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Preface

In recent years, hydrogen has drawn much attention due to its potential large-scale use in producing electrical energy through stationary fuel-cell technologies and its potential for replacing gasoline for use in transportation. Among the advantages of hydrogen are its abundance and its ability to produce electricity in some applications with virtually no harmful emissions. Among its disadvantages are that it cannot be used without being transformed through a series of processes that require significant energy input.

On December 9, 2004, the RAND Corporation hosted a forum on hydrogen energy that drew 40 experts in various fields from the United States, Canada, and Norway. The goal of the forum was to facilitate an open discussion on the analyses and actions that are needed to inform decisionmakers in the public and private sectors on the opportunities, benefits, and costs of various hydrogen-related programs and policies.

The forum participants represented a number of public and private organizations. They had varied interests in as well as varied perspectives on the future of hydrogen as an alternative energy carrier. The participants included energy consultants and members of Cali-

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Summary

In recent years, hydrogen has drawn much attention due to its potential large-scale use in producing electrical energy through stationary fuel-cell technologies and in replacing gasoline for use in transportation. Among the advantages of hydrogen are its abundance and its ability to produce electricity in some applications with virtually no harmful emissions. Among its disadvantages are that it cannot be used without being transformed through a series of processes that require a significant energy input.

Decisionmakers in the public and private sectors do not have all the information they need for determining whether to invest in hydrogen research or to make investments in the infrastructure that would be needed to use hydrogen as a source of energy. Decisionmakers also lack information to help them decide whether to formulate policies that will hasten the development of hydrogen as a viable energy source.

This report provides an overview of the discussions that took place during a daylong

- Introducing hydrogen as an alternative energy source could add diversity to the supply of transportation fuels, thereby making the United States less dependent on petroleum and making fuel costs more stable and predictable.
- If hydrogen-based fuel cells were put to use generating electricity on a small scale close to areas where electricity is needed, the burden on the current electric grid—the system that generates and distributes electricity—could be eased.
- If renewable energy is used to make hydrogen, fuel cells could provide a means of storing renewable electricity—something that cannot be done today.
- If communities and companies had the ability to generate their own electricity via small fuel cells using renewable energy to make hydrogen, they could fulfill their energy needs locally and would not have to depend as much on imported energy.
- Private companies that develop innovative technologies for using hydrogen as an alternative energy source have the potential to become highly profitable, world-class technology leaders.
- Developing nations that put hydrogen to work right away could leapfrog over the environmentally destructive practices that have occurred in other countries.
- Reducing the use of petroleum could also reduce the environmental impacts of exploring for, producing, transporting, and refining petroleum, including the potential contamination of groundwater and surface water.

Risks of Inaction Perceived as Being Substantial

In addition to the benefits that might accrue from making investments in hydrogen, the participants concluded that there are significant risks in *not* making investments in hydrogen. While the participants pointed out that there are risks in making too large an investment too quickly, they believed that the risks from no action are greater than those from some action for various scenarios of the future. The group cited risks to the environment (both locally, in terms of pollution, and globally, in terms of climate change) as the most significant risks, followed by economic risks, of not taking actions to invest in hydrogen. These risks derive

- The question of who is going to pay for the hydrogen development activity that needs to occur between the research phase (which might be funded primarily by the government) and commercial deployment (which would consist of investments by the private sector)
- Lack of a coherent energy policy, which will hinder investments in hydrogen
- Regulatory roadblocks to introducing hydrogen
- Perception problems with hydrogen—primarily regarding the safety of hydrogen (on the part of the public) and regarding market opportunities (on the part of the private sector)
- Lack of a consistent set of economic metrics to value hydrogen that are needed to produce robust cost-benefit estimates.

Going Forward

When decisions concerning major technological transitions are on the horizon, they can often be informed by lessons learned during similar transitions in the past. Participants cited lessons to be learned from past efforts to ramp up biomass fuel programs (the use of organic matter to produce heat energy) and natural gas fuel programs, but also noted that the transition to hydrogen may substantially differ from those earlier experiences. Participants discussed the possibility that lessons may be learned from technological transitions in other markets—e.g., computers, compact disks, and MP3 players. Technology-diffusion paradigms may be shifting, participants observed, and technical specialists and decisionmakers need to incorporate these new paradigms in their assessments of how a transition to hydrogen might occur.

A consistent message from forum participants expressing a public-policy point of view was that hydrogen as an energy source could provide substantial benefits for California and for the United States as a whole. Participants said that more information is needed to help policymakers determine what role the government should, or should not, play in furthering the development of hydrogen. The U.S. Department of Energy's Hydrogen Posture Plan and the California Hydrogen Highway Blueprint Plan are both good jumping-off points for the development of hydrogen, but participants pointed out that the transition to hydrogen will not happen unless more robust, more objective, and more transparent information is made available to public- and private-sector decisionmakers. There is clearly a role that the public sector can play in assisting in the development of this information.

The private sector needs to better understand the prospects for hydrogen energy and the value of investments in hydrogen, and its investment decisions need to reflect an understanding of the risks associated with current patterns of energy use. Participants said that it is critically important for companies that are already engaged in the development of hydrogen-use technologies to demonstrate that the technologies are reliable and that they have the ability to warranty their "product," thereby reassuring the financial community of the viability of hydrogen.

There seemed to be general agreement that sooner is better than later for the public and private sectors to invest in hydrogen as an energy carrier. While there were differing opinions on how large the hydrogen energy market would be today, the general opinion was that sufficient technological improvements have been made in the past few years to make the hydrogen energy marketplace viable for commercial development. However, the development of hydrogen energy needs a boost from government, and policymakers still need convincing to move aggressively forward on hydrogen policy, participants observed. Policymakers need more information on the unique potential benefits of hydrogen, the new opportunities for investments and jobs, and how a portfolio of policies and investment options can meet short-term and long-term goals for policy actions. While hydrogen as an energy carrier is not the only new technological and market opportunity available to investors, participants said that hydrogen, nevertheless, should be a significant part of the U.S. public and private investment portfolio.

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Special thanks also go to David Haberman from IF, LLC, for encouraging participation in the forum. I also want to express appreciation to a number of individuals at RAND: Sergej Mahnovski, who helped coordinate notes for the forum and contributed to the background sections of this report; Aaron Kofner and Jay Griffin, who took notes during the forum; Lloyd Dixon, Rob Lempert, and D. J. Peterson for their comments on the drafts of this report; Shelley Wiseman for helping to shape the report; and Nancy DelFavero for a fantastic editing job.

CHAPTER ONE

Introduction

In recent years, hydrogen as an energy carrier[1] has generated much enthusiasm and discussion among policymakers and industry over its potential large-scale use in stationary fuel-cell technologies to produce electrical energy and in fuel-cell powered cars. Hydrogen is the world's most abundant chemical element and is already used in various industrial applications. Among the commonly cited advantages of hydrogen as an energy carrier are its abundance and its ability to produce electricity in some applications with virtually no harmful emissions. Among the oft-cited disadvantages are that it is not a primary energy source, and it cannot be used without being transformed or "produced" by a series of processes that require a significant input of energy. Despite active research programs, fuel cell and hydrogen conversion and storage technologies still have not been perfected; therefore, hydrogen energy remains more expensive than energy produced with conventional fuel sources such as oil, coal, and hydroelectric power and alternative energy sources such as wind and solar power.

