Nurturing a Clean Energy Future in Hawaii:

Assessing the Feasibility of the Large-Scale Utilization of Hydrogen and Fuel Cells in Hawaii

Final Report

Prepared for:

State of Hawaii
Department of Business, Economic Development, and Tourism

Prepared by:

Hawaii Natural Energy Institute
University of Hawaii-Manoa

and

SENTECH, Inc.
Bethesda, Maryland

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Errata

The original version of this document omitted citations in Section 4: The Analysis of Hydrogen Energy Pathways for Hawaii, and in Appendix D: Energy Pathway and Life-Cycle Cost Analysis Methodologies. These citations have been added, and corresponding text has been altered, for this revised edition. They occur on pages 19, 21, 22, D-1, D-5, D-6, D-7 and D-8. Additionally, the documents cited have been referenced in Appendix G: References.

Executive Summary

Since the early 1970's, Hawaii has grown increasingly dependent on fossil fuels, with imported raw crude oil and finished petroleum products from Alaska and foreign counties currently supplying over 90 percent of the state's energy needs. To reduce this dependence, the state is exploring innovative ways to develop and use renewable energy derived from solar, wind, and geothermal resources. The use of hydrogen fuel also holds significant potential for diversifying Hawaii's energy mix – especially in the state's transportation and distributed power generation sectors – and could lead to a decrease in Hawaii's dependence on fossil fuels, higher energy efficiencies, and a reduction in polluting emissions and greenhouse gases.

Hydrogen's proponents view it as a long-term energy solution because it:
- Is potentially an inexhaustible supply of energy;
- Can be produced from many available primary energy resources;
- Converts easily to electricity with higher efficiencies than combustion processes;
- Improves the utilization of electricity from intermittent and distributed renewable resources;
- Is nonpolluting and nontoxic; and when generated using renewable energy, becomes a versatile, high-energy fuel with minimal environmental impact; and
- Can drive fuel cells, which provide a highly efficient and reliable source of energy "on demand" for low-noise, emissions-free transportation, as well as a modular means for providing distributed energy for the utility sector.

Despite these advantages, there is currently no large-scale use of hydrogen or fuel cells for applications such as transportation or utility power generation. In part, this is due to the high cost of producing and utilizing hydrogen (when compared with fossil fuels), and to the development challenges of fuel cell technology. As depicted in **Figure A**, building the hydrogen economy is a long-term process that will require most of the 21st century to become fully realized.

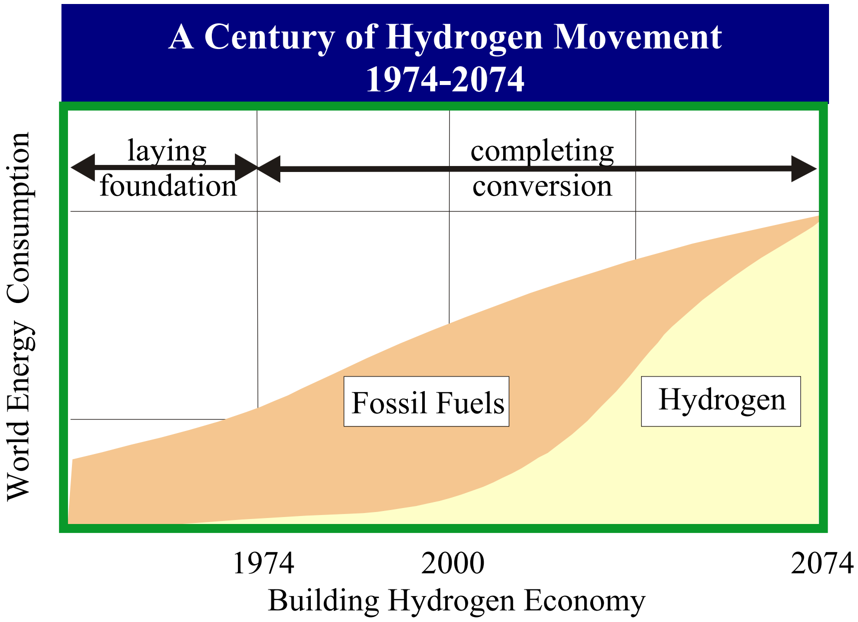

Figure A: Building Hydrogen Economy (Veziroglu 2000)

The eventual large-scale use of hydrogen fuel will require low-cost production (preferably using renewable energy); compact, safe, and cost-effective storage capabilities; and hydrogen-based energy infrastructure development. The state of Hawaii, with its vast renewable energy resources, energy expertise, critical need for greater fuel diversity, and stated policy to achieve increased energy self-sufficiency, provides a natural "testbed" for hydrogen and fuel cell research; and could also significantly benefit, both environmentally and economically, from the utilization of hydrogen in the state's transportation and power generation sectors.

Recognizing this potential, the state of Hawaii commissioned the Hawaii Natural Energy Institute (HNEI) to prepare a hydrogen and fuel cell feasibility study to analyze and recommend options that could result in hydrogen becoming a strategic component of the state's future energy economy. Specifically, the study was tasked to:

- Analyze the costs and benefits of incorporating large-scale hydrogen use into the state's energy economy;
- Assess the feasibility of incorporating new and existing technologies for hydrogen infrastructure and use;
- Develop an overall strategy to incorporate hydrogen into Hawaii's long-term energy economy; and
- Define specific "next steps" for implementing a hydrogen strategy statewide.

This undertaking included (1) a review of existing information and statistics on energy use, including those contained in the *Hawaii Energy Strategy 2000* (HES 2000); (2) meetings with Hawaii energy industry experts and stakeholders to gather additional background information; (3) use of a "life-cycle pathway" approach to analyze and validate the economic competitiveness of long-term strategies; (4) development of an action plan with specific, anticipated milestones; and (5) ongoing dialogue with Hawaii's Department of Business, Economic Development and Tourism (DBEDT) staff to discuss the focus and progress of this study. The primary goal was to assess the ability of hydrogen production and utilization in Hawaii to be competitive with other forms of energy generation within the next decade.

The "life cycle pathway analyses" of various types of energy production in this study incorporated each step in the energy development process (i.e., from primary energy extraction or capture through fuel production, storage, transport/delivery, and utilization), and used primary energy resource cost, capital amortization, and conversion efficiencies for each step in alternative energy pathways to determine those with the highest value (see **Figure B**). The study incorporated island- or county-specific characteristics for resource cost and availability for the islands of Oahu, Hawaii, Maui, and Kauai. For each island, cost and availability factors were examined using information developed for the Hawaii Energy Strategy, as well as additional information provided by DBEDT.

To identify pathways with the strongest potential for incorporating hydrogen into the Hawaiian energy system, the study focused on those pathways that utilized indigenous energy resources of Hawaii – specifically geothermal, wind, and biomass energies. Other locally available renewable resources, such as solar, ocean thermal, or tidal/wave energy, were excluded because of concerns over the cost, technical feasibility, and/or characterization of these resources. Additionally, the study recognized Hawaii's investment in refined fossil resource infrastructure and the technical and cost-effective benefits that fossil-derived hydrogen production might offer in the near- to mid-term. Accordingly, the study also reviewed the possibility of using imported liquefied natural gas (LNG) as an alternative energy supply.

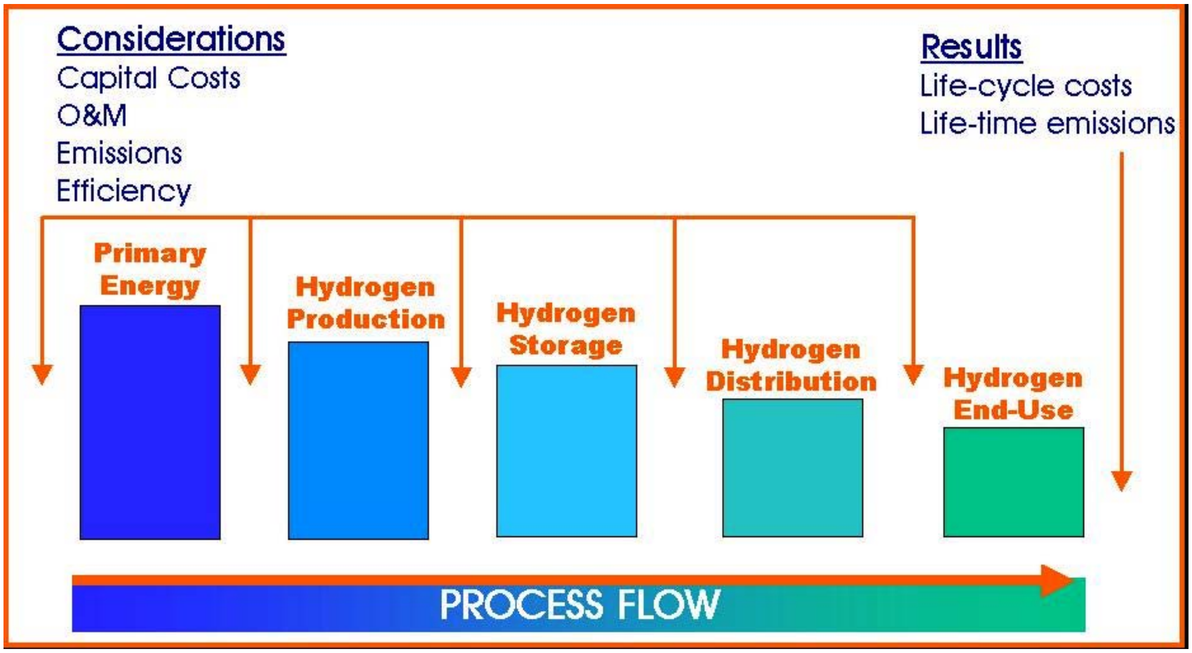

Figure B: Steps in a hydrogen pathway analysis _ an energy pathway is a conversion chain linking primary energy resources to ultimate consumption.

The study initially considered and compared current and projected future pathways for stationary applications of petroleum, coal, liquid natural gas, biomass, and geothermal resources, and for transportation applications of petroleum, biomass, geothermal, wind, and liquid natural gas resources. After careful analysis of the stationary applications, it was concluded that electricity generated through the production and utilization of hydrogen was more expensive than that generated from other energy sources (both fossil and renewable). As such, the study focused its final analysis on energy pathways using hydrogen as a transportation fuel.

Findings

The study determined that at current Hawaii-based prices ($1.63/gallon or $13/mmBtu), gasoline used in internal combustion engine automobiles results in transportation fueling costs of 8.2¢/mile. Each of the hydrogen pathways analyzed produces fuel above the assumed cost of gasoline. However, hydrogen can be competitive as a transportation fuel because the projected efficiency of fuel cell automobiles, estimated at 2.2 times that of conventional internal combustion engine vehicles, allows the hydrogen derived from some of the pathways analyzed to compete with gasoline on a fuel-cost-per-mile basis. The study concludes that geothermal-electricity-produced hydrogen (on the Big Island) and biomass-produced hydrogen (on the Big Island, Maui, and Kauai) can compete with gasoline at 9.0 and 4.6 ¢/mile, respectively. The study also concluded that LNG-produced hydrogen on Oahu could be cost competitive (at 8.1 ¢/mile), but that lack of infrastructure for LNG, unknown cost for infrastructure development, and safety and scale issues could prohibit LNG development. Hydrogen produced from wind electricity (on the Big Island, Maui, and Kauai) is not competitive, resulting in transportation fuel costs ranging from 11.4-14.3¢/mile. The high cost of hydrogen from wind is largely attributable to the intermittency of the wind resource. This is subject to the uncertainties of the study's analysis and assumptions, as well as the significant infrastructural and other barriers that will confront the introduction of any alternative energy option. However, it indicates that hydrogen can be a competitive transportation fuel in Hawaii by the end of the decade (see **Figure C**).

	Fuel Cost ($/mmBtu)	Fueling Cost (¢/mile)	Availability	Energy Security	Greenhouse Gas	Air Quality	Commercial Experience	Entry Barriers
Petroleum	12	5.0	State-wide	☹	☹	☹	☺	☺
LNG	14.7	2.6 +	Oahu	☹	😐	😐	☺	☹ ☹
Biomass	15.4	2.7	State-wide except Oahu	☺	☺	😐	☹	☹
Geothermal	20.5	3.6	Big Island	☺	☺	☺	😐	😐
Wind	28.1	5.0 +	State-wide	☺	☺	☺	😐	😐

Figure C: Summary of energy and fueling costs of hydrogen in fuel cell automobiles versus gasoline ICE transportation. Relative market values are indicated for each fuel option.

The study evaluated several key uncertainties and determined their sensitivity to fueling cost parameters. The uncertainties included feedstock costs, reformer efficiency, and hydrogen delivery costs for our LNG analysis; geothermal electricity cost, electrolyzer capital cost, electrolyzer efficiency, and hydrogen delivery cost for geothermal analysis; wind electricity cost, capacity factor, electrolyzer capital cost, electrolyzer efficiency, and hydrogen delivery costs for wind analysis; and biomass gasification costs and hydrogen delivery costs for biomass analysis. This sensitivity analysis reaffirmed that the study's assumptions on most of these parameters were conservative and that LNG-, geothermal-, and biomass-produced hydrogen can become competitive transportation fuels.

The study also considered and compared island-by-island evaluations of both resource availability and market demand.

- The **Big Island (Hawaii)** possesses the greatest diversity of renewables including solar, wind, biomass, and geothermal. It is the only island with a geothermal power plant, and its electricity demand patterns typically yield available off-peak electricity from which to make hydrogen. Much of the economic growth on the island centers on the commercial development on the Kona coast of the island. This region contains an airport, Natural Energy Laboratory, commercial resorts, commercial agriculture, and a burgeoning tourist industry from which an integrated hydrogen energy project can be developed. These resources represent an ideal mix and location, and should be able to attract both federal government and private industry resources to conduct such a project.
- **Oahu** contains the greatest population and the urban center of Honolulu; this represents the greatest opportunity to use hydrogen and fuel cells. Transportation applications including tourist transport, military transport, airport support vehicles, and other fleet applications create a large opportunity for a clean hydrogen-fueled fleet. Urban power issues such as transmission limitations, power quality, and commercial peak power create

additional opportunities for stationary fuel cells. Unfortunately, electricity demand patterns and limited availability of renewable resources makes it a less than ideal place to produce hydrogen. Significant quantities of hydrogen from imported oil are available from the existing refinery and synthetic natural gas capacity. This hydrogen may be useful for near-term projects, but will not offer the energy security benefits desired in the long term.

- Both **Maui** and **Kauai** have tremendous biomass, solar, and potential wind resources. High electricity costs from wind and fossil fuels make producing hydrogen from electrolysis imprudent. Large biomass availability makes hydrogen gasification an attractive option, although limited commercial experience makes that option unlikely for several years. A dispersed population makes transportation and utility (domestic) uses the highest likely value. Additionally, the feasibility of “importing” hydrogen from Hawaii to these islands will need to be explored.

Finally, the study addressed a number of additional challenges to hydrogen fuel development in Hawaii. For example, although LNG may represent an opportunity to serve the urban areas of Honolulu, it poses many of the same problems for Hawaii as other petroleum-based fuels – i.e., it must be imported from such places as Alaska or Indonesia, it still creates greenhouse gas emissions, and it is subject to even greater price volatility on the world market. Additionally, no LNG infrastructure exists on Oahu. Biomass resources are extensive on all islands except Oahu, and could fuel the entire state’s automotive fleet; yet there is little real-world experience with dedicated energy crop systems and even less commercial experience with biomass gasification or pyrolysis to produce hydrogen. The Big Island of Hawaii has commercial geothermal energy plants and even greater (>200 MW) potential to develop more plants to produce hydrogen via electrolysis, but its limited population and large size limit the application and utility of the hydrogen. All of the islands have significant wind resource potential, but the intermittent nature of wind makes it an expensive option for hydrogen production. Thus, an effective hydrogen energy strategy for the entire state must combine the objective analytical results that validate economic competitiveness in energy markets with pragmatic interpretations that recognize the resources and energy use requirements of each island.

Next Steps

The study concluded with the presentation of a “roadmap” of activities that both recognizes the unique attributes of each of the Hawaiian Islands and encourages business and government to work in partnership to share the risks of creating a hydrogen energy future in the state. The roadmap proposes seven major activities (see **Figure D**):

- **Hold a stakeholder workshop with existing energy and economic interests:** A meeting should be organized by DBEDT, involving energy industry representatives from both Hawaii and out of state, to discuss perspectives on hydrogen energy and incentives to develop clean energy and high-technology business, including the development and use of fuel cells. The end product should be a consensus blueprint for a public/private partnership to create hydrogen energy markets in Hawaii.

- **Perform a comprehensive engineering evaluation and market study for the production of hydrogen on Hawaii and Oahu:** The preliminary analysis conducted in this study does not suffice when considering specific hardware, policy, and economic investment concerns. Detailed engineering cost studies focused on Hawaii and Oahu should be conducted using actual cost data provided directly from industry sources for electrolyzers, hydrogen automobiles, off-peak electricity, synthetic natural gas, and fuel cells. Market characteristics for clean transportation, fleet transportation, distributed electricity, remote power, and domestic applications should be evaluated (with and without policy options). This more detailed study will assist legislators, regulators, companies, and investors in evaluating options for hydrogen energy.

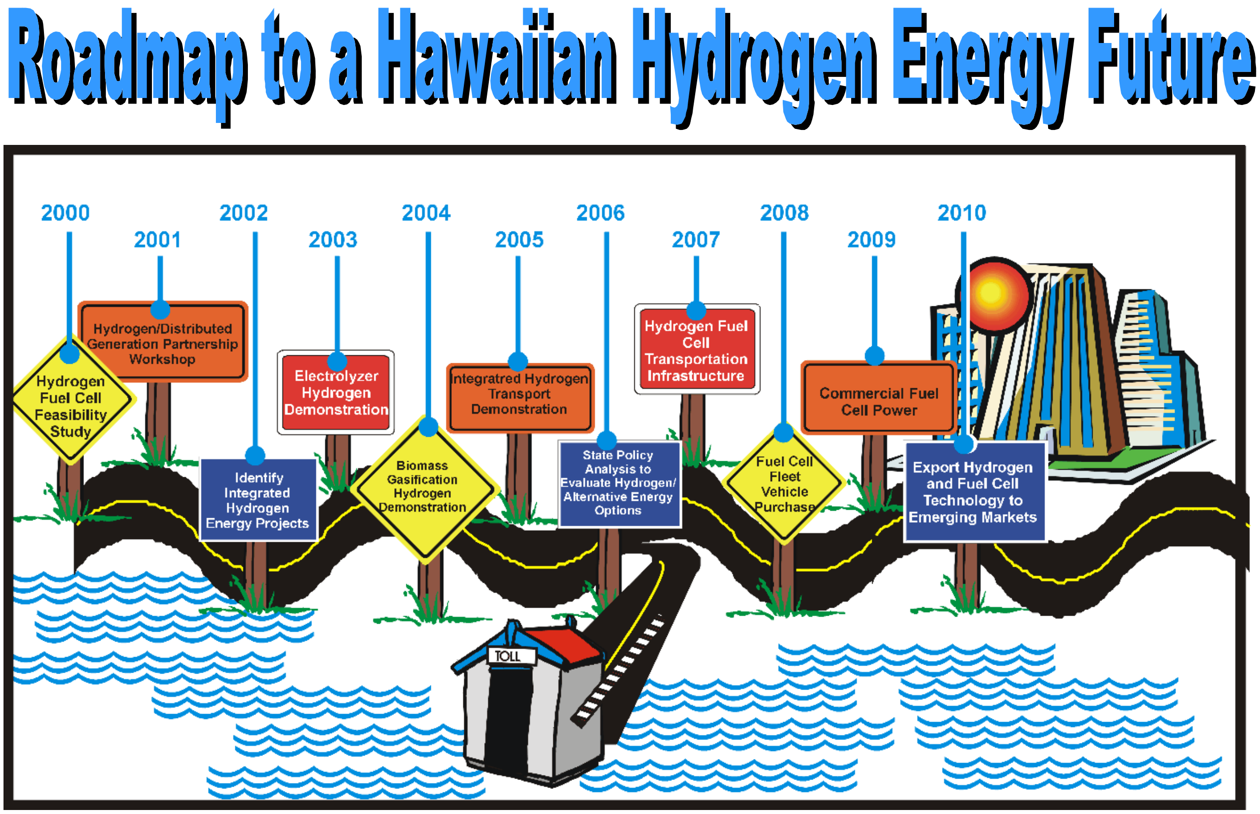

Figure D: Recommendations include a roadmap of activities to validate hydrogen energy.

- **Conduct engineering assessments of biomass for hydrogen for both Maui and Kauai:** The smaller and less populated islands have potential renewable resources from which to produce hydrogen, but fewer opportunities for utilization. Engineering assessments that evaluate gasification of biomass and fleet transportation should be evaluated.

- **Investigate pilot projects to install multi-megawatt electrolyzers to produce hydrogen from indigenous resources on the Big Island:** The Big Island of Hawaii possesses the most diverse renewable resource base from which to produce hydrogen. More than 50 MW of geothermal energy, extensive biomass feedstock, and potential wind energy represent opportunities to produce hydrogen via electrolysis or gasification.

Furthermore, a localized automotive fleet including airport, tourist transport, and personal transportation can likely be structured in the Kona region. Pilot projects to validate performance, reliability, and economics could be initiated over the next several years.

- **Re-examine current environmental and energy policies and evaluate options to promote hydrogen energy:** The state legislature must consider policy options if hydrogen energy market options are to become attractive for industry investment. Two types of options must be considered: 1) policies that open energy markets, including net metering and interconnection standards, and clean energy policies such as adoption of renewable portfolio standards; and 2) policies to attract high-technology business that would also stimulate hydrogen and fuel cell energy, and policies such as trade-free zones, investment tax credits, and other incentives to stimulate economic investment.
- **Investigate pilot projects that include distribution of hydrogen produced on Hawaii to other islands:** The Big Island of Hawaii clearly represents the best opportunity to produce hydrogen that is cost competitive with other energy carriers (electricity, gasoline, natural gas, etc.). However, many of the most favorable applications for using hydrogen exist on Oahu, Maui, and Kauai. The cost of transporting hydrogen over distances has been a key focus of research and development and represents significant cost uncertainties. A pilot project should be commissioned that tests the feasibility of "exporting" hydrogen from Hawaii to one or several other islands with promising applications.
- **Consider creation of a public/private sector partnership for economic development of hydrogen infrastructure:** Opening up energy markets for hydrogen and fuel cells will require a concerted effort from government and industry over a decade to create demand, encourage technology investment, educate the public, and build hydrogen infrastructure. The state of Hawaii should research and put in place policies to attract the industry and federal funding needed to make this happen.

Hydrogen has the potential to revolutionize the way we produce and use energy in the United States and the world. Hawaii, in turn, has the opportunity to assume a leadership role in the transition from a fossil-fueled energy society to a cleaner energy future. Hydrogen is the link between renewable energy and clean transportation fuel. The roadmap defined by this study will enhance Hawaii's leadership in the research and applications of hydrogen fuel, which in turn will likely attract significant economic investment to the state.

Section 1: The Potential for Hydrogen Energy

The element hydrogen offers the potential for an inexhaustible supply of energy at reasonable cost without harmful impacts on the environment. Since the early 1970s, when the Organization of Petroleum Exporting Countries (OPEC) embargo resulted in skyrocketing oil prices that shocked the United States, the country has wrestled with an energy policy that can balance national security, economic, and environmental interests. The use of hydrogen as a fuel has been proposed by many scholars and energy professionals as a long-term energy solution to U.S. reliance on fossil fuels. In fact, many esteemed scientific and technical panels have predicted a future "hydrogen energy economy" that will use hydrogen to produce electricity via power plants, fuel electric transportation, and serve domestic (heating and cooking) uses. In the past 30 years, significant research and development activities have focused on improving the cost of making, delivering, and using hydrogen.

Hydrogen's proponents view it as a long-term energy solution because it:

- Is potentially an inexhaustible supply of energy;
- Can be produced from many available primary energy resources;
- Converts easily to electricity with higher efficiencies than combustion processes;
- Improves the utilization of electricity from intermittent and distributed renewable resources;
- Is nonpolluting and nontoxic; and when generated using renewable energy, becomes a versatile, high-energy fuel with minimal environmental impact; and
- Can drive fuel cells, which provide a highly efficient and reliable source of energy "on demand" for low-noise, emissions-free transportation, as well as a modular means for providing distributed energy for the utility sector.

The drawback to the use of hydrogen energy has been cost, as it remains expensive to produce and use hydrogen when compared to fossil energy alternatives. However, significant progress and technological advances in the last five years for both producing and using hydrogen makes considering hydrogen energy today a prudent alternative. Hydrogen proponents once featured environmentalists and visionaries, but now industrialists such as Bill Ford, Chairman of Ford Motor Company, has proclaimed, *"The 100-year reign of the polluting internal combustion engine is coming to an end, it will soon be replaced in motor vehicles by the hydrogen fuel cell, which emits no pollution whatsoever and so can reduce the build-up of greenhouse gasses causing climate change. Fuel cell technology is the holy grail of the motor industry."* (Ford 2000). Clearly, hydrogen energy has progressed to where it cannot be ignored by energy policy makers as an alternative to fossil fuels.

What is Hydrogen?

Hydrogen (H), a colorless, odorless, tasteless, flammable gaseous substance, is the simplest member of the family of chemical elements.[1] Hydrogen is the basic building block of all the elements known to exist in the universe. It is also the most abundant element, accounting for about 50-75 percent of the mass of all matter. Hydrogen drives the reactions of the sun and all the stars in the universe in a process known as nuclear fusion. Hydrogen, collected by gravitational forces in stars, is converted into helium and eventually into all other elements by this process, which has been captured on photograph by the NASA Hubble Space Telescope in the formation of new galaxies (**Figure 1**).[2] It is the lightest and smallest of all elements, which accounts for many of its physical and chemical properties. Except for small quantities in the Earth's upper atmosphere, hydrogen does not exist on Earth in its "free" unbound or elemental state (H_2).

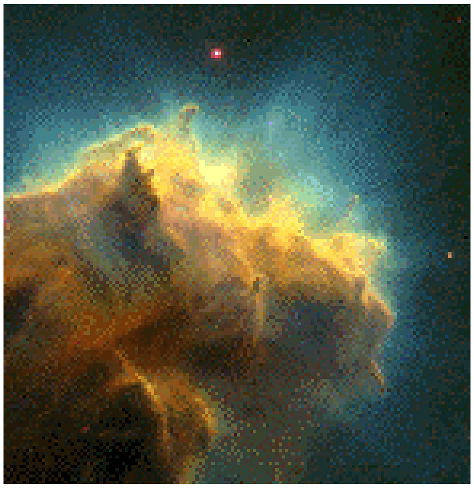

Figure 1: Hydrogen is postulated as the building block for all matter with origin at the Big Bang. Seen here through a NASA telescope is the formation of new galaxies.

While hydrogen is not commonly used today as an energy carrier, it is a widely used chemical intermediate and industrial gas with a mature production, storage, and delivery infrastructure. The domestic utilization of hydrogen, increasing at an annual rate in excess of 10 percent, meets the needs of several key industrial sectors, namely fertilizer, petrochemical, food and metal processing, electronics, computer chip manufacturing, and others. More than 3 quadrillion (10^{12}) cubic feet of hydrogen are produced annually with a shipment value exceeding $3 billion.

