not yet resulted in policies that all nations have accepted, there is growing recognition that steps to reduce greenhouse gases are needed, and many countries are adopting policies to accomplish that end. Energy and transportation companies, many of which have multi-national operations, are actively evaluating alternative sources of energy.

Hydrogen can play an important role in a low-carbon global economy. With the capture and sequestration of carbon from fossil fuels, hydrogen is one path for coal, oil, and natural gas to remain viable energy resources, should strong constraints on carbon emissions be required. Hydrogen produced from renewable resources or nuclear energy results in no net carbon emissions.

Population and Economic Growth

Many experts have pointed out that highly populated countries like China, India, and Indonesia seek to adopt energy consumption patterns similar to those of the United States or Europe, and consequently world energy supplies will have to increase enormously to meet demand. If this energy consumption were based on hydrogen fuel cells, the environmental consequences and national security issues would be much less.

Many international energy experts anticipate that developing countries may "leap frog" today's energy devices and infrastructure by adopting advanced technologies. The idea is that as economic growth spreads around the world, developing countries would be able to follow a pattern similar to the one being followed in telecommunications systems: wireless technologies are being installed in certain locations, "leap frogging" the need for telephone lines. Unfortunately, the advanced energy devices that would be needed to "leap frog" current infrastructure, such as hydrogen energy systems and fuel cells, are not yet cost competitive or commercially available on the required economies of scale. However, it should be noted that some advanced energy technologies are commercially available in some developing countries in cases where the electric grid and centrally generated power systems are weak or unavailable, such as photovoltaics and batteries, small wind and batteries, and farm biogas generation, which may allow leap-frogging of the centralized grid paradigm.

Air Quality

Air quality is a major public health concern. Most of the major metropolitan areas in the United States are in "non-attainment" with the requirements of the Clean Air Act. States are required to develop strategies detailing the steps they plan to take for reaching national ambient air quality goals. Motor vehicles and electric power plants are significant contributors to the nation's air quality problems.

Hydrogen Infrastructure Costs

America's energy infrastructure is aging and in need of significant upgrades, overhauls, and replacements over the next several decades. This infrastructure includes oil refineries, gas and oil pipelines, port facilities, power plants, and electricity transmission and distribution facilities such as power lines, transformers, and substations. The capital investment requirements to maintain and improve the infrastructure over the next several decades will total hundreds of billions of dollars.

While hydrogen may be able to use some of the existing infrastructure, specific upgrades and enhancements will be needed to accommodate the unique features of hydrogen, particularly in storage and distribution. The technologies needed to convert the natural gas infrastructure for the use of hydrogen are available today, but are not yet cost-effective. At present there is no motivation to convert to hydrogen, as there are essentially no markets for distributed use of hydrogen energy. Additional infrastructure costs will have to be incurred in the future, when cost-competitive products are available, to enable the transition to the hydrogen economy.

The technical and economic barriers to upgrading the Nation's fueling stations to provide hydrogen represents one of the major stumbling blocks to the expanded use of hydrogen-fueled vehicles. Some automakers estimate that hydrogen would have to be available in at least thirty percent of the nation's fueling stations for a viable hydrogen-based transportation sector to emerge. Private investment in such an infrastructure will not be forthcoming in the absence of sustained, supportive public policies.

Hydrogen Storage and Conversion Devices

The lack of low-cost and lightweight storage and commercially available and cost-competitive fuel cells interferes with the development of a hydrogen economy. For the hydrogen economy to evolve, consumers will need to have convenient access to hydrogen, and storage will be one of the keys. Better hydrogen storage systems will enable users to have easy access to hydrogen for vehicles and distributed energy facilities. Hydrogen storage could also enhance the value and potential market share of renewable electricity generation.

Fuel cells are clean, compact, and modular energy generation devices that have the potential to revolutionize the production of electricity and thermal energy, for both stationary and mobile applications. There are several different types of fuel cells; each has advantages and disadvantages. Design and manufacturing breakthroughs are needed to lower costs and enhance reliability and performance. The marketplace will determine which of the several fuel cell options will offer users the most favorable advantages.

Hydrogen internal combustion engine vehicles are being demonstrated and are nearer term than fuel cell vehicles. They offer many benefits, although they are not zero emissions vehicles.

