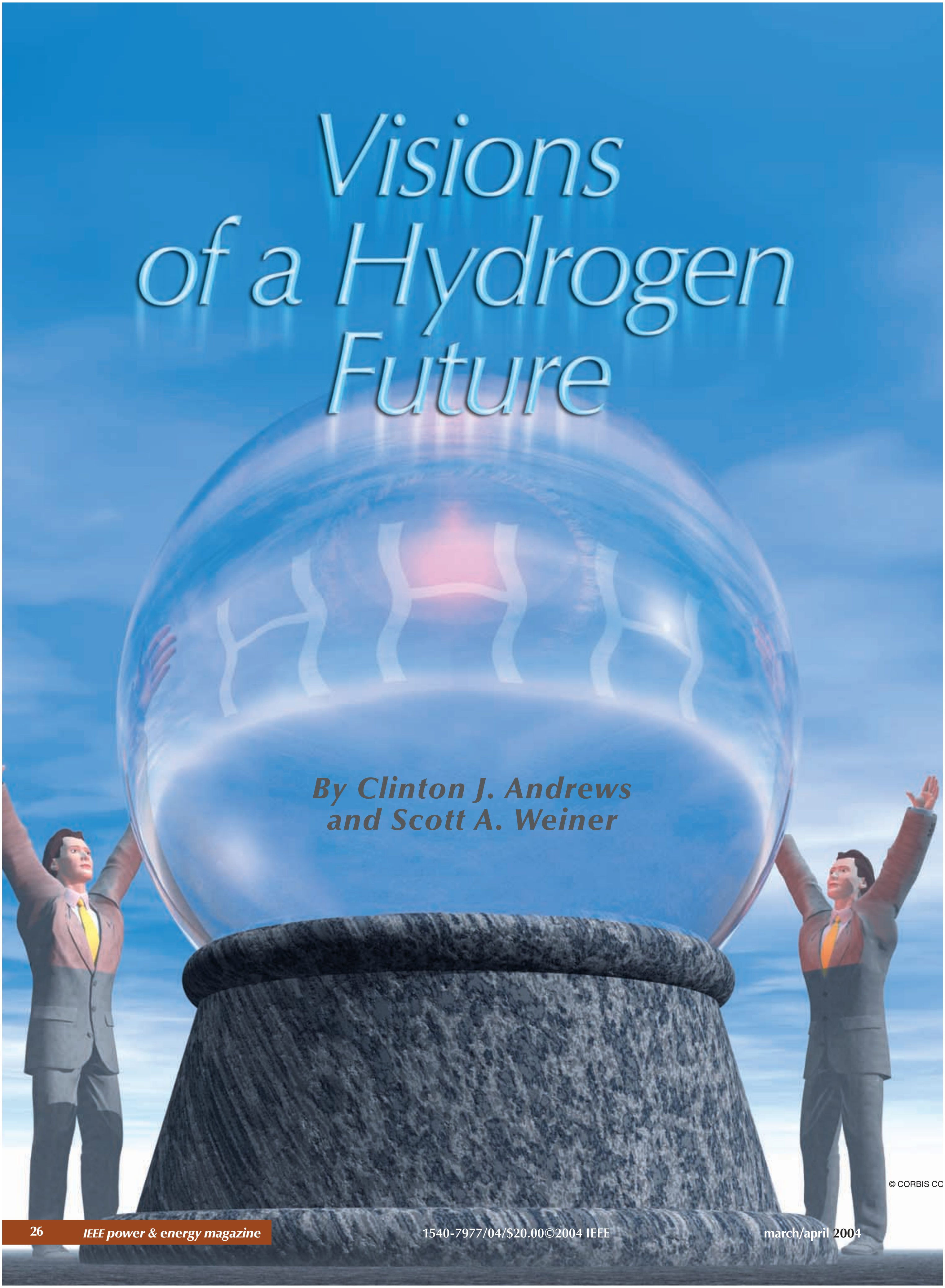
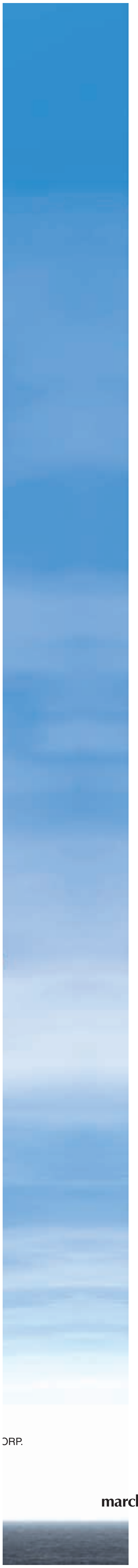
Visions of a Hydrogen Future

By Clinton J. Andrews and Scott A. Weiner



1540-7977/04/$20.00©2004 IEEE



Strategic Issues Affecting the Emergence of A Hydrogen Economy

PICTURE THIS: IT IS THE YEAR 2024 AND THE HYDROGEN ERA HAS ARRIVED. Almost all end users of energy have switched to electricity fueled by hydrogen. These energy carriers are interchangeable and can be readily transformed into one another. Urban air pollution and global climate change are now rapidly diminishing problems. Fuel cells power most new vehicles as well as many buildings and industrial processes. The world looks pretty good.