Hydrogen can be used for almost any energy application in what many call a "hydrogen economy." **Figure 2** depicts an overview of the hydrogen energy economy, in which hydrogen must be produced from primary energy sources, stored and delivered to its point of use, and utilized in a fuel cell, engine, or other combustion process. The following sections offer a greater description of hydrogen production, storage, and utilization.

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[1] Hydrogen at ordinary temperature and pressure is a light gas with a density that is only 1/14th that of air and 1/9th that of natural gas under the same conditions. By cooling to the extremely low temperature of -423°F at atmospheric pressure, the gas condenses to a liquid with a specific gravity that is approximately 1/10th that of gasoline.

[2] When the universe was formed in the Big Bang, the resulting elemental matter was about three quarters hydrogen, one quarter helium, and a few parts-per-billion of lithium (by weight).

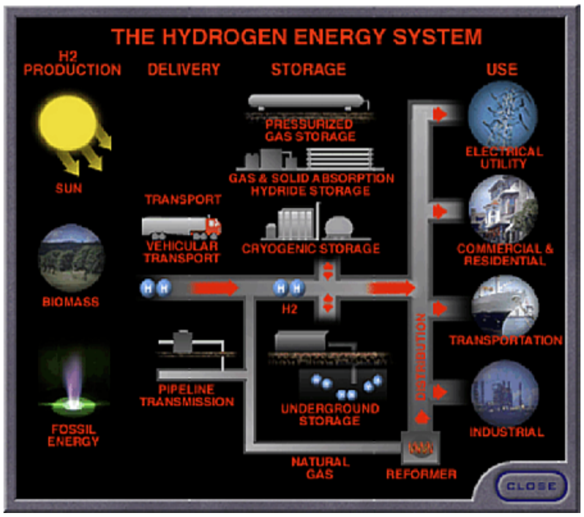


Figure 2: A depiction of the hydrogen economy, where hydrogen can be produced from a variety of fuels and used in virtually any energy application.

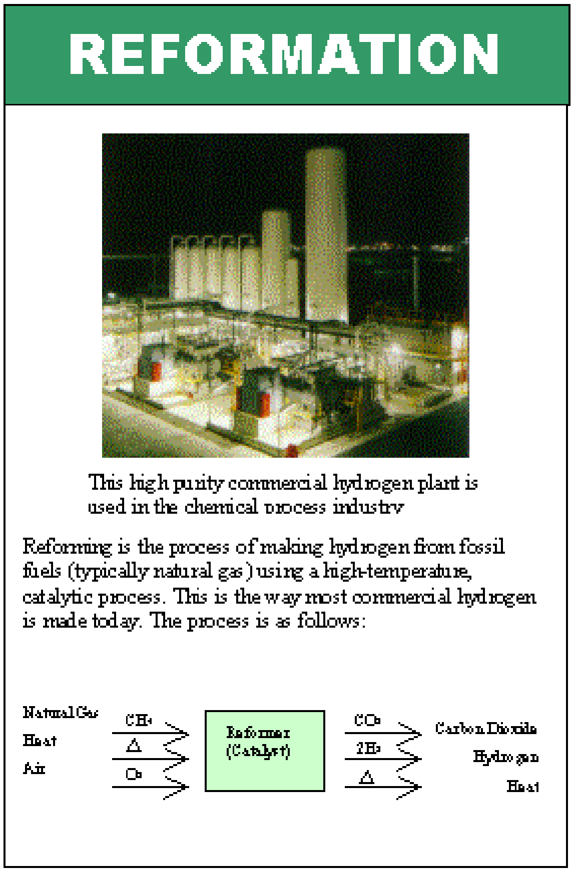
Hydrogen Production

While hydrogen is abundant in our air and water, producing pure or "free" hydrogen for an energy supply can be costly. Molecular "free" hydrogen can be separated or unbound from naturally occurring compounds such as fossil fuels, water, or biomass using several processes including steam reformation of natural gas (or other fossil fuels), electrolysis of water, or gasification of biomass.

Since hydrogen does not occur naturally, it must be produced. There are a number of processes that can be employed to produce hydrogen from various feedstocks. The three major methods are (a) reformation, (b) electrolysis, and (c) biomass gasification and pyrolysis. (See Appendix A for descriptions of various production technologies.)

Reformation:
Over 90 percent of commercial hydrogen used primarily in the chemical industry is made via the process called reformation (**Figure 3**). While either coal or natural gas can be used for this process, using natural gas (via steam reforming) is more popular and commonplace. In this process, natural gas (CH_4) is combined with oxygen (air), water, and heat (steam). Chemical bonds are broken and the resultant products include hydrogen (H_2), carbon dioxide (CO_2) and water vapor (steam). The process currently produces bulk hydrogen at the lowest cost, but also yields greenhouse gas emissions.

Electrolysis:
Electrolysis is the more desirable method used to produce hydrogen, but it is also one of the most costly. In this process an electric current is used to split water into hydrogen and oxygen gases (**Figure 4**). Using an electric current to produce hydrogen from water permits the use of renewable energy sources such as solar, wind, and hydropower. This can unfortunately make the process of producing hydrogen


REFORMATION

This high purity commercial hydrogen plant is used in the chemical process industry

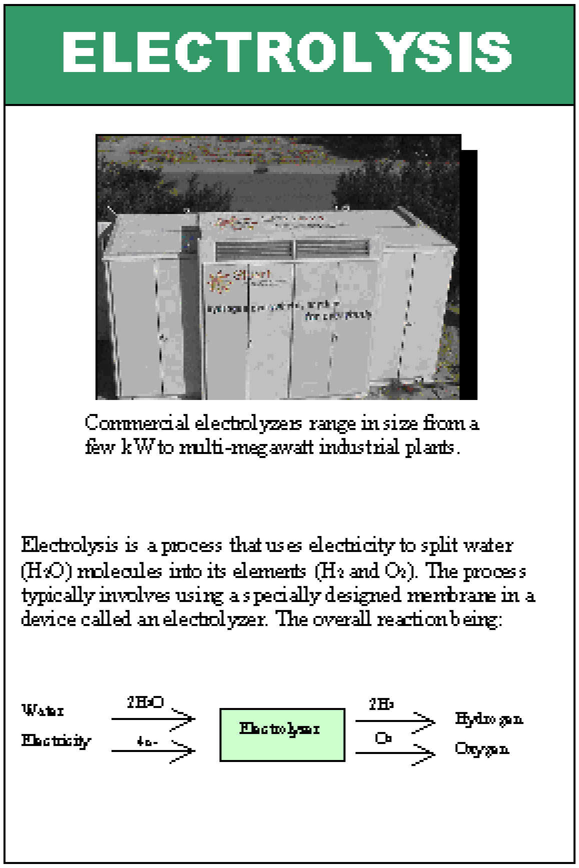
Reforming is the process of making hydrogen from fossil fuels (typically natural gas) using a high-temperature, catalytic process. This is the way most commercial hydrogen is made today. The process is as follows:

Figure 3: Steam methane reforming produces almost half of the world's hydrogen.

expensive, thereby creating a more favorable situation for the use of fossil fuels to produce the original electric current. Steam electrolysis can possibly provide for a more efficient way of producing hydrogen when combined with the electric current method.

Sunlight can also be used to split water molecules. Photoelectrolysis is accomplished using photovoltaic solar panels to harness the sun's energy and store it in a semiconductor. The solar energy is then used to split the water molecule and produce hydrogen. Another process involving sunlight, photolysis, adds a chemical catalyst to the collected sunlight to produce hydrogen in a process similar to photosynthesis. Certain photosynthetic organisms can also be used in a process called photobiological electrolysis.

***Biomass Gasification and Pyrolysis*:**
Production of hydrogen can also occur through the use of biomass resources. Biomass is a collective term used to describe such sources as wood chips, agricultural residues, and other organic wastes. All of these sources contain some amount of hydrogen, which can be isolated by high-temperature gasification or pyrolysis. Large stocks of biomass are required to produce a significant amount of hydrogen, making it more costly than using fossil fuels. Biomass also requires large land areas and does not contain a comparative amount of energy to fossil fuels.


ELECTROLYSIS

Commercial electrolyzers range in size from a few kW to multi-megawatt industrial plants.

Electrolysis is a process that uses electricity to split water (H_2O) molecules into its elements (H_2 and O_2). The process typically involves using a specially designed membrane in a device called an electrolyzer. The overall reaction being:

Figure 4: Hydrogen produced splitting water via electrolysis is more expensive today than production from fossil fuels.

Figure 5 provides the commercialization status of each hydrogen production process.

HYDROGEN PRODUCTION PROCESS	COMMERCIALIZATION STATUS
Steam Methane Reforming	Commercial
Noncatalytic Partial Oxidation	Commercial
Electrolysis	Commercial
Coal Gasification	Precommercial
Biomass Gasification	Precommercial
Biomass Pyrolysis	R&D
Photoelectrochemical	R&D
Photobiological	R&D

Figure 5: Technology Status of Hydrogen Production

Hydrogen Storage and Transport

Hydrogen storage is important if hydrogen energy systems are to become competitive alternatives to traditional energy systems. This is particularly evident for transportation applications where the need for high energy density and lightweight storage is clear. Long-range storage goals established by the U.S. Department of Energy for transportation are to achieve weight and volume storage densities comparable to gasoline. Less stringent interim goals may be developed as future vehicle systems studies may suggest. For utility and other stationary applications, the volume density and weight are not of prime consideration, but storage efficiency and system costs are major considerations. The storage efficiency goal is 75 percent, and system costs should not add more than 50 percent of the input hydrogen cost or about $2 to $3 per MBtu. Current storage systems are incapable of meeting these goals and R&D activities will need to resolve the technical challenges of these systems to satisfy these criteria. A variety of reliable storage solutions for hydrogen are currently being developed and put into use (detailed descriptions of these storage technologies are provided in Appendix A).

Compressed Gas Storage Tanks:

Like other gases, hydrogen can be stored in pressurized tanks. However, since hydrogen is lighter than other gases, a higher pressure must be used to store a usable amount of the gas in a tank. To solve this problem, new materials have permitted the production of new high-pressure storage tanks. Storing hydrogen in this way would allow for easy transport.

Liquid Hydrogen:

Hydrogen can also be liquefied for storage. By condensing hydrogen gas into a liquid, a larger amount of hydrogen could be stored than in similar containers holding gaseous hydrogen. However, the process of condensing gaseous hydrogen can use significant amounts of energy and be very expensive.

Chemical Hydrides and Gas on Solid Adsorption:

Hydrogen can also be combined with some pure or alloyed metals producing a metal hydride. The hydrogen can be stored by chemical combination with the metal and released from the hydride by the addition of heat. This process provides for storage at a higher density than the simple compression of gaseous hydrogen. Hydrogen can also be adsorbed by activated carbon. This method can store an amount of hydrogen close to that of liquefaction.

While all of these are successful methods for hydrogen storage, they still add large costs onto hydrogen production. In comparison, consumers of both natural gas and electricity do not have to pay an added cost for storage. This added cost keeps hydrogen from being a competitor to more traditional fossil fuels. However, developments with new technology and innovations should help provide an answer to this problem in the near future.

Figure 6 provides the commercialization status of the various hydrogen storage and transportation media.

HYDROGEN STORAGE MEDIUM	COMMERCIALIZATION STATUS
Compressed Gas	Commercial
Liquefied Gas	Commercial
Gas-Solid Adsorption	R&D
Metal Hydride	Precommercial
Carbon Based Materials	R&D
Chemical Hydrides	R&D

HYDROGEN TRANSPORT MEDIUM	COMMERCIALIZATION STATUS
Pipelines	Commercial
Truck/Tube Trailer Transport	Commercial
Rail Transport	Commercial
Ship Transport	Commercial

Figure 6: Technology Status of Hydrogen Storage and Transport Technologies

Hydrogen Utilization

The conversion of energy into useful work via an electrochemical or mechanical process is the key to the economic utility of energy, and it is the utilization of this energy that makes it valuable. Currently, our existing infrastructure relies on combustion of fossil fuels in engines, turbines, or other devices to perform work, but the advent of the fuel cell has the potential to revolutionize this traditional energy process.

Hydrogen Internal Combustion Engines:

Hydrogen burns and it can be used as a fuel in internal combustion engines (ICEs). Hydrogen's lower heating value and other chemical properties require significant engine modifications. Additionally, eight times as much hydrogen (by weight) would be needed to produce the same energy value as natural gas in an internal combustion engine. Engine emissions from hydrogen combustion would not produce carbon dioxide, but nitrogen oxide (NO_x) pollutants would still be produced. Research on hydrogen-fueled ICEs is underway, but specific costs on their use are not yet available. The cost of these systems is not likely to differ significantly from conventional diesel-powered ICEs for transportation or stationary applications. However, hydrogen-refueling infrastructure does not currently exist to distribute hydrogen as compared to the diesel fuel infrastructure.

Gas Turbines

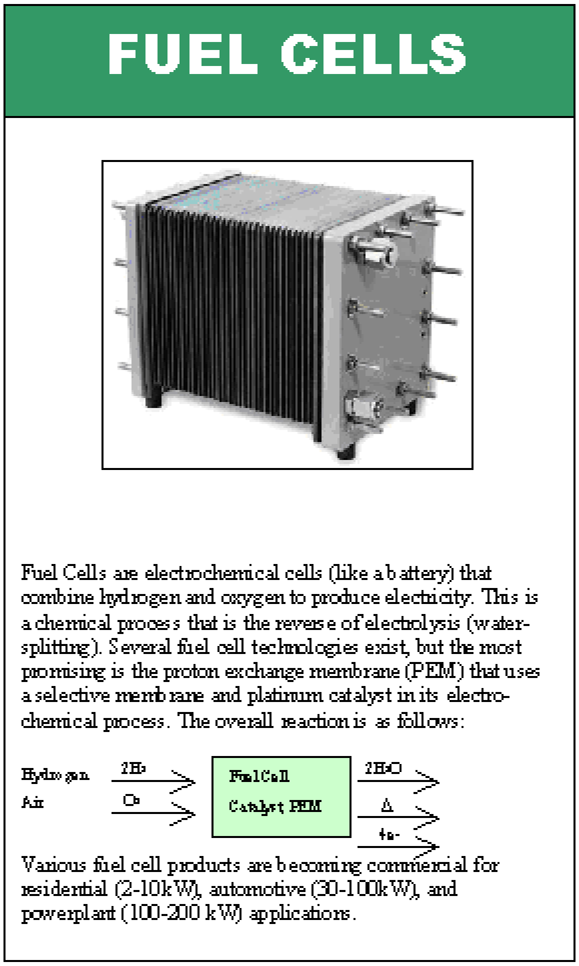
Gas turbine technology is well understood and commercialized for a variety of fuels, including natural gas and fuel oils. Operation of gas turbines on hydrogen fuels is still relatively new; however, one source reports that heavy-duty gas turbines (made in Europe by GEC Alstom) have more than 72,000 operating hours with a refinery gas of 70 percent hydrogen. Sources differ on the impact hydrogen fuel will have on the system design and operation. The government of Japan is working with several turbine manufacturers to develop hydrogen-based power systems that include combustion turbines. The overall goal of this 28-year program is the demonstration of a hydrogen-power system with 70 percent efficiency or greater by 2020.

Research suggests that the higher flame speed of hydrogen would require burner modifications; however, it is not expected that these would present significant technical or economic hurdles. Another potential technical hurdle for hydrogen-fueled gas turbines is the high operating temperature, which will require temperature-resistant materials and better cooling techniques. Finally, turbines using hydrogen will likely be more efficient than those using natural gas because of the potential for higher inlet gas temperatures. Costs for modified gas turbines that burn hydrogen are not available.

Hydrogen Fuel Cells:

The uncertain status of other hydrogen technologies makes fuel cells particularly attractive. Fuel cells were first used in practice by NASA in the 1960s to provide both electricity and water in space. Fuel cells are currently the focus of extensive research and development for terrestrial applications to be used both in the automobile industry and for power generation.

A fuel cell is an electrochemical energy conversion device that converts hydrogen and oxygen into electricity and heat. It is very much like a battery in that it can be recharged while you are drawing power from it. Instead of recharging using electricity, however, a fuel cell uses hydrogen and oxygen. A fuel cell consists of a central electrolyte layer, inserted between two catalyst layers. Various materials for these layers are used, but the basic process is the same (**Figure 7**).



FUEL CELLS

Fuel Cells are electrochemical cells (like a battery) that combine hydrogen and oxygen to produce electricity. This is a chemical process that is the reverse of electrolysis (water-splitting). Several fuel cell technologies exist, but the most promising is the proton exchange membrane (PEM) that uses a selective membrane and platinum catalyst in its electro-chemical process. The overall reaction is as follows:

Various fuel cell products are becoming commercial for residential (2-10kW), automotive (30-100kW), and powerplant (100-200 kW) applications.

Figure 7: Fuel cells are the key technology to the efficient utilization of hydrogen energy.

Fuel cells forego the traditional extraction of energy in the form of combustion heat, conversion of heat energy to mechanical energy (as with a turbine), and finally turning mechanical energy into electricity (e.g., using a dynamo). Instead, fuel cells chemically combine the molecules of a fuel and oxidizer without burning, dispensing with the inefficiencies and pollution of traditional combustion. The fuel cell itself can be roughly correlated to the alternator in a wind, hydro, or engine generator. The fuel cell itself is the mechanism that actually produces the electricity. However, in order for a wind, water, or engine generator to produce electricity, a propeller or engine must turn the alternator. In order for a fuel cell to produce power, something must supply it with hydrogen and oxygen.

Various methods are used to supply the fuel cell with the necessary hydrogen and oxygen. Some systems use a "fuel reformer" to extract hydrogen from another fuel source such as propane, and can extract oxygen from the surrounding air. Some systems (in laboratory or industrial settings) are designed to be attached to tanks of pure hydrogen and oxygen.

The most interesting method of obtaining hydrogen, from a renewable energy standpoint, is to use an "electrolyzer" to separate water into hydrogen and oxygen, which is then stored in tanks and fed into either end of the fuel cell. The "waste" water produced at the end of the fuel cell process is then fed back into the initial water source. A fuel cell generator set up to electrolyze and re-use water is known as a regenerative fuel cell. Any type of fuel cell could be used in a regenerative system, and the water electrolyzer could be powered with wind, solar, or hydro energy, resulting in a truly clean power system.

Fuel cells are direct current (DC) power generators. In some fuel cell vehicle applications the fuel cell's DC power is converted to alternating current (AC) to run AC induction motors, requiring the use of AC motor controllers. In other cases, DC motors are used, governed by DC motor control systems. Much of the work and resources committed to the development of electric vehicle drivetrains in recent decades is being applied to fuel cell vehicle applications.

Types of Fuel Cells:

There are several types of fuel cells: proton exchange membrane, phosphoric acid, solid oxide, molten carbonate, and alkaline. Descriptions of each are provided in Appendix A. **Figure 8** provides the development status of the various fuel cell technologies, as well as other hydrogen utilization technologies described earlier.

STATIONARY POWER TECHNOLOGY	COMMERCIALIZATION STATUS
Alkaline FC (AFC)	Commercial
Phosphoric Acid FC (PAFC)	Commercial
Proton Exchange Membrane FC (PEM) [Less Than 5kw]	Precommercial
Proton Exchange Membrane FC (PEM) [Greater Than 5kw]	Precommercial
Molten Carbonate FC (MCFC)	Precommercial
Solid Oxide FC (SOFC)	R&D
Gas Turbine[3]	R&D
Stationary Internal Combustion Engine[4]	Precommercial
TRANSPORTATION POWER TECHNOLOGY	**COMMERCIALIZATION STATUS**
Hydrogen Fuel Cell Vehicles	R&D
Hydrogen Internal Combustion Engines	Commercial
Hybrid Vehicles	Commercial

Figure 8: Technology Status of Hydrogen Utilization Technologies

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[3] **Gas turbines fueled by natural gas are a commercial technology, but hydrogen-fueled turbines are still in research and development.**

[4] **BMW introduced a dual-fueled combustion engine that can use hydrogen fuel.**

Advantages of Fuel Cells:

Fuel cells offer great promise in serving small- to medium-scale applications including light-duty vehicles, distributed generation/stationary power, and portable power. During the last three years, the world's major automobile manufacturers have embraced fuel cells as the power plant of the future, and many manufacturers have projected product introduction within this decade. The fuel cell is viewed as a disruptive technology that has the potential to thoroughly displace the conventional internal combustion engine technology, resulting in stranded assets and investments. Because of this, many companies are taking a proactive position to establish leadership in the development of fuel cell technology. While some companies are working on the development of this technology integration independently, licensing agreements and collaborations are common.

Fuel Cells for Transportation:

Fuel cells for transportation offer many potential advantages to internal combustion engines including greater efficiency, reduced emissions and noise, and abundant supply of fuel (hydrogen). The cost of fuel cells is the greatest barrier to their use in transportation, along with the limited availability of hydrogen energy infrastructure. Virtually all major automobile manufacturers are developing fuel cell powered vehicles for introduction to the market in the near future. Fuel cells also have been introduced for buses and in other fleet vehicle capacities.

Fuel Cells for Electricity:

Fuel cell power plants to produce electricity have been in operation since the early 1990s and are being sold by several U.S. manufacturers. In the type of fuel cells that are now commercial, the hydrogen is produced by reforming natural gas as part of the power plant's generation process. Thus, fuel cells can be powered either from fossil fuels or from hydrogen produced from renewable energy.

Fuel cells offer the benefits of increased efficiency, reduced emissions, and diversification away from fossil fuels. Our current power generation infrastructure is geared toward the use of fossil fuels, with coal supplying more than half of the electricity in the United States. Natural gas represents the fastest growing market segment for electricity and supplies more than 20 percent. Fuel cells are currently expensive (current prices are at least four times as expensive as other power plants) and their potential will only be realized if mass manufacture and design improvements can significantly reduce costs.

Section 2: Envisioning a Hydrogen Energy Future in Hawaii

Significant technological advances in the cost and performance of both hydrogen producing (reformers, electrolyzers) and hydrogen using (fuel cells, engines) technologies make it possible for hydrogen energy to address many of Hawaii's energy issues beginning this decade. Hawaii possesses many of the natural resources needed to produce hydrogen, especially renewable resources such as geothermal, wind, solar, and biomass. Hydrogen can be the key in these indigenous natural resources becoming a significant contributor to Hawaii's energy future.

The state has specified, through the *State Planning Act, Chapter 226 of the Hawaii Revised Statutes (HRS),* a number of objectives with regard to energy. A hydrogen energy economy is consistent with achievement of the stated Hawaii energy objectives to:

- Direct energy planning toward dependable, efficient, and economical statewide energy systems;
- Increase energy self-sufficiency where the ratio of indigenous to imported energy use is increased;
- Improve energy security in the face of threats to Hawaii's energy supplies and systems; and
- Reduce, avoid, or sequester greenhouse gas emissions from energy supply and use.

Furthermore, Section 226-18 of the HRS adds impetus for development of hydrogen energy by stating that it shall be the policy of the state to support research and development as well as promote the use of renewable resources. Thus, the commitment to a hydrogen energy future can aid Hawaii in achieving both energy and economic objectives.

Hawaii's energy economy is built around the need to provide fuel to transport people to and from the islands via air and over water. Since there are no indigenous fossil fuels (oil, natural gas, coal) in Hawaii, there is a near-complete dependence on imported oil. Nearly 90 percent of Hawaii's energy needs are met by oil, with most (71%) of this oil coming from foreign sources. This foreign oil dependence creates a great risk to the Hawaiian economy because of both the potential for supply disruptions and significant price volatility. In 1997, Hawaii spent more than $1 billion to purchase this oil. Oil is used to produce electricity (26.2%), for marine transportation (6.5%), ground transportation (16.5%), air transportation (32.4%), and other sectors (6.3%). An overall picture of Hawaii's energy system is depicted in **Figure 9** (HES 2000).

Transportation fuels are produced in Hawaii by refining imported oil in two refineries located on the southwest corner of Oahu at Cambell Industrial Park in Kapolei. One refinery (capacity 20 million barrels per year) operated by Chevron maximizes gasoline production while the second (capacity 33 million barrels per year) operated by Tesoro Hawaii maximizes production of jet fuel. The refineries and associated chemical plants produce gasoline, diesel fuel, naptha, propane, synthetic natural gas, and other distillates. More than 16% of Hawaii's energy demand is for gasoline to fuel approximately 900,000 motor vehicles that move the population as well as the tourists that make up Hawaii's largest segment of the economy. More than 17 billion gallons of jet aviation fuel was used by scheduled airlines in 1997. Inter-island marine shipping is the analog of mainland intrastate trucking, pipelines, and railroads. In 1997, almost 4 million barrels of diesel fuel, residual fuel oil, and gasoline were used in shipping and fishing operations. Thus, the entire transportation fuels infrastructure is totally reliant on imported oil with expectations to grow at least 30% over the next two decades.

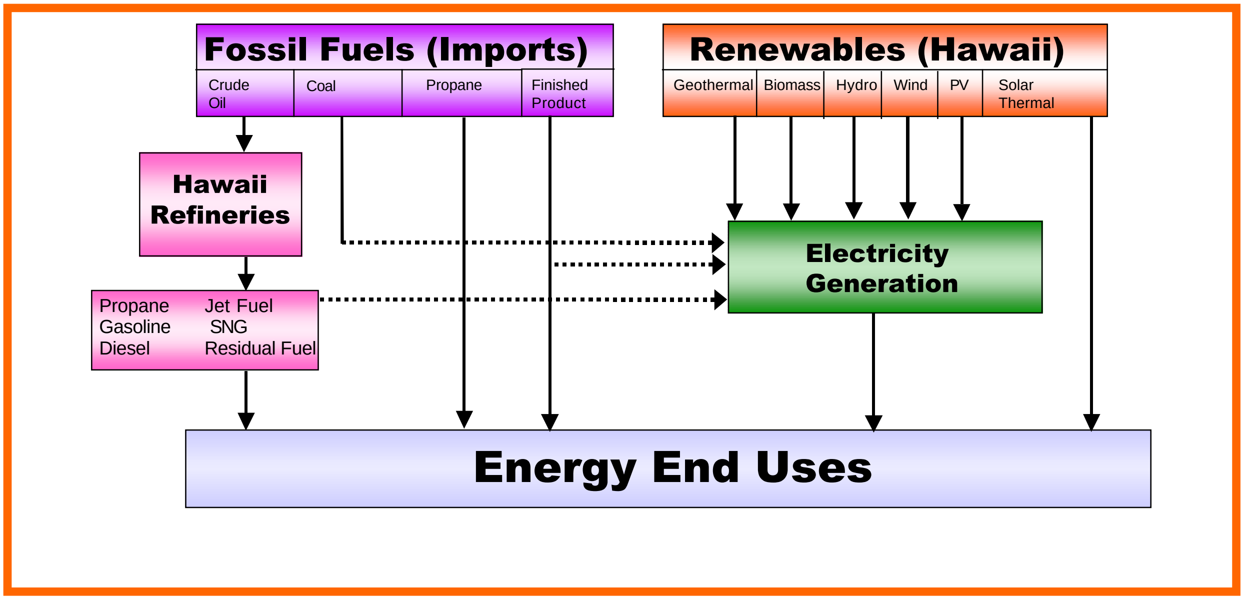

Figure 9: Depiction of Hawaii's energy system.