The public and private sectors are actively exploring hydrogen's potential as an energy carrier. However, it is also understood among those who are have an interest in hydrogen-energy issues that the analyses that have been conducted to date of the benefits, barriers, risks, and costs related to the development of hydrogen as an energy source are not necessarily conclusive; rather, they provide a basis upon which new tools can be developed for conducting robust analyses to guide decisionmaking regarding investments in hydrogen technology. In many ways, the uncertainty surrounding the future of hydrogen is representative of the challenges and pitfalls of long-term technology and energy forecasting and analysis in general (see the related discussion under "Forecasting the Future Is Not Simple: A Cautionary Tale").

RAND Forum Goals and Forum Participants

On December 9, 2004, the RAND Corporation hosted a forum on issues related to the development of hydrogen as an energy source. The goals of the RAND forum were to facilitate an open discussion of the opportunities and challenges associated with promoting hydrogen as an energy source and to describe a set of analyses and actions that are needed in the public and private sectors to improve decisionmaking about investments in hydrogen. The discussions took place at a time when the State of California was preparing a blueprint for its

[1] The term *energy carrier* refers to hydrogen's having to be produced (e.g., electricity is an energy carrier) rather than being an energy *source* (e.g., oil, which is found in nature, is a primary source of fuel).

CHAPTER TWO

Public-Sector and Private-Sector Benefits of Investing in Hydrogen

The goal of the forum's first facilitated discussion was to elicit from participants a description of the benefits that could accrue to public- and private-sector investors if hydrogen were fully developed as an alternative energy source, assuming of course that certain technological hurdles are overcome. (For a discussion of those hurdles, see Appendix A.) This discussion preceded the discussion of barria2eisvn, asors if hyelopednative con of ercrdleChaps ae fully

Problems with Ground-Level Ozone

Air pollution continues to be a problem in the United States despite the considerable progress that has been made over the past 30 years toward meeting clean air goals. With regard to automobile transportation, there are two key emissions of concern—nitrous oxides (NOx) and volatile organic compounds (VOCs). NOx and VOCs are key ingredients in the formation of ground-level ozone, which presents well-recognized health and environmental hazards. Many parts of the United States have experienced unhealthy air because of high concentrations of ozone, even though almost all geographic areas of the country have made progress in lowering their emissions of pollutants that are precursors to ozone. In 2002 in the United States, the annual number of days in which ozone levels were deemed to be unhealthy was nine higher (or more than 20 percent higher) than the average annual number of such days between 1998 and 2001. As of July 15, 2003, the number of unhealthy ozone-level days was already twice the number observed at that point in 2002 (Polakovic, 2003).

One-third of the U.S. population faces a risk of health effects related to ground-level ozone. Children, for example, are at greater risk of respiratory problems because they generally engage in more outdoor activities than adults and because their lungs are still developing. Individuals with existing respiratory problems are also at greater risk. A study of 271 asthmatic children in southern New England, reported in the *Journal of the American Medical Association* (JAMA), found that even ozone levels that fell within air quality standards set by the Environmental Protection Agency affected the severity of the children's asthma (Bell at al., 2004). These results are consistent with previous studies cited in the JAMA article that found that even with low levels of ambient ozone and controlling for the presence of fine particulate matter, children with severe asthma have a high risk of experiencing respiratory symptoms from ground-level ozone.

References: Bell, Michelle L., Aidan McDermott, Scott L. Zeger, Jonathan M. Samet, Francesca Dominici, et al., "Ozone and Short-Term Mortality in 95 U.S. Urban Communities, 1987–2000," *Journal of the American Medical Association*, Vol. 292, No. 19, November 17, 2004, pp. 2372–2378; Polakovic, Gary, "Smog Woes Back on Horizon," *Los Angeles Times*, July 15, 2003, p. A1.

Locating power sources closer to where electricity is used puts less strain on the electricity transmission and distribution lines. It is increasingly difficult and expensive to site and build new power lines, so if the old lines are nearing capacity, "load-centered generation" can postpone the need to build new lines and reduce the chance of power outages (see the discussion under "Benefits of Load-Centered Generation").

Participants pointed out that hydrogen-powered fuel cells might also complement renewable energy sources such as photovoltaics (PVs) (solar cells that absorb sunlight and convert it directly into electricity). The main problem with PVs is that they need sunlight and cannot generate power at night or on overcast days. Some PV installations have used batteries as supplementary power sources, but batteries are relatively inefficient and expensive. On the other hand, if some of the PV power is used as the needed power source to create hydrogen during the daytime, it may be possible that the fuel cell could be used at night when the PV is not producing electricity, thereby providing "storable" renewable energy (research in this area is ongoing at the National Renewable Energy Lab). Some technology improvements need to occur, participants observed, particularly in hydrogen storage efficiency, to make this "storable" renewable energy viable, but the opportunity to create storable energy can result in a key long-term benefit of using hydrogen. The complement of PV and hydrogen also provides a potential benefit for remote power applications. If the efficiency of electrolysis (the process by which water is separated into hydrogen and oxygen) improves, a hybrid system composed of PV and a hydrogen-powered fuel cell could be run nearly anywhere, assuming there is the necessary water for the electrolysis process, thus providing power in an isolated, remote setting.

Reducing Environmental Problems

The third general category of benefits mentioned by participants relates to the environment (beyond the environmental benefits specifically associated with reducing petroleum use).

Benefits of Load-Centered Generation

Load-centered generation refers to the practice of generating electricity as close as possible to areas where there is the most demand for it, thereby reducing the need to send the electricity long distances and reducing the reliance on the system of overhead and underground wires that make up the U.S. transmission grid. Much of California's grid of 26,000 miles of transmission lines is operating under great strain. It is part of the

These benefits are primarily associated with the potential to reduce greenhouse gas emissions, and they critically depend on how hydrogen is produced. If hydrogen is produced through non–carbon-intensive sources, then there can be a net reduction in greenhouse gas emissions.

A forum participant who is a representative of the energy industry initiated the discussion, saying that, “Carbon sequestration is something that we’re trying to accomplish. One of the big contributors is coal, an enormously abundant resource. The DOE [U.S. Department of Energy] spent a lot of money chasing synthetic methane. Can hydrogen play a role in creating synthetic methane, which would have an immediate impact on production of CO_2 on a global basis? Could methane then be used as a vehicle fuel? Why was the DOE’s vision from a generation ago aborted? Why does hydrogen have such momentum today?”

