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Hydrogen energy stations: along the roadside to the hydrogen economy

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1. Overview

Government in the form of leadership, public policy and as the initial market driver is needed to create the vision and set the objectives for innovations such as a hydrogen economy in particular. In order for the hydrogen economy to become a reality, there needs to be government leadership from the very top of the political spectrum with follow through from the administrative bureaucracy. Otherwise, this environmentally sound and clean energy innovation will not be taken seriously. Moreover, it will fail to become a reality. The hydrogen economy demands public leadership through a variety of processes.

One such process is the declaration that the hydrogen economy, for example, is to be national policy, such as Iceland did when its government and Prime Minister in the Spring of 2001 declared, "Iceland would be the world's First Hydrogen Economy". Shortly thereafter, former European Commission President Romano Prodi (2002) made a similar declaration for the European Union. Then in January 2003, President George W. Bush echoed the same sentiment in his State of the Union Address. One year later, in January 2004, Governor Arnold Schwarzenegger declared California would have a hydrogen highway[2] in his State of the State Address (2004) and subsequent Executive Order (2004).

Of course, none of the political statements were news for those working in the field of hydrogen. Schwarzenegger made it a part of his 2003 campaign for a recall of former Governor Gray Davis with his own election message through supporting working in the area for two years before that. Then in 2003, President Bush announced his FreedomCar program which included the "hydrogen economy". Bush's version of the hydrogen economy which some label as "dirty or black hydrogen" (Rifkin, 2004) rests upon federal program with roots in the US Department of Energy (e.g. clean coal, nuclear and fossil fuels) over decades and hundreds of millions of dollars spent. Clean coal is estimated alone to have cost over $3 billion in research and development with matching private sector funds as well. However, the Clinton administration tried a new approach with the Partnership for New Generation Vehicles (PNGV) which unfortunately did not consider hydrogen or fuel cells for political pressure reasons. And the list of support for hydrogen goes on. What is significant is that public leaders today have come forward and advocated for a hydrogen economy.

Innovations in general represent incremental changes. But the hydrogen economy is a dramatic "paradigm

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[2] The origin of the term "hydrogen highway" is debatable but credit must be given to Toyota of North America (Torrance, California) for conceiving and investigating the idea in 2001.

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change"(that is, a significant change in how society views an issue and empowers its leaders to make dramatic changes). Now it has been declared worldwide through public policy and actions. The US Department of Energy Secretary Spencer Abrahams announced awards in the Spring of 2004, more than USD$357 million in new matching funds for the hydrogen economy over the next five years. While the funds had not been distributed by the end of the summer of 2004, over 100 partner companies anticipate and are preparing for the program implementation by the end of 2004. President Prodi has declared that over USD$1.3 billion will be made available in the EU over the next five years. Project proposals are actively under consideration. Such high-level government executive decisions lead to attracting companies to the member states of the EU, thereby creating jobs and economic development. Similar initiatives are under way in Japan and mainland China.

However, governments can do other things besides providing funds, tax incentives and other funding resources. Government can establish "mandates" that lead to the formation of standards and codes with protocols set for the innovation (Stuart Energy, July 2003; Hexerberg, 2004). This is being done now in the area of hydrogen throughout the world. For example, the European Union has adopted a policy, led by President Prodi (2002, 2003) moving toward a "clean" hydrogen economy based primarily on renewable energy sources (EU, June 2003, 2003a,b,c,d). From that benchmarks and markers can be derived for measurement of performance and evaluative purposes. Governments can competitively procure products that are hydrogen based. In short, governments can become the "market driver" for the hydrogen economy.

In many ways, California with its 34 million population as the market driver has been the American testing ground for not only the hydrogen economy but also for the construction of the hydrogen highway and the parallel development of hydrogen energy stations. This paper will draw primarily upon the California experience in creating the stationary hydrogen energy "roadside" for power in local communities as the demand and mass production increases in the next few years. Along with other American states, the European Union and now Asian nations are committing to a hydrogen future. These initial government driven policies but then market-oriented programs create a clean and green hydrogen economy for stationary fuel production and distribution.

2. Introduction

Today, hydrogen is primarily used as a feedstock, or as an intermediate chemical and specialty chemical. However, most industries and academics envision a robust hydrogen future, in which hydrogen will be used as an energy carrier for vehicle fuel or, as presented here, stationary power.