Natural gas is not available in Hawaii, but synthetic natural gas produced from refinery feedstock is produced and distributed in the southern portion of Oahu by The Gas Company (TGC), a division of Citizens Communications. Synthetic natural gas (SNG) is produced at an SNG plant adjacent to the refineries and distributed at modest pressures through several hundred miles of pipelines around Honolulu. TGC also purchases other forms of petroleum-based gas (propane, butane, etc.) produced at the refineries, stores it in tanks, distributes it via trucks and barges, and sends to customers through localized distribution pipeline networks on Oahu, Hawaii, Maui, Kauai, and Molokai. The synthetic natural gas industry represents approximately 2% of Hawaii's energy needs, primarily for domestic uses including water heating, cooking, and drying; and also for transportation uses in propane fleet vehicles.

Electricity in Hawaii is generated by four electric utilities, several non-utility generators, and the sugar industry and is retailed to consumers via the utilities. Hawaiian Electric Company (HECO) serves Oahu, Hawaii Electric Light Company (HELCO) serves Hawaii County (the Big Island), Kauai Electric Division of Citizens Communications serves Kauai, and Maui Electric Company operates systems on the islands of Maui, Lanai, and Molokai. Electricity production is primarily via thermal and combustion turbine plants utilizing residual fuel oil from the refineries; in 1991 over 92% of the electricity sold was generated using oil. In the 1990s Hawaii diversified its fuels, and by 1997 oil produced 76.5% of electricity, coal 16%, municipal solid waste 3.2%, and renewable energy 3.3%. Electricity demand grew rapidly — and continues to grow — even as Hawaii's economy softened in the 1990s. Total statewide electricity demand grew by 15% between 1990 and 1997, with residential demand outpacing commercial/industrial demand. In addition, real-time electricity demand patterns in Hawaii are unstable, often driven by commercial air conditioning loads, with off-peak demand dropping below 50% frequently on several islands.

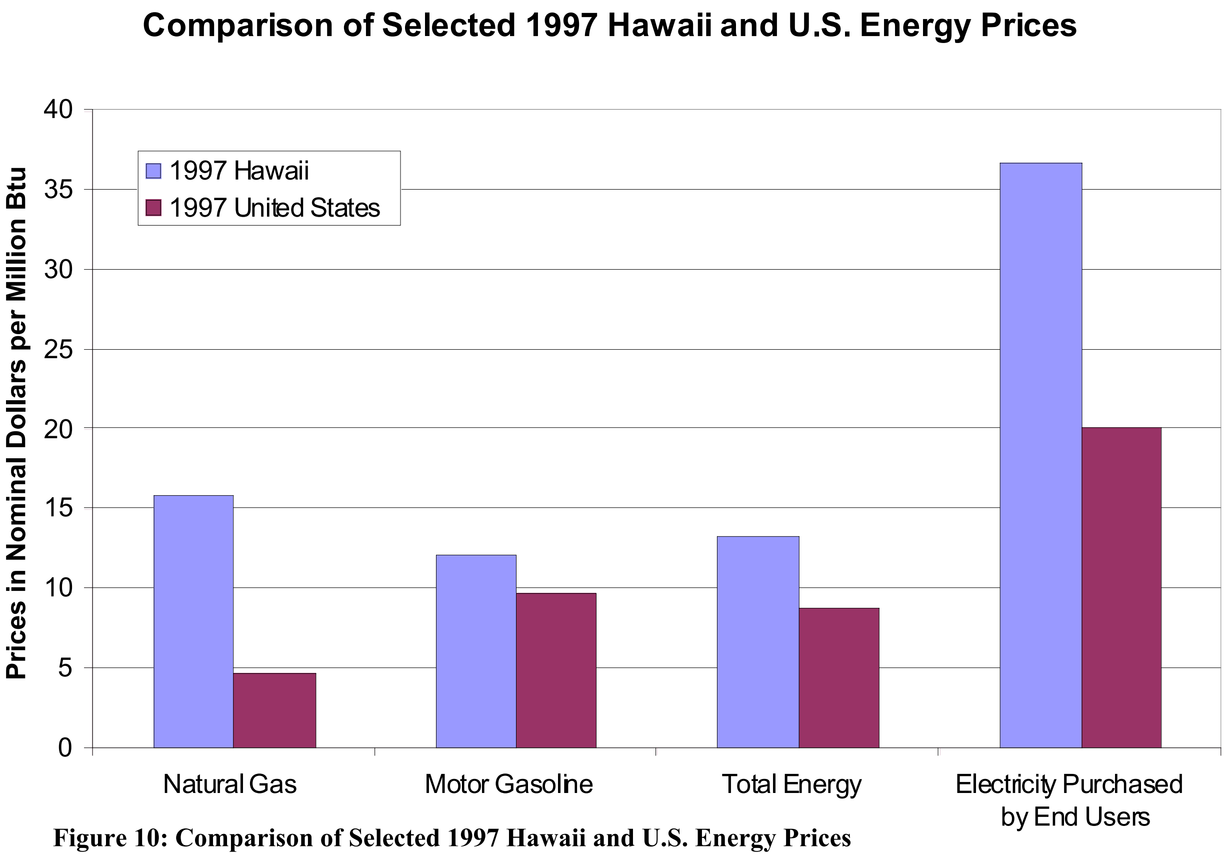

Figure 10: Comparison of Selected 1997 Hawaii and U.S. Energy Prices

The remote location and reliance on imported oil with significant world price volatility leaves Hawaii with the highest energy prices in the United States and with the greatest energy security risk to its economy. Electricity prices and utility gas prices are more than double the equivalent price on the mainland (**Figure 10**). Gasoline prices may average 25% higher than on the U.S. mainland and these prices are highly susceptible to oil price fluctuations on the world market. The reasons for Hawaii's high average electricity costs are discussed in some detail in the *Hawaii Energy Strategy 2000 Report*. In addition to the high fuels cost, issues that impact rates include the need to maintain six small independent systems, recent purchase power agreements with non-utility generators (NUGs), the cost of DSM programs, and general higher costs due to duplicative permitting and high floor prices for some non-fossil contracts. Reducing and stabilizing Hawaii’s energy prices are critical to the growth and stability of Hawaii’s economy, especially its ability to attract high-technology businesses. Energy policies and regulations, as well as use of alternative sources of energy (non-oil), will be important in achieving the desired energy price impacts.

Renewable energy resources including solar, wind, biomass, and geothermal energy represent a large potential indigenous energy resource in Hawaii. It is estimated that renewable energy could provide as much as 20% of Hawaii's energy needs in the future. A concerted effort over the last decade has resulted in a modest increase; renewable energy now makes up approximately 8% of total energy use. Renewable energy sources in 1997 were: 3.2% municipal solid waste, 2.3% geothermal, 1% sugar biomass, 0.7% hydroelectric, 0.2% landfill methane, and 0.1% wind (HES 2000). Solar water heating programs have also been installed for water heating in significant numbers in the islands. Renewable energy is an important source of energy diversification for the state, and renewable energy also allows for growth in the economy while reducing greenhouse gas emissions.

Hydrogen represents to Hawaii a future fuel that can potentially be produced economically from indigenous resources. Hydrogen's versatility makes it attractive to address virtually all of the primary energy and economic issues facing Hawaii including:

- Increased diversification of fuels and their supply sources
- Increased energy efficiency and conservation
- Increased use of indigenous renewable energy resources
- Enhanced contingency planning capabilities to effectively contend with energy supply disruptions[5]

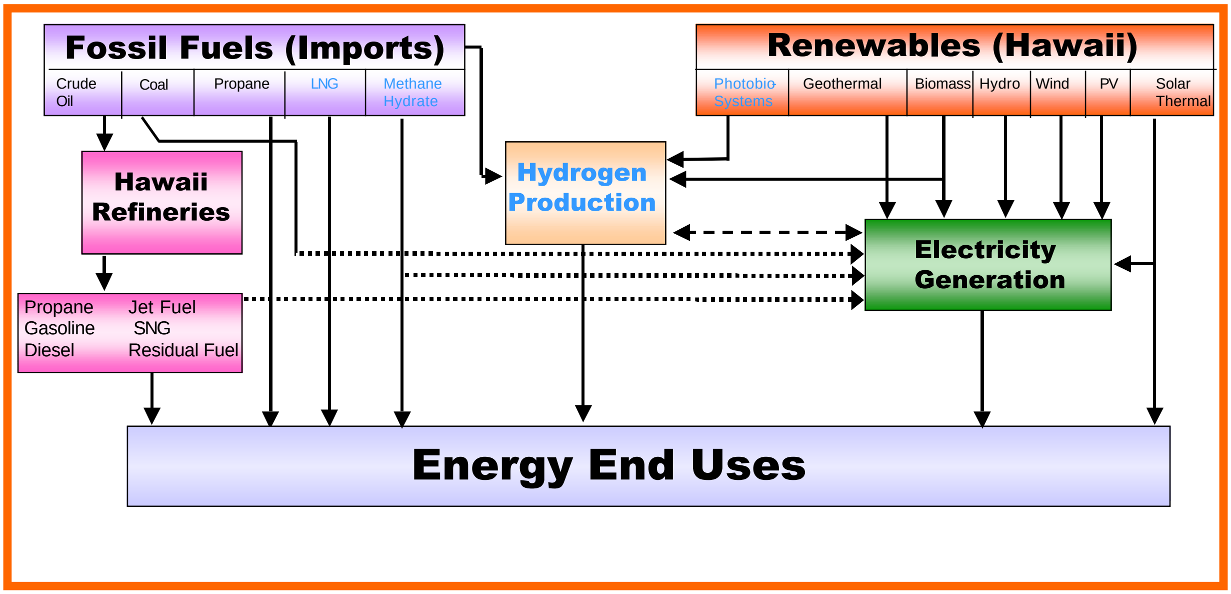

Figure 11: Hawaii's potential future energy system incorporating hydrogen.

Hydrogen's flexibility can be incorporated directly into Hawaii's energy economy as depicted in **Figure 11**. Hydrogen can be produced either as a byproduct of Hawaii's oil refinery feedstock or using indigenous renewable resources. It can be stored and distributed using methods similar to the existing utility gas and propane infrastructure. Hydrogen can be used as a transportation fuel to power automobiles and other ground transportation, thus creating the link between renewable resources and transportation fuel. It can be used to power fuel cells and provide clean, reliable,

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[5] **Portable fuel cells powered by hydrogen will be available to power devices and provide back-up power.**

high-quality electricity for commercial customers. Furthermore, it can also be used as a domestic fuel for water heating and cooking.

Hydrogen's potential creates a compelling case for the state of Hawaii to evaluate its feasibility as well as encourage its inclusion into the state's energy economy. From a strategic perspective, there is a tremendous need to support the development of energy systems that can help to alleviate the economic pressures and risk associated with Hawaii's dependence on oil. To date, Hawaii's fuel diversification efforts have yielded only modest success; hydrogen represents a quantum leap in potential fuel diversification. Environmental concerns have driven investment in the development of a new generation of energy technologies that have the potential to revolutionize the ways that we produce, store, and utilize energy. The fuel cell is the cornerstone of those efforts, as it can not only reduce emissions, but also represent a high-technology device that can be manufactured in Hawaii and bring tremendous economic growth.

Hydrogen must be part of the state of Hawaii's energy strategy that includes improving energy security, improving environmental characteristics, and building a high-technology economy. Hawaii must recognize this potential for hydrogen and fuel cells and encourage their development and deployment. Hawaii must become a strategic partner along with the federal government and numerous Fortune 500 and small companies who already recognize and are investing in the potential for hydrogen energy.

Section 3: Industry: Driving the Transition to a Hydrogen Energy Economy

In the last 100 years, the importance of energy to our society has grown from being an input to industrial production and a luxury of the affluent, to an absolute necessity in almost every facet of modern life. Energy use is omnipresent in our society, and is very closely related to our quality of life. This convenience has not come without a cost. There is an increased realization that human changes to the Earth's atmosphere are real, and that cost-effective corrective action through the use of energy-efficient technologies, clean burning fuels, and renewable resources is inevitable.

Only a few years ago, the world's largest energy companies said in a unified voice that global climate change was a dubious concept and an abundant supply of inexpensive fossil fuels was the only real option for our nation. Today, we see many of these same large international energy companies and a number of international manufacturing firms acknowledging the finite nature of the world's fossil fuel resources and promoting renewable energy, cleaner burning fuels, and hydrogen as a solution to the mounting environmental problems that our society must face (**Figure 12**). Based on these statements, and on concomitant actions by industry and government, many believe that we have already entered into the first stage of the transition to a cleaner energy economy, where hydrogen will be an important aspect.

Recent Public Statements from Industry Leaders

"I believe that if we're going to meet the world's needs for energy—including oil and gas—we have to help resolve the risks of climate change. That's why we've set our own target to reduce emissions from our activities by 10 percent over the next decade."
Sir John Browne, Chief Executive Officer,
BP Amoco
September 13, 1999

"There is clearly a limit to fossil fuel. But what about the growing gap between demographics and fossil fuel supplies? Some will obviously be filled by hydroelectric and nuclear power. Far more important will be the contribution of alternative, renewable energy supplies."
Chris Fay
Chairman and CEO, Shell UK Ltd.

"The 100-year reign of the polluting internal combustion engine is coming to an end, it will soon be replaced in motor vehicles by the hydrogen fuel cell, which emits no pollution whatsoever and so can reduce the build-up of greenhouse gasses causing climate change. Fuel cell technology is the holy grail of the motor industry."
Bill Ford
Chairman of Ford Motor Company
The Independent (UK) October 6, 2000

Figure 12: Selected quotes from industrial leaders regarding the impacts of fossil fuels.

This transition, driven by technological progress in clean energy technologies such as fuel cells, photovoltaics, microturbines, and energy-efficient technologies, could revolutionize the way electricity is manufactured, delivered, and used. It is only through technology advancement that clean energy can compete with the fossil fuel infrastructure that has developed in the last century.

Progress in hydrogen and fuel cell technology has been driven by federal and state energy policies established to further clean air and climate change concerns. States such as California, Massachusetts, and New York have established stringent policies for zero- or low-emission vehicles. California represents such a large segment of the automobile market that the demand for clean vehicles could not be ignored. State policies creating this demand have been a primary stimulus for much technology investment.

California embarked on a plan in 1990 to reduce vehicle emissions to zero through gradual introduction of zero-emission vehicles (ZEVs). Specifically, the California Air Resources Board (CARB) mandated that 2 percent, 5 percent, and 10 percent of new-car sales be zero-emitting by 1998, 2001 and 2003 respectively. Although economic issues and slower-than-expected technology progress has extended the original schedule, CARB (in its January 2001 directive) is still mandating 10 percent ZEV between 2003-2008 with subsequent percentage increases to a maximum of 16 percent in 2018. These mandates will create a market for clean-burning automobiles to number at least 100,000 by 2003.

Other states are eyeing California, and two other states (New York and Massachusetts) have issued clean vehicle mandates. State energy policies to create clean technology demand and incentivize clean technology investment will continue to be the key to private sector investment.

While there is compelling evidence that society has entered the first stage of the transition to a cleaner energy economy, it is expected that the transition will progress on a slow and consistent path until the critical technologies are demonstrated and proven to be safe and reliable. As such, the transition to a hydrogen-based energy economy will require an extensive investment of public and private resources over a sustained period of time, before this vision is fully realized.

Industries Are Investing In Hydrogen Technologies

The fuel cell is viewed as a disruptive technology that has the potential to thoroughly displace the conventional internal combustion engine (ICE) and result in stranded assets and investments. Because of its potential, many companies are taking a proactive position to establish leadership in the development of fuel cell technology.

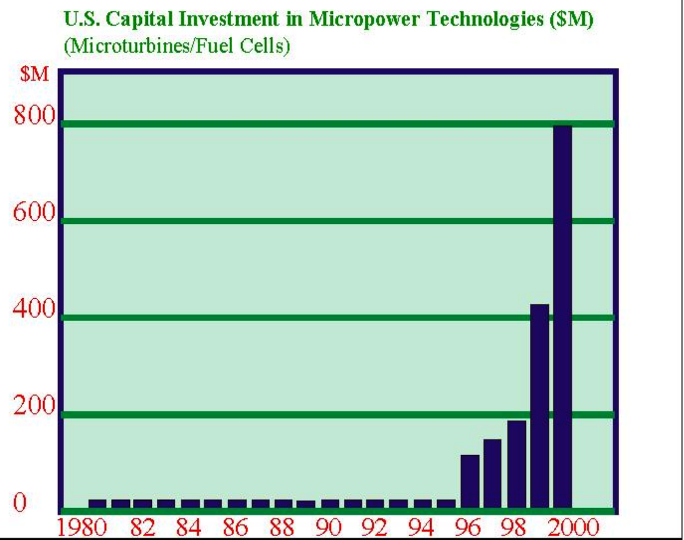

Figure 13: The last five years have witnessed a surge of investment in fuel cells and other distributed energy technologies (The Economist 2000)

Private industry investment in hydrogen and fuel cell technology has been extraordinary over the last few years and capitalization of fuel cell companies exceeds $10 billion. Furthermore, the need for high-reliability power to drive our digital economy has sparked interest in distributed energy technologies (fuel cells, microturbines, etc.) and has stimulated more that $800 million of investment in the United States alone in

2000 (**Figure 13**). Fortune 100 companies such as Shell, Texaco, and Daimler Chrysler, as well as dozens of start-ups, are developing fuel cell and hydrogen technologies. Technological advances in fuel cells and small-scale production have improved, and cost competitiveness is currently attainable in niche applications. The auto industry and others are investing substantially to position themselves for future market success (e.g., DaimlerChrysler, Ford). Also, restructuring of the electricity industry is creating consumer choice and new market opportunities for distributed power (e.g., Plug Power).

Industries are investing in all areas of hydrogen energy — production, storage, transportation, and utilization. They are investing in such technologies as electrolyzers, reformers, gasifiers, compressed gas storage tanks, gas turbines, and fuel cells, and are leading the push for hydrogen power as a successful energy alternative. Summary profiles of a number of the key companies that are currently aggressively working to develop and introduce technologies for hydrogen power and its applications are presented in Appendix B. The summaries are separated into sections that highlight automotive, energy, fuel cell, and industrial gas companies.

Large-Scale Integrated Hydrogen Energy Projects Are Being Initiated

The transition to a hydrogen-based energy economy will require an extensive investment of public and private resources over a sustained period of time before the vision is fully realized. During the course of any technology transition, there are early supporters, transition leaders, transition followers, and stubborn adopters. There have been early supporters of the hydrogen energy concept since the 1970's, but only in the last three to five years have we seen the emergence of transition leaders around the world who are positioning themselves to serve as the early adopters of hydrogen energy technologies. These transition leaders are driven by common characteristics that increase the probability of success in their particular situation. Whether they are niche applications of the technology or a larger-scale "cluster" utilization, these characteristics are essential:

- Availability of adequate resources to produce or obtain high quality hydrogen at a reasonable cost;
- Existence or threat of mandated environmental drivers that necessitate consideration of environmentally friendly or zero emission technologies;
- Economic conditions that drive resource substitution and consideration of higher cost, higher benefit resource options;
- Actual or mandated resource constraints that result in requirements for diversification of supply to meet demands;
- Ability to attract and collaborate with domestic and international industry, and;
- Consciousness of societal, cultural, or wildlife conservation issues that places higher than market value on quality of life and the environment.

The following projects have been initiated and represent opportunities for early, large-scale introduction of hydrogen energy technologies into the energy economy. Adoption of policies to stimulate hydrogen energy investment will place Hawaii among a select group of states and companies becoming leaders in this effort. Many of these efforts are built around programs or flagship projects to validate hydrogen energy (see Appendix C for more details). Several of these projects to introduce large-scale hydrogen integrated systems include:

- California Fuel Cell Partnership
- Nevada Test Site/Las Vegas hydrogen transportation infrastructure
- State of Florida Hydrogen Research and Applications Center
- Proposed hydrogen economies for Iceland and Vanuatu
- SunLine Transit Agency renewable hydrogen transportation system
- Houston Advanced Research Center stationary fuel cell demonstration
- BPA, EPRI, and other utilities testing residential (3-5 kW) fuel cell systems

Additionally, there are fuel cells currently in operation at a number of landfills and wastewater treatment plants across the country, proving themselves as a valid technology for reducing emissions from these sources. Currently, companies have tapped 140 U.S. landfills and are considering collecting methane (CH_4) at another 750, according to the EPA's Landfill Methane Outreach Program.

If hydrogen is to enter the energy economy of Hawaii, integrated hydrogen demonstration projects will be needed to anticipate performance and economics. The aforementioned projects and companies have made major investments, but Hawaii has not yet emerged as a willing partner. Therefore, leadership from the Hawaii state government would likely spur investment from energy, automotive, and industrial gas companies in integrated hydrogen energy projects.

Section 4: The Analysis of Hydrogen Energy Pathways for Hawaii

Incorporating hydrogen into Hawaii's energy economy will require the identification of specific "pathways" with the strongest potential. To assess the potential impact of various energy delivery scenarios from the perspective of economic costs and benefits, we employed pathway analysis and full life-cycle cost analysis methodologies. This section introduces the concept of energy pathway analysis and guides the reader through the development of pathways for hydrogen generation, distribution, and utilization in the state of Hawaii. The text and graphical elements presented in this section are designed to explain the concept of pathway analysis to the reader and introduce them to the analytical process employed to evaluate energy technologies in this report.

An energy economy, such as the one that currently exists in Hawaii, developed over many years and is comprised of a diverse set of energy technologies and pathways serving the needs of the various demand sectors. An energy pathway is a series of source-to-end-use processes defined by particular technologies. Pathways include primary energy sources, conversion processes, energy storage, methods of delivery, and end-use technologies. Currently, the Hawaii energy economy relies on fossil fuels for about 92 percent of all energy demand.

In order to introduce hydrogen to this energy mix it is necessary to identify a subset of candidate pathways that are capable of meeting some segment of the state's energy demand. One of the primary objectives of this report was to identify energy market segments where hydrogen could be competitive within the next decade. The analyses conducted as part of this effort were designed to provide options for informed consideration of hydrogen energy technologies in Hawaii, and to identify potential opportunities for the large-scale use of hydrogen in Hawaii's energy economy. In considering the objectives of this study, we focused on the energy resources available in the state and the consideration of all the processes involved in delivering this energy to the point of utilization.

What is Pathway Analysis?

Figure 14 illustrates an energy pathway. An energy pathway, which often consists of multiple series of processes, is a method to evaluate a technological process from the start to finish (final usage) in the form of energy (kWh).[6] These are sometimes referred to as "cradle to grave" analyses. For additional information on the underlying methodology, please refer to Appendix D.

The figure provides a detailed example of how a pathway is organized and the various inputs and outputs associated with this analytical framework. The colored bars of the Pathway Components are read from left to right, and include the Energy Source (Green), Fuel Production (Teal), Distribution (Blue), and Utilization (Purple). This color-coded format is continued in the text of this section where applicable. Also presented in the figure are the specific Conversion Process or Technology in each segment of the pathway component and its respective Incremental Cost; the Required Energy Input; Conversion Efficiency; and the Cumulative Cost of Energy.

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[6] "Energy Pathway Analysis – A Hydrogen Fuel Cycle Framework for System Studies." Badin, J.S., Tagore, S. *International Journal of Hydrogen Energy*, Volume 22, Number 4, April 1997.

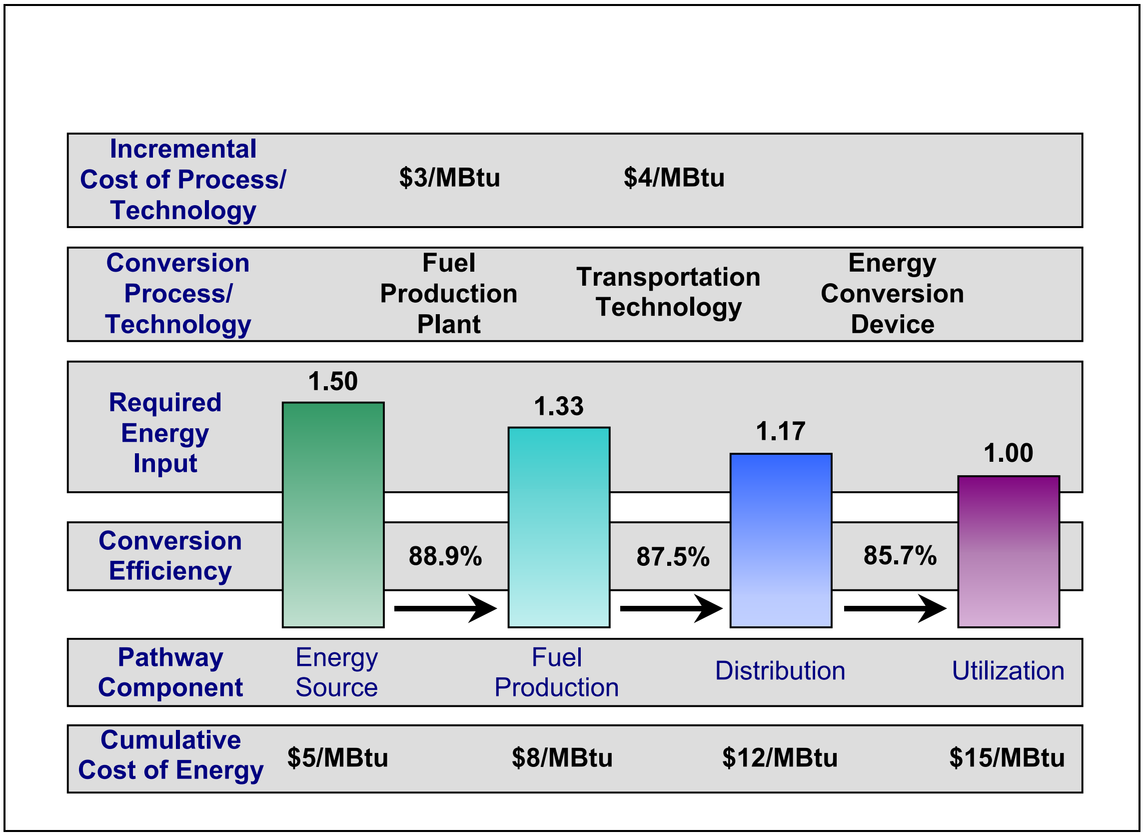

Figure 14: Energy Pathway Layout

The example pathway clearly displays the quantity of primary energy necessary to produce the energy form and identifies the process or processes where energy losses are greatest. In this manner, the analysis helps to focus attention on those steps where the potential for technology advancement is highest. When combined with detailed life-cycle cost analysis, the pathway analysis can also help to sharpen economic estimation and comparative pollution evaluation. Pathways provide a more accurate understanding of energy capacity levels required at each step, which in turn leads to improved assessment of capacity-dependent functions such as capital investment and emissions quantities.

Finally, pathway analysis evaluation allows direct (relative) comparison of various aspects of competing paths and provides a framework for making judgments regarding potential benefits of individual approaches. To make informed decisions regarding energy choices, it is important to evaluate relevant factors on equivalent bases. The principal factors being considered in this plan are energy efficiency, capital cost, emissions, and fuel importation. To bring these characteristics into focus, competitive energy pathways (pathways employing different energy systems to meet the same consumer demand), need to be developed and evaluated.

The application of the pathway analysis methodology is especially useful when comparing conventional technologies with renewable energy technologies and hydrogen. This is based on the fact that manufactured forms of energy exhibit a set of costs and benefits that are difficult to compare with conventional technologies. Usually, these benefits include reduced health or environmental impacts that are not incorporated into the costs of conventional technologies. For the purpose of our analyses, we recognize that hydrogen must be produced and delivered at a cost comparable to Hawaii's conventional energy carriers, but the environmental, efficiency, and domestic sustainability benefits of hydrogen should not completely be disregarded.