On the other hand, some participants countered, if advances occur in the ability to sequester carbon (store it in a form that will not migrate to the atmosphere), it would still be possible to use carbon-rich energy sources such as coal to produce hydrogen and gain environmental benefits. Carbon dioxide is one of the potentially harmful byproducts that result from producing hydrogen when using energy sources such as coal. The assumption is that it will be easier and more cost effective to sequester carbon in large-scale facilities and less likely that carbon sequestration will be possible in smaller settings or “on the fly” in mobile applications such as cars. Hydrogen could be produced using coal at large, centrally located facilities that are equipped to sequester the carbon that results from the process. In this scenario, the hydrogen fuel would be produced in a way that minimizes emissions of greenhouse gases, and it could then be distributed or applied to mobile applications.

Other Public Benefits

One participant, a representative from the energy industry, noted that there is a “tremendous amount of worry and a sense of there being problems in the world related to oil in the Middle East and personal security. [The potential for hydrogen to help] reduce tensions and ameliorate foreign policy problems could benefit people’s sense of well being.”

Participants offered other examples of benefits: Hydrogen technologies could also provide opportunities for developing nations to take more control over their energy sources (relying more on their own sources rather than on international ones) and provide electrical services to rural areas where almost two billion people now have no access to electricity. Hydrogen technologies could allow these countries to provide more energy to their citizens with less impact on the environment than the impact that has occurred in industrialized nations. In one scenario posited by a participant, micro-grid applications in remote villages might allow local water supplies to be used with PV, wind, and/or biomass (organic matter) energy to accomplish two goals—make use of water supplies to convert the hydrogen for energy and at the same time clean the water for human consumption. As such, micro-grid applications can be an efficient and effective option for remote locations.

Finally, participants mentioned the potential for spin-off technologies and applications. For example, advances in membrane technologies for fuel cells may have medical applications. Other spin-offs could occur, and while it is not possible to quantify these benefits now, the potential opportunities from spin-offs could be great.

Private-Sector Benefits

Forum participants felt that it was important to discuss the benefits that can accrue from investments in hydrogen technology by private-sector companies and that, in general, those benefits are overlooked in cost-benefit analyses that tend to focus on social benefits. The discussion focused on why companies might choose to invest in the early stages of hydrogen development and deployment, as well as investing in the later stages when the technology is commercialized.

One industry analyst noted that in some areas hospitals are looking to use distributed generation for a "pure electrical supply, particularly in applications where reliability of energy supply is crucial."

Using hydrogen as an energy source could reduce a company's environmental liabilities in the future. In particular, if companies were to use some hydrogen today to replace oil as transportation fuel or to replace coal in coal-based electricity, and if they are able to reduce pollution, they will also reduce their potential future liabilities associated with provide more reliable power sources for private companies that want to take more control of their energy needs. The additional benefit from hydrogen in this application is that it produces no pollution. In areas of the country that already do not meet air-quality goals, it may not be possible to introduce micro-turbines and generators, which produce some levels of pollution.

Participants pointed out that other technologies can decrease nations' dependence on oil, reduce pollution, relieve the burden on the electric grid, or provide opportunities for rural development. But hydrogen-based applications can provide all of these benefits. This is one characteristic of hydrogen that might differentiate it from other energy sources or technologies.

Timing of Benefits

Participants felt that it was important to discuss when the benefits from hydrogen technology could start to accrue and when investors would need to see evidence of the benefits to feel that their investments are worthwhile. As an industry representative noted at the top of the discussion, "It takes so long to get private benefits [out of a new technology]." The expected timeframe for starting to accrue benefits could help shape investment decisions, because, to the extent that the amount of the investment can influence how quickly benefits accrue, government and private-sector investors would want to ensure that potential investments are large enough to achieve the intended benefits. However, there is a difference between the timeframe that is needed to achieve benefits and the speed with which the infrastructure and technologies can be developed. The group defined a short-term timeframe as one of less than ten years and a long-term timeframe as one greater than 25 years.

Some of the participants felt that hydrogen must become a viable energy source in the short term—within ten years—for important benefits to be achieved in the medium term. These benefits, in particular, are related to air pollution and climate change, but also to the energy security benefits that could result from reducing the demand for oil. Other participants said that while it may be important for hydrogen to become viable quickly, it might need to be a mid-term undertaking, requiring ten to 25 years for full development. As a comparative timeline, participants cited the example of getting a new automobile technology to market, which takes at least ten years, and even then the technology may be introduced in a limited number of cars.

Forum participants expressed the view that short-term action is required for the following reasons:

- The opportunity for motivating a change in the energy infrastructure is here now; it may be gone in ten years.
- If long-term impact is going to be realized, short-term action is needed now.
- Benefits can grow over time, but it will be critical to address carbon dioxide issues sooner rather than later.

One idea in particular generated a good deal of discussion among forum participants—there may be market niches that exist today, such as markets for distributed generation and small-scale hydrogen production systems, that can be deployed quickly. As one analyst noted: "A small system at home would sell like hotcakes around the world. If we don't do it, someone else will [i.e., Japan, Europe, or China]. It can happen in the near term."

One participant's industry perspective was stated this way: "Market segment affects the timeframe and potential of a new technology. Some small-scale, niche applications are ready today or soon will be. Others are further away. There is a different time scale in different markets."

These market niches could provide the basis for expanding and accelerating new technology deployment. A representative of a policymaking body offered the following thought: "There is potential in the next ten years for demand for distributed, small-scale power [generation] around the world [to increase substantially] and for a couple of companies to emerge and be world class leaders. It may not have a big impact on public benefits, but companies that get a foothold can really start to shine."

As one participant observed, while the short-term impact of a new technology in terms of benefits may be small, the infrastructure would be in place for a more rapid acceleration of benefits in the future. Companies should focus on finding these niches and exploiting the opportunities they present, the participant stressed. Of course, there may be a disruptive event that changes expectations, and technologies that are in use now may not be those that are in use ten to 20 years from now.

Critical to future expectations about hydrogen technology and the analysis that may be done to assess future hydrogen energy opportunities, participants pointed out, is how fast a transition to hydrogen can happen. This transition will depend heavily on capital turnover rates (see the discussion under "Capital Cycles and Timing of Climate-Change Policy"), the mention of which led to a discussion of "adoption curves" (the timing of adoption of new technologies) and analogies to infrastructure changes. The state of an existing infrastructure and the rate of capital turnover can impact how fast emerging hydrogen technologies could penetrate worldwide energy markets.

As one participant observed, "The delivery of benefits depends on capital turnover more than it does technology. There was a compelling value proposition in locomotives. The [transition from vinyl records] to the CD was quick, though. If you can have a car with a compelling value proposition to consumers, like the Prius, even though it costs more than a similar car with a conventional engine, you'll start to see rapid turnover. Large-scale power plants are depreciated over 40 years, and a utility company will not throw out a power plant after 15 years. So, the introduction of hydrogen will depend on the amount of capital put into incumbent technologies, too."

