Special Issue on the Hydrogen Economy

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Hydrogen is an energy carrier that has gained much attention in recent years as a potential solution to problems of air pollution, climate change, energy security, and high fuel prices. The term *hydrogen economy* is shorthand for the complex system of institutions, organizations, and technologies needed to produce, transport, distribute, and ultimately allow widespread use of hydrogen in place of gasoline or electricity. This special issue of the PROCEEDINGS OF THE IEEE explores the technical, economic, and political challenges associated with bringing about a hydrogen-based future.

Long-standing hydrogen research and business communities received a dramatic boost in January 2003 when U.S. president George W. Bush proposed a major hydrogen economy initiative in his State of the Union address. A variety of industry road-mapping exercises around the world highlighted official interest in moving the hydrogen vision closer to reality. Boosters and skeptics soon added their views on these proposals, and public debate became both noisy and confusing. In April 2004, IEEE stepped into the breach with a special symposium in Washington, D.C., that was designed to clarify what was and was not known with certainty about the technical elements of the hydrogen economy. The success of this symposium sparked plans for a special issue of the PROCEEDINGS. A few of the papers in this special issue had their origins in the symposium, but most were recruited through a subsequent solicitation and invitation process.

Researchers are examining the specific challenges involved in creating a hydrogen economy and this special issue covers the research and insights on the plausibility of such a transition.

Interest in the hydrogen economy has only grown since 2004. U.S. policy has aggressively advanced the Bush vision "that the first car driven by a child born today could be powered by hydrogen, and pollution-free." The European Union has launched research and regulatory initiatives designed to promote hydrogen, and so has Japan. Both energy and automotive companies have begun placing financial bets on a possible hydrogen economy. Researchers are now examining in detail the specific challenges involved in making a hydrogen economy feasible and desirable. In so doing, they have identified several potential show-stoppers that could very well derail the hydrogen juggernaut. This special issue brings together some of the most thoughtful research and insights on the plausibility of making the transition to a hydrogen economy.

It is unusual for the PROCEEDINGS OF THE IEEE to include papers written by policy analysts, lawyers, and other nontechnologists. This special issue does exactly that because it intends to help interested technologists understand the broader context of their work. If the hydrogen economy succeeds, it will be because technological, social, economic, and political factors converged favorably. IEEE's leadership has embraced this new focus on context, so expect to see more of it in IEEE conferences and publications.

I. TECHNICAL CHALLENGES

There are technical challenges all along a hydrogen production chain that includes producing hydrogen

Digital Object Identifier: 10.1109/JPROC.2006.883713

from primary energy sources, sequestering the carbon dioxide generated from fossil fuel-based energy feedstocks, transporting hydrogen, storing it, and using it efficiently in fuel cells. The challenges are so daunting that a failure to overcome any one of them could foreclose the possibility of a successful hydrogen economy.

Focusing on the first step in the value chain, hydrogen production, Solli *et al.* illustrate the environmental tradeoffs associated with alternative production technologies. This is important because a major rationale for pursuing a hydrogen economy is to reduce environmental impacts. They compare hydrogen production via: 1) nuclear-assisted thermochemical water splitting and 2) steam reforming using natural gas. For each alternative, they measure the potential impacts on global warming, human toxicity, acidification, eutrophication, and radiation. The nuclear scenario performs better on global warming, acidification, and eutrophication, but it performs worse on human toxicity and radiation.

More important than the outcome of this particular tradeoff analysis, however, is its methodology, which can be applied widely to guide better decision making. Solli *et al.* employ a hybrid life cycle assessment approach that distinguishes among direct and indirect effects, as well as revealing the incidence of effects at each stage of the life cycle from raw materials extraction through operation of the hydrogen production plant. Their analysis reveals, for example, that most of the radiation hazards associated with the nuclear scenario are due to mine tailings, not the operation of the power plant. More subtly, the analysis also shows that most of the human toxicity impacts of the natural gas scenario are not associated with the construction and operation of the steam reformer, but rather with more distant sectors of the economy that have upstream linkages. Tradeoff analysis based on a comprehensive consideration of relative life-cycle environmental impacts is as important to good engineering practice as is the more familiar tool of life-cycle cost analysis.

During the decades-long transition away from fossil fuels to nonfossil alternatives such as solar and nuclear power, there may be a need to capture and sequester carbon. Given that the hydrogen economy is touted as a solution to the problem of climate change, it will be important to achieve actual net emissions reductions. In their paper, Benson and Surles survey the options for capturing and storing carbon dioxide in order to reduce the pressure on the climate system from greenhouse gas emissions. The options include low-tech approaches such as planting trees, managing forests for carbon retention, and changing soil tilling practices. There is also a suite of higher tech options that includes deep ocean storage and underground storage in deep geologic formations. Industry now has several years of experience with each of these options, and it is possible to glean a sense of their feasibility. Although it sounds like a radical idea, Benson and Surles offer evidence that underground storage in deep geological formations is both feasible and attractive. Many of the component technologies are mature, the industries to implement deep storage already exist, and systematic processes of scaling up from bench experiments, to pilot plants, to full scale systems are well under way. Benson and Surles report that electricity costs would increase by US$0.02 to 0.05/kWh with sequestration.