For the purposes of uniformity and comparison, all pathways discussed in this report are normalized to supply 1 kW of equivalent power to end-users in stationary power applications, or 1 mile/kWh of equivalent power to end-users in transportation applications. Annual power capacity factor and annual operating hours are the main time factors used for determining the energy delivered (in equivalent kWh) in the pathways analysis.[7]

Life-Cycle Cost Analysis Methodology

Evaluating the economic impact of various technologies for use in a pathway is not an easy task. Differences in costs, efficiency, fuel consumption, reliability, lifetime of the system, etc. are all factors to be considered. Additionally, different combination of technologies used in the pathway can produce different results in terms of costs, technological performance, and system efficiencies.[8]

In calculating life-cycle cost, the cost of energy resources is a major cost factor. Typically, the cost of energy resources includes the major cost contributors such as initial capital cost, operation and maintenance, fuel cost, and various fixed charges. Less obvious cost contributors such as health care expense, pollution control expense, economic impacts on material and agricultural resources, and other externalities are typically excluded from cost calculations.[9]

Inclusion of externalities into cost calculation can be difficult, but ignoring externalities can have a large impact. Improper accounting for the costs of externalities can lead to improper economic decision making in choosing the right energy resource.[10] The scope of this study did not include the complex considerations associated with internalizing the cost of externalities, which would likely include the monetization of emission estimates, but they may be worth pursuing in follow-on investigations.

For the purposes of this report, we focused on the difference between total consumption benefits and total production costs. When this condition is maximized (i.e., the highest benefits for the lowest costs is reached), economic efficiency is achieved. Differential life-cycle cost criteria can be used to judge whether a considered pathway improves economic efficiency relative to the status quo or to other possible energy investments. It is emphasized that our analyses are framed by economic considerations of decision making.

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[7] "Energy Pathway Analysis" in *Proceedings of the 1994 DOE Hydrogen Program Review*, Badin, J.S., Kervitsky, G., and Mack, S.

[8] "Energy Pathway Analysis – A Hydrogen Fuel Cycle Framework for System Studies." Badin, J.S., Tagore, S. *International Journal of Hydrogen Energy*, Volume 22, Number 4, April 1997.

[9] Ibid

[10] Ibid

Deployment of hydrogen as an energy resource can only happen if various technologies used in the new energy production system are compatible and well integrated. Well organized and funded research from the public sector can identify all the barriers to entry for the hydrogen energy economy. In transitioning to a hydrogen economy, pathway and economic analysis can be employed to identify and anticipate potential issues of technical feasibility, economic impacts and effects, and infrastructure challenges. By conducting this analysis, hydrogen energy applications that have the highest potential to be deployed can easily be identified.[11]

Each step in an energy pathway has certain efficiencies and costs associated with it. In the following section, several hydrogen energy pathways and the costs associated with them are developed in a step-by-step fashion. The analysis performed in support of this report divided the pathways into four basic components: energy source, conversion technology, transportation and distribution, and utilization. Each of these components is color coded to refer back to the generic pathway chart shown above. For additional information on Hawaii's current energy economy or the energy sources considered in this report, refer to the *Hawaii Energy Strategy 2000*.

Energy Source

Hawaii's remote South Pacific location and generous array of indigenous renewable resources required careful consideration of these resources, which include wind, geothermal, and biomass derived energy, in the generation of hydrogen. Hydrogen produced from such sources will result in minimal air pollution and substantially reduced greenhouse gas emissions when compared with the petroleum that currently meets the bulk of Hawaii's energy needs. Furthermore, energy derived from indigenous resources will improve the state's energy security. With nearly all of its energy needs being met by imported petroleum, Hawaii is very vulnerable to oil price spikes and supply shortages. Diversifying the state's energy portfolio to include native resources will reduce the impact of oil price excursions and supply problems, resulting in a stable energy economy.

While environmental issues and energy security are important to both the health of Hawaii's economy and that of its residents, no energy technology can be deployed unless it is technologically and economically feasible. In spite of their abundance on the Hawaiian Islands, a few renewable resources were excluded from this study based on technical barriers or high costs. Wave, tidal, and ocean thermal energy were not considered since they are not mature technologies and still face considerable technical barriers to widespread deployment. Photovoltaics (PV) are a mature technology, but the cost of PV arrays is still too high to justify their use in hydrogen generation.

Biomass

Hawaii's tropical climate makes it an ideal location for energy production from biomass feedstocks. Hydrogen can be produced from a number of plant and animal residues, including both crop waste residues (such as bagasse) and dedicated energy crops. While crop residues represent a low cost feedstock, much of the crop residues currently available in the state are

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[11] "Energy Pathway Analysis – A Hydrogen Fuel Cycle Framework for System Studies." Badin, J.S., Tagore, S. *International Journal of Hydrogen Energy*, Volume 22, Number 4, April 1997.

being used in cogeneration plants for electricity and heat production. Furthermore, crop residues are produced at a fairly low yield per acre. The amount of land area required to support a biomass energy conversion plant would therefore be much larger than the land required for dedicated energy crop production, resulting in higher transportation costs for the crop residues. The HES 95 transportation analysis estimated costs of $40-60 per dry ton of biomass from dedicated energy crops such as banagrass (Parsons Brinckerhoff Quade & Douglas, Inc. 1995). This study used a plant-gate feedstock estimate of $46.20 per dry ton that was developed by the National Renewable Energy Laboratory (NREL) for their study on the economics of hydrogen production from biomass (Spath et. al. 2000). This corresponds to a cost of $4.74 per million Btu (MBtu) of hydrogen produced from biomass.

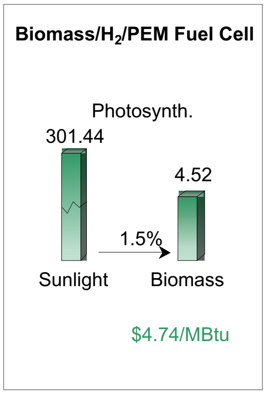


Figure 15

Geothermal

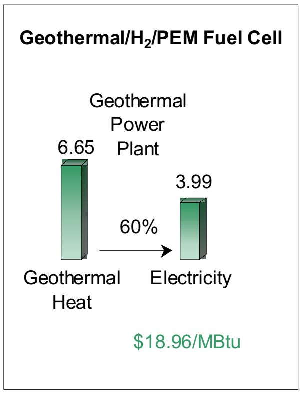


Figure 16

The volcanic origins of the Hawaiian islands make another renewable energy resource available: geothermal power. Only present on the island of Hawaii, geothermal power plants represent a relatively low cost renewable electricity generating technology. The 2001 Analysis of Renewable Portfolio Standard Options for Hawaii estimates the cost of electricity from new geothermal projects on Hawaii to be around 4.4¢/kWh (Global Energy Concepts 2000). While this is the lowest cost renewable-generated electricity available in the state, it still represents a fairly expensive feedstock for hydrogen generation. Electricity costs account for $18.96/MBtu of hydrogen generated from geothermal power.

Wind

The tradewinds blowing past the Hawaiian Islands provide another abundant supply of clean energy. However, wind-generated electricity is even more expensive than geothermal power. Projections for the cost of electricity from new wind generating projects range from slightly more than geothermal electricity (4.5¢/kWh) on the Big Island to much more expensive estimates of 6.5¢/kWh and 6.9¢/kWh on Maui and Kauai, respectively (Global Energy Concepts 2000). These feedstock costs account for a large portion of the delivered cost of hydrogen generated from wind power: $19.40/MBtu on Hawaii, $28.02/MBtu on Maui, and $29.74/MBtu on Kauai.

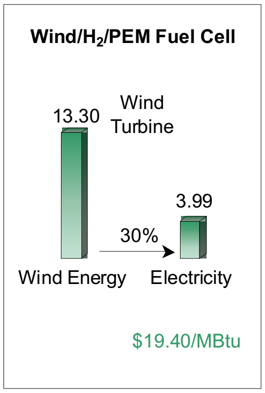


Figure 17

Liquefied Natural Gas

LNG is imported from countries with natural gas fields via large, specially insulated tankers. Once it reaches the destination port, the LNG must be offloaded and regasified into natural gas. Then it can be distributed to end users via pipeline infrastructure. Oahu has an existing synthetic natural gas (SNG) utility infrastructure, which could provide a market for additional LNG shipments. Accounting for nearly two thirds of the energy consumed in the state, Oahu is an attractive (perhaps essential) market for deployment of hydrogen production and utilization technologies in Hawaii. Unfortunately, it also has very limited renewable energy resources available. There are no known geothermal reserves, and land on the most populated island comes at a premium, making most renewable energy projects expensive. Thus, hydrogen production from indigenous renewable resources does not appear to be feasible at present. Furthermore, due to the uncertainties regarding the economics of storing and transporting hydrogen, producing hydrogen on the other islands and shipping it to Oahu was not considered as an option for this analysis. If methane hydrates prove to be a safe and reliable energy resource, they may provide a plentiful feedstock for hydrogen on Oahu. In the short term, importing some sort of feedstock appears to be the best way to provide hydrogen for Hawaii's largest energy market. This will allow Oahu to develop a hydrogen distribution and utilization infrastructure, putting it in a position to utilize hydrogen from untapped resources (such as methane hydrates) as they become economically feasible or from neighboring islands if hydrogen transportation costs decrease significantly. Based on market maturity and a desire to diversify Hawaii's energy imports, liquefied natural gas (LNG) was selected as a potential feedstock for hydrogen production on Oahu.

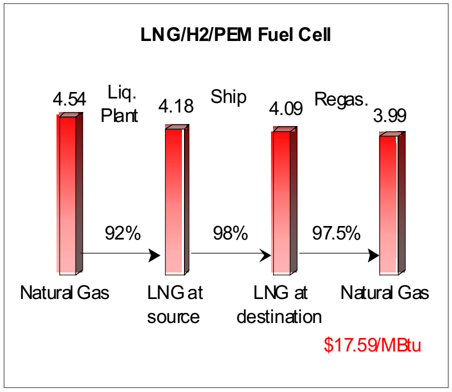


Figure 18

Based on The Gas Company's assessment, construction of an LNG shipping terminal to handle imports of about 3 million MBtu per year would cost $113 million (The Gas Company 1999). This estimate includes unloading facilities, storage, a regasification plant, a pipeline link to the existing SNG infrastructure, and enough land to accommodate all of the facilities. If LNG is purchased on the spot market for $3.50/MBtu (delivered), natural gas could be imported at a cost of $11.96/MBtu (regasification plant gate). This would account for $17.59/MBtu of the cost of hydrogen produced by reforming imported natural gas.

To reduce this feedstock cost, Hawaii could take advantage of the economies of scale inherent in LNG handling and storage facilities. Based on our estimated costs of ~$12/MBtu for landed natural gas from a small project, LNG could prove to be economically competitive with SNG. Substituting imported natural gas for SNG would require no modifications to the gas delivery system or customer end use equipment. Furthermore, the environmental impacts of operating the SNG plant, as well as their associated expenses, would be avoided (The Gas Company 1999). Imported natural gas burns cleaner and produces less greenhouse gas emissions over its life cycle than SNG. A larger LNG market would increase facility size and utilization, resulting in lower unit costs. Converting other parts of Hawaii's energy infrastructure (such as power plants) over to imported natural gas could further reduce the costs of LNG, while simultaneously diversifying the state's energy portfolio and reducing greenhouse gas emissions.

Fuel Production

Biomass Gasification/Reformation

Biomass materials can be converted into hydrogen via several processes. Both Battelle/FERCO and IGT have developed direct gasification reactors that convert biomass into a syngas. This syngas is then steam reformed and run through two water gas shift reactors to convert residual CO to CO_2 and H_2. The resulting hydrogen gas stream is purified in a pressure swing adsorption (PSA) unit. Alternatively, the biomass material can be converted to bio-oil through pyrolysis and subsequently reformed into hydrogen via a process very similar to the one used by the direct gasification reactors.

The National Renewable Energy Laboratory (NREL) has developed detailed cost estimates for biomass to hydrogen conversion plants based on component costs for similar processes (Spath et. al. 2000). In their analysis, the economics of pyrolysis plants compare favorably to direct gasification systems due to income from coproducts that are separated from the bio-oil intermediate. Since the market for these coproducts in Hawaii is uncertain, this study focused on direct gasification.

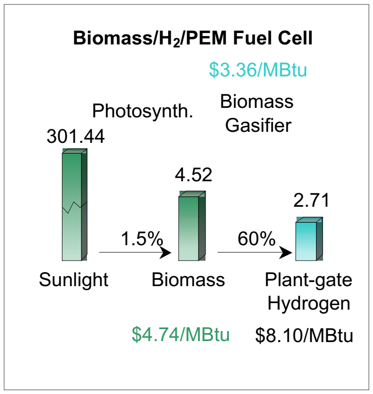


Figure 19

NREL estimated the initial capital investment required to build a 22,737 kg H_2/day plant at $53.8 million. The total costs for building and operating such a plant amount to $3.36/MBtu of hydrogen produced. Adding this figure to the feedstock costs of $4.74/MBtu mentioned above gives a gasification plant gate cost of $8.10/MBtu. This figure compares favorably with the consumer price of the three fuels currently available in Hawaii: gasoline ($13.08/MBtu), synthetic natural gas ($12-17/MBtu), and propane ($11-26/MBtu).

Electrolysis

Electricity from any energy source can be used to generate extremely pure hydrogen by splitting water in an electrolyzer. The pathways starting with both geothermal and wind power utilize electrolyzers to convert the electricity to hydrogen.

The use of electricity as a feedstock for hydrogen opens up a couple of options for siting of the hydrogen generation facility. A large-scale electrolyzer plant can be built next to the renewable power plant to create a centralized source of hydrogen, which can be transported via trucks or pipelines to end use facilities. Alternatively, electricity generated by the renewable power plant can be transmitted via the existing grid infrastructure to smaller, distributed electrolyzers near the point of use. There are a couple of technical and economic tradeoffs between the two options. Utilizing the existing grid infrastructure to send energy to the point of use via electricity and converting it to hydrogen in distributed electrolyzers would significantly reduce the transportation and distribution costs of the hydrogen. However, this could place considerable demands on the islands' grid infrastructures, which in some locations are already nearing capacity. Furthermore, there are considerable economies of scale involved in electrolyzers, and building a centralized electrolysis plant reduces the initial capital costs involved in the system. This study focused on the central hydrogen generation option since better-cost estimates were available for larger electrolysis systems. However, the lower transportation and distribution costs of distributed electrolysis could offset the increased electrolysis capital investment, so the two options would probably generate hydrogen at comparable costs.

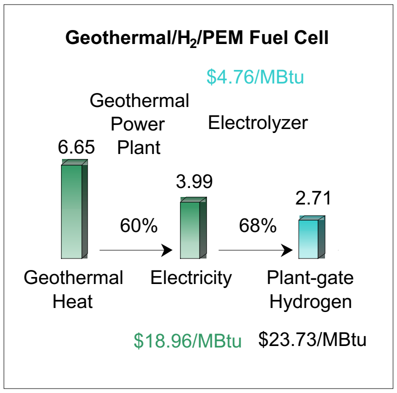


Figure 20

Hydrogen from electrolysis tends to be much more costly than hydrogen generated from other sources because the feedstock (electricity) is very expensive. The capital costs for a large-scale electrolyzer designed to utilize the output of a new 23 MW geothermal plant amount to roughly $9.4 million. When the annual operating and maintenance costs of about $1 million are included, the electrolysis plant contributes $4.76/MBtu to the $23.73/MBtu plant-gate price of hydrogen generated from geothermal power. The electrolysis plant only accounts for about 22% of the cost of the generated hydrogen. The remaining 78% pays for electricity. Geothermal-powered electrolysis is the second least expensive renewable hydrogen generation technology, but due to the higher feedstock expenses it costs over twice as much as biomass gasification.

Hydrogen from a wind-powered electrolyzer is even more expensive than its geothermal-derived counterpart. This is true for two reasons. First, electricity from wind turbines is even more expensive than geothermal power. Second, the electrolyzer costs for wind-generated hydrogen are much higher due to sizing constraints brought about by the nature of the resource. Since wind power is intermittent, a much larger nominal capacity of wind generation must be built to meet the same energy requirements as a non-intermittent plant. For example, based on a capacity factor of 33%, 63 MW of wind turbines would be necessary to provide the same hydrogen production as 23 MW of geothermal power on the Big Island. Even though the annual throughput for the two systems may be the same, the electrolyzer must be sized large enough to handle all of the potential peak output power from the wind turbines. This results in much higher electrolyzer costs, and thus more expensive hydrogen.

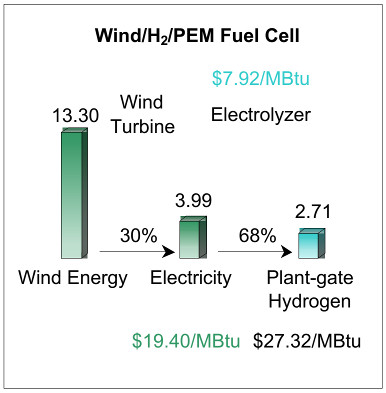


Figure 21

Returning to the island of Hawaii, the feedstock cost for wind-generated electricity is only slightly more than that for geothermal power: $19.40/MBtu of hydrogen produced as compared to $18.96/MBtu. However, the 63 MW electrolyzer has a price tag of $25.7 million. When this is added to the annual operating and maintenance expenses of about $620,000, the cost of the electrolyzer adds $7.92/MBtu to the cost of the hydrogen produced from wind power. This accounts for about 29% of the plant-gate cost of wind-generated hydrogen on Hawaii, which is $27.32/MBtu. Even though the facility investment in this case is higher than what is required for the geothermal powered electrolyzer, the majority of the cost of the hydrogen (71%) still comes from electricity.

This is even more apparent on Maui and Kauai. The electrolyzer still contributes $7.92/MBtu to the cost of the hydrogen generated on these islands. However, as mentioned above, electricity accounts for $28.02/MBtu of hydrogen produced on Maui and $29.74/MBtu on Kauai. These represent 78% and 79% of the plant-gate cost of hydrogen produced from wind power on Maui and Kauai, respectively. At $35.94 and $37.66/MBtu, wind-generated hydrogen on Maui and Kauai is the most expensive hydrogen conversion process studied.

Liquefied Natural Gas

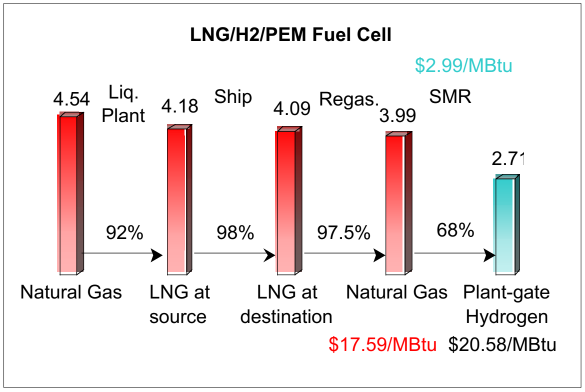


Figure 22.

Once the LNG has been regasified, it can be converted into hydrogen via a conventional steam methane reforming (SMR) plant. A plant large enough to produce about 1.8 million MBtu of hydrogen per year (roughly enough to handle the throughput from the port facility described above) would cost around $31.7 million to build and $1.6 million/year to operate. These costs would contribute $2.99/MBtu to the costs of the hydrogen produced from the facility. This is a fairly small fraction of the $20.58/MBtu plant gate cost of hydrogen reformed from LNG.

Figure 23 shows the plant-gate costs of hydrogen derived via the four pathways analyzed here. It also lists the range of delivered prices for fuels currently available in Hawaii: gasoline, synthetic natural gas (SNG), and liquefied propane gas (LPG). While hydrogen derived from geothermal power, wind power, or imported LNG is considerably more expensive than the fuel options currently available in the state, hydrogen derived from biomass could be cost competitive.

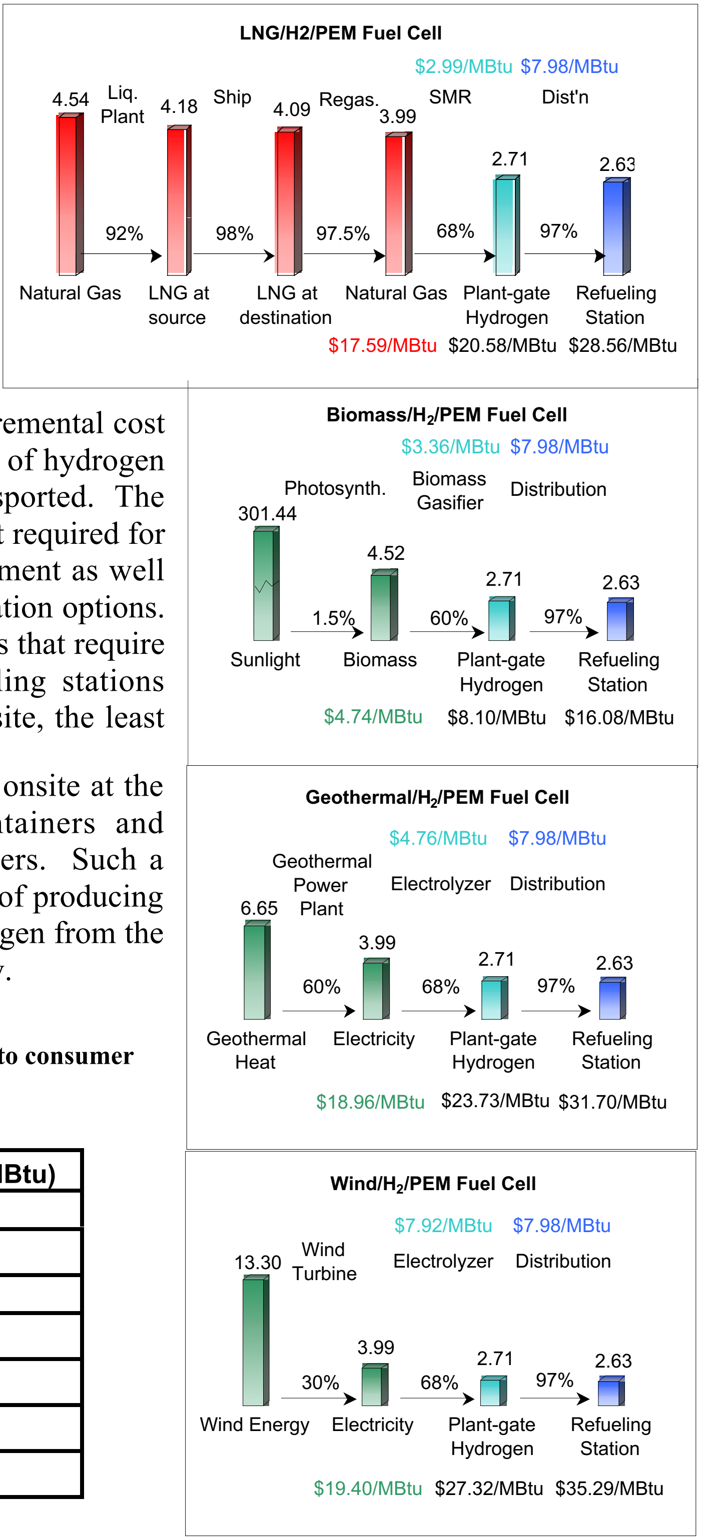
Fuel	Fuel Source	Cost or Price ($/MBtu)
Gasoline	Petroleum	$13.08
SNG	Petroleum	$12.31 –16.92
LPG	Petroleum	$11.05 – 25.97
Hydrogen	Biomass	$8.10
Hydrogen	Geothermal	$23.73
Hydrogen	Wind	$27.32 – 37.66
Hydrogen	LNG	$20.58

Figure 23: Plant-gate cost of hydrogen compared to consumer price of existing fuels in Hawaii

Distribution

There are a number of ways to store and transport hydrogen, none of which are inexpensive. Since the utilization section of this study focused primarily on the transportation sector (see discussion below), the analysis of distribution options centered on options for hydrogen delivery to refueling stations.

Figure 24



NREL has developed a spreadsheet model of various transportation and storage technologies that indicates the incremental cost of hydrogen distribution given the amount of hydrogen produced and the distance it must be transported. The spreadsheets include the capital investment required for storage facilities and transportation equipment as well as labor and fuel for the various transportation options. For relatively small-scale production plants that require weekly delivery to a network of refueling stations within a 80 km radius of the production site, the least expensive option is to store the hydrogen onsite at the production facility in pressurized containers and distribute it via metal hydride truck trailers. Such a system would add $7.98/MBtu to the cost of producing the hydrogen. The delivered cost of hydrogen from the various sources is shown in the table below.

Figure 25: Delivered cost of hydrogen compared to consumer price of existing fuels on Hawaii

Fuel	Fuel Source	Cost or Price ($/MBtu)
Gasoline	Petroleum	$13.08
SNG	Petroleum	$12.31 –16.92
LPG	Petroleum	$11.05 – 25.97
Hydrogen	Biomass	$16.08
Hydrogen	Geothermal	$31.70
Hydrogen	Wind	$35.29 – 45.64
Hydrogen	LNG	$28.56

Utilization

The final component of an energy pathway is the utilization of the fuel in some application. Three market sectors where hydrogen could be utilized were considered: stationary power generation, utility fuel applications, and transportation. The benefits and drawbacks of hydrogen use in each of these sectors are discussed in this section.

Stationary Power Generation

Through the use of fuel cells, turbines, engines, or other conversion technologies, hydrogen can be converted into electricity at central power generation facilities as well as in distributed generation applications. As already discussed, hydrogen is an extremely clean fuel, generating little or no emissions and no carbon dioxide. However, it is unlikely that hydrogen will prove to be economic for stationary power generation in the near term. This is true for a couple of reasons.

First, hydrogen is a secondary fuel that must be derived from another energy source (such as electricity, biomass, or natural gas). Each of these energy sources could be used directly for electricity generation, avoiding the losses and expenses of converting to hydrogen as an intermediate step. For example, wind turbines generate electricity. This electricity could be used to run an electrolyzer to generate hydrogen, which could then be converted back into electricity in a fuel cell. Electrolyzers are roughly 68% (LHV) efficient, so 32% of the electrical energy is lost in the conversion process. The most efficient fuel cells may be able to achieve a fuel to electricity conversion efficiency of 60%. If cogeneration is considered, fuel cells could achieve 80% energy conversion efficiency. This would correspond to a loss of 45% of the total electrical energy that is converted to hydrogen and back to electricity. Furthermore, the additional conversion steps would add considerably to the cost of the electricity produced. These losses and expenses could be avoided by using the electricity from the wind turbines directly.