Some participants suggested that adoption curves might be shortening. They cited examples of adoption of new technologies that happened more quickly than conventional analyses might suggest—-e.g., compact disks, the Apple iPod, and the Prius (although there was disagreement on the last item). It is possible that analogies to other products or technologies could provide some lessons for understanding how quickly hydrogen could penetrate the U.S. energy market. There were some disagreements on how quickly that might happen, as the following exchange shows:

"Look at the CD versus the LP [long-playing record]. This is arguably in the most price-sensitive segment [of personal entertainment] . . . you would have to replace a whole record collection, worth thousands of dollars sometimes. Why [did people shift to CDs]? Because there was a compelling value proposition."

"The problem with the analogy is that record companies stopped selling LPs. The technological analogies to hydrogen, such as personal computers and cell phones, can provide lessons for both the analysis of and understanding of how quickly hydrogen can be introduced and as a guide for policymakers to understand the role that policy can play in this regard.

Concluding Thoughts

In concluding the discussion of benefits, forum participants emphasized the fact that achieving benefits will depend on public-private partnerships. No matter how soon hydrogen is needed as an alternative energy source, or how quickly it can be established within the energy sector, forum participants felt strongly that public-private partnerships will be critical for achieving the benefits they discussed. Long before benefits are realized, these partnerships are critical to research and development and to establishing the regulations, codes, standards, and infrastructure to support hydrogen. They pointed to Germany's increasing market penetration of wind-generated electricity as an example of how the public and private sectors can work together to speed the introduction of a technology (see the discussion under

One policy participant made a case for how federal and state governments are changing their approach to regulation. "Historically, we tried to advance technologies by technology-forcing regulations. This has and hasn't worked at times . . . [current] initiatives provide opportunities for all to work together. Industry now has an input into policy, unlike in the past, when it was simply regulated."

Members of the group said that if the implementation of hydrogen energy was going to happen, the applicable regulations, codes, and standards would need to be adaptable to the changing technologies and new information that will emerge over the next ten years, and

CHAPTER THREE

Barriers to Hydrogen's Development as an Alternative Energy Carrier

The forum's third discussion session focused on the barriers that could prevent hydrogen from becoming fully developed as an alternative energy source and as a viable player in the energy markets. This discussion was from the point of view of government and private-sector investors who, due to these barriers, could be prevented from realizing all the benefits that hydrogen is capable of delivering. Understanding the potential barriers to the development of hydrogen energy can help stakeholders shape their hydrogen-related policies and investment strategies. These barriers, participants observed, are not very different from the barriers that other new and emerging technologies in the energy sector have faced and that have been overcome in reducing air pollution (see the related discussion under "Overcoming Barriers: How California Managed to Reduce Its Air Pollution"). These barriers include regulatory roadblocks, competition from other energy sources, technological and cost barriers that hinder implementation, resistance from the public, and a lack of coherent state and federal government energy policies. (This session did not include a detailed discussion of technology issues. See Appendix C for a brief discussion of technological hurdles.)

Forum participants were asked to brainstorm on key barriers that might prevent hydrogen technologies from penetrating energy markets. This chapter provides a brief summary of three key barriers that may serve to differentiate hydrogen from other energy sources or technologies in other sectors:

- Policy barriers, which include regulatory barriers and barriers to conducting quality analysis
- Corporate risk barriers, which include those related to liability and time horizons for realizing revenues from commercialization of hydrogen energy
- Public perception barriers (i.e., does the public believe energy is a problem?).

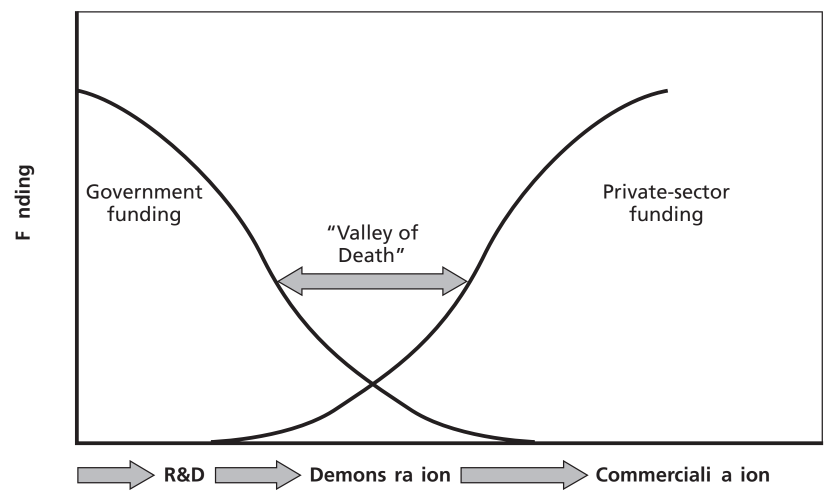
These barriers and the problems they present are independent of each other for the most part, but occasionally they interact and overlap. In fact, a fourth barrier cuts across all of the other three: the lack of a robust set of economic metrics to value hydrogen. For a full list of the barriers identified by forum participants, see Appendix B.

Overcoming Barriers: How California Managed to Reduce Its Air Pollution

While many U.S. cities continue to have air pollution problems, significant reductions in

Mind the Gap: Bridging the Valley of Death

The "valley of death" is a term that is widely used by business and policy analysts to describe the period after new-product research and development (R&D) when the product has been shown to be technologically viable but before it is proven to be commercially viable. During this period, there is a lack of funding for marketing the new product. In the initial stages of development of a product, significant opportunities exist to secure funding from the government (see the figure below). As the bulk of the research winds down, funding also declines, particularly if the government chooses not to fund demonstration and commercialization efforts. Toward the end of the R&D stage, private financing begins to pick up, including venture capital at initial stages, and then private entities take over the funding as the product moves to the commercialization stage. In essence, the valley of death is the dip in the funding continuum during which government and basic research funding declines and when private-sector investors believe the risks are still too high for large capital investments in a new product. This lack of funding during the middle stage from R&D to commercialization is believed to hinder the deployment of new and emerging technologies.



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Another industry representative added: "This problem exists even for well-capitalized companies. Unless government provides investment opportunities (for example, through tax credit and investment regimes), smaller companies will continue to drop off. This is a critical

Participants said that one contributing factor to the valley of death is the potential for significant liabilities from a new technology—i.e., some companies may be reluctant to invest in hydrogen because they fear that as the technology and infrastructure get up and running, they will not work perfectly at first, and that persons or property may be harmed, leading to potential lawsuits and other liability issues for the companies that own and/or operate the hydrogen facilities. While this is a barrier for other new and emerging technologies besides hydrogen, there may be the perception of greater liability associated with hydrogen, especially among early adopters of the technology.

In response, the argument was raised that hydrogen may not be that unique in terms of liability. A participant from the energy industry said the following: "Most industries wouldn't operate if they knew how [difficult] it was to run a utility because of regulations. There's a lot of fantasy out there. Electric operations have enormous liability. You can get sued by customers. Actions in legislatures go against utilities. There are a lot of hazards, because utilities support food [systems], life safety systems, etc." The participant also said that it would be difficult to allow those who do not want to share liability to enter the market freely. However, if there is a law that shields utilities from liability, "utilities will buy all sorts of technologies."