Hydrogen transportation by pipeline, ship, or truck is a challenging proposition. Its lightness means that it has a low energy content per unit volume relative to conventional fuels, and its low evaporation temperature means that compressing and liquefying it are energy-intensive operations. Elemental hydrogen can embrittle or corrode materials commonly used in pipelines and storage tanks. Particularly problematic is the storage of hydrogen on board motor vehicles. Even with composite materials, storage tanks for compressed gaseous hydrogen are prohibitively heavy. The cooling equipment necessary to store liquid hydrogen makes that option similarly unattractive. In their paper, Bannerjee *et al.* evaluate the prospects for novel carbon nanotube storage of hydrogen. Their paper focuses on molecular simulation studies which can identify the most promising structures and compositions to maximize hydrogen storage. They explore several crucial parameters including pressure, temperature, chirality, and metal particle encapsulation that influence hydrogen storage in carbon nanostructures. Since there are different purity, composition, and chirality depending on the mode of synthesis of carbon nanostructures, there is a relative lack of agreement among experimental results. The authors believe that the ideal method to investigate storage characteristics is to simulate hydrogen storage using molecular modeling tools and then validate the results against data obtained from experiments.

When hydrogen reaches the point of end use, it must be converted into useful electrical, thermal, or mechanical energy. Fuel cell technology is the leading candidate for this task, indeed, the interest in hydrogen stems largely from its suitability as a feedstock for fuel cells. In his paper, Scott assesses the evolution of fuel cell technology from niche aerospace applications to potentially widespread use in terrestrial transportation systems including cars, trucks, and buses. His review makes it clear that there is great promise, but that significant barriers to cost-effective commercial fuel cell deployment remain. In particular, Scott suggests that research breakthroughs in materials, by-product management, susceptibility to contamination, component lifetime, and load response are needed.

Each of the technical challenges identified during this tour of the hydrogen supply chain is daunting. Taken together in a systems view, it is clear that much work remains to be done. The paper by Bossel provocatively asks whether hydrogen can ever overcome its challenges to become more attractive than electricity, a more familiar energy carrier. Bossel accounts for the efficiency losses associated with each stage of the hydrogen supply chain and shows that under reasonable assumptions, these parasitic losses make the hydrogen economy uncompetitive. His findings underscore the need for research breakthroughs and not mere incremental improvements. This paper also lays the groundwork for thinking about the economic and political challenges associated with the proposed hydrogen economy.

II. ECONOMIC AND POLITICAL CHALLENGES

Transforming a large-scale sociotechnical system involves more than technological challenges. The current automotive transportation system is a result of a century of coevolution of the automobile and fossil fuel industries, operating within political and economic constraints. The transition to a hydrogen economy would require dramatic changes within both of these industries. Given that much of the impetus for change lies in public policy concerns regarding climate change, environmental protection, and energy security, it is clear that both political and economic challenges also lie ahead.

There will be no hydrogen economy if the hydrogen-fuel cell package cannot successfully compete with the existing liquid fuel-internal combustion engine regime. In their paper, Yeh *et al.* perform an economic analysis of the conditions under which hydrogen-fuel cell vehicles are likely to penetrate into the U.S. light duty vehicle fleet. They find that economy-wide reductions in energy use and carbon dioxide emissions would result if the fleet successfully turned over. However, economics alone would not yield a significant level of hydrogen-fuel cell vehicle penetration by the year 2030, given current prices and reasonably anticipated technologies. Technical challenges to bulk hydrogen production, transportation, and storage are significant. While public policy interventions will be helpful, major technical breakthroughs will be necessary to make hydrogen available as readily as gasoline is today. Dramatically higher petroleum prices will also facilitate the move to hydrogen economy.

In his paper, Andrews offers a systematic way to devise and analyze public policies for new energy carriers such as hydrogen. He identifies defensible rationales for governmental intervention in the marketplace, including pursuit of improved efficiency, equity, and stability. There is a large toolkit available to policymakers that includes liability waivers, regulations, disincentives, incentives, public investment, information, voluntary agreements, and planning, often applied in combination. Part of the challenge for governments is to intervene in ways that do not prejudge the outcome of technological evolution but instead steer innovation in socially preferable directions. Implementation issues such as intergovernmental coordination will also strongly influence political and economic outcomes. Given the uncertainty associated with the ultimate attractiveness of a hydrogen economy, prudent governments will conduct careful, limited policy experiments and encourage a diversity of technological approaches.

An example of an economically prudent hydrogen transition strategy appears in the paper by Felder and Hajos. They evaluate the potential for producing hydrogen using the off-peak production capability of the electric power system. In a simulation study of the PJM Interconnection that serves the U.S. midatlantic states, they find that the existing capital investment in electric power plants can serve a dual purpose by producing hydrogen at night via electrolysis. Although this is not a highly efficient solution in engineering terms due to the losses associated with fossil fuel combustion and electrolysis, it may be an economically efficient solution during the transition period when uncertainty remains regarding whether the hydrogen economy will really come to pass.

Prudent investors will anticipate legal and regulatory barriers to the growth of a hydrogen economy. In their paper, Power and Trope identify several likely legal challenges, including export restrictions on sensitive technologies, lack of standards for new technologies, interactions of patent laws and governmental sponsorship of research, and concern over consumer safety.

III. SKEPTICAL OPTIMISM

The papers in this special issue of the PROCEEDINGS suggest that there are good reasons to be skeptical regarding the feasibility of the hydrogen economy. Yet there are many opportunities for technological innovations that could quickly justify optimism. Much research done to advance the vision of a hydrogen economy is also likely to be socially beneficial and economically attractive for other reasons. In sum, we suggest that it is worthwhile to read this special issue and learn more about the possibility of a hydrogen economy, both because it has a chance of coming into being, and because it provides a wonderful illustration of how to think systematically about large-scale change in fundamental sociotechnical systems. ■

ABOUT THE GUEST EDITORS

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Prof. Andrews served on the IEEE Board of Directors as Division VI delegate from 2005 to 2006. He is a past president of the IEEE Society on Social Implications of Technology, and a member of the IEEE Power Engineering Society and the IEEE-USA Energy Policy Committee. He was licensed as a professional engineer in 1982.