Technically, hydrogen is becoming increasingly cost competitive and plentifully available from the reforming of natural gas and other fossil fuels. Hydrogen is an energy carrier that needs to be derived from other fuel sources. Today the amount of energy produced by hydrogen per unit weight of fuel is about 3 times the amount of energy contained in an equal weight of gasoline, and almost 7 times that of coal (FOET, 2004). In launching space vehicles, NASA was just as concerned about the weight of vehicles fighting Earth's gravity as it was about power during and after launch.

As the FOET White Paper (2004) notes hydrogen energy density per volume is quite low at standard temperature and pressure. Storing the hydrogen under increased pressure or storing it at extremely low temperatures as a liquid can increase volumetric energy density. High-pressure storage and improved vehicle efficiency enable hydrogen fuel cell vehicles to increase their payload and range. Commercial companies such as Quantum, have both the advanced technology needed and mass market products available for installation at 5000 psi and soon to the consumer market at 10,000 psi.

3. Infrastructure: creating the mechanisms and systems for the hydrogen highway

Central to the entire discussion, however, is the issue of infrastructures for energy and transportation. Or as some pundits, economists and policy makers put it, the "chicken and egg" syndrome: which comes first, the hydrogen infrastructure or the vehicles? On the other hand, *The Economist* published an insightful article called the "Energy Internet" (March 13, 2004) which compares today's "conventional energy infrastructure" to the transformation of energy systems for tomorrow which will be modeled after the internet. These new "agile energy systems" as Clark and Bradshaw (2004) call them combine central grid power systems with diverse and flexible on-site distributed energy systems (Isherwood et al., 2000; Clark and Lund, 2002).

Installed costs for renewable energy fueling stations in 2003 ranged from about $1 million per station. By mid-2004, the costs have been reduced to approximately $700,000 and are rapidly declining. Additionally, regions in California and elsewhere in the USA are installing stations today. South Coast Air Quality Management District (SCAQMD) in Southern California is one of the world leaders. Norway passed legislation in 2003, creating a hydrogen highway from Oslo to the west coast. Northern Italy has plans for a similar roadway and several American States are planning hydrogen infrastructures.

Other regions in North America and the EU are doing much the same. The EU has issued reports on regional innovation, arguing the same point—that local and regional creative projects in sustainable development, including hydrogen will propel the hydrogen paradigm (EU, 2004). Lipman et al. (2004) completed a study for the California Air Resources Board and Stationary Fuel Cell Collaborating, concluding that the pathway to a hydrogen economy clearly was first to have stationary hydrogen for power usage in local communities.

By the spring of 2003, over 100 hydrogen refueling stations were operating in the USA. Consider Southern California, where according to the South Coast Air Quality Management District (SCAQMD, see Attachment 1), nine hydrogen fueling stations are now being installed and more than twice as many are planned. These stations, somewhat modeled on the Sunline Transit System in Palm Springs, will use technologies for reforming for natural gas into hydrogen, but the stations are also equipped with electrolysers for renewable energy sources such as water, solar, bio-gas and wind for the future. These stations will also be required to be "open to the public" as well as to regional government vehicles and contractors.

On the hydrogen vehicle side, Los Angeles City Government currently has two Honda hydrogen fuel cell cars in service. San Francisco also has two Honda hydrogen fuel cell cars. Toyota has two hydrogen fuel cell demonstration vehicles located at the University of California, Irvine and Davis campuses. Air Products has provided a portable hydrogen storage unit for refueling for the Los Angeles and San Francisco governments while Prax Air is installing a refueling station in partnership with BP at the Los Angeles International Airport.

Today, the number of hydrogen fueled cars is so few in number that refueling stations for vehicles are economically unfeasible. That is why a number of companies and regions, including SCAQMD, are advocating and installing "hydrogen energy stations" first for stationary energy storage and off-peak power which can supply stored hydrogen supplies to homes and business in the local community from renewable resources until the demand for hydrogen fuel for vehicles arrives. The future, however, may well go beyond public commercial stations and see hydrogen powered fuel cells located in homes for both domestic power and fuel for family cars. Furthermore, leveraging existing solar powered electric vehicle recharging stations at various public parking lots could serve as a key inter-modal transportation component to station feasibility.

The hydrogen infrastructure issue need not limit the evolution of fuel cells and hydrogen technology. Rather, many companies are now commercializing "hybrid technologies" (Clark, 2004) envisioning a distributed model for hydrogen production and delivery to integrate the gas, electricity, building, and mobility infrastructures. Instead of building a costly new distribution infrastructure for hydrogen, excess existing gas and electricity distribution capacity can supply local hydrogen production needs. Only after this decentralized approach has built up a large hydrogen market for power to buildings and then vehicles later will central production merit substantial investment.