Now look closer: Is this a future that generates its hydrogen from large-scale nuclear plants and coal-fired power plants with carbon sequestration? Or does the hydrogen come from more dispersed and renewable sources such as solar, wind, and biomass primary energy production? (See “How Much Hydrogen Do We Need?” for a snapshot.) Do pipelines continue to carry natural gas for reforming into hydrogen at the point of use, or are there now hydrogen transmission and distribution networks? At the point of end use, is there widespread use of cogeneration that delivers useful heat and electricity together, or do competing electricity and gas distributors still vie to serve each component of energy demand? Is there a standard global model for the hydrogen economy or is there regional diversity? How does the hydrogen system relate to the electricity system?

The closer one looks, the more ambiguous this vision of the hydrogen economy becomes. There are several common elements but also many strategic choices. Need there be a *particular* outcome? Which *particular* hydrogen era is best? What roles can leaders in business and government play to identify the common elements?

Backcasting, or working backwards from a desired vision of the future to today’s choices, is a valuable tool for strategic thinking provided there is a common vision. The current U.S. Department of Energy Road Map for a Hydrogen Economy is a good illustration. It develops a very plausible set of strategic recommendations. Some elements of the Road Map share broad support, but debate rages over other elements. In addition to debate over the appropriateness of some sources of hydrogen, differing views characterize discussion on how to break the chicken-or-egg commercialization challenge and design elements of a hydrogen fuel infrastructure. Only the common elements that advance shared goals are likely to enjoy sustained support over decades, whereas the controversial elements will disappear the next time the political winds shift. The immediate challenge is broad-based action to develop the next level of detail about objectives and strategies.

This article examines key issues facing public and private decision makers advocating for—or affected by—the possible emergence of a hydrogen economy. It offers alternative visions of a hydrogen future, explores the extent to which society can manage this technological transition, identifies key business and public policy issues, and offers recommendations.

Can We Really Manage Technological Transitions?

There’s no disputing the world’s progression through several energy eras, from the predominance of wood, to coal, to oil, toward less carbon-intensive natural gas and nonfossil sources. In freight transportation, there has been a centuries-long evolution from walking, to beasts of burden, to ships, to railways, to trucks, to aircraft. Similar transitions are apparent in most areas of human endeavor. Historians of technology point to regularities in technological transitions, showing that major innovations follow an S-shaped trajectory of market penetration, only slowly wax and wane in popularity, and depend on complementary innovations to be successful. The historians have identified regular stages from innovative market niche, to rapid adoption and imitation, to saturation and maturation, to decline and substitution. Managers, especially in industries with short product cycles such as consumer electronics, have embraced these models of technological transitions and use them in strategic planning. Government officials charged with managing the public R&D portfolio also use these models widely.

But just because successful innovations follow a regular path, does that mean we can actually engineer large-scale technological transitions? There is good reason to be skeptical. Introducing the hydrogen era is no one manager's job. If it happens, it will require concerted efforts by thousands of individuals, lucky breakthroughs on several technological fronts, and support from society's largest and sometimes most recalcitrant economic and political institutions.

But neither does that mean that modern technology evolution has been the outcome of random acts nor that private and public institutions do not have an essential proactive role to play in charting the course to the next era of fuel. "Free markets" versus "planning" is a false dichtotomy. In fact, the evolution from horses to horsepower and kerosene lamps to electric lights represents the interplay of discovery, consumer demand, public incentives, and private motivation by both suppliers and consumers. We need not and must not leave the evolution to the next generation of fuel to be characterized as the result of random actions that resulted in an unpredictable outcome.

In contrast, all sectors of society should prepare to participate in that process. That preparation will take many forms and will be selected by each acting organization. We suggest that among them should be: 1) Understanding the issues and objectives that satisfy the needs of the organization; 2) developing a set of strategic interventions that are likely to achieve the sought after objective; and 3) standing ready to implement a strategic intervention when a window of opportunity arises.

As sectors, industries, and individual organizations define objectives from their unique perspective, each will be able to effectively identify opportunities for collaboration that can lead to success in the terms desired by the organization.