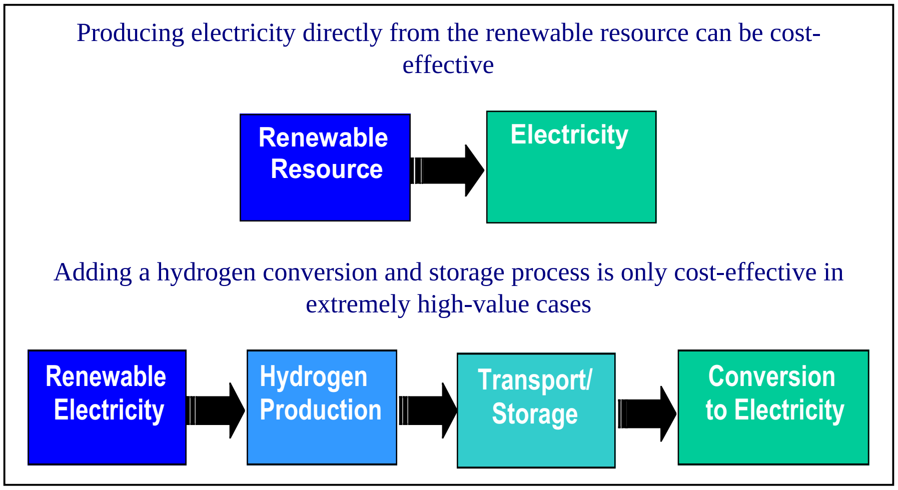


Figure 26: Generating electricity from renewable energy via a hydrogen intermediate will always result in higher cost electricity.

Second, distributed generation utilizing hydrogen as a fuel would require extensive hydrogen distribution or transportation infrastructure. It would be difficult for hydrogen to economically compete with the existing SNG and propane distribution system.

Utility Fuel

Hydrogen can be used just like any other gaseous fuel for heating, cooking, drying, and lighting. Furthermore, it is an extremely clean alternative to the synthetic natural gas and propane currently being used on the Hawaiian Islands. Burning hydrogen produces no carbon dioxide, no carbon monoxide, and no sulfur oxides. As the analyses above indicate, hydrogen could possibly compete on a fuel cost basis with both SNG and LPG in higher value markets. However, use as a utility fuel requires extensive distribution infrastructure, just as for stationary power generation. At present, SNG is only available on certain parts of the island of Oahu where a pipeline system is in place. Conversion of this pipeline system to carry hydrogen would require substantial capital investment. Areas not served by the SNG pipeline rely on LPG for their fuel needs. Most LPG is transported between the islands via barge and delivered in relatively small containers on trucks to the location of use. It is unlikely that hydrogen could be distributed in a similar fashion economically.

Transportation Fuel

Using hydrogen as a transportation fuel makes more sense than the other two sectors in the near term for two reasons. First, the distribution infrastructure required to transport hydrogen from a central generating plant to several refueling stations is far less extensive and capital intensive than one that could provide hydrogen to hundreds or even thousands of commercial and residential buildings. Second, hydrogen is the ideal fuel for fuel cells, which show promise as highly efficient energy conversion systems for vehicles. In fact, it is expected that fuel cell vehicles will be about 2.2 times more fuel efficient than conventional gasoline-powered internal combustion engine vehicles (Thomas *et. al.* 2000). Even though the tables above indicate hydrogen is more expensive than gasoline, the improved efficiency of fuel cell vehicles could make hydrogen competitive on a fueling cost per mile basis.

To compare the fueling costs of the various hydrogen pathways with that of a gasoline internal combustion engine vehicle, the expected energy efficiency in million Btu (MBtu) per mile of both types of vehicles was determined. This allowed the previously calculated energy-equivalent fuel costs (in terms of $/MBtu) to determine the specific fueling cost of each pathway (cents/mile). Note that the purchase price of the vehicle is specifically omitted from this calculation. The stated goal of the U.S. automotive industry (through such research and development efforts as the recently announced Freedom Car initiative and the California Fuel Cell Partnership) is to produce fuel cell vehicles with the same first-purchase price as comparable, conventional cars. Industry (as previously cited) is committed to achieving the goal of commercial introduction of fuel cell vehicles this decade. The maintenance costs for fuel cell vehicles are uncertain, but could potentially be lower than conventional vehicles because of the simpler electric drive train of the fuel cell vehicles. Much depends, however, on the ability of fuel cell manufacturers to achieve R&D goals with respect to stack life and maintainability.

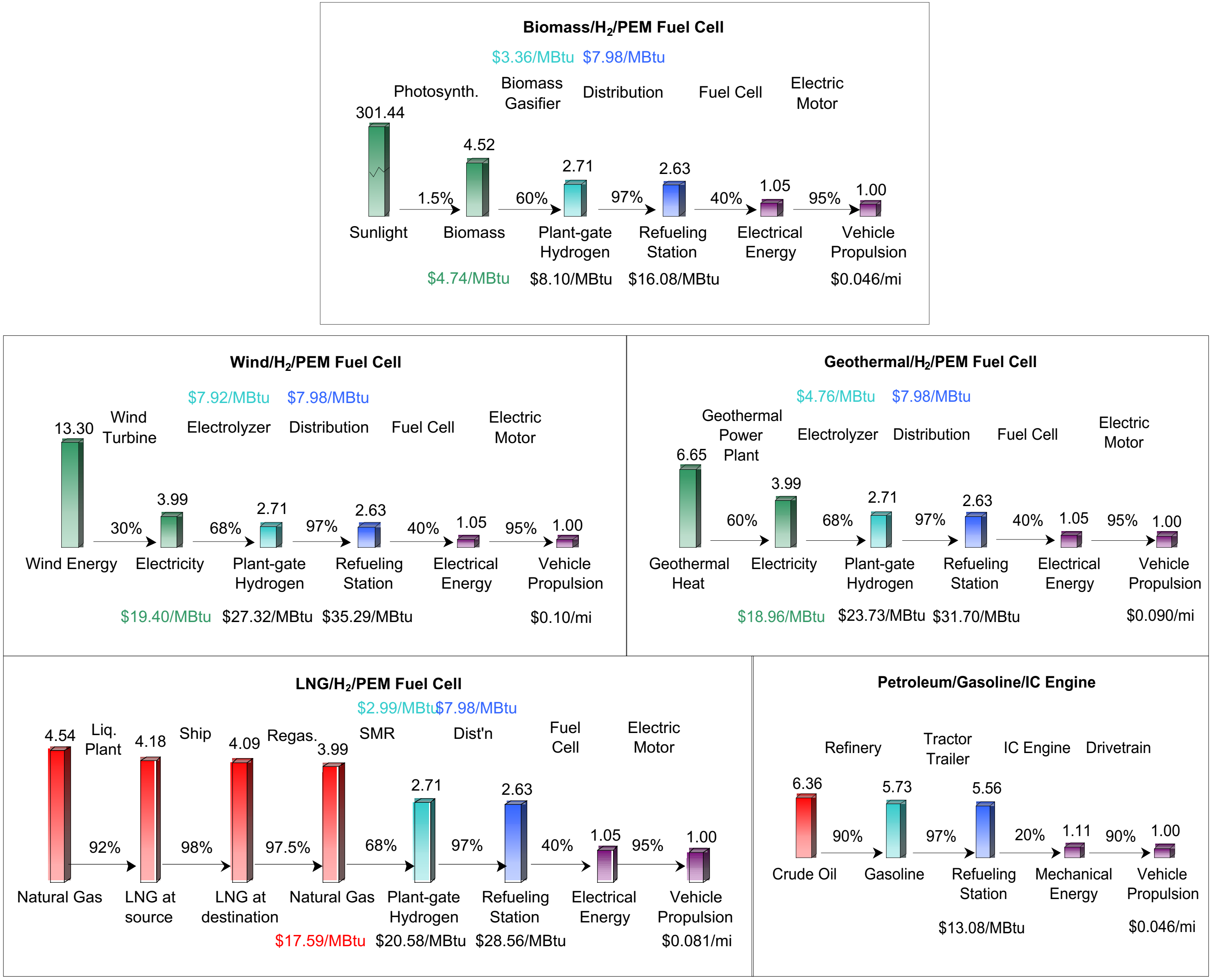
Figure 27 summarizes the results of the fueling costs analysis. The projected fueling costs indicate that fuel cell vehicles run on hydrogen produced from biomass, geothermal, and LNG could be economically competitive with conventional gasoline internal combustion engine vehicles.

Figure 27: Vehicle fueling costs from transportation fuel energy pathways

Fuel	Fuel Source	Delivered Fuel Cost ($/MBtu)	Conversion Device	Fueling Cost (¢/mile)
Gasoline	**Petroleum**	$13.08	IC Engine	8.2
Hydrogen	**Biomass**	$16.08	Fuel Cell	4.6
Hydrogen	**Geothermal**	$31.70	Fuel Cell	9.0
Hydrogen	**Wind**	$35.29 – 45.64	Fuel Cell	10.0 – 12.9
Hydrogen	**LNG**	$28.56	Fuel Cell	8.1

The complete pathway charts summarizing the full conversion process from primary energy resource to vehicle application for all four hydrogen sources as well as the baseline gasoline case are shown below in **Figure 28**.

Figure 28: Complete Hydrogen Energy Pathways



Comparative Metrics

In addition to the economic considerations described above, there are a number of other characteristics of the four pathways developed in this study that will determine the feasibility and desirability of their implementation. Those characteristics are described here.

Energy Security

Currently, nearly 90% of the energy used in the state of Hawaii comes from imported petroleum. This leaves the state very susceptible to the deleterious consequences of oil price spikes and shortages. Given the political instability found in many of the regions that provide oil for the world market, this is a very undesirable situation. One of the potential benefits of using hydrogen as a fuel in Hawaii's energy economy is a reduction in dependence on imported oil. The magnitude of this benefit depends on the primary energy resource used to generate the hydrogen.

Since biomass crops for hydrogen production would be grown on the islands, hydrogen via biomass gasification will significantly reduce the state's dependence on imported energy sources. However, some petroleum products will still be needed to grow and harvest the biomass crops. Fertilizer, which is produced from petroleum, will be required, particularly to generate the high crop yields necessary to generate low cost biomass feedstock. Harvesting equipment and trucks to transport the biomass material from the fields to the gasification reactor will most likely run on gasoline or diesel fuel. In spite of these petroleum requirements, biomass gasification derived hydrogen will improve the state's energy security.

Hydrogen derived from both geothermal and wind power is an entirely native energy source and requires no imported fuels or feedstocks. These two pathways would provide the greatest benefits to Hawaii's energy security.

LNG poses many of the same problems as imported petroleum. There are no available natural gas reserves on or around the Hawaiian islands at present, so it must be imported from elsewhere. Nevertheless, use of LNG would help to diversify Hawaii's energy imports, leaving the state less susceptible to price spikes and shortages.

Greenhouse Gases

Global warming is particularly important to island residents, especially in a location with as many indigenous species as found on Hawaii. Depending on the energy resource and conversion process, implementation of hydrogen energy pathways could substantially reduce Hawaii's emissions of carbon dioxide (CO_2).

Both the gasification and reforming steps of converting biomass to hydrogen produce CO_2. However, the vegetation used in the gasification reactor absorbs an approximately equivalent amount of CO_2 during the growing process. Thus, hydrogen produced from biomass gasification results in very little net emissions of greenhouse gasses. Some greenhouse gasses will be released due to the use of petroleum-derived fertilizers and fuel for the harvesting and transporting the biomass, as mentioned above.

Geothermal power plants release very small quantities of CO_2, which is dissolved in geothermal fluids. The quantity of CO_2 released is roughly 1000 times smaller than the amount released by fossil fuel power plants.

Converting wind power to hydrogen would not release any greenhouse gases, making this hydrogen pathway the most effective means for Hawaii to reduce its global warming emissions.

Like any other fossil fuel conversion process, reformation of natural gas produces significant quantities of CO_2. However, the amount of CO_2 produced per unit of energy delivered is less than that generated by direct combustion of petroleum products or coal. This pathway does much less to reduce greenhouse gas emissions than the three renewable hydrogen generation options.

Air Quality

While the Hawaiian Islands have sufficient wind to prevent compliance issues with air quality standards, localized air pollution is still a concern. Hydrogen is an extremely clean fuel with little or no emissions. When used in a fuel cell, the only product of conversion of hydrogen to electricity and heat is water. Combustion of hydrogen can generate small quantities of nitrogen oxides, but the overall amount of air pollution generated will be significantly less than that caused by burning fossil fuels. In fact, most of the pollution generated from a hydrogen generation and utilization pathway will probably be created during the hydrogen production step.

A small amount of pollutants will be produced by the gasification/reforming plant, primarily carbon monoxide and possibly some nitrogen oxides or particulate matter. All of these pollutants can be reduced or eliminated using conventional exhaust gas scrubbing techniques.

Geothermal plants can release some sulfur dioxide. However, the amount of pollution is significantly less than that generated by conventional fossil-fueled power plants.

Wind powered electrolysis generates no air pollution, and therefore has no adverse impacts on air quality. In fact, this technology is probably the cleanest of the three renewable pathways to hydrogen considered in this study.

Natural gas reformation into hydrogen produces some air pollution, but it is less than what is generated by burning petroleum products in a conventional power plant.

Availability

In addition to the potential benefits of implementing hydrogen energy pathways in Hawaii, the inherent limitations of the pathways must be considered. Most of the primary energy sources considered in the pathways for this study are not available on all of the islands in Hawaii. Since hydrogen storage and transportation technologies are expensive, inter-island transport of hydrogen was not considered as an option for this study. Therefore, for a given pathway to be available on a particular island, the primary energy source must be available on that island.

Hawaii's tropical climate could be ideal for high yield year-round energy crop production. Preliminary analysis using HES 95 transportation study assumptions for "available" land indicates that ample productive land could be available to fuel the entire state's ground fleet in the foreseeable future with hydrogen just from biomass grown on the Big Island. Further detailed agricultural and economic studies should be performed to increase confidence in this result. There is also considerable land suitable for energy crop production on Maui and Kauai. However, on the more heavily populated island of Oahu, it is assumed that agriculture is a low-value use for real estate, and thus it is unlikely that significant quantities of biomass could be produced for hydrogen production. Unfortunately, being the most populated of the islands, Oahu is also the largest market for energy. If the productivity assumptions of the HES 95 transportation study prove true, there may be enough biomass production capacity on the other islands to provide hydrogen for Oahu as well. As previously mentioned, this study assumes that transportation of hydrogen between islands is cost prohibitive. If this situation were to change, the other islands could conceivably export hydrogen to Oahu. In the near term, shipping the biomass materials directly to Oahu and converting it to hydrogen there may prove to be more cost effective.

Geothermal reserves are only available on the island of Hawaii. A 30 MW plant is already in operation, and some 30 MW of additional capacity are planned for the coming years. Some of this could be set aside for hydrogen generation.

All of the Hawaiian Islands have sites with excellent wind resources. However, wind power projects on the island of Oahu have historically been very expensive due to land costs and siting issues, so wind-generated hydrogen was not considered as a viable option there. Wind turbine/electrolyzer combinations are expected to be feasible for the other three well-populated islands: Hawaii, Maui, and Kauai.

LNG imports require a deep water port with the facilities to handle off-loading and storing large quantities of fuel. The only island that might be capable of providing such facilities is Oahu.

Commercial Experience

Even if the technologies involved in a particular pathway look promising, there is no guarantee that they will operate as expected in real world applications. For this reason, the level of commercial experience with a particular pathway is an important consideration in selecting potential pathways for demonstration or deployment.

To date, no one has built a full-scale biomass gasifier/reformer to generate hydrogen, so commercial experience is practically nonexistent. However, the gasification/reformation process is essentially an integration of several other technologies: biomass gasification, SMR, and water gas shift reactors. Biomass gasification is still a fairly new technology, but a demonstration plant that uses the product gas in a turbine to generate electricity is currently operating in Vermont. On the other hand, both SMR and water gas shift reactors are widely used in industry today. Hawaii does have substantial experience in using agricultural/food-processing wastes for energy production, but it is more likely that a plant would be run from dedicated energy crops rather than waste residues. Neither Hawaii nor the U.S. in general has significant experience in producing dedicated energy crops. This hydrogen production pathway has the least commercial deployment experience of the four considered for this study.

Producing power from geothermal energy is a well-developed and widely used technology. The Big Island has been generating electricity from geothermal energy for years. Electrolyzers have also been commercially used for decades, although research and development is still underway to make them cheaper and more efficient. The integration of these two technologies into a hydrogen generation plant should be straightforward. Similarly, wind turbines have been in widespread use for many years. Using an intermittent resource such as wind to run an electrolyzer may result in new operating and maintenance issues, but it is unlikely that these will prevent integration of the two technologies.

LNG is a fully commercialized import/export technology. The U.S. has been working with LNG for decades, and a number of countries without natural gas reserves (particularly Japan and South Korea) are turning to LNG as a way to import fuels that produce less pollution and greenhouse gas emissions than petroleum. SMR has been used extensively in commercial installations to produce hydrogen.

Entry Barriers

Each of the four hydrogen pathways considered (geothermal, wind, biomass, and LNG) faces “market entry barriers” that would have to be surmounted to establish a viable hydrogen fuel industry in Hawaii. These include:

- **Large up-front expenses not supported by near-term sales:** The hydrogen fuel market will likely develop in an incremental fashion, but many of the technologies considered here achieve the most favorable economics with large-scale production. Although the market may support such investments in the long-term, quick recovery of capital investments is unlikely. Wind turbines coupled with electrolyzers, both highly modular technologies, would minimize the up-front investment risk and allow the market to grow to the point where higher capacity plants are justified. The other pathways involve technologies that are less modular in nature and would probably require large initial capital investments.

- **Resource uncertainty:** Biomass is subject to extensive uncertainty with regards to fundamental resource price (no commercial models exist for dedicated energy crop production), as well as variable price uncertainty associated with annual fluctuations in weather and other factors that affect yield and harvest costs. Much as with drilling for oil or natural gas, exploration of geothermal reserves is a capital-intensive process without guarantee of success. Even well characterized resource areas require the drilling of test wells to determine the optimal locations for the production wells. On the other hand, wind resources and LNG availability are much more predictable.

- **Siting and land use issues:** Given the environmental and safety issues inherent in developing a large-scale fuel handling facility, finding a suitable site for LNG receiving, storage, and regasification facilities will prove difficult, perhaps even impossible (East West Center 1993). Locations for wind farms have to be reasonably close to the point of use to avoid increases in distribution costs and/or additional transmission infrastructure. They also have to be sited so as not to detract from the scenic beauty of tourist destinations on the islands. And the ability of a parcel of land to produce significant quantities of biomass crops does not necessarily imply that agriculture generates the highest value for that land.

- **Complex, multi-partnered business models:** Biomass and LNG systems, in particular, would require close coordination among a wide variety of diverse functionaries on the supply chain to establish a viable production system. Biomass, for example, would require the construction of a large, central processing plant. To supply this plant, one or more local farmers would need to provide dedicated energy crops, preferably on a long-term supply contract. Similarly, drying facilities and transportation would also be required. LNG has an even longer supply chain, requiring arrangements among natural gas producers, port-of-origin facilities, port-of-destination facilities, shippers, re-gasifiers, and reformers. Wind "farming", by comparison, requires an agreement with a landowner for facility siting and transmission right-of-way.

- **Uncertain Transportation Costs for Hydrogen:** Transporting hydrogen from renewable resource rich areas (Hawaii, Maui) to demand-rich areas (Oahu) would be an optimum method to utilize the energy resources. Transporting hydrogen via barges will require upgraded standards for high-pressure (5000 psi) hydrogen; infrastructure including tanks and trucks/trailers; and education of personnel on safety of this alternative gaseous fuel. Even intra-island distribution will require significant infrastructure investments. While none of these represent significant technical hurdles, there is much infrastructure modification to be considered for transitioning to a new gaseous fuel for transportation. Thus, the uncertainty of these costs and institutional issues represent a significant barrier.

Observations

Both the economic analysis results and the comparative metrics for all four hydrogen pathways and Hawaii's existing fuel options are summarized in **Figure 29**.

Figure 29: Summary of Analysis Results

		Economics		Comparative Metrics								
				Availability								
Fuel	**Fuel Source**	**Cost ($/MBtu)**	**Fueling Cost (¢/mile)**	**Oahu**	**Hawaii**	**Maui**	**Kauai**	**Energy Security**	**Greenhouse Gas**	**Air Quality**	**Commercial Experience**	**Entry Barriers**
Gasoline	**Petroleum**	13.08	8.2	X	X	X	X	☹	☹	☹	☺	☺
SNG	**Petroleum**	12.31 –16.92	-	X				☹	☹	☹	☺	☺
LPG	**Petroleum**	11.05 – 25.97	-	X	X	X	X	☹	☹	☹	☺	☺
Hydrogen	**Biomass**	16.08	4.6		X	X	X	☺	☺	😐	☹	☹
Hydrogen	**Geothermal**	31.70	9.0		X			☺	☺	😐	😐	😐
Hydrogen	**Wind**	35.29 – 45.64	10.0 – 12.9		X	X	X	☺	☺	☺	😐	☺
Hydrogen	**LNG**	28.56	8.1	X				😐	😐	😐	😐	☹☹

These results indicate that Biomass Gasification/Reformation represents the most economically viable hydrogen generation option. Based on the projected production and distribution costs generated for this analysis, hydrogen derived from this source could compete with Hawaii's existing fossil fuel options. It would also substantially improve Hawaii's energy security while reducing greenhouse gas emissions. The biggest hurdle to implementation of this pathway is the lack of experience with the technologies involved. The processes for producing high yields of energy crops and converting the resulting biomass material to hydrogen are still in the research and development phase. Implementation of a biomass-to-hydrogen pathway would require large investments in land, infrastructure, and equipment, but the uncertainties resulting from the lack of commercial experience may deter investors.

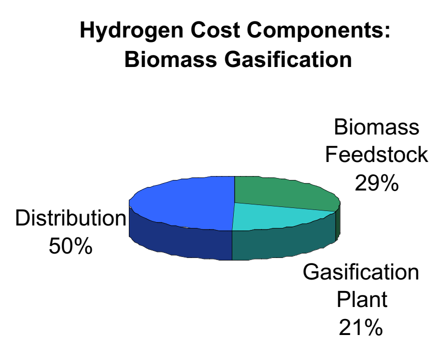


Figure 30

Figure 30 illustrates the primary cost components for hydrogen produced from biomass. Half of the delivered cost of hydrogen from this source stems from distribution expenses, so efforts to reduce costs should focus on hydrogen storage technologies. Nearly a third of the cost of hydrogen from biomass is attributable to feedstocks, indicating that R&D focused on improved crop yields could have a beneficial impact on the cost of hydrogen from biomass.

Hydrogen derived from geothermal power would also improve Hawaii's energy security and reduce its greenhouse gas emissions. Geothermal power is already available in Hawaii, so the market entry barriers for this pathway would not be as difficult to overcome. However, hydrogen produced from geothermal-powered electrolysis is projected to be nearly twice as expensive as that generated from biomass, and more expensive than existing fuel options. Its availability is limited to the Big Island, the only island with proven geothermal resources. The cost component breakdown for hydrogen derived from this pathway (see **Figure 31**) illustrates that the biggest cost driver is the electricity, which accounts for 60% of the delivered cost of hydrogen. More favorable rate structures could significantly improve the economics of this pathway. Although the electrolyzer represents a fairly small fraction of the cost of the system (15%), technology improvements that improve the conversion efficiency would reduce the amount of electricity required and thus the electricity costs.

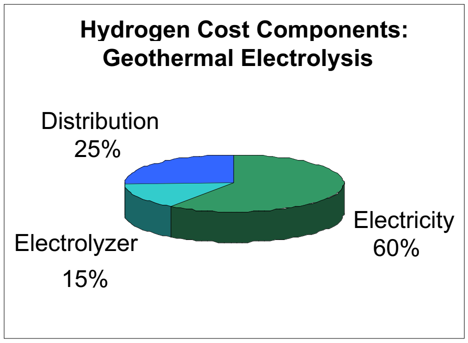
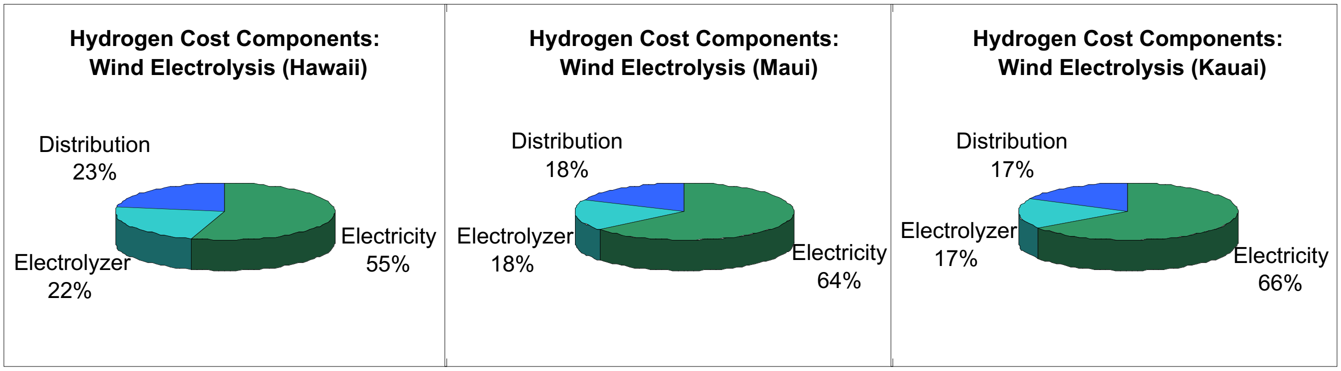


Figure 31

Wind power is the most environmentally benign pathway to hydrogen, resulting in no emissions of greenhouse gases or air pollutants. This resource is available on most of the Hawaiian islands, and the modular nature of the technologies involved precludes the need for large up-front capital investments. The wind power pathway to hydrogen is, however, the most expensive of the four pathways studied. Hydrogen from wind power costs nearly three times as much as that derived from biomass. As **Figure 32** illustrates, most of this higher cost derives from electricity costs, which account for 55% (Hawaii) to about 65% (Maui and Kauai) of the cost of delivered hydrogen. Electrolyzer costs are also higher for wind-generated electricity, due to the lower capacity factor for wind turbines. Cost reduction efforts should focus on less expensive wind-generated electricity or more efficient electrolyzers, which would reduce the amount of electricity required.

Figure 32



Imported liquefied natural gas was considered as an interim source of hydrogen for Oahu, where it is unlikely that renewable hydrogen pathways will be implemented. LNG-derived hydrogen would be less beneficial to Hawaii's energy economy and environment than renewable-derived hydrogen, but it would still reduce greenhouse gas emissions and increase the diversity of the energy supply. Fuel cell vehicles running on hydrogen derived from LNG may be able to compete with gasoline as a transportation fuel. However, significant barriers to the implementation of this pathway exist, including siting concerns and infrastructure investments required for the establishment of an LNG receiving facility. As **Figure 33** indicates, the primary cost driver for hydrogen derived from this pathway is the LNG feedstock. These costs could decrease significantly as the global LNG market develops or if Hawaii takes advantage of economies of scale and utilizes imported natural gas in other sectors of its energy economy.

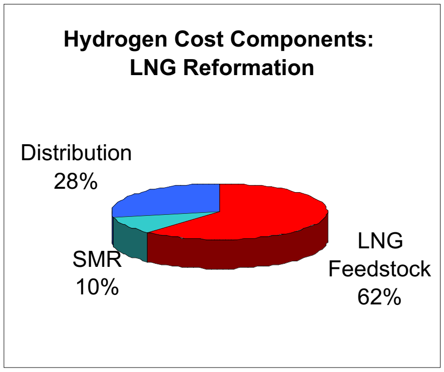


Figure 33

This study focused on long-term, sustainable sources for hydrogen production. The analysis considered each of the production technologies in a dedicated hydrogen generating facility. However, the Hawaiian Islands' electricity supply and demand patterns may present an opportunity for the purchase of lower cost off-peak electricity. A detailed analysis of the Islands' generating capacity, load profiles, and tariff structures was out of the scope of this study, so this option was not covered in the present work. However, we recognize that off-peak electricity could provide a potentially lower cost pathway to hydrogen that could provide an effective near term market entry strategy during the development of hydrogen supply infrastructure and applications.