Concerns About Hydrogen Safety

Perceptions about the safety of hydrogen remain a deterrent to many consumers. The public needs to be aware that safety issues related to hydrogen are being addressed, and perceptions based on misinformation need to be corrected. A public information campaign can help eliminate many of the concerns about hydrogen safety. Effective codes and standards are needed to ensure that these concerns are addressed in equipment design, manufacturing practices, and operation and maintenance procedures.

Appropriate field tests and demonstrations will be needed to increase public confidence and acceptance of hydrogen technologies.

Availability of Fossil Energy Resources

Affordable coal, oil, and natural gas supplies are available around the world. Analysts warn, however, that world oil production cannot be sustained at current levels indefinitely and that the development of America's natural gas resources, while extensive, are not inexhaustible. Coal is the major fuel for electricity production in America. Clean coal technologies improve efficiency and reduce emissions. Fossil fuels are expected to be America's fuels of choice for the foreseeable future.

As demand for fossil fuels continues to increase, resource constraints will push fossil fuel prices up over the next several years (energy analysts differ as to how much and when). This will spur the development of non-fossil alternatives such as solar, wind, geothermal, biomass, and nuclear, and fossil alternatives that sequester carbon dioxide, and encourage the transition to hydrogen. In the meantime, the current availability and relatively low cost of fossil fuels moderate the pace of development of alternative sources of energy.

Consumer Preferences

There are energy consumer trends that require high-value services that command premium prices. For example, extra high reliable electric service is required by a growing number of businesses relying on digital equipment, such as computers, or operating 24 hours a day, seven days a week. Premium power markets include high value manufacturing (e.g., semiconductors, pharmaceuticals), hospitals, communications centers, emergency management facilities (police, fire, rescue, 911 call/dispatch), air traffic control facilities, and defense installations. Protection against energy price volatility is another possible high-value service. These premium markets, like distributed energy and power parks, provide growing opportunities for hydrogen energy, especially early in the transition.

In contrast, public support for low energy prices is strong. Americans enjoy gasoline prices that are among the lowest in the world. Until recently, consumers ranked fuel economy relatively low on the list of desired attributes for automobiles. Despite record highs, Americans still pay relatively low inflation-adjusted petroleum energy prices, and Americans are very reluctant to impose consumption disincentives on carbon fuels which would help increase conservation practice, or make alternative carbon-free energy more attractive.

Summary

There are several key drivers that will likely affect hydrogen energy development. Concerns regarding national security, global climate change, and worldwide population and economic growth will increasingly promote systems that support hydrogen development. The lack of a national consensus on energy policy priorities, a hydrogen infrastructure, commercially viable hydrogen technologies, and the public perception of hydrogen safety issues have the potential to inhibit hydrogen energy development. Drivers that could both support and inhibit the development of hydrogen are the rapid pace of technological change in energy technologies, the current availability of low cost fossil fuels and their eventual depletion, recognition of environmental (including climate change) impacts of current energy systems, and mixed consumer preferences for clean and cheap energy.

PART IV

A Vision of the Virginia Hydrogen Economy

VISION

Hydrogen is one of America's and Virginia's clean energy choices. It is flexible, affordable, safe, domestically produced, used in many sectors of the economy, and throughout the Commonwealth. The Hydrogen Economy supports economic growth, environmental protection, and energy security.

In the early stages, hydrogen in Virginia will be produced principally from coal and other fossil fuel resources with carbon capture and sequestration, with an increaseing focus on clean and renewable carbon-free energy sources. Hydrogen will be used in limited energy storage and critical electric power systems and as a fuel option in transportation sector demonstrations.

In a mature transportation-based hydrogen economy, hydrogen will be produced in accordnace with centralized facilities using coal and perhaps biomass feedstocks. Hydrogen will be distributed by a network of pipelines to urban vehicle refueling sites and power parks. This mass-market state will be achieved after undergoing a transitional phase where hydrogen will have been produced at the community level from transportable fossil fuels such as natural gas in urban centers, and perhaps propane in rural communities. The possibility also exists for community-level biofuels-based hydrogen production in both rural and urban settings during the transition. Further, it may eventually be viable for off peak nuclear, wind, and ocean generated power to be used to produce hydrogen though, as described on the next page, economic constraints limit the shorter term practicality of this. Urban commuters may also have the option of producing hydrogen at home from natural gas or electrolysis.