So, recognizing that the stakes are indeed divided among all stakeholders, we offer our observations of some of the policy issues to be confronted by business and public institutions.

Business Issues

Innovation is an essential element of sustained economic success. It may take the form of new ways to see the needs of current customers, expanding the customer base, or developing new ways to address new needs of new customers. Innovation is not static and will be manifest in an infinite variety of forms that will respond to the factors that are unique to each business enterprise. Neither the technology pioneer nor the company that competes to be second has an inherently better approach. The culture and organizational design of the enterprise will influence the most appropriate strategy for a specific company at a specific point in time. Only time and the context of a specific enterprise will determine if internal R&D was a better strategy than monitoring and eventual acquisition of technology. Experience has demonstrated that both approaches can succeed. Think of Xerox PARC and the rise of Apple and Dell as different points along a continuum.

Proponents of hydrogen's use as a fuel should recognize that the form and character of innovation is an enterprise-specific decision. Hydrogen advocates should take the time

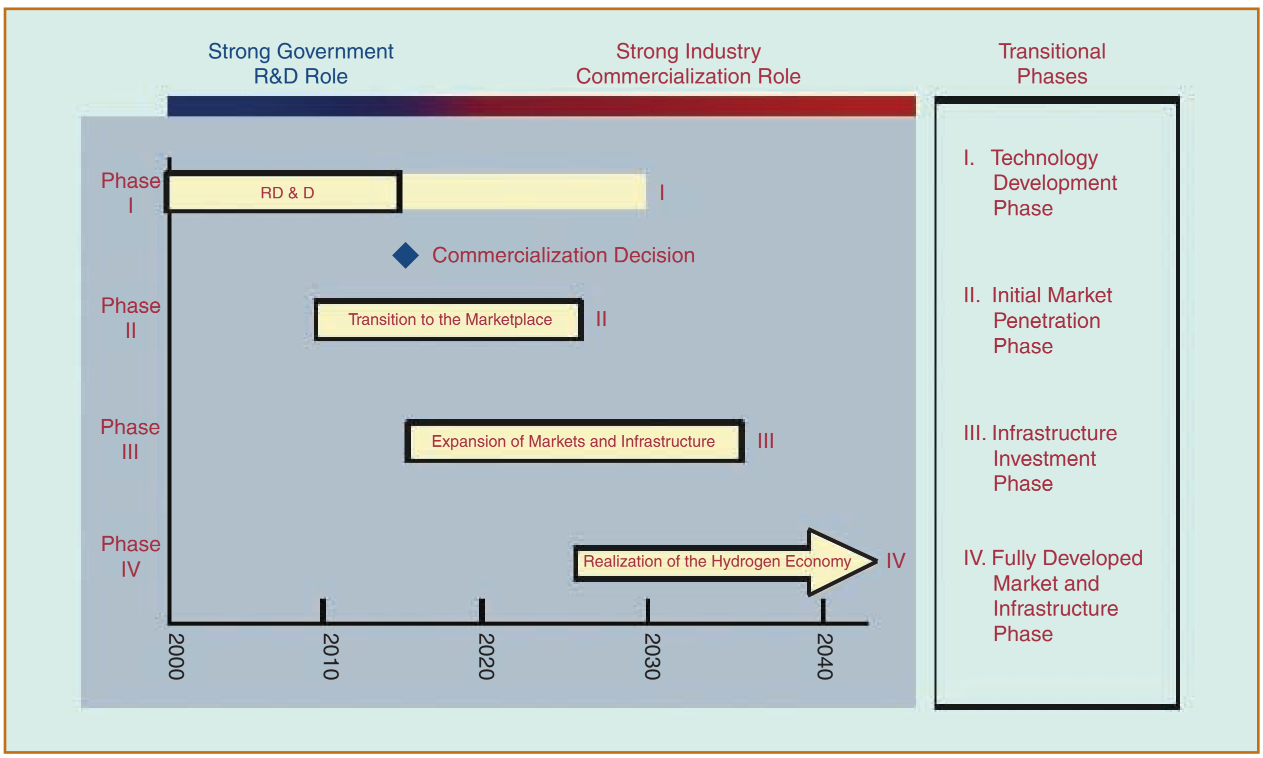


figure 1. Hydrogen research and development timeline. Source: U.S. Department of Energy.

> Hydrogen advocates should take the time to understand the culture of a sector, industry, or enterprise to enable identification of the events and circumstances that will prompt action.

to understand the culture of a sector, industry, or enterprise to enable identification of the events and circumstances that will prompt action. That approach will provide greater insight to business enterprise decisions, enabling other stakeholders to distinguish between a disagreement as to goals from a disagreement as to tactics that reflect the enterprise's approach to resource allocation or risk tolerance. The resulting depth of understanding will avoid having a disagreement over means overshadow a fundamental agreement as to the desired end. Moreover, alignment of goals provides the foundation for the development of mutually acceptable means to achieve shared goals.