Participants said that some assessment of the liabilities would be useful, and those assessments could lead to policies that may limit liabilities, which could have a positive impact on corporate investments.

Another issue that was raised with regard to the "valley of death" is the need for companies to "perform," and the timeframe for demonstrating performance has been shrinking. Innovative ways for private investment to achieve some short-term returns may be necessary to bridge the investment gap.

Participants on the corporate side discussed the problem of companies lacking an understanding of the potential for the hydrogen market. The hydrogen market is more complex and perhaps more uncertain than other markets in which companies may consider making investments, and these factors can present a considerable hurdle standing in the way of corporations investing in hydrogen. Another hurdle, as one participant noted, is "the lack of understanding of the entire energy-supply chain, particularly when trying to finance a project."

For example, the natural gas industry, which could be the industry supplying the main fuel source for near-term hydrogen production, has taken little notice of and made little or no investments in researching or developing capabilities for hydrogen. It is likely that those companies do not perceive near-term opportunities for hydrogen, and they fear that investing in hydrogen diverts them from their core businesses. A more complete understanding of the opportunities that hydrogen offers the natural gas industry in terms of hedging against price fluctuations and against the potential for competition from other sources might influence some of those companies to make investments in future hydrogen technologies as a market opportunity.

Public-Perception Barriers

Forum participants discussed the fact that the public's perception of hydrogen also plays a part in whether, and how quickly, hydrogen can be developed as an alternative energy source. If the public does not understand hydrogen as an energy carrier, or perceives it to be a potential problem, it may pose a significant barrier to commercialization of hydrogen that will require a concerted effort to overcome.

The potential value of hydrogen is difficult to explain to the public, because it is not something found in the ground, and it can be produced and used in many different ways. One representative of the energy industry noted: “We have branding issues. Hydrogen means different things to different people.”

In a similar vein, an industry consultant suggested the following: “The semantics used in the public debate are a barrier. For example, physicists talk about hydrogen being an energy carrier, rather than a fuel . . . [using that terminology] just obfuscates what’s going on. Also, discussions of energy efficiency are in the wrong context. These discussions totally ignore why we want to do a project in the first place. For example, it is often forgotten that the efficiency of getting gasoline to your car is negative. [Meanwhile,] people are doing detailed studies of ethanol efficiency.”

Some participants noted that the benefits of hydrogen (see Chapter Two) are diverse and complex, and that they are very difficult to explain to the public. The public discussion on hydrogen has sometimes obfuscated the critical issues rather than shed light on them. A policymaking representative defined part of this problem: “People aren’t going to buy hydrogen because of public benefits. The key is that the fuel cell or conversion device has to offer something better [to the individual user]. The chicken or the egg [issue] is oversimplified.” Another participant noted, “The technology must be better than what it’s replacing, from a

CHAPTER FOUR

Evaluating the Risks and Impacts Associated with Hydrogen-Investment Policy Options

For both government and private-sector investors, making decisions about potential investments in hydrogen requires an evaluation of the risks and impacts associated with various investment approaches and of how well those approaches might hold up in various possible future scenarios. For governmental bodies, “investment” decisions include not just those concerning how to spend public funds but also policy decisions and evaluations of which policy actions will bring about desired change. Both government *policy* portfolios and instia hydrogen transportation economy in California. (The next chapter of this report describes the exercise in more detail and summarizes the findings reported by the three groups.)

Exercise Format

This session's exercise, to assess the risks and impacts associated with investing in hydrogen, consisted of three interdependent elements:

- First, participants were to assume that government policymakers would take one of three approaches to hydrogen investment and hydrogen-related policymaking—a laissez-faire approach that would rely on market forces to make hydrogen a viable part of the energy market, a very aggressive approach in which policymakers would

- Market-only. In the market-only approach, the government would take no action to make hydrogen a viable part of the energy market. For example, it would step away from funding hydrogen demonstration and deployment projects. Hydrogen would not penetrate the energy markets significantly before 2050.
- Moderate action. This approach could by 2020 result in
  - 150,000 hydrogen-fueled vehicles on the road in California
  - 5 percent of electricity demand in California fueled by hydrogen
  - 50 percent of hydrogen produced from coal or nuclear sources.
- Aggressive action. This approach could by 2020 result in
  - one million hydrogen-fueled vehicles on the road in California
  - 20 percent of electricity demand in California fueled by hydrogen
  - All of the hydrogen produced would be climate neutral, as compared with alternatives that would not be so, and half of the hydrogen would be produced by renewable resources.

Future Scenarios

The impacts and risks of the three approaches above and the actions they imply depend on what the future holds for the energy supply, energy prices and their impact on the economy, and environmental concerns such as climate change and regional air pollution. Because it is impossible to forecast the future with any reasonable accuracy, we suggested, for discussion purposes, four different "futures" that California might find itself in 15 years from now. Each of the three policy approaches would have different risks and impacts depending on what the future holds. The four future scenarios are as follows:

- No problem. By 2020, climate impacts will be mild, regional air quality improves, energy prices are stable, and supplies are adequate.
- Environmental problem. By 2020, scientific studies are more convincing that climate impacts will become severe, and regional air quality continues to deteriorate, but energy prices are stable and energy supplies are adequate.
- Energy problem. By 2020, climate impacts will be mild, and regional air pollution improves, but energy prices are highly volatile and energy supplies are disrupted.
- Big problem. By 2020, there are both environmental and energy problems. Scientific studies are more convincing that climate impacts will become severe, urban and regional air quality continues to deteriorate, and, at the same time, energy prices are highly volatile and energy supplies are disrupted.

In these scenarios, if the government were to take aggressive action immediately, the impacts and risks would play out differently with a "big-problem" future than they would with a "no-problem" future. If the government were to take aggressive action in a big-problem future, then it would have already taken measures to reduce emissions, local impacts would be less, and oil consumption would be reduced, which means that volatility in prices would have a smaller impact. On the other hand, in a no-problem future, there are likely to be some investments in technologies that are not used or are not cost-effective, and investments made in hydrogen would have less of a payoff than investments made elsewhere.

Goals for the California Government's Hydrogen Investment and Policymaking

Governments generally have goals for their policy actions. In considering whether to make

E.1), the group felt that one outcome (indicated by the dominant color) was most likely, but there is a small chance that another outcome is possible.

Impacts of a Market-Only Policy Approach

For the approach in which the government funds only R&D and allows market forces to run their course, the group was of the opinion that there would be significant risks to the environment and to the economy with the big-problem and environmental-problem (climate change and regional air pollution) scenarios.

A forum participant representing the policymaker perspective noted the following: "The big risk is that you don't know that you will have a problem in 2020 until you reach 2020. You're responding to it in short-term market solutions. There will be more volatility created by dealing with the supply curve marginally." An industry representative elaborated on that point: "It depends on how problems manifest themselves. It depends on whether the problems manifest themselves incrementally (in which case the market is more efficient) or whether there is a huge market disruption (then the market will not be capable of reacting fast enough, or doesn't effectively address issues)."