In the hydrogen economy, Virginia consumers will have access to hydrogen energy to the same extent that they have access to gasoline, natural gas, propane, and electricity today. It will be produced cleanly, with near-zero net carbon emissions, and it will be transported and used safely. Virginia's hydrogen energy industries will be among the world's leaders in hydrogen-related equipment, products, and services.

One major foundation for this vision is the development of an energy infrastructure that can support the expanded production, delivery, storage, and use of hydrogen energy. Construction of this infrastructure will take time and will require significant resources. As a result, the hydrogen economy will take many years to build.

The need for large quantities of hydrogen in a future energy economy is almost entirely dependent on how competitive hydrogen end-use technologies are in the transportation sector. There is only limited value in producing hydrogen for the power generation sector, if the transportation sector does not generate a demand for hydrogen as a fuel.

In order for the transportation hydrogen economy to come to fruition, hydrogen storage weight and volume reductions, mass production of fuel cells, construction of the necessary vehicle refueling infrastructure, and expanded use of distributed power generation devices will be required. These actions will in turn require significant technology breakthroughs to occur, implying a long-term commitment to fundamental and applications research by Virginia government and industry.

A strong public investment in cooperation with private industry will be a key feature of this evolutionary process. Together, the Commonwealth and private organizations will facilitate appropriate research, development, and demonstration programs; educate the public; and implement codes and standards. In Virginia, mounting public pressures for cleaner, more secure sources of electric power generation energy supplies, in conjunction with the potential of the hydrogen economy, could radically transform how we exploit the Commonwealth's most abundant energy resources.

Future Hydrogen Production

At the time the vision for a mass-market hydrogen economy becomes a reality, several years from now, hydrogen in Virginia will be produced predominantly from coal and other fossil fuels, although some hydrogen will be produced from biomass and water via thermal and electric processes.

In order for hydrogen to be produced from water via electrolysis, photochemical or photoelectrochemical devices, or by biological systems such as algae, these processes will need to be cost-competitive with hydrogen produced at centralized facilities. Very low cost electricity will be needed for cost-competitiveness, such as off-peak power at one to two cents per kilowatt-hour, and the amount of hydrogen produced in this manner will be limited in comparison to future demands for fuel. Electrolysis could make locally important contributions where low cost power is available, although the overall contribution to a full-scale hydrogen economy will depend on the relative costs.

Virginia could have a combination of central station and distributed hydrogen production facilities, however, the current resource endowments in Virginia tend to favor centralized production from coal (gasification with carbon sequestration) under a mass-market scenario. Central station facilities will consist of multi-product refineries that use coal as the principal feedstock, and that provide hydrogen, electricity, thermal energy, chemicals, and other industrial products. One can also envision central station nuclear, solar, wind, or geothermal facilities for the production of hydrogen by splitting water, although the presence of such facilities in Virginia's future mass-market hydrogen economy will be a function of those technologies' share in the overall electricity production mix. It is also generally foreseen today that, especially at relatively low levels of penetration in the electric power generation market (e.g. less than 20%), renewable electricity sources such as wind and solar power, when viable, will probably not be devoted to the production of hydrogen. This is substantially due to the fact that these energy sources have much higher economic and environmental value displacing conventional electricity sources rather than using them to produce hydrogen.

During the transition phase to the mass-market hydrogen economy, distributed production of hydrogen will occur on-site (at homes, offices, and factories) or at the community level at places such as fueling stations or power parks. The continuing share of distributed production in the mass-market economy will depend on the ability of this mode of hydrogen generation to provide additional value to consumers with respect to the centralized production systems.

Future Infrastructure

In a mass-market Virginia hydrogen energy economy, a statewide network will be in place to provide hydrogen to users in every region and locality. Pipelines will be the preferred choice for distributing hydrogen to high-demand areas. Trucks and rail will be used to distribute hydrogen to rural and other lower-demand areas, probably in the form of liquid hydrocarbon hydrogen carriers such as biofuels and/or propane which are then reformed at local production centers.[5] On-site hydrogen production and distribution facilities will be available where demand is high enough to sustain maintenance of the technologies in the face of centralized production and distribution.