While innovation can take many forms, its sustainability is enhanced by the essential element of financial resources. Like all investment decisions, the allocation of capital to energy innovations will be based upon a perception of an acceptable return of value upon the investment. Again, some enterprises are better geared to initiating innovation while others are best at acquiring and adopting previously developed technology. Financial incentives can be designed to support innovation through all stages of development and commercialization. The public sector has a well-recognized role in the provision of direct financial support. Government grants, loans, and an array of tax policies will continue to provide a foundation and direction for innovation. In addition, financial incentives can be more than the provision of money to support research, development, and demonstration activities. Important outcomes are achieved through the identification and elimination of unintended barriers arising from conflicting regulations, policies, and even financial incentives. Outcome-based incentives can provide critical resources to those enterprises best able to respond through early innovation, thereby clearing a path for other enterprises and organizations to follow. Moreover, policy makers should align financial resources with the incentive system of the recipient.

In the early 1990s, utility investment in demand-side management (DSM) did not accelerate because of the mere provision of financial resources that simply reimbursed a company for expenditures. The sought-after goal of replacing brick and mortar investment with DSM investments remained unfulfilled. However, when regulators treated DSM expenditures similar to investments for facilities, by allowing a return on DSM expenditures, there was alignment between DSM policy and investment choice. Expenditures and investment increased as desired. Admittedly, a number of weaknesses were discovered with the program design. However, that fact underscores the importance of constant innovation and evaluation. It does not negate the importance of alignment between the incentive systems of the provider and recipient.

Such strategically designed financial incentives can best allocate scarce resources. However, to be effective, policy makers throughout the public sector must have an insight into the external and internal issues and challenges that are faced by the organizations whose actions are intended to be motivated. Ironically, in the United States, the federal government has indicated intent to fund an array of hydrogen-related education and outreach activities. Yet little of those resources have been targeted to reach out to or educate public sector leaders or private sector executives who may be in a position to influence the availability and use of financial resources.

Other effective incentives beyond direct financial support can emerge when policy makers understand the nature of the commercialization barriers and accompanying risks that confront an emerging technology. One example arises from the

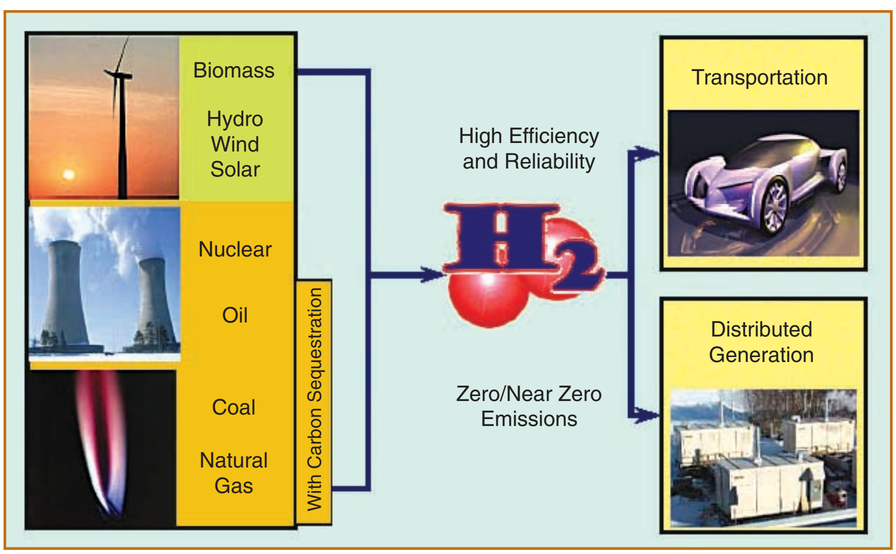


figure 2. Hydrogen production and use diagram. Source: U.S. Department of Energy.

need for demonstration programs to deploy products that will deliver or use hydrogen in a safe, reliable, and environmentally appropriate way. Among the risks a technology developer or project host must consider is the regulatory enforcement risk that a particular demonstration will not perform as expected. This risk can appear in many forms such as the loss of a needed permit or imposition of punitive financial penalties. Of course, the risk perception of the technology developer or project host is the inverse of the public sector perception of risks to human health and the environment.