The group believed that under the energy-problem scenario, market forces would respond quickly enough to generate some positive impacts. The group envisioned some short-term economic disruptions; therefore, a portion of the economic-growth matrix is red (see Figure E.1). The group thought that there would be some potential positive impacts in the no-problem scenario, primarily driven by outcomes from R&D that could be applied to other areas, but mostly the impact would be neutral.

Impacts of a Moderate Policy Approach

The group that discussed the moderate policy approach disagreed about the potential impacts of moderate action on the part of the government. For the scenarios other than the big-problem scenario, the group saw some positive impacts on one measure—economic growth—as a result of moderate action, but not much in the way of impacts on the other measures. On the big-problem scenario, however, there was significant disagreement. Some in the group said that moderate actions would be enough and that, as big problems hit, the state would be ready to address them quickly and efficiently, and consequently, there would be positive impacts. Other members of the group said that these actions would not go far enough to prepare the state for the big problems and would not create enough infrastructure to achieve positive benefits, and that the impacts of the problems would be negative.

The following is an exchange between industry and policy representatives discussing this issue:

"The ramp-up time will be shorter [than previously], but otherwise you're rearranging the chairs on the Titanic. You will have a learned-by-doing experience, you'll have addressed the regulatory issues, and [you] will have an impact by demonstrating technology."

"You remove the 'first provider' hesitancy, but it's a band-aid on a hemorrhage."

"I'm not sure why it's a band-aid. This implies you are ignoring the problem, but you've positioned yourself for an upswing, and since there is so much unknown, you at least have to throw resources at it and see what's happened."

Although two members of the group remained neutral, the debate was both informative and spirited and could have gone on longer than the forum's schedule allowed.

Impacts of an Aggressive Policy Approach

The group that addressed an aggressive policy approach saw large positive benefits in the big-problem scenario and some positive benefits in the other scenarios, with potentially some small negative impacts to the economy in the environmental-problem scenario. In the no-problem scenario, an aggressive approach makes the energy system even more efficient and reduces environmental problems even further, so there is still some potential for positive impacts. However, the group felt that there would be significant risks to the state's economy if energy costs were higher in California than in other states or in foreign countries, and significant risks of opportunity costs associated with investments that were not needed (i.e., money for those investments might have been better spent elsewhere).

The group recognized that developing policies to achieve positive outcomes would not be easy, and they spent considerable time discussing the types of policies—from taxes on carbon emissions, to clean-air credits, to education in public schools—that could be put in place to achieve certain benefits. One industry representative added, "[It is] important to look back to the past at what didn't work and make sure we don't repeat the same mistakes."

Concluding Thoughts

In examining the figures in Appendix E, some observations can be made. If there is a chance of having environmental problems, then the market-only approach is never a robust strategy for the government to follow, because there are significant downside risks (see the accompanying discussion under "Making Policies Robust"). These risks include not only the direct

Making Policies Robust

In a recent *Scientific American* article, Popper, Lempert, and Bankes (2005) discuss a new approach to developing robust long-term planning. The authors posit that a robust planning strategy performs well when compared with alternative strategies across a wide range of plausible futures. A robust strategy need not be the optimal strategy in any future scenario; it will, however, yield satisfactory outcomes in both easy-to-envision futures and difficult-to-anticipate contingencies. This approach replicates the way people risk of environmental problems, but also risks associated with losing technological advantages if other states or other countries developed technologies to deal with these problems.

If the no-problem scenario is unlikely, then the aggressive policy approach would be robust, with small downside risks to the economy given the environmental-problem scenario.

The moderate policy approach could be the most robust if one believes that the moderate policy actions would move California and the nation far enough toward the direction of increased use of hydrogen to alleviate potential problems should the big-problem scenario emerge. However, if one believes that those actions will not be enough to avoid big problems, then this scenario is not a robust solution.

CHAPTER FIVE

Information Needed for Decisionmaking by Public-Sector and Private-Sector Investors

As was stated at the top of this report, the purpose of the RAND Forum on Hydrogen Technology was to engage experts with an interest in hydrogen as an alternative energy source in an open discussion on the subject and to identify analyses and actions that the public and private sectors need to inform their decisionmaking about hydrogen. The forum ended with a discussion designed to integrate the findings and feedback from the earlier sessions and extract a set of issues and recommendations for engaging decisionmakers in a discussion on hydrogen and guiding future analyses. This chapter provides a sample of the comments from participants during the wrap-up session, and it describes a recommended set of analyses and actions that constitute next steps in an effort to evaluate hydrogen as an alternative energy source.

Sample Comments

“Today, an entrepreneur, a lab, or a big company that decides to embark on commercialization of a device, subsystem, or control software faces a lack of economic references, and therefore, what they encounter is that every person in the process is padding his own estimates, and the aggregates of that padding debilitate progress,” said an industry consultant.

Some sense of certainty about government commitment is necessary before funding bodies will make substantial investments in that technology. This is true not only for companies in the private sector with a stake in hydrogen, but also for regulators, who need to have consistency in their actions and a long-term perspective on hydrogen. One industry participant said, “If I’m going to throw you the football, are you ready to catch it, from a societal and customer-acceptance point of view?”

Continuing on that theme, an industry representative added, “You need to know you can make money,” to which another industry representative replied, “Eventually.” And another said, “While I don’t know the future, the question is, what is the ideal portfolio, and where does hydrogen fit in7 Tl5Tsdustry rprogr0(aan1 knowrEmakisrecomc7“an-Fi Arepionowr57 Tl5Tsoan1 kdc

Understand Public Perceptions. Participants also said that it was important for policymakers to gain a better understanding of public perceptions of energy and environmental problems and the role hydrogen can play in the energy sector. Questions for which the participants did not have an answer are whether the public perceives that there are energy problems that need to be dealt with now and whether the public believes that environmental problems are severe enough that the government should take action to promote hydrogen as a cleaner fuel source.

Inform the Public. The government has a responsibility to inform the public of issues that impact their well-being and to provide objective information. There was a general feeling among participants that the government should devote resources to better inform the public about both future risks and opportunities and the options that exist to mitigate the risks associated with energy. Participants also believed that the government has a role to play would definitely require public-private partnerships and cooperation among diverse groups with varying viewpoints–(1) shifting the analytical paradigm and (2) conducting independent and transparent analysis to answer the many questions that arise about hydrogen.

Analytical Paradigm Shift. Participants mentioned that the framework for analysis and the framework for policy and corporate investments may need a "paradigm shift." It is possible that hydrogen as an energy source will not succeed if the innovation path is based on previous paths associated with energy technology development. Alternative fuels have largely failed to gain an appreciable market share, and new technologies have had a long and slow development and commercialization process. Can public-private partnerships change the paradigm and show how the transition to hydrogen can be more like the relatively rapid transition to personal computers and cell phones? Participants said that it was important to direct the nature of the analysis and debate away from the conventional petroleum-centric view to one that reflects a broader set of costs, benefits, risks, and rewards.