4. A "paradigm change": the hydrogen economy

A significant paradigm shift is now under way as a major change in the way government policy makers and industry leaders are looking for clean fuels and renewable energy for their own nation-states. Current and future markets in fossil fuels subject to volatile prices changes (e.g. gasoline and natural gas) as well as national and international energy/environmental crises, conflicts and now war in the Middle East are combining to motivate this dramatic paradigm shift from the fossil fuel age to a worldwide hydrogen future. Moreover, the international limitations on fossil fuel supplies cause more concern not only on the economic, but also on domestic and international political levels. The motivation, furthermore, is to find new clean sources of fuels to convert to hydrogen in both economical and efficient ways so that the industrial and developing worlds do not become dependent upon "foreign" fossil fuel sources.

The paradigm change can be construed furthermore as a new "mindset" or as "social constructionism" which is a European social science term that applies to a social-cultural revolution or change in public opinion. In spite of ideological or political agendas, the hydrogen economy is such a change since it is basically a non-political movement supported by science and technology that the public wants without any universal vote or election. In California, there is very real awareness of the effects of pollution in the environment (air and water) with our dependency on fossil fuels. The general public has become increasingly aware of these issues and now polls show consistently that over 80% want governmental oversight, protection and dramatic change.

5. The public sectors: local, regional and state governments

The role of governments should be a combination of policy making, procurement and transportation plans that include collaboration with the private sector in both setting standards and lowering prices. The public sector leadership, as noted above, must make public announcements about innovation and promote its implementation even if extensive additional funds and financing mechanisms do not exist today. Many government mechanisms exist already in the form of public policy but also as standards, codes and procurement programs. Businesses and local regions need to know that government leadership support innovations such as hydrogen. There must be cooperative work for example, in creating new standards and codes that fit the chemical properties of hydrogen. There is an unknown level of risk management for insuring hydrogen facilities and vehicles.

For state or regional government-sponsored support for hydrogen, a number of issues need to be considered which can be expedited by the public sectors: (1) operating hydrogen powered programs set to operate fleet vehicles; (2) standards, codes and regulations which are monitored by an air resource committee; (3) implementation of public polices that are monitored by state and local districts; (4) procurement of equipment through competitive bidding process; (5) creation of master contracts for purchases of hydrogen vehicles; (6) mechanisms to revise and monitor codes, standards, as well as fire standards and mitigation and management of risks; (7) advance research and development resources for deployment funds and support; (8) create and leverage finance, bond, procurement and investment mechanisms; and (9) use insurance programs along with risk management tools.

The public sector plays a number of collateral roles as well. For example, they can provide safety labeling or "good housekeeping seals" for hydrogen which is important for providing consumer confidence given the historical myths about hydrogen (Lovins, 2003; Lipman, 2003). For local communities resources for job creation, training and workforce development along with the involvement of labor unions for new careers can be created by the hydrogen economy. Education institutions (public schools, colleges and universities) also need to be created to meet the current and future demands. One kind of educational focus on hydrogen can be done by holding a competition of academic school to promote student design of a hydrogen refueling station. The U.S. Department of Energy, for example, did just that by holding a "Hydrogen Station" competition. The winner in 2004 was the University of Victoria in British Columbia, Canada. Now corporations, such as ChevronTexaco, are doing the same thing with competitions for their own private sector hydrogen refueling station purposes. Hence more competitions are anticipated in the future.

Innovations and advanced technologies emerge historically when national government helps clear the way for the establishment of mass markets. Edison, for example, was only able to establish a commercial electricity company when the costs could first be "supported" (i.e., paid for) by local governments and then be made available at reasonable prices to the mass market. Since the end of the World War II, the industrialized nations have all used government research and development monies to support the commercialization of everything from diesel fuels to the internet. In fact, American government officials traditionally justify the funding of national labs, NASA and even the U.S. Department of Defense, based on the "dual use" or "transfer of technologies."

National and local government incentives, tax breaks, and even procurement are critical to the commercialization of more advanced technologies, such as hydrogen. Government assists in the introduction of new technologies in still another way: regulations and standards. Today, the advancements of technology to speed communications and to slow global warming are often linked to government regulations and oversight. California has often helped lead the way in this regard with its emission controls, environmental laws, and atmospheric regulations. The hydrogen economy is no different.