FOOTNOTES

[5] This scenario implies higher energy costs for rural communities, and may require considerations of public support to bring a hydrogen choice to remote areas – one is reminded of the process that brought electricity to these communities under the Rural Electrification Act of 1936. This scenario also has implications for the "near net-zero" carbon emissions goal set forth as an indispensable aspect that justifies and provides motivation for the hydrogen vision. In the event that pure hydrogen transport by truck or rail is economically prohibitive, local carbon sequestration during the reformation process may also be economically unattractive.

Future Storage Devices

A selection of relatively lightweight, low cost, and low volume hydrogen storage devices will be available to meet a variety of needs, and in particular the needs defined by the transportation sector. Presumably, a solution to the transportation requirements for on-board hydrogen storage may resolve issues with the bulk transport and distribution of hydrogen to low demand areas (see discussion under previous heading Future Infrastructure).

Future Conversion Technologies

Fuel cells will be mass-produced and will be cost-competitive with mature technologies, particularly in the transportation sector. With widespread availability of hydrogen, advanced hydrogen-powered energy generation devices such as combustion turbines and reciprocating engines will be in commercial use.

Future End-Use Energy Markets

Hydrogen will be available for every end-use energy need in the economy, including transportation, power generation, and portable power systems. Hydrogen will need to be the dominant fuel used for the transportation sector, generating high levels of demand, thus justifying future centralized co-production facilities and positioning hydrogen as the cost-effective fuel of choice. It will be combusted directly in turbines and reciprocating engines for cogeneration of electricity and thermal energy. And it will be used in fuel cells for both mobile and stationary applications.

PART V

Aspects of the Virginia Transition to the Hydrogen Economy Vision

There are certain achievements to be made and pitfalls to avoid in the transition to a hydrogen economy. Rather than offering predictions or specific prescriptions, the following section discusses various goals and hazards and outlines plausible scenarios.

PHASE I: Progress in Technologies, Policies, and Markets

Significant laboratory progress is needed in the first transition phase in the form of research and demonstration that supports industry's pre-commercial efforts. Carmakers will test several types of hydrogen-using prototypes. Research will focus on bringing down the cost of fuel cells and storage devices.

Testing, validation, and demonstration of transportation technologies will characterize this pre-market phase. As progress is made and demonstrated with transportation technologies, industry markets for proton exchange membrane fuel cells for stationary power and cogeneration applications will be further developed. It is expected, however, that investment in direct-hydrogen stationary technology will only progress as vehicle demonstrations and validations continue to be successful.

Natural gas steam reforming will continue to be the primary means for producing hydrogen, although during this phase, demonstration of advanced hydrogen production technologies will also take place. Hydrogen use in internal combustion engines will help support infrastructure technology development by providing relatively cost-effective hydrogen end-use transportation technologies that can generate demand for hydrogen in field demonstrations.

The first phase will also require the creation of hydrogen-related policies on energy and the environment, including the reduction of energy imports, managing greenhouse gas emissions, and strengthening the control of air pollution. Standards for the safe use of hydrogen will need to be implemented across the U.S., and around the world. State-level demonstration programs are required during this phase to test implementation of these standards in real-world environments, and also to open communications and education channels to local officials. These state-level demonstrations are also needed to begin addressing liability, insurance, and permitting issues, which in addition to the appropriate codes and standards will provide a framework for commercial development to proceed.

PHASE II: Early Market Preparations

Many significant technology developments will need to have occurred before the next phase can begin. These breakthroughs will include at a minimum a demonstration of hydrogen transportation technologies, including fuel cells and storage systems, that will be cost-effective at volume production. Cost-effective carbon sequestration technology will need to be validated, and shown to be supportive of cost models that show hydrogen as a potentially competitive fuel.