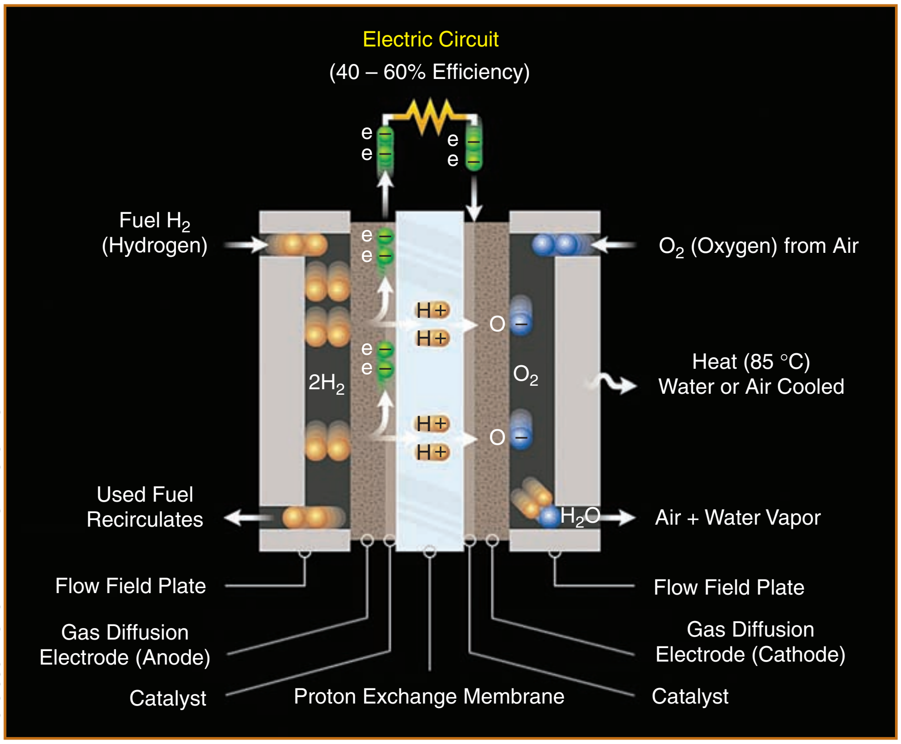


figure 3. The core of this Ballard fuel cell consists of a membrane electrode assembly (MEA), which is placed between two flow-field plates. The MEA consists of two electrodes, the anode and the cathode, which are each coated on one side with a thin catalyst layer and separated by a proton exchange membrane (PEM). The flow-field plates direct hydrogen to the anode and oxygen (from air) to the cathode. When hydrogen reaches the catalyst layer, it separates into protons (hydrogen ions) and electrons. The free electrons, produced at the anode, are conducted in the form of a usable electric current through the external circuit. At the cathode, oxygen from the air, electrons from the external circuit, and protons combine to form water and heat.

These differing views of risk can be reconciled into a strategic initiative when the initial focus is upon the shared concern about the reasonableness of the risk. For example, if the public believes that, after analysis, a particular technology is capable of doing what it purports to do and the risk to human health and the environment is considered reasonable, incentives can be granted based on that determination. Such incentives can be provided through permitting as well as some limitation on the potential liability in case the technology does not perform as anticipated. The New Jersey Corporation for Advanced Technology (NJCAT) administers one such program. Under that program a technology developer can seek a verification of claims that will be conducted by evaluators from the state's public universities together with the opportunity to negotiate a tailored regulatory construct with the New Jersey Department of Environmental Protection. This approach has the potential to provide a much more informed limitation of liability than the blanket approach employed by the U.S. Price-Anderson Act protecting nuclear power.

Codes, standards, and other performance criteria exist as national, state, and municipal requirements. The commercialization barriers that arise from multiple, overlapping, and conflicting requirements are well known. However, that is not to say that every jurisdiction must forgo local or policy specific elements in its regulatory framework. Rather, if a jurisdiction is intent on providing an early market for the deployment or commercialization of hydrogen technology, one of its first policy initiatives should be to understand the impact of the existing regulatory framework upon the intended and sought-after program goals. On the other hand, just as some companies "rush to be second" in the commercialization of a new technology, so too may a particular city, state, region, or country make the choice to lead or adopt.

Public Policy Issues

Many current policy analysts prefer minimal policies that, above all, do no harm to the economic and social spheres. Yet even Adam Smith, known for extolling the virtues of the "invisible hand" of the unfettered marketplace, seeks at least a night watchman's role for government. Even Milton Friedman, known for linking capitalism and freedom, sees a major role for government as rule maker and umpire in the economic game. Political decision makers of all stripes invite governmental interventions in the marketplace to improve allocative efficiency, distributional equity, and macro stability.

Markets operate inefficiently by allowing externalities like air pollution and distortions like monopoly power or inadequate information, and they fail entirely to provide public goods like national defense. Markets tend to concentrate wealth in relatively few hands. Markets are vulnerable to speculative spirals, external shocks, inflation, and other forms of instability.