Appropriate and targeted government regulations can ease the way for public/private partnerships. Together, government and the commercial sector can work collaboratively to create new industries and jobs, as evidenced by the zero emission vehicle (ZEV) regulations in California which began in the early 1990s with a focus on electric battery-powered vehicles (Clark and Paolucci, 1997, 2001). This California standard set the standard and goals for ZEV for the entire USA and impacted other nations. More importantly, the size of the California forced auto-manufacturers to produce vehicles to meet these standards (see CARB and Fuel Cell Partnership, 2000, 2001, 2003).

California's progressive regulatory regime has stimulated the market for clean running automobiles as well as new advanced technologies for the vehicles themselves and the infrastructure that serves them. With regard to regulation or privatization, the international carmakers have been the driving force for change while the Detroit carmakers have either stalled or sued the state of California to stop the regulations from being implemented. The last of these was only settled in August 2003 despite the fact that the company had been heavily invested in research and developed vehicles that exceeded the California standards (Shnayerson, 1996).

Over the years in California, both the California Public Utility Commission (CPUC, 2003) and the California Energy Commission (CEC, 2000, 2001) have funded the development and deployment of renewable and distributed technologies. The consumers of power literally funded natural gas and electric vehicle infrastructure through rate paying, which exemplifies the need for state regulators to become more involved in the initial investment in hydrogen fueling infrastructure. By utilizing a dedicated account similar to the approach adopted by the CPUC to fund the low emission vehicle refueling infrastructure, participating states and nations also will be able to jumpstart the necessary public investment without constraining their general revenue budgets, while simultaneously attracting private investment. For some examples of how larger regions and diverse nation-states specifically focused on hydrogen, see various European Union reports throughout 2003 (EU, 2003a,b,c,d).

6. The private sector: small and medium size enterprises

Small and medium size enterprises (SMEs) need to be brought into the hydrogen research, development, and deployment playing field. In California, the combination of research, development, and implementation for new advanced technologies by entrepreneurial firms and SMEs has been one of the key "economic engines" for stimulating growth over the last few decades. With a number of world-class universities and national research labs such as the University of California campuses at Berkeley, Irvine, and Davis, the transfer of innovation to the marketplace has been astonishing and has now fueled the growth of the "Golden State" into its "Next Economy" (Clark and Feinberg, 2003).

The U.S. hydrogen industry currently produces more than 9 million tons of hydrogen per year (enough to power 20–40 million cars or 6–12 million homes) for use in fields such as: fertilizer and chemicals production; petroleum refining; metals treating; and electrical applications. Some of these sectors, such as fertilizers have been electrolyzing hydrogen for over 60–70 years (Hexerberg, 2004; Stuart Energy, August 2003). According to the U.S. Department of Energy, steam reforming of methane (natural gas) and oil accounts for 95% of the hydrogen produced in the U.S. Other methods of hydrogen production are gasification of fossil fuels (e.g. coal), splitting water using electricity (electrolysis), heat or light, and thermal or biological conversion of biomass. However, the consensus appears to be that natural gas reforming is the transition approach to producing hydrogen. Nonetheless, the definition of time for the transition period has yet to be settled.

In terms of the transportation sector, the cost of 1 kg of hydrogen production can be compared to that of 1 gallon of gasoline, the energy content of which is roughly equivalent to 1 kg of hydrogen. Typically, a gasoline internal combustion engine (ICE) with a mechanical drive train is 15–20% efficient, while a hydrogen ICE is about 25% efficient. Hydrogen fuel cell vehicles with electric hybrid drive trains can be up to 55% efficient—about 3 times better than today's gasoline fueled engines.

Because the production of hydrogen, by steam reformation of natural gas or electrolysis of water, is expected to be about 75–85% efficient, the net energy efficiency of hydrogen fuel cell vehicles will still be better than twice that of gasoline ICE vehicles. Hydrogen, today, at a delivered price of $3.00 per kg (or gallon gasoline equivalent) would be on a par with $1.50/gallon gasoline in a fuel cell automobile. The bottom line is that the costs of hydrogen for the transportation sector provide an economic model for hydrogen energy stations.