Independent and Transparent Analysis. As one industry analyst said, "[Much of] the existing work has not been done by honest brokers, but by people who have something in particular they want." The group was in unanimous agreement that a rigorous, objective, and independent valuation of the lifecycle costs and benefits of hydrogen as compared with other alternative fuels and incumbent technologies was needed. Further, the analysis needs to have "open" access—i.e., transparent models and analysis that can be evaluated and replicated. The analysis needs to take into account differing viewpoints and evaluate the consequences of a variety of policy and investment actions, assessed against a number of future scenarios.

APPENDIX A

Background Information on Hydrogen

This appendix provides general background information on hydrogen—what it is, how it is produced, and what its current and potential applications are. This appendix also describes some technological hurdles to the use of hydrogen as an energy source.

What Is Hydrogen?

Hydrogen has the number-one spot in the periodic table of elements. It is the most abundant of all the chemical elements in the universe. Although pure hydrogen is a gas, very little of it is found in the atmosphere. On earth, most hydrogen is found in combination with oxygen in the form of water (H_2O), but it is also present in almost all organic matter, such as living plants and energy sources such as petroleum and coal.

How Is Hydrogen Produced?

Hydrogen (H_2) is often described as an energy source, but it is more accurately defined as a "refined fuel" or an "energy carrier." Hydrogen is not a primary energy source, in the sense that it is not found readily in nature and cannot be physically mined or extracted from geological formations. Rather, hydrogen must be obtained through a transformation of molecules or "produced" by a series of controlled chemical or biological processes that involve significant inputs of both energy and hydrogen-rich molecules.

Currently, hydrogen is almost exclusively produced from natural gas, although heavier fossil fuels and water can also be used for this purpose. Natural gas is considered to be the most favorable fossil-fuel feedstock for hydrogen production due to its high hydrogen-to-carbon ratio, widespread supply infrastructure, and ease of use. Producing hydrogen from natural gas typically involves a high-pressure, high-temperature reaction in the presence ofressure, highsfro0w Is gen in the next decade. However, a major shift toward the use of hydrogen with the emergence of a robust fuel-cell vehicle market may pose challenges to the natural gas industry's ability to accommodate additional demand for natural gas for hydrogen production. If natural gas prices rise due to increased demand, coal-based or nuclear-based options may emerge as viable substitutes for the production of hydrogen in the near to medium term.

Although hydrogen production technologies currently exhibit significant economies of scale, the demand for hydrogen as an energy carrier would occur in new, relatively small, geographically dispersed markets. Thus, distributed hydrogen technology applications could emerge to address nascent markets outside of the traditional markets for petrochemical and refinery applications. Distributed hydrogen could be produced primarily through natural gas reforming and electrolysis in regions of the country where it is economically favorable. The hydrogen produced in such a way would have a higher unit cost, but would be a much less risky investment. Thus, the initial hydrogen supply chain would be highly regionally heterogeneous (how it is produced and moved would differ regionally) and would depend on local energy infrastructure endowments, energy commodity prices, and regulations.

Uses of Hydrogen

Hydrogen is now used primarily to produce ammonia and methanol, and to upgrade and desulfurize petroleum products at refineries. Hydrogen is also used in the manufacture of semiconductors, in food processing, and in the production of ammonia-based fertilizers.

Hydrogen may be used in a number of energy-related applications—in stationary power generation, as a blend with natural gas for low–nitrous oxide (NO_x) applications, as an energy storage mechanism in regions where peak-shaving (reduction in the peak demand for electricity) is important or where remote wind or solar power (located at a distance from the source of demand) is prevalent, or for hydrogen vehicle refueling.

One transportation-sector application for hydrogen energy is in fuel-cell vehicles. Currently, transportation fuels are derived almost entirely from crude oil, and hydrogen may provide an opportunity to diversify transportation fuels. Fuel cells are highly efficient electrochemical energy-conversion devices that consume hydrogen and oxygen to create electricity and heat, with steam as the sole emission. Another application for hydrogen is stationary power generation (as opposed to power generation for a moving vehicle), particularly smaller-scale, distributed applications. Fuel cells can be used in small-scale power-generation applications, perhaps located near power-demand centers. Although some current experimental fuel cells for stationary power generation are able to operate directly from methanol or natural gas (and therefore with some carbon-containing emissions), it is expected that fuel cells for cars would need to be smaller than those for stationary power generation, and they would not be able to use methanol or natural gas directly.

Hydrogen can also be used in modified internal combustion engines, turbines, and residential natural gas burners. For example, BMW has introduced a research-scale, internal-combustion engine vehicle that can run on pure hydrogen. Turbine and residential applications, if they emerge, would most likely use a mixture of natural gas and hydrogen. Under certain conditions, the addition of small amounts of hydrogen to natural gas can lessen NO_x emissions during combustion.

Future potential markets for fuel-cell vehicle refueling and distributed-power generation (small-scale generation located close to where there is demand for power) will require an infrastructure for the production, storage, and transport of hydrogen. Such an infrastructure might be geographically heterogeneous, depending on existing energy supply chains, local energy prices, and local regulations. Large-scale, centralized hydrogen production facilities could be located in remote areas near fossil fuel, nuclear, biomass (organic matter), or renewable resources, and potentially near geological formations that allow for carbon sequestration from fuel if fossil fuels are used for making hydrogen. The hydrogen that is produced could be stored as a compressed gas at several hundred times the normal atmospheric pressure or as a cryogenic liquid. Large quantities of hydrogen could be transported through pipelines. Smaller quantities could be transported by tube trailer truck or in liquid form by rail or truck. Potential breakthroughs in solid-state storage of hydrogen may favor truck or rail transportation over pipelines in some cases. Alternatively, hydrogen can be produced locally at the site of vehicle refueling stations or "energy stations," or even in homes through small-scale natural gas reforming or electrolysis. Distributed generation of hydrogen could avoid the need for a transportation infrastructure, but would still require storage and dispensing equipment. As the market for hydrogen develops, networks of hydrogen refueling stations might emerge. For example, some stations might produce excess hydrogen and ship that hydrogen to stations with storage capability, rather than production capability, producing a "hub-and-spoke" hydrogen supply network.

Who Produces Hydrogen?

The United States produces more than 50 percent of the 220 billion cubic meters of hydrogen produced worldwide each year. World hydrogen production doubles approximately every decade, mostly due to increasing demand for hydrogen by oil refineries; demand

Distribution and dispensing of hydrogen, and related public safety concerns, are other key infrastructure challenges. The petrochemical industry has experience with hydrogen pipelines and tube trailers, including a pipeline network near the Gulf of Mexico in support of the refining and petrochemical complexes in the region. However, the construction of additional pipelines near densely populated areas poses safety issues. In particular, the retrofitting of natural gas pipelines for transporting hydrogen or blends of hydrogen and natural gas raises safety issues associated with leaking of hydrogen.