In addition to correcting market failures, citizens also expect government to enforce social norms and pursue social objectives. More cynically, it is also true that special interests seek special favors, and bureaucracies work to justify their continued existence. Widely accepted rationales for creating energy policies are to reduce and stabilize energy prices, protect the environment, assure energy availability and reliability, and enhance national security. Hydrogen could help on all of these fronts.

Most countries apply a full spectrum of energy policy tools including regulations, taxes, incentives, public investment or ownership, provision of information to consumers and producers, and planning to develop a shared vision of future needs. Particularly important for a future hydrogen economy are governmental research, development, and demonstration policies. At the precompetitive stage, private firms are usually reluctant to invest in fundamental research because they will not be able to capture the associated benefits. Governments step in to perform research directly in national laboratories or to fund research at universities or in private firms. Much has been learned in recent years about the need to ensure that such research gets disseminated to potential developers using explicit technology and personnel transfer strategies.

The public policy maker's toolbox is stocked with proven resources. Supply stimulus can be fashioned through patents, grants, and tax policy. Likewise, demand stimulus can be provoked by government purchases, user subsidies, tax credits, and energy set-aside programs such as a renewable portfolio standard. Each of these tools share the common risk that their use can result in government action that has the inappropriate effect of picking winners or determining losers. However, that risk can be addressed through integrated policy analysis that will identify the objectives sought to be achieved, rather than the means to achieve them. In the context of hydrogen's use as a fuel, public policy can and should define the range of acceptable environmental impacts based on a "well to wheels" analysis. Moreover, those considerations can and should also include a comparative impact analysis of the fuel that would be displaced. By so doing the policy and incentives would be focused on the outcome, allowing a range of technologies to compete and possibly evolve to meet those stated outcomes. The issue is not merely whether natural gas or coal is an appropriate source of hydrogen. Rather, the issue should be whether natural gas or coal is an acceptable source to be developed and deployed in light of the relative lifecycle impacts, taking into consideration the specific application, product design, comparative cost, and impacts of competing technologies and fuel sources.

We suggest that the key issue is whether alternative processes for producing, transporting, and using hydrogen can meet the array of societal expectations concerning environmental and economic impacts. Moreover, the specific application must also be considered so that displaced impacts can be integrated into the analysis and choice. Are there near-term identifiable applications that can be currently supported by hydrogen derived from renewable sources? Are there applications and geographic locations that are positioned to lead early demonstrations and deployment of a hydrogen fuel infrastructure or product commercialization? Ultimately, we must decide, as a community, whether a well-to-wheels analysis is to be a strict gatekeeper of public investment and deployment or one of many sources of data to inform public and private decision making. Rarely will one policy driver overshadow all other considerations. The array of actions that will lead to the postcarbon energy future will be a complex calculus of ideas, actions, philosophies, and policies. While this process cannot be scripted, it can be structured through a framework based on an understanding of market and policy drivers.

PHOTO COURTESY OF BALLARD POWER SYSTEMS.

figure 4. A 250-kW natural-gas-fueled PEM fuel cell stationary power generator.

Policy Implementation

Many countries around the world, such as the United States, Brazil, Canada, Germany, and India, have a federal governmental structure that will profoundly affect hydrogen policy

Hydrogen, as currently conceived, can be expected to evolve from a local market to a continental market over time, implying that state and local policies will also strongly influence its development.

implementation. Even in nonfederalist nations like the United Kingdom, policymakers frequently assign responsibilities to the central government when they want to take advantage of scale economies, enforce national norms, pool risks, and reduce spillover effects. They devolve responsibilities to lower levels of government in order to allow experimentation, tailor policies to local circumstances, and encourage diverse civic cultures.

PHOTO COURTESY OF BALLARD POWER SYSTEMS.

figure 5. A fuel cell generator that uses oxygen from air and hydrogen fuel to create electricity with heat and water as the byproducts.

Some energy markets are global but others are regional or even local in scale. The price of petroleum is set in a global marketplace with many producers and consumers interacting in transnational commercial relationships. Regional initiatives—on behalf of producer states like Texas or consumer states like New Jersey in the U.S. context—have little direct impact on the world oil market, although they fuel fierce national energy policy debates. Coal markets are also global, although transportation costs limit long-distance flows to a few routes. Natural gas markets are continental rather than global in scale, so that prices throughout North America, for example, track fairly closely, even as they may diverge from European prices. Electricity markets in many parts of the world are currently regional in scale, but growing. Solar, wind, and biomass energy sources share a global technology marketplace but have highly localized resource availability. Nuclear energy production technology is globally diffused although politically constrained because of safety, environmental, and security concerns.