7. Renewable energy: on-site hydrogen generation

Hydrogen can be produced from renewable resources, such as biomass—however, the process emits some carbon dioxide. Hydrogen can also be derived by using wind, hydroelectric, or solar power, to electrolyze water. Today electrolysis is still expensive, but companies like Stuart Energy (August 2003) in Toronto and Norsk Hydro (2003) in Norway see the costs rapidly declining. Others like Proton (now listed as Distributed Energy Systems Corporation, DESC on Nasdaq) integrate hydrogen systems for stationary power supply to reduce costs even more. The key for renewable hydrogen energy stations is to provide base load or constant energy supply for consumers. Renewables by themselves are intermittent and hence need to be integrated with other technologies in order to be economic. Power purchase agreements for stationary energy generation can do just that with long term contracts for energy on a 24-h and seven day a week basis.

The energy required to produce hydrogen via electrolysis is about 48 kWh/kg. At 5 cents/kWh, electrolytic hydrogen contains about $2.50 worth of electricity in one-gallon gasoline equivalent. Wind electricity at utility scales is now 4.5–6.5 cents/kWh and in some locations even less. These costs have been reduced by a factor of two in the last five years alone, and further reductions in production costs through lower cost electrolyzers, and the use of low-cost, off-peak renewable electricity could dramatically reduce the future cost of electrolytic hydrogen.

Higher public policy priority must be placed on renewable sources of energy in the creation of "clean" hydrogen. Clearly, one of the key factors in "driving" or creating a market for new clean technologies is the ability to set benchmarks or standards, both voluntary and mandatory. Renewable portfolio standards should emphasize government and the private sector working together. Such a partnership is called the "civic markets" (Clark and Lund, 2001) approach rather than the extremes of government regulatory versus the market privatization.

California and Texas, among a growing list of other states, have done this successfully by developing renewable portfolio standards (RPS) and other states and nations are following their lead. California has enacted a 20% RPS by 2017 but according to most estimates, and the current governor, 2010 is seen as being the actual date for achieving that benchmark. California Governor Schwarzenegger has issued an Executive Order to set even higher standards of 30% by 2017. The same benchmarks are being discussed for the transition to a sustainable hydrogen economy. California and several other states also have enacted renewable investment programs through system benefits or public goods charges, which have played a significant role in improving energy efficiency and reducing the cost of deploying commercially viable renewable products and systems.

Since hydrogen is a paradigm change of enormous magnitude, the need for a robust and well thought out transition is critical. In order to accelerate both the timely development and installation of the hydrogen economy, the use of natural gas needs to be seen as merely a transition fuel for producing hydrogen. The key will be to ensure that the expenditures for reforming natural gas are coupled with the electrolyzing of renewable electricity sources into hydrogen. As *The Economist* (May, 2004) indicated in "The Energy Internet" it would be a financial and environmental disaster to delay this paradigmatic revolution 30–50 years, if large investments were made solely in the central electric grid and natural gas or liquefied natural gas infrastructure rather than devoting the necessary funds to lowering the costs spent on renewable production of hydrogen. Such investments, and at lower numbers, in the billions of dollars could be better spent on renewable energy hydrogen generation.

In the short-term, most hydrogen will come from distributed production using natural gas (steam reformation) and/or electricity (electrolysis). The ability of the central utility grid to provide affordable, reliable, and stable power will be enhanced through a greater reliance on more distributed and regional power generation, including "on-site" generation from renewable energy technologies and from the cogeneration of combined heat and power. Some major manufacturing companies, such as auto-makers, Honda and Toyota in California at their North American Headquarters, have started to lead this effort. Those in public policy and industrial planning should take advantage and leverage such short to mid-term transition phases, and plan capital investment strategies accordingly.

The economic advantages of distributed energy resources are diverse and compelling, although realizing these benefits requires further regulatory market reform. Moreover, the application of distributed fuel cell cogeneration can save enough natural gas in displaced power plants, furnaces, and boilers to compensate for much of the gas needed to fuel hydrogen vehicles. In addition, because the generation of energy will be far more dispersed and clean, end users will be less dependent on centralized grid operated fossil-fueled power plants and the transmission of electrons over long distances. The analogy by *The Economist* (May 2004) to the "internet" is very significant and a good working model to consider. Clark and Bradshaw (2004) argue in their book, "Agile Energy Systems" for a very similar idea whereby the analogy with the internet means rather than one central grid or computer center, there are dispersed sources of energy generation. Hence like the internet, energy needs to be a mix of local on-site and central grid generation. Herein is both the real economic and market competition as well as the secure and diverse sources of power.