Industry in the transportation sector will need to have vehicle designs that are ready to industrialize, and that are also shown to be affordable (at volume), and marketable to the general public. These vehicles will need to be equivalent to standard vehicles in performance, range, cargo-carrying capacity, and operational cost. In fact, the sizeable cost premiums expected in this phase will need to be justified by additional customer value. Today, one can envision this added value to be potentially provided by the ability to refuel at home.[6] Alternatively, these cost premiums will need to be offset by subsidies to

[6] A significant test of this added value is currently underway with the market introduction of relatively affordable natural gas home refueling units. For large fleets, however, it is difficult to see at this point what the added value would be in the face of higher initial purchase and operating costs. This implies additional regulatory action or subsidies in order to place vehicles in these fleets, which in turn would help make a positive business case for the required refueling infrastructure.

help bring volumes to levels where the economies of scale are such that the cost premiums are made negligible.

Once the economic viability of hydrogen production and end-use technologies is demonstrable[7], industry and government will be able to work cooperatively to begin actions that are consistent with a transition roadmap to the mass-market economy.

During this phase, one can expect federal and Virginia government facilities to play a significant role in moving hydrogen technologies into the marketplace. One example could be increased use of hydrogen-fueled distributed energy devices to ensure reliable, continuous power for applications (e.g. hospitals) where elimination of emissions and reduced noise are valuable features justifying the cost premiums during this technology transition phase.

PHASE III: Early Market Formation

This phase begins when most of the required production and end-use technologies have been validated, particularly in the transportation sector, and industrialization of consumer products can begin. Market pilots have shown the appeal of hydrogen-fueled vehicles for the general consumer. The cost of natural gas-based distributed refueling infrastructure technologies are reduced sufficiently to allow for a positive business case for their construction and operation.[8]

With these elements in place, industry and government will work together to develop the appropriate market incentives and rules that will facilitate and accelerate expansion of hydrogen technologies. This phase will then lead to installation of distributed production

and refueling infrastructure that eliminates concerns of refueling availability for the average consumer, whether private individuals or fleet administrators.

PHASE IV: Realization of the Mass-Market Hydrogen Economy Vision

Eventually, hydrogen will be used for most end-use energy market applications. The transportation sector consists mainly of hydrogen-fueled vehicles. Stationary power is generated by cost-effective devices that benefit from the economies of scale afforded by the transportation sector. Demand for hydrogen grows, and centralized production facilities are constructed and operated, delivering hydrogen through networks of pipelines. Carbon capture will limit emissions, and new industrial uses will put captured carbon to work for industrial feed stocks, building materials, and other applications.

A national infrastructure that supports the use of hydrogen for fuel and electricity production will be in place. Consumers will be enjoying the economic benefits of a financially sound hydrogen energy sector and the environmental benefits of clean energy systems.

At this point, many years from now, the hydrogen economy will be a reality.

FOOTNOTES

[7] "Demonstrable" means shown in theory that at volume production, costs are competitive. For example, this is not the case with automotive fuel cell systems today, where at-volume costs are still an order of magnitude higher than the cost competitive industry targets set by existing technology.

[8] It is conceivable that these business cases will be made in the fleet environment, however, this will require demonstrating additional value of hydrogen technology to the fleet administrators. In the absence of emissions or alternative fuels requirements, or significant subsidies, it is not clear today how this technology would become attractive to these end-users during this phase where the hydrogen options carry additional cost burdens. On the other hand, the value proposition of home refueling may allow for market expansion to begin through the general consumer.

PART VI
A Path Forward

The ultimate vision for the hydrogen economy is many years in the future and the amount of research, development, public education, institution building, and infrastructure construction needed to get there is very costly, but also a very worthwhile goal.

A useful next step will be the development of a Virginia hydrogen energy plan. The development process can provide Virginia industry, government officials, and technologists from our academic institutions with the opportunity to collectively identify near-, mid-, and long-term actions. The process can be used to set priorities for research, development, and demonstration programs, and it can outline the relative roles of industry, government, universities, and non-governmental organizations.