State and local policies have strongly influenced the development paths of natural gas and electricity markets over the past century. This is evident in the mix of public and private utility ownership, types of energy sources tapped, siting requirements for plants and transmission lines, efforts at demand-side management, and pricing and financial policies, among others. Hydrogen, as currently conceived, can be expected to evolve from a local market to a continental market over time, implying that state and local policies will also strongly influence its development.

State and local governments vary greatly in their preferences, capabilities, and circumstances. Jurisdictions have unique community cultures. Some communities will adopt environmental quality as a foundation to policy initiatives. Larger and wealthier jurisdictions will have a relatively greater capacity to implement aggressive public policies than elsewhere. Natural resource endowments, urban agglomerations, and other circumstantial factors will strongly influence the range of viable policy options and the focus of political actors. Thus the seeds of the hydrogen transition will encounter more fertile soil in some jurisdictions than in others.

The most likely places for elements of the hydrogen economy to take root are those that prefer to be innovative, have the capacity to act in a well-informed and decisive manner, and have unique circumstances that make hydrogen attractive. These circumstances might include a strong need for less-polluting transportation; land use patterns and population densities that support mass transit (and corporate) fleets or combined heat and power production; a preexisting hydrogen infrastructure; and a cost-effective local source of hydrogen.

Among nations, the one most committed to the hydrogen transition is Iceland, a progressive social democracy with strong green values and a wealthy, homogeneous population that is located on a remote island where imported fossil transportation fuel is expensive and geothermal primary energy is cheap. In North America, relatively few states and provinces have the combination of preferences, capabilities, and circumstances on both the supply- and demand-side to become early natural leaders in the hydrogen transition. Currently, Hawaii is pursuing a transition to hydrogen while California and Michigan have launched programs focused upon the commercialization of fuel-cell-powered vehicles. British Columbia, Connecticut, and New York State have begun programs to support the fuel cell manufacturers located in their jurisdictions. Combinations of factors make Washington State, Texas, and New Jersey additional potential candidates for early-adopter, first-mover status.

An early and ongoing role for the federal government is to promote the adoption of standards. This standardizing role provides access to markets for producers while at the same time providing comfort to consumers and users. Standardization could be limited to reliability, health, and safety issues, or it could extend as far as creating a national industry structure that supports a large-scale commodity hydrogen marketplace. In the United States, the natural gas industry has reached this high level of standardization but the electricity sector has not. However, the rush to standardization should not foreclose needed experimentation on what works in specific, varied circumstances.

Strategic Recommendations

As decision makers plant the seeds of what may someday become a viable and ubiquitous hydrogen economy, they should consider the following recommendations. This is strategic advice, couched in U.S. terms, but it is widely applicable elsewhere.

Plan for Both State and Federal Roles in Hydrogen Policy Formulation and Implementation

In R&D, there should be distinct roles, with the central government sponsoring fundamental research at a significant and stable level, and the states sponsoring or implementing applied research, cost-effective demonstration projects, outreach, and education. Make federal funds available on a competitive grant basis to states and other intermediary organizations like the National Association of State Energy Officials for demand stimulus. Elements of the hydrogen economy will emerge from highly localized confluences of

How Much Hydrogen Do We Need?

Once applications for hydrogen as an energy carrier have become well established, the United States will require much more hydrogen than it now produces. An estimated 40 million tons of hydrogen will be required annually to fuel about 100 million fuel-cell-powered cars, or to provide electricity to about 25 million homes.

Each of the following scenarios could produce 40 million tons per year of hydrogen.

Distributed Generation Production Methods

Electrolysis: 1,000,000 small neighborhood-based systems could fuel some of the cars and provide some power needs.

Small reformers: 67,000 hydrogen vehicle refueling stations, which is about one third of the current gasoline stations.

Centralized Production Method

Coal/biomass gasification plants: 140 plants each about like today's large coal-fired plants.

Nuclear water splitting: 100 nuclear plants making only hydrogen.

Oil and natural gas refinery: 20 plants, each the size of a small oil refinery, using oil and natural gas in multi-fuel gasifiers and reformers.

"A Production Mosaic"

Many factors will affect the choice of production methods, how they will be used, and when they might be demonstrated and commercialized. Visualizing a mosaic of future production methods provides a perspective for the Roadmap. The combination of distributed and centralized production, plus advanced methods that are not yet available, could be combined to create a future industry producing 40 million tons of hydrogen per year. Here is one scenario:

100,000 neighborhood electrolyzers:	4 million tons
15,000 small reformers in refueling stations:	8 million tons
30 coal/biomass gasification plants:	8 million tons
10 nuclear water splitting plants:	4 million tons
7 large oil and gas SMR/gasification refineries:	16 million tons.