Perhaps the greatest hurdle in the development of a hydrogen infrastructure is hydrogen storage that would allow smaller, lighter fuel tanks and more efficient transport. Cur-

the California Stationary Fuel Cell Collaborative, Energy and Resources Group, University of California, Berkeley 2004.

Rifkin, J., *The Hydrogen Economy: The Creation of the World-Wide Energy Web and the Redistribution of Power on Earth*, New York: Jeremy P. Tarcher/Putnam, 2002.

Romm, J. J., *The Hype About Hydrogen: Fact and Fiction in the Race to Save the Climate*, Washington, D.C., Island Press, 2004.

APPENDIX B

Perceived Benefits from and Barriers to Using Hydrogen as an Alternative Energy Source

Tables B. 1 and B.2 list the perceived benefits from and the barriers to using hydrogen as an alternative energy source, which were discussed in Chapter Two and Chapter Three, respectively.

Table B.1
Perceived Benefits of Hydrogen Cited by Forum Participants

General Category of Benefits	Examples	Other-Technology Opportunities
Reduced oil consumption	Diversify transport fuels	Compressed natural gas, biofuels, hybrid vehicles, fuel-efficient vehicles, and ultra-low-emission vehicles
	Reduce trade deficit	
	Reduce international tension	
	Reduce risk of water contamination	
	Reduce air pollution	
	Extend life of natural resources	
	Reduce waste, including toxic waste	
	Create potential for more-predictable costs	
	Improve transmission and distribution efficiency	
	Defer transmission and distribution investments	
	Provide storable electricity	

Table B.1—Continued

General Category of Benefits	Examples	Other-Technology Opportunities
	Leapfrog to cleaner technologies	
	Provide efficienmc0.0001 BT/F135.014 1.1T/F88 Hechnology	

APPENDIX C

Forum Agenda

8:00 a.m. Breakfast and check-in

8:30 a.m. Welcome, statement of purpose, and introductions

8:45 a.m.–9:30 a.m. Setting the stage—Various perspectives on the benefits and costs of hydrogen

- Industry
- Policy
- Business investment
- Technology
- Valuation

9:30 a.m.–10:30 a.m. Why hydrogen? (i.e., What are the potential benefits?)—Differing perspectives and the rationale for hydrogen

- Public sector or private sector
- Short term or long term
- National, local, or international

10:45 a.m.–11:45 a.m. What are the obstacles to introduction of hydrogen?

- Is there a "valley of death?"
- Are technologies ready for prime time?
- How long is too long for profitability in the private sector?
- Can the public and private sectors really work together?
- Is hydrogen development too fractured?

11:45 a.m.–12:00 p.m. Breakout session: Four Scenarios for Assessing Future Risk

Breakout groups will use four future scenarios regarding energy and the environment to assess the risks of various options relating to energy security, climate change, local air pollution, and economic growth.

12:00 p.m. Lunch

1:00 p.m.–2:30 p.m. Three breakout sessions

Members of each group will assess the risks of various policy options and their and impact on California and the United States as a whole.

2:45 p.m.–3:30 p.m. Five-minute reports from each team, followed by a discussion period

3:30 p.m.–4:15 p.m. What do you need to know to make a case for (or against) a near-term, more rapid investment in hydrogen?

- What measures would you use?
- What do you know now?
- What don't you know now?

4:15 p.m.–4:45 p.m. Next steps in a policy research agenda

APPENDIX D

Forum Participants and Their Affiliations

Walter Baer, Senior Policy Analyst, RAND Corporation

John Barclay, Chief Technology Officer, Prometheus Energy Company

Mark Bernstein, Senior Policy Analyst, RAND Corporation

Robert Boehm, Distinguished Professor, Mechanical Engineering, and Director, Center for Energy Research, University of Nevada, Las Vegas

Hazen Burford, Vice President, Operations, Intelligent Energy

Michael Canes, Director, LMI Research Institute

Steve Chalk, Hydrogen Program Manager, U.S. Department of Energy

Andres Cloumann, Marketing Director, Electrolysers, Norsk Hydro Electrolysers AS

Tama Copeman, Director, Future Energy Solutions, Air Products and Chemicals, Inc.

Gary Dixon, Manager, Special Assignments, South Coast Air Quality Management District

Lloyd Dixon, Senior Economist, RAND Corporation

Ronald A. Friesen, Executive Director, Stationary Fuel Cell Collaborative, California Air Resources Board

Devinder Garewal, Director, Strategy Development and External Affairs Office of Chairman, California Air Resources Board

Allan Grant, Manager, Hydrogen and Fuel Cell Program, BC Hydro

Jay Griffin, Doctoral Fellow, Pardee RAND Graduate School

Thomas J. Gross, United States Naval Reserve (RADM, Retired); Associate, IF, LLC

David Haberman, IF, LLC

Nanci Haberman, IF, LLC

Barbara Heydorn, Senior Consultant, SRI Consulting Business Intelligence

Ray Hobbs, Chief Engineer, Future Fuels Program, Arizona Public Service

Karen Kimball, Vice President, Parsons Corporation

Aaron Kofner, Associate Quantitative Analyst, RAND Corporation

Stephen Kukucha, Director, External Affairs, Ballard Power Systems

Robert Lempert, Senior Physical Scientist, RAND Corporation

Sergej Mahnovski, Doctoral Fellow, Pardee RAND Graduate School

Marissa Mittelstadt, Administrative & Logistics Coordinator, Advanced Technologies Group, Toyota

Matt Miyasato, Technology Demonstration Manager, South Coast Air Quality Management District

Charles A. Myers, Director of Sales, Nuvera Fuel Cells

Catherine Padro, Project Leader, Hydrogen Systems, Los Alamos National Laboratory

Geoffrey Partain, Manager, TMS Environmental Vehicles Group, Toyota

D. J. Peterson, Associate Policy Analyst, RAND Corporation

Bill Reinert, National Manager, Advanced Technologies Group, Toyota Motor Corporation

Jim Reinsch, Senior Vice President, Bechtel Power Corp; President, Bechtel Nuclear

Douglas M. Rode, Principal and Managing Director, Hydrogen Safety, LLC

Gerry Runte, Applied Research and Engineering Sciences (formerly Executive Director, Hydrogen Energy Systems Center, Gas Technology Institute)

Maxine Savitz, Honeywell (retired)

Paul Scott, Chief Scientific Officer, ISE Research

Jon Slangerup, CEO, Solar Integrated Technologies (formerly President and CEO, Stuart Energy)

George Sverdrup, Technology Manager, Hydrogen, Fuel Cells, and Infrastructure Technologies, National Renewable Energy Laboratory

Alfred Unione, Santa Fe Operations Manager, Applied Research and Engineering Sciences

Nicholas Vanderborgh, Advisor, South Coast Air Quality Management District

Cynthia Verdugo-Peralta, Board of Governors, South Coast Air Quality Management District

Rick Zalesky, President, Hydrogen Business, Chevron Corp.