Currently, hydrogen is transported by pipeline (more than 400 miles in the U.S. today) or by road via cylinders, tube trailers, and cryogenic tankers, with a small amount shipped by rail or barge. Pipelines, which are owned by merchant hydrogen producers, are limited to a few areas in the U.S. where large hydrogen refineries and chemical plants are concentrated, such as Indiana, California, Texas, and Louisiana. Hydrogen distribution via high-pressure cylinders and tube trailers has a range of 100–200 miles from the production facility. For longer distances of up to 1000 miles, hydrogen is usually transported as a liquid in super-insulated, cryogenic, over-the-road tankers, railcars, or barges, and then vaporized for use at the customer site.

Hydrogen would be better controlled, stored and less costly if produced locally from renewable energy sources and used for hydrogen power generation as well as refueling vehicles. Hydrogen can be stored as a compressed gas or liquid, or in a chemical compound. The key issue today is not to have stranded or sunk costs made in the conventional infrastructures for natural gas or other methods converting fossil fuels into hydrogen. The same, and even cheaper, costs can be invested in renewable energy production that is converted into hydrogen.

8. Agile energy systems: on-site hydrogen power generation

Public buildings in California are using the Leadership in Energy and Environmental Design (LEED) standards for construction whereby new and recycled materials are saving energy costs and providing a cleaner atmosphere. Soon, the LEED standard may include fuel cells as well as hydrogen powered fuel cells. Cost analyses are changing as well, providing a far more accurate accounting of the life cycle analysis of products and externalities such as the negative impact of mobile and stationary sources of pollution on the health and safety of citizens. These "environmental justice" issues are critical to preventing global warming as well as local air and environment pollution.

Hydrogen technology will complement, rather than compete with, energy efficiency, especially in vehicles. Highly efficient vehicles (ultra-light, ultra-low-drag, highly integrated design) will soon greatly accelerate market capture by hydrogen fuel cells. Indeed, there are strong engineering synergies between highly efficient vehicle designs and fuel cells in cars, and these advancements are under development throughout the industry and are in the current and next generation gasoline hybrid electric vehicles. Markets are rapidly developing in the public sector and within 3–5 years will be available to mass market consumers according to some industry analysts and companies. In the auto industry, hybrid vehicles have already begun the transition.

Hydrogen fuel cells need to be more highly leveraged at the state and federal levels. Stationary fuel cells have moved from research uncertainty into the marketplace. In the spring of 2001, partly in reaction to the California energy crisis, another model of civic market was formed with a government–industry partnership, known as the California Stationary Fuel Cell Collaborative (CSFCC), with leadership from the Chairman of the California Air Resources Board (CARB), The National Fuel Cell Center at the University of California, Irvine and the California's Governor's Office (CSFCC, 2004). For stationary applications, the Collaborative was able to mobilize and leverage resources from the public sector and gather support from the growing fuel cell industry. Part of its mission is also to seek opportunities for fuel cell deployment in public buildings while encouraging businesses to locate in the state.

Based on the success of that initiative, several states and nations now have similar programs. The micro fuel cell industry stands ready to be the leading edge of large-scale profitability for the rest of the industry. It is leveraging public funds in small and large companies. In northern Italy, for example, ASM (the Piedmont Region energy supplier) in partnership with Pianeta (private company) have designed and created such hydrogen energy stations for on-site local power and transportation refueling. The capital generated could exceed the expectations of the most ambitious public programs, similar to the leading growth edge of the microcomputer industry. Once profitable, the fuel cell and allied hydrogen and renewable industries will evolve in a self-sustaining way, more effectively solving the technical challenges that lead us to the large-scale sustainable energy economy.

As fuel cell system costs decline, the economics of fuel cells—supported by the public sector through buy-downs and tax breaks—will gradually be able to be transformed into more demand-driven business and consumer markets. This process should be aided by the multiple economic benefits of distributed stationary on-site generation and fuel cell vehicles. Importantly, there presently are hindrances to these benefits being included in project planning assessments that need to be addressed, such as valuing the full fuel cycle emissions of various vehicle types and the valuation of stationary fuel cell systems and other DG/CHP in distributed generation networks, particularly where they are supplying important services to the grid as well as power to the local loads.

9. Summary and conclusion

Clean energy and a healthy environment are the concerns of all citizens. Our children are depending on us. Aggressive improvement in energy efficiency, along with well thought out and executed transitional strategies, are essential to enable the growth of renewable energy production and the development of technologies, markets, and infrastructure to support a green hydrogen economy.

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