Section 5: Recommendations: A Roadmap for Realizing a Hydrogen Energy Future in Hawaii

The prospect of utilizing hydrogen as an energy carrier in Hawaii could help achieve all four primary energy objectives outlined in the state's revised statutes. These objectives and hydrogen's potential contributions include:

- **Dependable, efficient, and economical statewide energy systems capable of supporting the needs of the people:** Hydrogen in fuel cell-powered cars can compete economically with gasoline internal combustion engine cars in Hawaii by the end of the decade. With investment in hydrogen infrastructure, other applications including commercial power, domestic (heating and cooking), and power plants may prove economical.

- **Increased energy self-sufficiency where the ratio of indigenous to imported energy use is increased:** Hydrogen can dramatically improve Hawaii's energy self-sufficiency as it can be manufactured from geothermal, wind, or solar electricity or via gasification of indigenous biomass feedstocks. Using these domestic energy resources for transportation fuel can dramatically reduce reliance on imported oil.

- **Greater energy security in the face of threats to Hawaii's energy supplies and systems:** Hydrogen can reduce vulnerability to both supply and price volatility that significantly impact Hawaii's economy. Furthermore, technology and expertise for hydrogen can be exported to other nations that are incorporating hydrogen energy.

- **Reduction, avoidance, or sequestration of greenhouse gas emissions from energy supply and use:** Hydrogen can reduce greenhouse gas emissions when it is both produced and used. Hawaii can help itself and at the same time assist the United States in meeting its commitments for greenhouse gas reduction targets.

In May 2001 the National Energy Policy Development Group released the document, *National Energy Policy* (NEP), ISBN 0-16-050814-2. The report offered a comprehensive review of U.S. energy issues and indicated that, "alternative energy technologies such as hydrogen show great promise." The document also recognized that "the primary challenge to using more hydrogen in our energy systems is the cost of producing, storing, and transporting it. A serious challenge confronting a move toward distributed energy is the transition away from the centralized energy systems of supply and production." The report identifies that "General Motors, Ford, Daimler Chrysler, Texaco, Shell, and BP are collectively spending between $500 million and $1 billion per year on fuel cells, hydrogen storage, and infrastructure development for passenger vehicles. Ongoing bus demonstrations are expected to commercialize fuel cell power hydrogen buses in the next five years." The NEP report concludes with a series of recommendations to the Secretary of Energy, which included the development of hydrogen as a next generation technology. These recommendations included the following:

- An education campaign that communicates the benefits of alternative forms of energy, including hydrogen;
- Focused R&D efforts on integrating programs on hydrogen, fuel cells, and distributed energy; and
- Support for legislation reauthorizing the Hydrogen Energy Act.

The NEP report underscores the heightened national concern over energy prices, supply, and reliability coupled with technology advances that have attracted substantial investment by industry. The findings of this report and national energy interests have created unprecedented interest in the development of hydrogen energy technologies and unique opportunities for the public and private entities with expertise in this area. Hawaii is well positioned to assume a leadership role to demonstrate and validate hydrogen and fuel cell technology because of its island economy, isolation, high energy prices, and the United States business infrastructure. The following are characteristics of Hawaii that are the most attractive attributes to the hydrogen energy industry:

- **Available geothermal and other indigenous renewable resources:** Hawaii’s rich renewable resource diversity provides a variety of primary energy sources from which to produce hydrogen. The availability of geothermal energy on the Big Island is a specific opportunity to use low-cost renewable electricity to produce hydrogen.

- **High transportation fuel and other energy costs:** Hawaii’s energy costs (including gasoline, electricity and natural gas) are typically at least 25 percent greater than energy prices experienced on the U.S. mainland. These higher prices create easier competition for new technologies and fuels to compete in Hawaii’s energy economy.

- **Pacific Rim trade opportunities:** Hawaii represents an excellent opportunity for Japanese and U.S. companies and governments to work together on hydrogen projects. Several industrial joint ventures and world projects already exist, creating trading and marketing opportunities for both nations as well as for developing economies of the Pacific Rim.

- **University Center of Excellence:** Hawaii has developed scientific and technical expertise in hydrogen and fuel cells at the University of Hawaii as part of their Hawaii Natural Energy Institute. The availability of talent is attractive to companies looking to conduct performance testing of hydrogen energy systems.

- **Market for integrated large-scale projects:** An integrated hydrogen project requires hydrogen production from renewable energy, storage tanks, distribution infrastructure, fuel cells, and a fleet of hydrogen-powered vehicles. Hawaii has the ability to create these projects in controlled situations from which to test and validate integrated hydrogen systems.

The technology advances, industry interest, environmental concerns, and high energy prices are not enough, though, to make hydrogen energy a reality in Hawaii. First, there are energy interests in Hawaii that will understandably want to protect the status quo and their economic interests. Second, institutional and regulatory policies favor traditional energy technologies and infrastructure. Hydrogen energy represents a significant paradigm shift from which to view energy and economic possibilities. It will take political and industry leadership to modify policies and invest resources to make hydrogen in Hawaii a reality.

Our analytical results indicate that biomass-, geothermal-, and/or LNG-produced hydrogen will be able to compete in Hawaii's transportation fuel markets by the end of the decade with the predicted availability of fuel cell transportation. Wind energy can produce low-cost electricity, but its intermittent nature results in low capacity factors and higher-cost hydrogen. These results are predicated on the availability of the primary energy resource, which is island specific. Thus, an opportunities analysis for each island to incorporate hydrogen was conducted.

The Big Island (Hawaii) possesses the greatest diversity of renewables including solar, wind, biomass, and geothermal. It is the only island with a geothermal power plant, and the electricity demand patterns typically yield available off-peak electricity from which to make hydrogen. Much of the economic growth on the island centers on the commercial development on the Kona coast of the island. This region contains an airport, the Natural Energy Laboratory, commercial resorts, commercial agriculture, and a burgeoning tourist industry from which an integrated hydrogen energy project can be developed. These resources represent an ideal mix and location and should be able to attract both federal government and private industry resources to conduct such a project.

Oahu contains the greatest population and the urban center of Honolulu; this represents the greatest opportunity to use hydrogen and fuel cells. Transportation applications including tourist transport, military transport, airport support vehicles, and other fleet applications create a large opportunity for a clean hydrogen-fueled fleet. Urban power issues such as transmission limitations, power quality, and commercial peak power create additional opportunities for stationary fuel cells. Unfortunately, electricity demand patterns and limited availability of renewable resources makes Oahu a less than ideal place to produce hydrogen. Large quantities of hydrogen from imported oil are available from the existing refinery capacity. This hydrogen may be useful for near-term projects, but will not offer the energy security benefits desired in the long term.

Both Maui and Kauai have tremendous biomass, solar, and potential wind resources. High electricity costs from wind and fossil fuels make producing hydrogen from electrolysis imprudent. Large biomass availability makes hydrogen gasification an attractive option, except limited commercial experience makes that option unlikely for several years. A dispersed population makes transportation and utility (domestic) uses the highest likely value. Additionally, the feasibility of "importing" hydrogen from Hawaii to these islands will need to be explored.

The unique attributes of each of the Hawaiian Islands cause us to recommend a roadmap or blueprint of activities that incentivize business and government to work in partnership and share the risks of creating a hydrogen energy future. To achieve this energy future, we recommend the following roadmap activities to be implemented by the state of Hawaii. **Figure 29** shows the roadmap graphically; it contains the following roster of activities:

- **Hold a *stakeholder workshop* with existing energy and economic interests:** A meeting should be organized by DBEDT to hold discussions with energy interests from both inside and outside the state of Hawaii. The state should discuss its perspectives regarding hydrogen energy and incentives to develop clean energy and high-technology business. Energy companies from both within and outside Hawaii should discuss their perspectives on hydrogen and fuel cells and the prospects for bringing them to market in Hawaii. The end product should be a consensus blueprint for a public/private partnership to create hydrogen energy markets in Hawaii.

- **Perform a comprehensive engineering evaluation and market study for the production of hydrogen on Hawaii and Oahu:** The preliminary analysis conducted in this study does not suffice when considering significant hardware, policy, and economic investment. Detailed engineering cost studies focused on Hawaii and Oahu will be conducted using actual cost data for electrolyzers, hydrogen automobiles, off-peak electricity, natural gas, and fuel cells provided directly from industry commercial sources. Market characteristics for clean transportation, fleet transportation, distributed electricity, remote power, and domestic applications will be evaluated both with and without policy options under consideration. This more detailed study will assist legislators, regulators, companies, and investors in evaluating options for hydrogen energy.

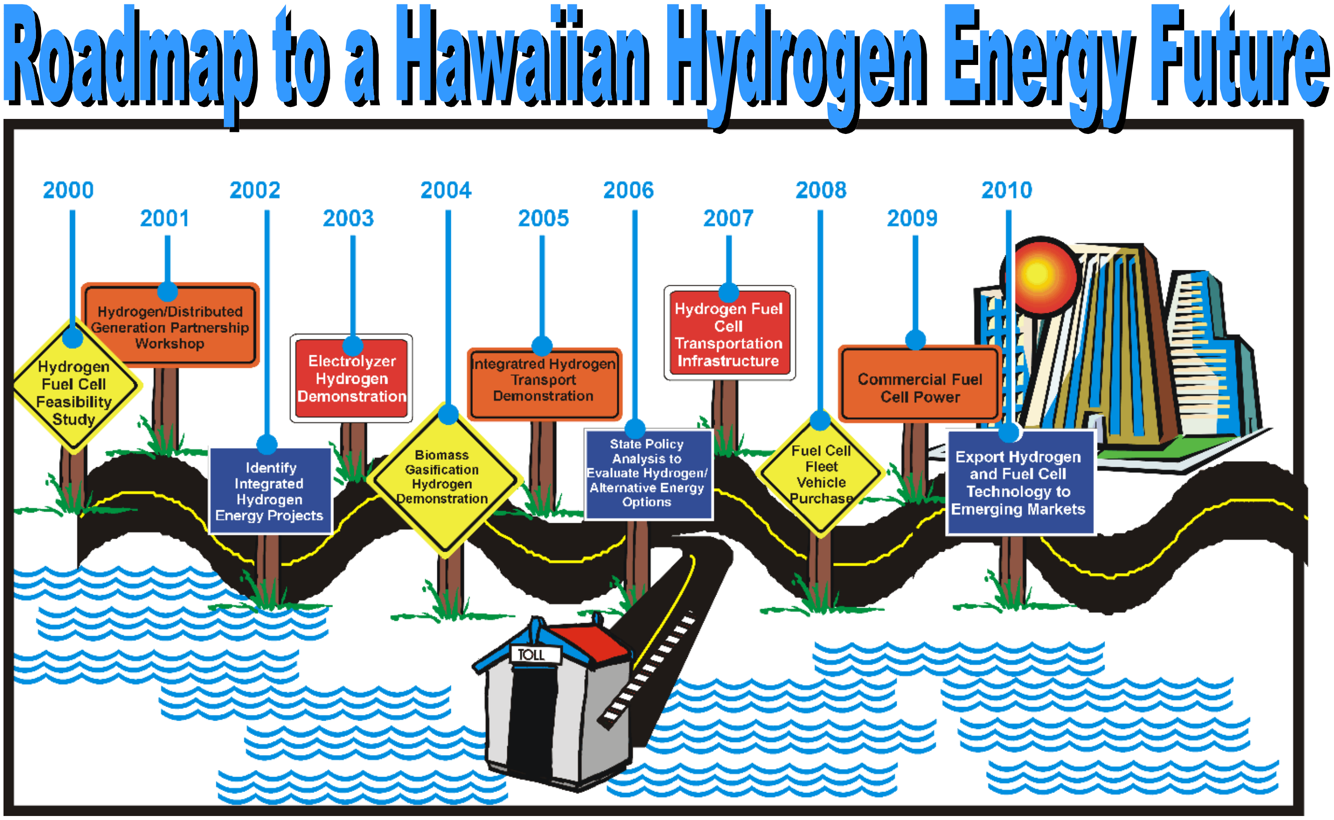


Figure 29: Recommendations include a roadmap of activities to validate hydrogen energy.

- **Conduct engineering assessments of biomass for hydrogen for both Maui and Kauai:** The smaller and less populated islands have potential renewable resources from which to produce hydrogen, but fewer opportunities for utilization. Engineering assessments that evaluate gasification of biomass and utilization of fleet transportation will be evaluated. Hydrogen produced on Hawaii or Oahu and shipped to Maui and Kauai will also be investigated.

- **Initiate pilot projects to install a multi-megawatt electrolyzer to produce hydrogen from indigenous resources on the Big Island:** The Big Island of Hawaii possesses the most diverse renewable resource base from which to produce hydrogen. More than 50 MW of potential geothermal energy, extensive biomass feedstock, and potential wind energy represent opportunities to produce hydrogen via electrolysis or gasification. Furthermore, a localized automotive fleet including airport, tourist transport, and personal transportation can likely be structured in the Kona region. Pilot projects to validate performance, reliability, and economics could be initiated over the next several years.

- **Re-examine current environmental and energy policies and evaluate options to promote hydrogen energy:** The state legislature must consider policy options if hydrogen energy market options are to become attractive for industry investment. Two types of policy options must be considered. First, policy options to open energy markets including net metering and interconnection standards, and promote clean energy policies such as adoption of renewable portfolio standards. Second, policies to attract high-technology business that would also stimulate hydrogen and fuel cell energy, and policies to stimulate economic investment via trade-free zones, investment tax credits, and other incentives.

- **Initiate pilot projects that include distribution of hydrogen produced on Hawaii to other islands:** The Big Island of Hawaii clearly represents the best opportunity to produce hydrogen that is cost competitive with other energy carriers (electricity, gasoline, natural gas, etc.) However, many of the most favorable applications for using hydrogen exist on Oahu, Maui, and Kauai. The cost of transporting hydrogen over distances has been a key focus of research and development and represents significant cost uncertainties. A pilot project should be commissioned to test the feasibility of "exporting" hydrogen from Hawaii to one or several other islands with promising applications.

- **Consider creation of a public/private sector partnership for economic development of hydrogen infrastructure:** Opening up energy markets for hydrogen and fuel cells will require a concerted effort from government and industry over a decade to create demand, encourage technology investment, educate the public, and build hydrogen infrastructure. The state of Hawaii should research and put in place policies to attract the industry and federal funding needed to make this happen.

Hydrogen has the potential to revolutionize the way we produce and use energy in the United States and worldwide. Hawaii, in turn, has the opportunity to assume a leadership role in the transition from a fossil-fueled energy society to a cleaner energy future. Hydrogen is the link between renewable energy and clean transportation fuel. The roadmap we have defined will result in a highly visible worldwide leadership position for Hawaii likely to attract significant economic investment into the state.

The state of Hawaii has played a hydrogen leadership role for more than two decades. The Hawaii Natural Energy Institute has been a recognized Center of Excellence in hydrogen research and development activities. On the policy front was the passage of the Spark Matsunaga Hydrogen Research and Development Act of 1990 that resuscitated a dormant federal research and development program. State Representative Hermina M. Morita is continuing the tradition begun by Senators Matsunaga, Inouye, and Akaka and has espoused a vision to move Hawaii from a petroleum-based economy and energy importer to a hydrogen-based economy and energy exporter. Progress in new technologies; unprecedented industry investment; movement to a service-based, high-tech economy; and changing federal energy policies indicate the time is now for Hawaii to seriously investigate this possibility. Our analysis indicates that opportunities exist in Hawaii for hydrogen to be cost-competitive and that those opportunities will likely increase throughout this decade.

APPENDICES

APPENDIX A: Hydrogen Energy Technologies

Production

Steam Methane Reforming (SMR)

Steam methane reforming (SMR) is the most common and least expensive method of producing hydrogen − almost 48% of the world's hydrogen is produced from SMR. SMR can be applied to hydrocarbons such as ethane and naphtha, but heavier feedstocks cannot be used because they may contain impurities and the feed to the reformer must be a vapor. Other processes, such as partial oxidation (POX), are more efficient with higher hydrocarbons. There is a significant economy-of-scale for these systems; capital costs represent 32-48% of large hydrogen plants, but more than 60% of the costs for smaller plants. Hydrogen prices from this process range from $5-8/Gigajoule (GJ).

Coal Gasification

Hydrogen production from coal gasification is a well-established commercial technology, but is only competitive with SMR where oil and/or natural gas are expensive. Three primary types of gasifiers are used: fixed bed, fluidized bed, and entrained flow. Because there are significant coal reserves in many areas of the world, coal could replace natural gas and oil as the primary feedstock for hydrogen production. However, this technology has environmental impacts (e.g., feedstock extraction) that may prove significant in the future.

Noncatalytic Partial Oxidation Hydrocarbons

The noncatalytic partial oxidation (i.e., gasification) process can be used to produce hydrogen from heavy hydrocarbons such as diesel fuel and residual oil. Any hydrocarbon feedstock that can be compressed or pumped may be used in this technology. However, the overall efficiency of the process is less that that for SMR (65-75%) and pure oxygen is required. Two commercial technologies, the Texaco Gasification Process and the Shell Gasification Process, have been developed and are available. Feedstock costs represent 15-25% of the final cost of hydrogen produced from this method. Like other thermal processes, there is a significant economy-of-scale that favors large plant sizes.

Biomass Gasification

As with coal gasification, biomass may be gasified using a variety of methods, primarily indirect and direct gasification. Indirect gasification, as exemplified by the Batelle-Columbus Laboratories and Future Energy Resources Corporation (BCL/FERCO) gasifier, uses a medium such as sand to transfer heat from the char combuster to gasification vessel. In direct gasification, heat to the gasification vessel is supplied by the combustion of a portion of the feed biomass.

The major operating cost, by far, for this technology is the feedstock. Using projected biomass costs of $46.30/dT (dry ton), the feedstock price is about 40% of the cost of hydrogen from large facilities (1-3 million Nm^3/d). This represents the expected feedstock price from dedicated biomass production. Waste biomass, however, may be available for as low as $16.50/dT. Another important factor in the price of the hydrogen is the by-product steam credit; this credit is roughly equivalent to all variable operating costs, except feedstock. In general, hydrogen produced via direct gasification is expected to cost slightly more (about 5%) than that from the indirect mode.

Biomass Pyrolysis

The process of biomass pyrolysis (complete combustion of the feedstock) is still in the development stage and not a commercial process. In this process, biomass is thermally decomposed at a high temperature (450-550 degrees C) in an inert atmosphere to form a bio-oil composed of about 85% oxygenated organics and 15% water. The bio-oil is then steam-reformed using conventional technology to produce hydrogen. Alternatively, the phenolic components of the bio-oil can be extracted with ethyl acetate to produce an adhesive/phenolic resin co-product, and the remaining components can be reformed as in the first option. The product gas from both alternatives is purified using a standard pressure swing adsorption (PSA) system.

Electrolysis

A small amount (4%) of the world's hydrogen is produced by electrolysis of water. For users requiring small amounts of extremely pure hydrogen, electrolysis can be a cost-effective means of obtaining the required hydrogen. The major cost factor for electrolysis is the electricity. In some cases, using an electricity price of $0.049/kWh, this cost is more than 80% of the resulting hydrogen selling price. For renewable technologies, the capital costs dominate. For example, the annual capital costs of the photovoltaic (PV) system could be as much as 85% of the hydrogen price. The cost of electricity is a major concern because it is three to five times more expensive a "feedstock" than fossil fuels. In fact, the high cost of the electricity is the driving force behind the development of high-temperature steam electrolysis. In this process, some of the energy driving the process can be from steam instead of electricity. For example, at 1000 degrees C, more than 40% of the energy required could be supplied as heat.

The cost of hydrogen from water electrolysis is higher than many other options, estimated at $11-$25/GJ. However, in today's electrolysis applications, the hydrogen is produced on-site and on-demand, without the need for transportation and storage costs. This results in a competitive cost compared to the cost of small amounts of "delivered" hydrogen. Cost for proton exchange membrane (PEM) electrolyzer systems are expected to be less than the conventional alkaline electrolyzers once capital cost reductions for automotive PEM Fuel Cell Systems are realized.

Photochemical

There are two types of photochemical systems that can be used to produce hydrogen: those that use semiconductor surfaces as catalysts and those that use in-solution metal complexes as catalysts. In either case, the catalysts capture solar energy and trigger chemical reactions that produce hydrogen from water molecules.

In the first type, the semiconductor surface absorbs solar energy and acts as an electrode for water splitting. While significant progress in this area has been achieved, this technology is still at an early stage of development. Reported photo-conversion efficiencies have increased from less than 1% (hydrogen energy as a percentage of incident sunlight energy) in 1974 to more than 8% currently. Even higher efficiencies have been obtained with devices using an external voltage bias, but these systems may be less economic because they would require an outside electric source to help drive the reaction. In either case, operating lifetimes have been limited because of conductor or semiconductor corrosion or other chemical effects. A promising approach to improve the efficiency is a tandem cell consisting of gallium-arsenide and gallium-indiumphosphide layers. Theoretically, operating efficiencies exceeding 30% are achievable with this design.

The second type of photochemical systems is the use of soluble metal complexes as photochemical catalysts. When the dissolved metal complex absorbs energy, it creates an electric charge separation that drives the water-splitting reaction. Research has been directed toward theoretical efforts to create a new catalyst molecule that can more efficiently dissociate water to separate out the hydrogen. This approach is currently less advanced than the semiconductor methods but offers the prospect of avoiding corrosion problems.

Photobiological

Hydrogen can be produced by some biological systems, as seen in certain algae that generate hydrogen under specific conditions. Pigments in algae absorb solar energy, and enzymes in the cell act as catalysts to split water. Some bacteria can also produce hydrogen, but unlike the algae they require a substrate for growth and are presently less attractive economically. Research has been performed to understand the detailed biological mechanisms in these systems, but conversion efficiencies, however, are still low. Also, the conditions required to produce hydrogen stress the algae and therefore reduce their productivity.

In general, these types of systems require substantial improvements in efficiency and reductions in projected capital investment costs to become attractive hydrogen production processes. Efficiency improvements could result from increased understanding of the role of absorbed energy that is not used to produce hydrogen. Lowering the cost of biological reactor systems could be achieved with genetic improvement or immobilization techniques. It is also important to address the need to improve stability by extending the active periods of hydrogen production in batch or continuous cultures.

Storage

Physical

Compressed gas and cryogenic liquid storage of hydrogen are both commercially available today. But, for cryogenic liquids, there are significant energy penalties associated with the liquefaction process and the costs are high. Also, common compressed gas storage at 2000 to 2500 psi is similarly unattractive because weight and volume penalties of the required containers are high. However, new, lightweight graphite composites developed for aerospace applications offer the potential for high-pressure (up to 6000 psi) hydrogen storage in lightweight containers for transportation applications. Additional materials research and safety testing are needed to develop practical designs with these materials to assure safe and reliable operation and fail-safe characteristics.

Gas-Solid Adsorption

In addition to physical storage, hydrogen can also be stored using activated carbon. The volumetric storage density of hydrogen adsorbed on a solid can actually be higher than compressed gas storage. Total weight and energy efficiency of the complete storage system, however, have to be considered.

One storage option emerging from the space program is low-temperature adsorption of hydrogen at 150 K (123.2 °C) on activated carbons. This approach has stimulated considerable interest for both stationary and mobile applications. The gravimetric and volumetric energy densities achievable from activated carbon systems are comparable to liquid hydrogen systems. Experimental storage capacities have exceeded the 4 wt% level, which is equivalent to the corresponding volumetric storage density of liquid hydrogen, and additional improvements are possible.

Metal Hydrides

Another storage option that has received much research attention is metal hydrides. Hydrides are safe and have high volumetric storage density, but are expensive compared to compressed gas or projected adsorption systems. Low-cost hydrides capable of storing large amounts of hydrogen need high temperatures to liberate the hydrogen. Alternatively, hydrides that require low temperatures for hydrogen liberation are more costly and provide less storage capacity.

The cost of a hydride system will depend on the type of hydride used, the desired operating temperature and capacity, and the system component costs such as packaging and heat exchangers. If practical systems are to be developed, these operating characteristics must be addressed. Also, hydride systems must demonstrate long life under repeated cycling without significant loss in storage capacity. The storage capacity can be adversely affected in the presence of trace amounts of impurities in the hydrogen, but additional research efforts could make the materials less susceptible to impurity effects.

A potentially new approach in hydride storage is the use of polyhydride complexes based on cobalt and other transition metals. These materials show higher storage capacities as well as faster recycling, both of which are attractive characteristics for hydrogen storage systems. Research on phase-change materials to maintain the thermal balance of a hydride storage system has also shown promising results and may warrant further attention.

Chemical Hydrides

Chemical hydrides constitute another method for storing hydrogen, primarily for seasonal storage (i.e., > 100 days). Seasonal storage would be an option for countries, such as Canada, that have a surplus of hydropower during the summer but an energy deficit during the winter. Numerous chemical hydrogen carriers, including methanol, ammonia, and methyl-cyclohexane, show promise to facilitate this type of storage. Use of a chemical system is advantageous because the transport and storage infrastructure is already in place, the technology is commercial, and liquid storage and handling are easier.

Carbon-Based Materials

Theoretically carbon-based hydrogen storage materials can store significant amounts of hydrogen at room temperature. Carbon nanostructures could provide the needed technological breakthrough that makes hydrogen-powered vehicles practical. Two carbon nanostructures of interest are single-walled nanotubes and graphite nanofibers. Single-walled carbon nanotubes, which are elongated pores with diameters of molecular dimensions, absorb hydrogen by capillary action at noncryogenic temperatures. Single-walled nanotubes have recently been produced and tested in high yields using a number of production techniques, and have demonstrated hydrogen uptake of 5-10% by weight at room temperature. Graphite nanofibers are a set of materials that are generated from the metal catalyzed decomposition of hydrocarbon-containing mixtures. Carbon nanostructure systems are expected to significantly reduce costs because there is no cryogenic requirement, but the technology is still in the early development stages and costs have not yet been developed. Currently there are no commercial applications of carbon-based hydrogen storage.

Utilization

Proton Exchange Membrane Fuel Cell

The PEM fuel cell has an efficiency of 40-60% and operates at near ambient temperatures (80 degrees C) using an ion exchange membrane (e.g., fluorinated sulfonic acid) as an electrolyte. Platinum-based catalysts are used at both the cathode and anode. Because of its low operating temperatures internal reforming is not possible, but the PEM has excellent load-following capabilities and a startup time of 1-3 seconds. Current capital costs of PEM fuel cells are estimated at $10,000/kW in the pre-commercial phase and are projected to be $1,000/kW for commercial systems (Carlsson et. al. 1997 and Wurster 1998). Many automotive experts believe that capital cost will need to drop to $100/kW for automotive applications to be cost effective.

Phosphoric Acid Fuel Cell

The PAFC is commercially available for stationary applications. ONSI, a division of International Fuels Cells, produces the most well-known PAFC system today. More than 100 of these systems have been sold at the prototype price of $3,000/kW and portable units have been demonstrated. Other developers include Fuji Electric Corporation, Toshiba Corporation, and Mitsubishi Corporation.