As was the case at the national level during the roadmapping exercise coordinated by the U.S. Department of Energy, the Virginia-level hydrogen plan process will need to address a number of areas:

- Technologies for hydrogen production
- Technologies for hydrogen delivery and transportation
- Technologies for hydrogen storage
- Technologies for hydrogen conversion
- Scope and directions for public-private partnerships
- Codes and standards for safe production, delivery, and use of hydrogen
- Education of the general public and government and private decision makers about the potential benefits from the expanded use of hydrogen
- End-use energy markets for hydrogen including the potential for "first use" fleet applications in government facilities, vehicles, and equipment

Working together, industry, universities, and government can help Virginia realize the hydrogen vision. This entails building on our existing energy infrastructure and current hydrogen energy technologies to meet mutually set milestones. Public and private entities can cooperate to overcome hurdles and develop technologies and policies that fit Virginia's drive for clean, affordable, secure, and efficient energy systems.

The U.S. Department of Energy's **"National Hydrogen Energy Roadmap"** (November 2002), available from www.hydrogen.energy.gov/pdfs/national_h2_roadmap.pdf, will be consulted in developing the Virginia hydrogen energy plan.

APPENDIX

Roundtable Participants

Organization	Representative
Air Products	Tom Elzey
Avalence	Thomas Jackson
Ballard Power Systems	Ethan Brown
BP	John Curry
City of Chesapeake	George Hrichak
City of Richmond - Public Utilities	Chris Beschler
Dominion Resources, Inc.	Herbert Weary Linda Haskins
Ecron	Boris Maslov Andrey Shlyakhtenko
Gas Technology Institute	William Liss
GM	Keith Cole Raj Choudhury
H2Gen Innovations	C.E. “Sandy” Thomas
Hampton Roads Clean Cities Coalition	Chelsea Jenkins
Hampton Roads Economic Development Alliance	Steve Cook
Hampton Roads Hydrogen	Bob Brown
Honorable William Haskins	Bill Haskins
James Madison University	Ron Kander CJ Broderick Jonathan Miles
MidAtlantic Hydrogen Consortium	Andre van Rest
NASA	Doug Dwoyer Jim Batterson Rise Williams
National Hydrogen Association	Patrick Serfass
North Carolina Advanced Vehicle Research Center	Richard Dell
North Carolina Solar Center	Anne Tazewell
Northrop Grumman Newport News	Larry Blanchfield Bill Laz Charles Smith
Ohio Department of Development	Mike McKay
Old Dominion University	Bob Ash
Plug Power	Erin Lane
Princeron Group, Inc	Roy Reynolds
Propane Vehicle Council	Brian Feehan
Proton Energy Systems	Mark Schiller

APPENDIX *cont.*
Roundtable Participants

Organization	Representative
Science Museum of Virginia	David Hagan
Sentech, Inc.	Patty Kappaz
Shell Hydrogen	Peter Terminie Henk Mooiweer
U.S. Army	William "Bill" Haris
U.S. Department of Energy – Clean Cities	Shelley Launey
U.S. Department of Energy – Hydrogen, Fuel Cells, & Infrastructure Technologies Program	Steve Chalk Christy Cooper
U.S. Navy	Leo Grassilli
University of Maryland Department of Mechanical Engineering	Greg Jackson
University of Virginia School of Engineering and Applied Science	Prof. Bob Davis Prof. Don Kirwan
Virginia Advanced Shipbuilding and Carrier Integration Center	Irwin Edenzon Peter Diakun
Virginia Clean Cities	Al Christopher
Virginia Commonwealth University	Kenneth Wynne Michael Peters Sean Brahim, Ph.D.
Virginia Department of Education	Eric Rhoades
Virginia Department of Environmental Quality	Rodney Sobin Keith Boisvert
Virginia Department of General Services	Donald Unmussig
Virginia Department of Mines, Minerals and Energy	Steve Walz John Warren
Virginia Department of Transportation	Amy Costello Monica Franz Jim Ponticello
Virginia Economic Development Partnership	Mike Lehmkuhler Mike Carruth
Virginia Senate Staff	Dan Haworth
Virginia Tech Department of Mechanical Engineering	Mike Ellis Doug Nelson Michael von Spakovsky
Virginia Tech – Dept. of Mining and Minerals Engineering, Center for Coal and Energy Research	Mike Karmis Nino Ripepi
Virginia's Center for Innovative Technology	Nancy Vorona

The Roundtable wishes to acknowledge Nic Van Vurren for his efforts initiating the original Roundtable.