Source: U.S. Department of Energy, "National Hydrogen Energy Roadmap," 2002, pg. 11.

preferences, capabilities, and circumstances. Small jurisdictions have no incentive to stimulate the demand for hydrogen technologies because the benefits will leak away to other jurisdictions. The central government, however, can internalize this leakage by offering funds to local actors who share what they learn. To make this distributed innovation process work, it is necessary to foster closer technical communication in the R&D community among federal funders and those who perform the research, both in and outside of government. In public utilities regulation, the central government should push for common reliability and safety standards while leaving much else in the hands of state regulators so that needed experimentation can occur. Indeterminate aspects of the hydrogen future—centralized versus distributed production, nuclear versus renewables, and so on—should not be decided a priori by ideology. Instead it is crucial that enough experimentation takes place so that we find out empirically what approaches will bring about the desired outcomes.

Reinvigorate the Practice of Technology Assessment and Establish Hydrogen's "Value Proposition" in Specific Contexts

Since the U.S. Congressional Office of Technology Assessment was de-funded in 1995, there has been no objective source of science and technology policy advice. The creation of a hydrogen economy is a vastly complex undertaking involving public and private actors, and policymakers need the help of balanced experts to avoid doing harm. An early step is to explain why hydrogen warrants our attention—what is the magnitude of the expected environmental improvements and how cost-effective will they be? The public policy value proposition needs to be developed by and for each participating jurisdiction, perhaps using the NJCAT model discussed earlier. The interaction of security/independence, environmental stewardship, sustainability, and economic development will shape the type of policies, incentives, and demonstrations that will make sense in a particular locale.

Foster Education and Outreach Targeted to Public and Private Sector Leaders

Many decision makers know very little about the technologies and the systemic needs of the hydrogen transition. Yet these same leaders are being asked to decide scientific, technological, regulatory, land use, transportation, and other issues that affect the viability of the hydrogen economy. They need to know why hydrogen is interesting and which particular innovations are succeeding. Funds are currently being targeted to support general public education about hydrogen. While this is immensely valuable, there should also be efforts targeted at informing public and private sector leaders. To keep such efforts from degenerating into propaganda, they should be broad-based, authoritative, and transparently produced analyses of alternatives their implications.

For Further Reading

U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy, Hydrogen, Fuel Cells, and Infrastructure Technology Program, "National hydrogen energy roadmap," Nov. 2002 [Online]. Available: http://www.eere.energy.gov/hydrogenandfuelcells/pubs.html

C.J. Andrews, "Diffusion pathways for electricity deregulation," *Publius*, vol. 30, no. 3, pp. 17–34, Summer 2000.

R.M. Margolis, "Understanding technological innovation in the energy sector," Ph.D. dissertation, Woodrow Wilson School, Princeton Univ,, Princeton, NJ, Jan. 2002.

J.M. Ogden, "Prospects for building a hydrogen energy infrastructure," *Annual Rev. Energy Environ.*, vol. 24, pp. 227–279, 1999.

B.G. Rabe, "Power to the states: The promise and pitfalls of decentralization," in *Environmental Policy: New Directions for the 21st Century*, 5th ed, N.J. Vig and M.E. Kraft, Eds. Washington, DC: CQ Press, 2003, pp. 33–56.

Biographies

Clinton J. Andrews directs the planning program at the E.J. Bloustein School of Planning and Public Policy, Rutgers University, New Brunswick, New Jersey, where he is an associate professor. He was educated at Brown and MIT as an engineer and planner. Previous experience includes working in the private sector on energy issues, helping to launch an energy policy project at MIT, and helping to found a science policy program at Princeton. Dr. Andrews is the immediate past president of the IEEE Society on Social Implications of Technology, a recipient of the IEEE's Third Millennium Medal, and a member of the IEEE Power Engineering Society and the IEEE-USA Energy Policy Committee. Among his publications are the books *Humble Analysis: The Practice of Joint Fact Finding, Industrial Ecology and Global Change* and *Regulating Regional Power Systems.*

Scott A. Weiner directs the Center for Energy, Environmental, and Economic Policy at the E.J. Bloustein School of Planning and Public Policy, Rutgers University, New Brunswick, New Jersey. He received his B.A. from New York University and J.D. (magna cum laude) from New York Law School. His private sector experience includes having served as president of Ballard Generation Systems, Inc., where he led the development of distributed generation systems based on the Ballard fuel cell technology. He has held a number of public offices including serving as commissioner of the New Jersey Department of Environmental Protection and Energy and president of the New Jersey Board of Public Utilities. He has also served as a trustee of organizations that promote technology commercialization including the Business Council for Sustainable Energy, the New Jersey Corporation for Advanced Technology, the Solar Energy Industries Association, and the National Hydrogen Association.