The PAFC uses platinum-based catalysts at both electrodes, and as the name suggests, the electrolyte is concentrated phosphoric acid. PAFC systems operate at 150-220 degrees C and can achieve 37-42% efficiency (HHV) on natural gas. Because of the relatively low temperatures, hydrocarbons must be reformed externally. In addition, carbon monoxide (CO) is a catalyst and must be below 3-5 vol%.

Solid Oxide Fuel Cell

The SOFC uses a solid-state system that operates at high temperatures (1,000 degrees C). Because it is a two-phase system (solid and gaseous) instead of the three-phase systems found with other fuel cells, it is a simpler design. Other advantages of this system include the absence of noble metal electocatalysts; CO is not a poison and can be directly oxidized; high-grade waste heat is available for steam generation or other applications. In addition, because of the high operating temperatures, the SOFC can reform hydrocarbon fuels internally without a catalyst. Thus, it is expected to operate on hydrocarbons rather than on pure hydrogen.

Currently, the SOFC is not commercially available, although many companies are developing these systems. SOFCs could be used to supply the electrical and thermal requirements of commercial buildings, and they could probably provide a better match for the thermal-to-electric ratio for buildings than current cogeneration systems. SOFC systems would also likely be good candidates for industrial cogeneration applications because of high thermal load and the potential for integration. Costs for SOFC systems for distributed power systems are not available, but the estimated operating cost is currently in the $10,000/kW range.

Molten Carbonate Fuel Cell

The MCFC uses a mixture of alkali (sodium and potassium) carbonates as its electrolyte, contained in a ceramic matrix. Inexpensive nickel and nickel oxide are used as the anode and cathode, respectively. With an operating temperature of 600-700 degrees C, internal reforming is possible with the addition of a catalyst. Another advantage of the high temperature is the potential for heat integration of steam generation. Although CO is not a system poison, sulfur (H_2S) is detrimental at greater than ppm levels (Hirschenhofer et al. 1994). One of the most significant drawbacks to the use of this fuel cell with pure hydrogen is the requirement for CO_2 at a 1:1 ratio with hydrogen at the cathode. Recycling CO_2 from the anode to the cathode would meet most of this demand, but not all the CO_2 could be recovered. Obtaining the makeup CO_2 for a pure hydrogen feed could prove unworkable.

The Electric Power Research Institute completed a detailed design of a 2-MW MCFC system. This technology sheet estimated that the cost of a pre-commercial 2-MW MCFC system would be $1,700/kW and would fall to $1,200/kW for commercial units.

Alkaline Fuel Cell

Alkaline fuel cells use an alkaline electrolyte such as sodium hydroxide (NAOH) or potassium hydroxide (KOH). They operate at atmospheric pressure and 70 degrees C. Unfortunately, CO_2 will react with the electrolyte and render it ineffective and so it must be removed. Currently, AFC systems are used primarily in space and submarine applications. Their costs are high, but several companies are working aggressively on designs and cost-reduction improvements for terrestrial applications.

APPENDIX B: Companies Pioneering the Transition to a Hydrogen Economy

Automotive Companies

The Ultimate
Driving Machine

BMW has been researching and developing engines and cars that can run on hydrogen for over two decades. The stumbling block is the absence of either a nationwide network of filling stations for the new fuel or the means to produce sufficient quantities of hydrogen economically. BMW is working to hasten the development of both. For now, BMW's **hybrid cars**, along with the natural gas-powered models already available, represent the immediate future of alternative fuels. Hybrids have the advantage that they can run on either gasoline/diesel or liquid hydrogen, switching automatically between the two, and are an important step on the road towards a new era in propulsion technology. Also, the world's first filling station for liquid hydrogen, developed by BMW together with big-name partners, has already gone into operation.

The new 750hL is the latest in a line of BMW hydrogen-powered vehicles. This production-ready car is a hybrid 12-cylinder combustion engine whose two independent electronically controlled fuel induction systems allow it to run on either gasoline/diesel or hydrogen. In contrast to a fuel cell-powered electric motor, the 5.4-litre hydrogen engine offers excellent acceleration and pulling power, while the specially insulated 140-litre tank for the liquid hydrogen ensures a range of 400 kilometers. On February 1, 2001, the BMW hydrogen fleet started its world tour entitled "CleanEnergy WorldTour 2001" that included stops in Dubai, Brussels, Milan, Tokyo, and Los Angeles.

DAIMLERCHRYSLER

DaimlerChrysler has been developing fuel cell technology for automobile applications since 1991 and plans to mass-market **fuel cell vehicles by the middle of this decade**. In February 1999, the Icelandic consortium Vistorka hf. (EcoEnergy Ltd.) signed a cooperation agreement with DaimlerChrysler, Norsk Hydro, and the Royal Dutch/Shell Group setting up a joint venture to investigate the potential for eventually replacing the use of fossil fuels in Iceland with hydrogen and creating the world's first "hydrogen economy". The joint venture, called the Icelandic Hydrogen and Fuel Cell Company Ltd., will test various applications using hydrogen or hydrogen carriers with fuel cells. One of the first results could be a hydrogen/fuel cell-powered bus service in Reykjavik, with additional projects being introduced through 2002. Norsk Hydro has a long history in the production of hydrogen and hydrogen carriers and the development of hydrogen systems. Shell recently set up a hydrogen business and has developed technology to convert liquid fuels into a hydrogen-rich gas.

DaimlerChrysler is developing an array of possibilities that tie in with the goals of the recently announced Freedom Car initiative, a consortium of the U.S. Federal Government, DaimlerChrysler, Ford, and General Motors. This is a new partnership with the goal of producing commercially available fuel cell vehicles, and is a continuation of the efforts from the Partnership for a New Generation of Vehicles (PNGV). One such vehicle produced through PNGV is the world's only four-wheel-drive electric vehicle, the Jeep® Commander. This vehicle offers 50 percent greater fuel efficiency and 90 percent lower emissions than the cleanest internal combustion engine available today.

Ford Motor Company is aggressively pursuing and implementing advancements that reduce the environmental impact of automobiles on the planet. Specifically, TH!NK Technologies is dedicated to **engineering fuel cell and battery electric vehicles**, which produce zero emissions and may replace conventional vehicles. Ford is taking a leadership role in moving fuel cell technology from the laboratory to vehicles on the road. Their commitment is demonstrated by their zero-emission Ford Focus FCV hydrogen fuel cell vehicle and their active participation in the California Fuel Cell Partnership. In August 1999, Ford opened the first filling station in North America that can refuel vehicles with either liquid or gaseous hydrogen. Ford invested $1.5 million in the station for design, construction, equipment rental and a five-year fuel supply. The hydrogen is supplied by Air Products, the world's largest supplier of hydrogen and the sole supplier of the fuel to NASA for the space shuttle and other programs.

Ford Motor Company is committed to developing next generation family vehicles that deliver the same drive and convenience as today's cars and trucks, while significantly improving emissions and fuel efficiency. Ford believes fuel cell vehicles are a leading technology to provide the solutions needed. As part of a partnership with Ballard Power Systems and DaimlerChrysler, Ford is developing the world's leading fuel cell technology. Ford also is the only automaker with a gaseous and liquid hydrogen refueling station on site. Ford is part of an alliance working to reduce the size of the fuel cell powertrain so it can operate on a liquid fuel and not require large onboard storage tanks, which add weight and intrude into passenger space. The company also is working to lower the cost of the system so it is comparable to conventional internal combustion engines.

GM believes that hydrogen will be the future fuel for automotive fuel cells and is a leader in developing next generation fuel cell systems. In the late 1960s, GM was the first manufacturer to demonstrate a vehicle powered by a fuel cell. In 1998, GM demonstrated the Opel Zafira fuel cell vehicle, featuring a methanol fuel processor. In 2000, GM introduced and demonstrated an Opel Zafira fueled with liquid hydrogen. GM is the first manufacturer to operate a fuel cell from start-up to full power in temperatures as cold as minus 40 degrees centigrade. They are leading the industry in the development of gasoline processor-based fuel cell systems and are also continuing to break ground with fuel cells by currently testing a **new fuel cell design every four months**. A fuel cell advancement in GM's partnership with Exxon Mobil is their highly efficient gasoline fuel processor. This processor pulls the hydrogen out of gasoline and uses it to power the fuel cell. Additionally, GM recently joined the California Fuel Cell Partnership, which is working to put more than 70 fuel cell vehicles on California roads by 2003.

Hyundai Motor Company (HMC) is striving to be a leader in the era of clean, hydrogen-based energy, as seen in the Hyundai fuel cell vehicle (FCV) development program. Hyundai aims to be at the forefront of the 21st century "industrial revolution" through ongoing efforts to develop and commercialize fuel cell vehicles. HMC succeeded in developing a **working prototype of a hydrogen-fueled vehicle** in 1994. This vehicle features a high-capacity engine with ultra-low emissions and was the first vehicle of its type developed in Korea. HMC has formed close ties with prominent foreign companies specializing in FCVs and is partnering with them in certain development projects.

Hyundai Motor Company is currently developing FCVs that use liquid fuel, which already has a production and supply infrastructure, to make the fuel cell vehicle available to the public as quickly as possible. Their development focus is mainly on the methanol-powered FCV, as methanol is an alternative to fossil fuels and can be supplied through the same distribution channels used for gasoline. Reformer (fuel processor) technology appears it will be applied to hydrogen production and supply facilities of the future, when society has switched over to hydrogen as its main energy source. Therefore, HMC is working closely with leading foreign companies as well as major domestic energy suppliers to develop reformers.

Energy Companies

BP is the holding company of one of the world's largest petroleum and petrochemicals groups. Their main activities are exploration and production of crude oil and natural gas; refining, marketing, supply and transportation; and manufacturing and marketing of petrochemicals. They also have growing activity in gas and solar power generation. To promote involvement in hydrogen as it becomes accepted in the long-term energy future, BP appointed a business development manager for **hydrogen** in 1999 who is specifically looking at a number of possible small ventures that BP might be involved with in the future. BP is working on several projects that involve converting natural gas and other hydrocarbons into efficient sources of hydrogen (and sequestering the carbon dioxide produced in the process). BP is also beginning to think about more efficient ways of producing hydrogen from water. To do this, improving the efficiency of solar power is probably the best short-term option, which BP's solar company, BP Solarex, has as one of its main objectives.

BP is in cooperation with several organizations that center on specifically defined programs with individual companies. First off, they have a package of environmentally driven cooperative activities with General Motors. This includes jointly developing a fuel processor and fuel quality requirements for a gasoline **fuel cell vehicle**, expanding the UK LPG vehicle/cleaner fuel market, fueling a low emission diesel-electric hybrid bus in New York City, developing novel clean diesel fuels, and funding some innovative in-vehicle and community outreach ventures. With Ford Motor Company, BP has announced joint project funding for a major novel carbon dioxide management research project at Princeton University, and they are actively studying options for joint activity in improved vehicle efficiency and developing world initiatives. BP also has two key fuel cell development activities with DaimlerChrysler. The first is a joint study of the potential for using methanol as a clean retail fuel for fuel cell vehicles. The second is their involvement in DaimlerChrysler's Citaro fuel cell bus program in Europe and Australia, in which they will provide clean hydrogen as the fuel at six of the proposed bus company sites.

Shell Hydrogen is a global business of the Royal Dutch/Shell Group of companies, with headquarters in Amsterdam and regional bases in Houston, Hamburg, and Tokyo. Shell Hydrogen was set up in 1999 to pursue and develop business opportunities related to hydrogen and fuel cells. Shell Hydrogen hopes to provide energy solutions by bringing fuel cells to market and promoting a **hydrogen-reliant fuel economy**. They predict that, as the internal combustion engine led to the oil age, the fuel cell has the potential to lead to the hydrogen age. In this light, Shell Hydrogen are currently working to find a solution enabling fuel cell vehicles to become commercially available and viable in the coming decade.

In April 1999, a joint venture involving Vistorka H.F. (an Icelandic consortium), DaimlerChrysler, Norske Hydro, and Shell Hydrogen was set up in Iceland. The Icelandic New Energy Ltd. will investigate the possibility of replacing fossil fuels with hydrogen and creating the world’s first “hydrogen economy”. The joint venture will test various applications for the capacity to utilize hydrogen fuel cells or a hydrogen carrier. One of the first applications to be analyzed is a hydrogen/fuel cell-powered bus service in Reykjavik. In addition to its fuel cell activities for transport applications, Shell Hydrogen is cooperating with Siemens Westinghouse Power Corporation to develop and bring to market a unique power generation technology fueled by natural gas, which would aim to eliminate the release of greenhouse gases to the atmosphere. These advanced Solid Oxide Fuel Cell (SOFC) power plants would produce only water and carbon dioxide as by-products.

Texaco is an integrated global energy company that operates in some 150 countries around the world. The company explores for and produces oil and natural gas; manufactures and markets high-quality fuels and lubricants; operates trading, transportation, and distribution facilities; and produces power. Texaco is involved in the development and commercialization of advanced energy technologies such as **fuel cells, photovoltaics, advanced batteries, and hydrogen storage**. It is also actively engaged in developing advanced forms of energy. The company believes hydrogen will eventually become part of the energy mix and has established a wholly owned subsidiary, Texaco Energy Systems (TESI), to focus on developing fuel cells and other advanced energy technologies, including viable fuel-processing technology for fuel cells.

As a natural extension of the company’s ongoing efforts, a new business unit called Texaco Technology Ventures (TTV) was formed in August 2000. TTV is responsible for managing the company’s 20 percent equity interest in Energy Conversions Devices Inc. (ECD). TTV and ECD continue to establish joint ventures for the sustained development and commercialization of advanced energy technologies. Specifically, Texaco and ECD formed two joint ventures. The first was the formation of Texaco Ovonic Fuel Cell Company, L.L.C, a 50-50 joint venture to further develop and advance the commercialization of the Ovonic Regenerative Fuel Cell $^{\text{TM}}$. The second was again a 50-50 joint venture to further develop and advance the commercialization of ECD’s technology to store hydrogen in metal hydrides.

Fuel Cell Companies

Avista Corp. is an energy, information, and technology company whose utility and subsidiary operations focus on delivering superior products and innovative solutions to businesses and residential customers throughout North America. Avista Corp.'s affiliate companies include Avista Utilities, which operates the company's electric and natural gas generation, transmission, and distribution business. Avista's non-regulated businesses include Avista Advantage, Avista Labs, Avista Communications, Avista Energy, Avista Energy Canada, Ltd., Avista Power, and Avista Ventures.

Avista Labs is Avista's fuel cell development subsidiary. Avista Labs has pioneered **modular fuel cell cartridge technology** for distributed generation and is also known for its unique, modular fuel cell, designed to be simple and reliable for the end user. The company's proton exchange membrane (PEM) fuel cell, coupled with a compatible fuel processor, can convert practically any fuel containing hydrogen into electricity. Avista Labs also provides PEM fuel cell systems and key components to end-users and other distributed power businesses. The company hopes that their unique, modular fuel cell will someday power homes, businesses, and commercial buildings. Avista also recently announced that Avista Labs has formed a new company, H2fuel, LLC, to develop and commercialize a new technology for manufacturing hydrogen for fuel cells.

Ballard Power Systems, Inc. was founded in 1979 under the name Ballard Research Inc. to conduct research and development in high-energy lithium batteries. In 1983, Ballard began developing **proton exchange membrane (PEM) fuel cells**. Proof-of-concept fuel cells followed beginning in 1989 and from 1992 to 1994 sub-scale and full-scale prototype systems were developed to demonstrate the technology. Ballard Power Systems is recognized as a world leader in developing, manufacturing, and marketing zero-emission PEM fuel cells for use in transportation, electricity generation, and portable power products. Ballard Power Systems' proprietary fuel cell technology is enabling automobile, electrical equipment, and portable power product manufacturers to develop environmentally clean products for sale.

Today, their systems have evolved into pre-commercial prototypes proving the practicality of the Ballard® fuel cell. Ballard's focus is now on working with its strategic partners to develop competitive products for mass markets by reducing costs and implementing high volume manufacturing processes. Ballard is partnering with strong, world-leading companies, including DaimlerChrysler, Ford, GPU International, ALSTOM, and EBARA, to commercialize Ballard fuel cells. Ballard has also supplied fuel cells to Honda, Nissan, Volkswagen, Yamaha, Cinergy, Coleman Powermate, and Matsushita Electric Works, among others. For example, XCELLSIS Fuel Cell Engines, a venture between DaimlerChrysler, Ballard Power Systems, and Ford, is focused on developing, manufacturing, and commercializing fuel cell engines for buses, cars, and trucks.

FuelCell Energy, Inc. (FCE), based in Danbury, CT, is a leader in the development and commercialization of fuel cells. FCE has teamed with a long list of supporting organizations such as the United States Environmental Protection Agency (EPA), the U.S. Department of Energy (DOE), and the MTU Division of DiamlerChrysler. FuelCell Energy has developed a unique type of fuel cell it calls the "Direct FuelCell®" that is multi-fuel capable. It can utilize natural gas, methanol, ethanol, bio-gas, and any other fuel that contains methane. FCE is a leading developer and manufacturer of clean and efficient electric power generators based on the company's Direct FuelCell® (DFC) technology.

In recent news, it was announced on May 07, 2001 that the MTU Division of DaimlerChrysler, a FuelCell Energy partner, began operating a 250 kW Direct FuelCell® power plant at the Rhon-Klinikum Hospital in Bad Neustadt, Germany. The plant will be connected to the internal power supply system of the hospital and will also provide heat energy. It contains DFCs® manufactured by FuelCell Energy and configured in a power plant design by MTU.

International Fuel Cells (IFC), a unit of United Technologies Corp., is a world leader in fuel cell production and development for commercial, transportation, residential, and space applications. One of the largest companies in the world solely devoted to **fuel cell technology**, IFC has more than 40 years of experience in the fuel cell business. Since 1966, all of the more than 100 U.S. manned space flights have operated with IFC-supplied fuel cells. IFC's mission is to be the recognized market leader in the fuel cell industry measured through market penetration and customer satisfaction.

IFC is the only company in the world producing commercial stationary fuel cell systems. IFC's PC25™ fuel cell power plant produces 200 kW of electricity and 700,000 BTUs of usable heat. IFC has delivered more than 200 PC25 systems and has installed units in 15 countries on four continents. One of the milestones that IFC reported in 2000 is their involvement with the largest commercial fuel cell system in the nation, which is comprised of five IFC PC25™ fuel cell power plants. It became operational at the U.S. Postal Service facility in Anchorage, Alaska. It was also the first time a fuel cell system was part of an electric utility's grid. Another milestone highlighted was IFC's delivery of its 200th PC25™ power plant to Toshiba. The fleet of PC25™ fuel cell systems, which went into production in 1991, has achieved more than 3.5 million operating hours. The final milestone for 2000 was that IFC's PC25A power plant achieved 49,000 hours of operation in Japan. The unit has delivered more than 6.5 million kilowatt-hours since it was installed at the Tokyo Gas Research & Development facility on April 13, 1992.

Plug Power was founded in June 1997 as a joint venture between DTE Energy (a diversified energy services company and parent of Detroit Edison) and Mechanical Technology Inc. (an early developer of fuel cells). Plug Power immediately began working toward developing and manufacturing **proton exchange membrane (PEM) fuel cell systems** for electric power generation in residential, small business, and transportation applications. The company's efforts have been met with a substantial measure of success and the company has grown from 22 to over 500 employees. Plug Power's mission is to be the first fuel cell developer to make and sell one million systems, and to reach this goal they are building and testing hundreds of systems over the next year to ensure the best product is ready for the marketplace.

In July of 1997, the company was awarded what was then the largest award given by the Department of Energy for PEM fuel cell research. Three months later, Plug Power became the first company to demonstrate a gasoline-to-electricity fuel cell. In June of 1998, Plug Power unveiled a prototype fuel cell system at a residence located just outside of Albany, New York. Since then, the system has run on a regular basis, marking the first time the electricity needs of a home have been provided by a fuel cell. In February 1999, Plug Power entered into an agreement with General Electric for distribution and service of the company's residential fuel cell systems. In March 2000, Plug Power and GE signed an agreement with Vaillant, one of Europe's leading heating appliance manufactures, to develop a combination furnace, hot water heater, and fuel cell system that will provide both heat and electricity for the home. Also in 2000, Plug Power signed agreements with Advanced Energy Systems for inverter technology, Celanese of Frankfurt Germany to try and simplify Plug Power's residential fuel cell systems and decrease their costs, and Engelhard Corporation to develop and supply advanced catalysts to increase the overall performance and efficiency of Plug Power's fuel processor.

Industrial Gas Companies

Founded in 1902, **Air Liquide** operates in 60 countries through 125 subsidiaries and employs more than 30,000 people. They combine the resources and expertise of a global group with a powerful local presence, based on independent customer-focused teams. Air Liquide are an international group specialized in industrial and medical gases and related services. They supply oxygen, nitrogen, hydrogen and many other gases and services to most industries (steel and oil refining, chemistry and glass, electronics and paper, metallurgy and food-processing, healthcare and aerospace).

To meet more stringent transportation fuel specifications (i.e., gasoline and diesel), refiners will need more hydrogen. But before producing new hydrogen volumes to meet the more regulated operating conditions in existing or new processes, Air Liquide suggested to recover and purify as much hydrogen as is economically feasible. Since 1989, they have set up a separate subsidiary to develop and perfect **hydrogen purification and recovery** using membrane technology. They also have proprietary Pressure Swing Adsorption (PSA) units − technologies that help refiners purify and recover hydrogen. Also, through exclusive alliances with Haldor Topsoe and Howe Baker Engineers, Inc., Air Liquide offers refining customers a range of advanced and affordable hydrogen production technologies. These technologies are used specifically by Air Liquide in their hydrogen plants, which supply a large and growing customer base in the United States and Europe.

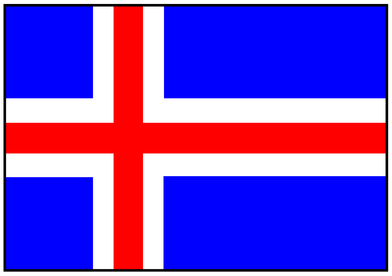
Air Products are working with many public, private, and government organizations to develop and promote the commercialization of hydrogen as a fuel, and are developing applications in the portable, transportation, and stationary fuel markets that show high potential. Since the early 1990s, Air Products' hydrogen safety engineering teams have participated in various safety hazards reviews involving advanced hydrogen energy systems, including hydrogen, fuel cell-powered vehicles, **refueling stations**, and numerous demonstration projects. In addition, the company's experts are actively participating on both national and international (ISO) committees for developing codes and standards for hydrogen technologies. In March 2001, Air Products and Chemicals, Inc. launched their hydrogen safety services for hydrogen fuel cell applications. Recognizing the growing market need for hydrogen safety services, Air Products and Chemicals are now offering their extensive safety experience to the hydrogen and hydrogen fuelling industries. Air Products' comprehensive expertise, to be marketed as KnowH$_2$ow^{SM} Safety Services, is intended to provide technical assistance to engineers, technicians and other personnel involved in the design, installation, operation and/or maintenance of **hydrogen supply and distribution systems**, including hydrogen fuel cell applications. Air Products have been involved in several demonstrations of hydrogen and Hythane® (a blend of hydrogen and natural gas) as potential fuels for ground transportation in Palm Springs, California; Denver, Colorado; Erie, Pennsylvania; Atlanta, Georgia; and Brussels, Belgium.

Praxair is a global leader in industrial gases, supplying a wide range of products, technologies, and related systems and equipment. Praxair is the largest industrial gases company in North and South America, and one of the largest worldwide. Praxair supplies a complete portfolio of large-volume industrial gases, cylinder gases, and specialized services to its refinery customers and is a leading supplier of hydrogen to customers worldwide. It operates 22 steam methane reformers and 7 major hydrogen pipeline systems that deliver more than 500 million cubic feet (15 million cubic meters) of hydrogen each day. Praxair supplies more than 50 refineries and petrochemical plants from its 280 miles of hydrogen pipeline networks in the Gulf Coast, which stretch from Baton Rouge, Louisiana to the Houston, Texas ship channel.

In April 1999, Praxair announced a long-term agreement with Valero Energy Corporation to build, own, and operate a **hydrogen purification plant** at Valero's Texas City, Texas refinery. Praxair's hydrogen plant purifies 69 million cubic feet (2.07 million cubic meters) per day of hydrogen and supplies high-purity hydrogen to Valero's Texas City refinery and to Valero's Houston refinery via pipeline, as well as to other customers connected to Praxair's Gulf Coast hydrogen pipeline. Valero uses the hydrogen to enhance its capability to manufacture clean-burning gasoline, diesel fuel, and jet fuel from lower-cost sour crude oils.

APPENDIX C: International Hydrogen Energy Partnerships

Iceland



Iceland has adopted an ambitious project aimed at converting their current power infrastructure to one that is based on hydrogen fuels. Currently Iceland already produces most of its energy from renewable resources such as geothermal and hydroelectric power. The entities involved in the program have developed a series of phases to accomplish their goal and believe that it could be accomplished as early as 2030.

Icelandic New Energy Ltd., the company set up to run this project, has laid out plans involving five steps to achieve the ultimate goal of a hydrogen-based society. They will begin by running three hydrogen-fueled buses in Rejkjavik. This will transition to the replacement of the entire bus fleet and eventually spill over into fuel cell cars for private transportation. The final two steps involve replacing Iceland's large fleet of seafaring vessels, which will begin with a demonstration of new hydrogen-fueled vessels. This will hopefully culminate in the general replacement of the whole fleet. Most of these plans will be dependent upon the introduction of new technologies, which is why a projected span of 30 to 40 years will be necessary for the realization of this project.

There are several reasons why Iceland is a good candidate for this type of experiment. Rejkjavik is a European-style city, and has a similar infrastructure to most major cities worldwide. This makes the results of such a project easy to apply to other cities to help them develop their own energy conversion plans. Iceland also provides a climate that will test hydrogen power systems in severe conditions.

Program Participants

Icelandic New Energy Ltd.

- Vistorku hf (EcoEnergy)
- *Icelandic New Venture Fund*
- University of Iceland
- IceTech
- Fertilizer Plant
- Suournes Regional Heating Corporation
- Iceland National Power Company
- Reykjavik Energy
- DaimlerChrysler AG
- Norsk Hydro ASA
- Shell Hydrogen BV
- Ballard Power Systems

California Fuel Cell Partnership

In 1999 the California Air Resources Board (CARB) joined forces with other private and public entities to form the California Fuel Cell Partnership. The formation of this partnership was announced by California Governor Gray Davis in an April 1999 press conference. This partnership has grown to include a multitude of car and energy manufacturers as well as several federal and state governmental agencies.

The California Fuel Cell Partnership was formed for the intention of demonstrating the viability of fuel cells in vehicles. In addition, fuel companies have the opportunity to demonstrate the ability to create a fueling infrastructure for hydrogen. It is also the hope that this partnership will help to educate and familiarize the public with fuel cell technologies. A subsequent benefit will be providing the car manufacturers with valuable data to address maintenance costs of fuel cell vehicles.

Initially, 10 cars and 5 buses were introduced in 2000 to test fuel cell efficiency and technology. By 2003, the intention is to introduce 40 more cars and 20 additional buses. Ballard Power Systems and International Fuel Cells will provide the fuel cells and the energy companies will provide the hydrogen. Tests are to be carried out in “real-life” driving conditions.

Participating Entities

Governmental Agencies
- California Air Resources Board (CARB)
- California Energy Commission (CEC)
- U.S. Department of Energy
- U.S. Department of Transportation

Car Manufacturers
- DaimlerChrysler
- Ford
- Honda
- Hyundai
- General Motors
- Nissan
- Toyota
- Volkswagen

Energy Manufacturers
- BP
- Shell Hydrogen
- Texaco

Other Entities
- Ballard Power Systems
- International Fuel Cell
- South Coast Air Quality Management District

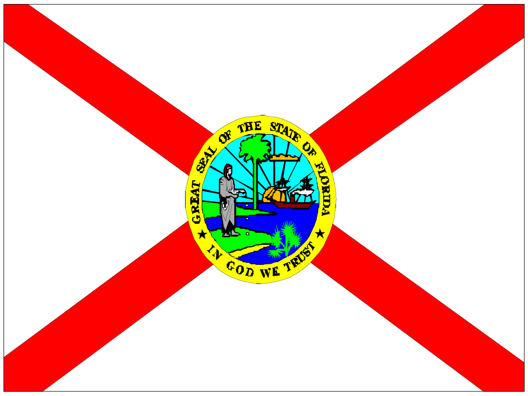
SunLine Transit Agency

SunLine Transit Agency (STA) has proven to be a leader in demonstrating the business case, both environmentally and economically, for advanced commercial vehicles (buses, taxis, and street sweepers). Serving as the public transit agency for Coachella Valley, California, STA converted its entire bus fleet to compressed natural gas in 1994. They also built the first commercial refueling station in the United States. Since then SunLine has convinced Ace Taxi service to convert their automotive fleet to CNG. They are also in the process of converting their street sweepers to use compressed natural gas.

STA has provided the base case for converting transportation vehicles to use alternative energy sources. Currently, SunLine has produced several models of vehicles that will run on hydrogen. They are attempting to introduce these vehicles and transition the rest of the fleet to hydrogen. This program has provided important information about hydrogen production, storage, and utilization technologies to the transportation industry.

STA's involvement with alternative energy vehicles has led it to partnerships in other programs with the Department of Defense and Schatz Energy Research Center. Schatz Energy Research Center is even attempting to produce hydrogen from solar and wind energy. This would make the environmental effects of using fossil fuels to produce energy obsolete and completely benign!

Florida



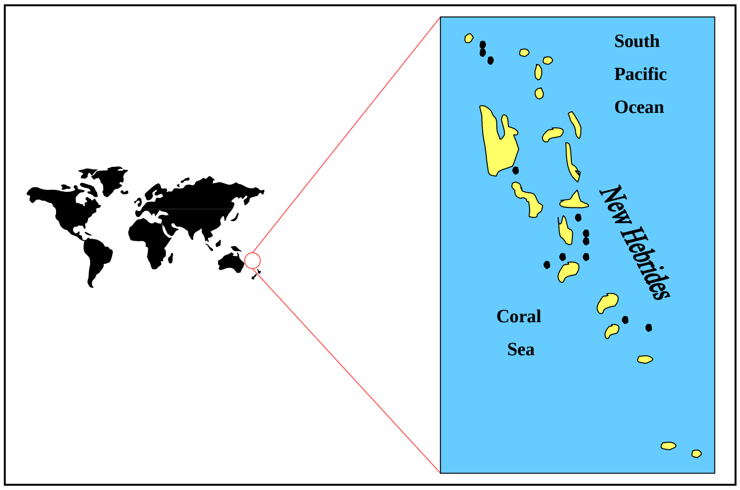
Florida is attempting to be the first state in the contiguous United States to introduce hydrogen technologies as part of its energy needs. Florida's economy is largely dependent upon tourism. This makes fuel for transportation an important issue in Florida's economy. Currently, Florida imports a large portion of its energy, including both fuel for transportation and resources for power generation. This dependence on imported energy, added to concerns over global warming and pollution from fossil fuels, have led Florida to look for alternative forms of energy.

Florida has decided to fund the creation of a special center for the research of hydrogen as a viable energy source for the state. The Hydrogen Research and Applications Center (HRAC) would expand the current university-based research center with a greater focus on hydrogen and an international and national scope. The outcomes of such a center would be to provide jobs as well as an environment that could attract the budding fuel cell market.

The hope is that creating this center with the help of NASA will create a situation where these new technologies will be applied to Florida. Most of our current spacecraft and space technologies are already powered through hydrogen fuel cells. This makes the creation of a hydrogen research center in Florida, with the help of NASA, a logical course of action.

Through the action of helping companies and technologies grow in this center, it is believed that they will then stay located in Florida. As fueling stations and other hydrogen technologies are constructed, such projects would also ease Florida's own conversion of public transportation to hydrogen fuel. However, the most important part of this plan rests on the development and construction of the HRAC, which is Florida's first priority before charting a direct course for hydrogen.

Vanuatu



Three quarters the way from Hawaii to Australia lie a group of islands called Vanuatu. Vanuatu covers an area slightly larger than Connecticut and has a mild tropical climate. These islands are mostly volcanic in nature and are home to approximately 200,000 inhabitants. Unfortunately, Vanuatu is classified as an underdeveloped nation and has no fossil fuel resources. This leaves Vanuatu completely dependent on imports of crude oil and petroleum to meet its energy needs. Vanuatu's energy situation has led its government to seek new ways of providing electricity.

Vanuatu has decided to develop the first hydrogen-based economy in the world. By 2020 Vanuatu Council Ministers wish to have an economy that is based wholly on renewable energy and hydrogen. They have targeted 2010 as the year that they will stop importing petroleum as well. This is a very ambitious plan, but resources for wind, solar, hydroelectric, and geothermal energy production are found in abundance on these islands, which gives Vanuatu confidence that it will be able to accomplish these goals with the help of fuel cells.

APPENDIX D: Energy Pathway and Life-Cycle Cost Analysis Methodologies

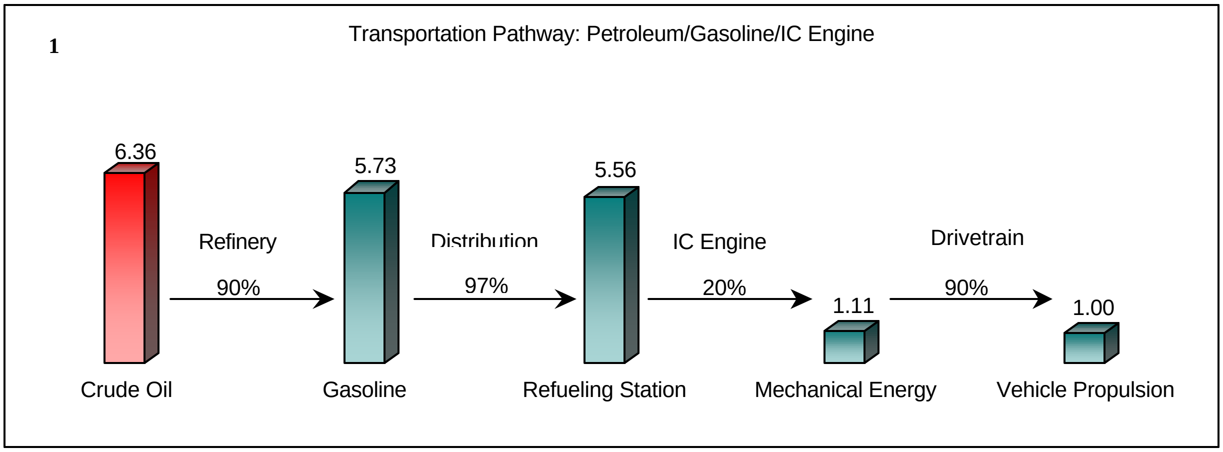
Energy Pathway Analysis Methodology

An energy pathway, which often consists of multiple series of processes, is a method to evaluate a technological process from the start to finish (final usage) in the form of energy (kWh). The energy pathway follows the conversion of a primary energy resource through the conversion processes that makes it a useful energy commodity and its subsequent storage, delivery to the point of end-use, and end-use process that concludes each pathway.[1] These are sometimes referred to as "cradle to grave" analyses.

The application of the pathway analysis methodology is very useful when comparing conventional technologies with renewable energy technologies and hydrogen. This results from the fact that manufactured forms of energy exhibit a set of costs and benefits that are difficult to compare with conventional technologies. Usually, these benefits include reduced health or environmental impacts that are not incorporated into the costs of conventional technologies. For the purpose of our analyses, we recognize that hydrogen must be produced and delivered at a cost comparable to Hawaii's conventional energy carriers, but the environmental, efficiency, and domestic sustainability benefits of hydrogen should not completely be disregarded.

For the purposes of uniformity and comparison, all pathways discussed in this report are normalized to supply 1 kW of equivalent power to end-users in stationary power applications, or 1 mile/kWh of equivalent power to end-users in transportation applications. Annual power capacity factor and annual operating hours are the main time factors used for determining the energy delivered (in equivalent kWh) in the pathways analysis.[2]

Figure AE-A: The current transportation pathway in Hawaii.



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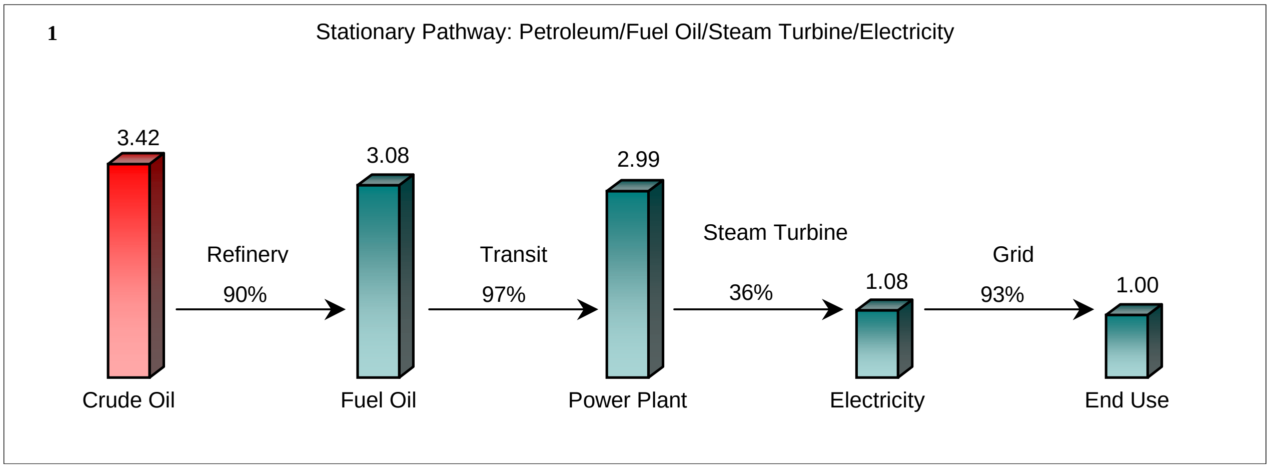
[1] "Energy Pathway Analysis – A Hydrogen Fuel Cycle Framework for System Studies." Badin, J.S., Tagore, S. *International Journal of Hydrogen Energy*, Volume 22, Number 4, April 1997.

[2] "Energy Pathway Analysis" in *Proceedings of the 1994 DOE Hydrogen Program Review*, Badin, J.S., Kervitsky, G., and Mack, S.

Figure AE-2: Current stationary generation pathways in Hawaii



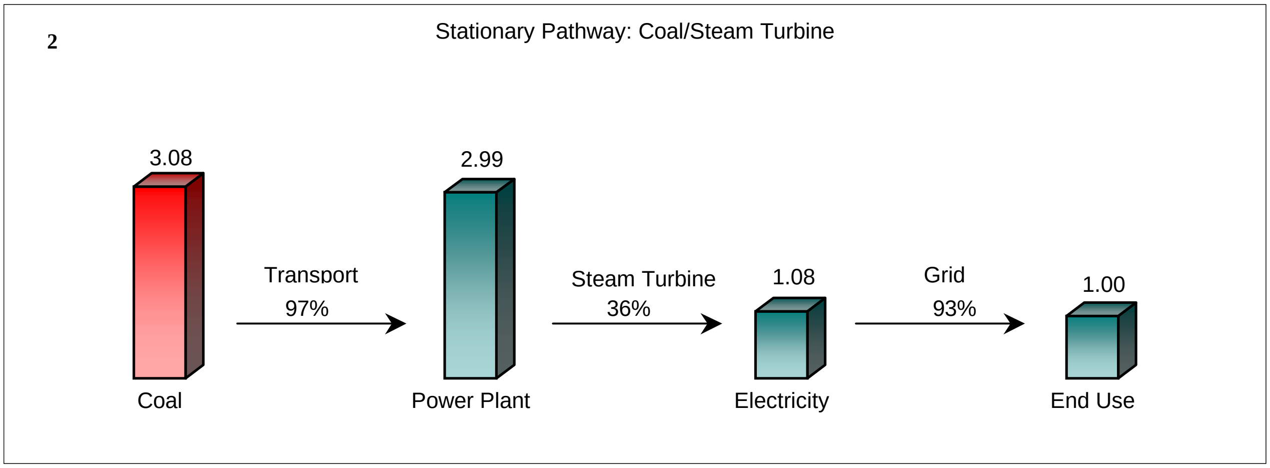
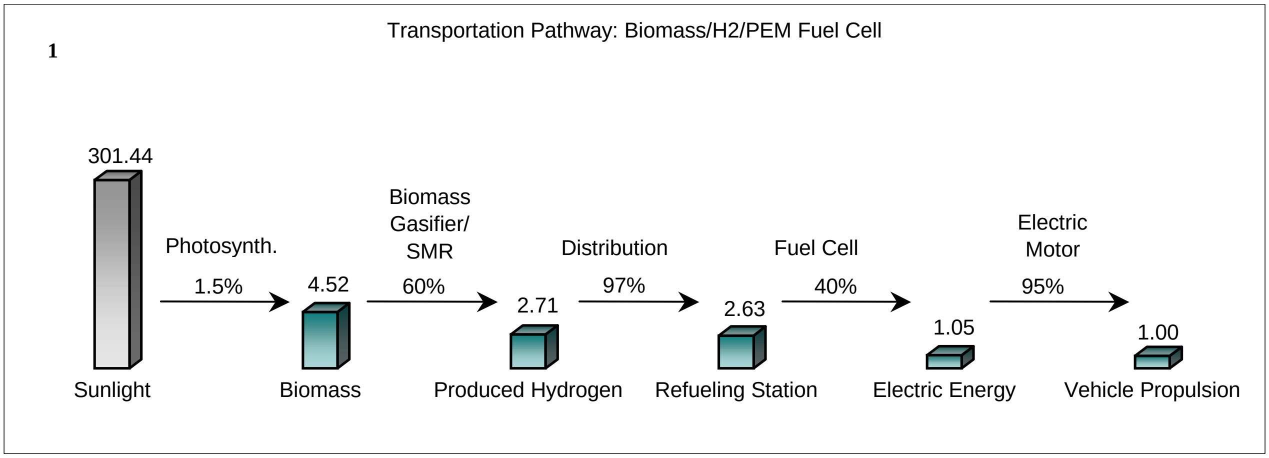
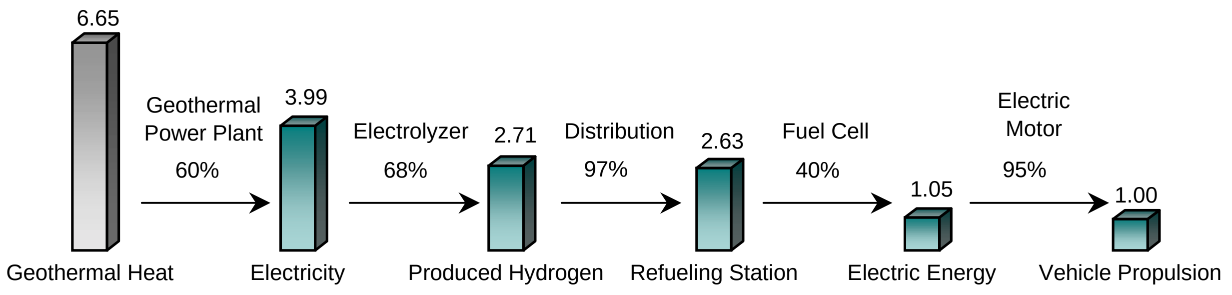


Figure AE-3: Future transportation pathways in Hawaii



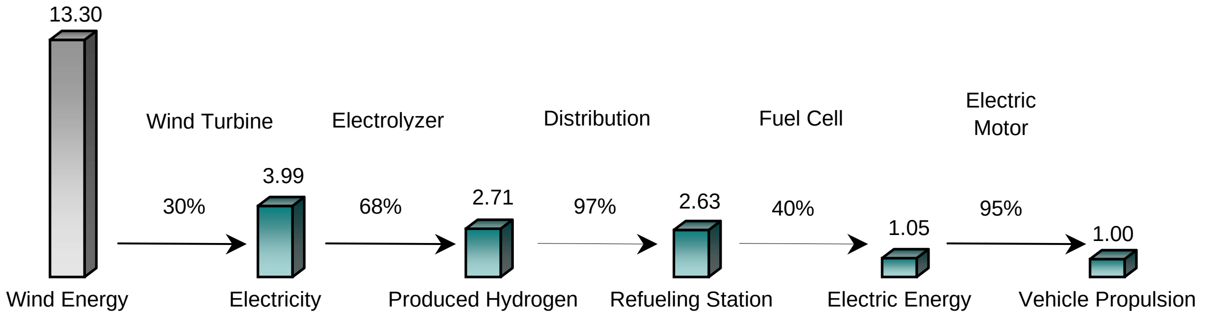
2

Transportation Pathway: Geothermal/H2/PEM Fuel Cell



3

Transportation Pathway: Wind/H2/PEM Fuel Cell



4

Transportation Pathway: LNG/H2/PEM Fuel Cell

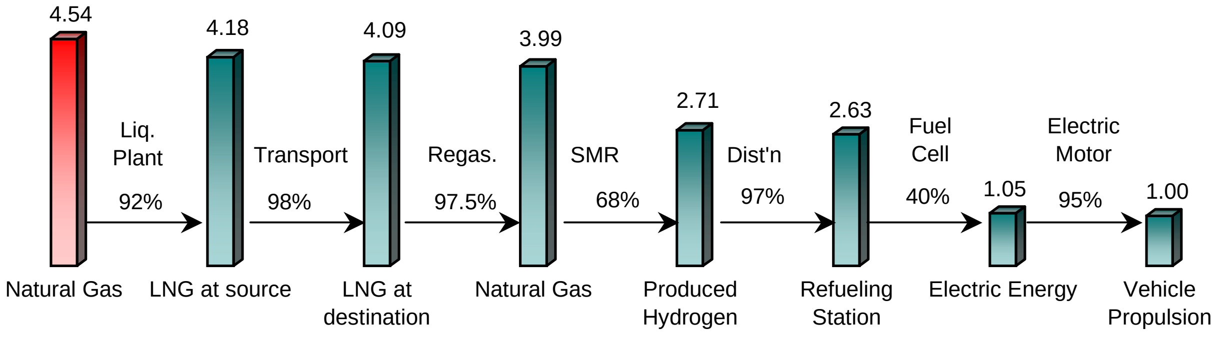
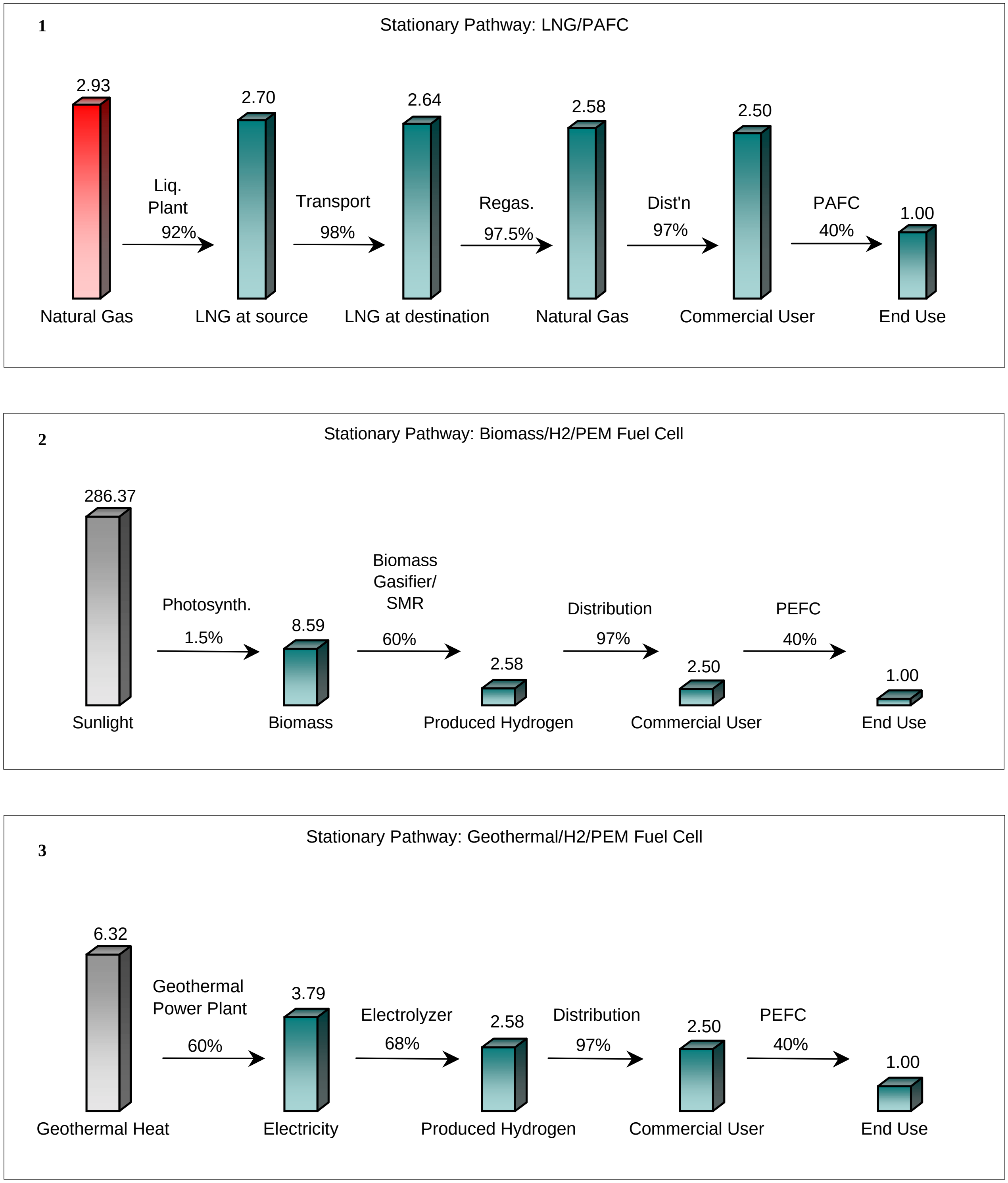


Figure AE-4: Future stationary generation pathways in Hawaii



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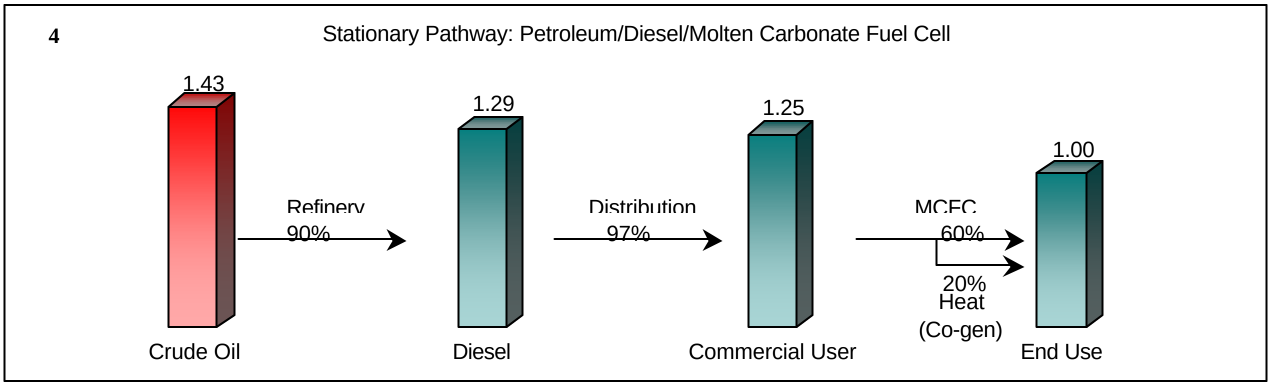

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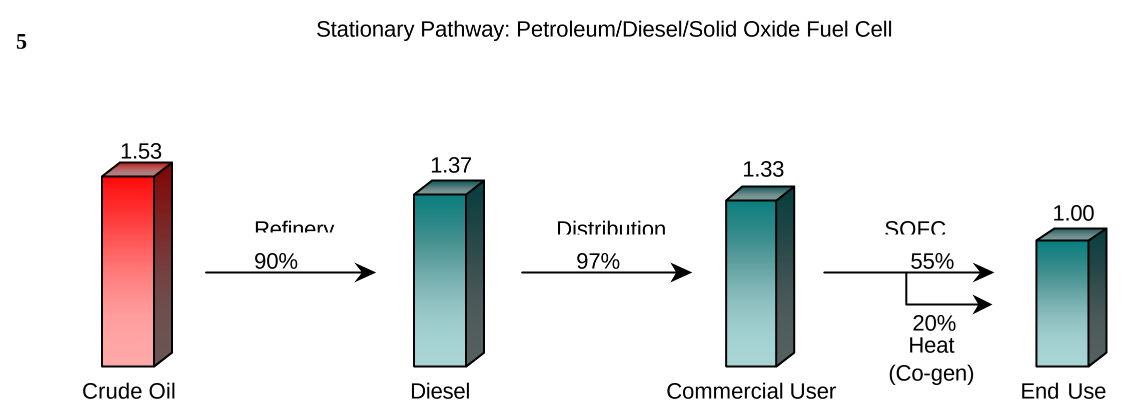

System components with different sizes are obligated to provide an adequate amount of energy or power to the proceeding downstream system components. Even though these differences in efficiencies might occur among the various pathways, the calculated component cost, based on component capacity, can capture the differences in efficiencies in its cost. This is demonstrated in the following equation:

$$\text{Capacity}\,i = \text{Capacity}(i + 1)/\text{Efficiency}(i + 1)$$

where (i + 1) is the next step in the downstream process. To calculate the necessary capacity of each component in the pathway process, total power produced by the system is divided by the product of efficiency of each component in the pathway process. Using these numbers, the overall system cost can be accurately estimated by including technology cost as well as the required capacity of each component in the pathway.[3]

The pathways clearly display the quantity of primary energy necessary to produce the energy form and identify the process or processes where energy losses are greatest. In this manner, the analysis helps to focus attention on those steps where the potential for technology advancement

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[3] "Energy Pathway Analysis" in *Proceedings of the 1994 DOE Hydrogen Program Review*, Badin, J.S., Kervitsky, G., and Mack, S.

is highest. When combined with detailed life-cycle cost analysis, the pathway analysis can also help to sharpen economic estimation and comparative pollution evaluation. Pathways provide a more accurate understanding of energy capacity levels required at each step, which in turn leads to improved assessment of capacity-dependent functions such as capital investment and emissions quantities.

Finally, pathway analysis evaluation allows direct (relative) comparison of various aspects of competing paths and provides a framework for making judgments regarding potential benefits of individual approaches. To make informed decisions regarding energy choices, it is important to evaluate relevant factors on equivalent bases. The principal factors being considered in this plan are energy efficiency, capital cost, emissions, and fuel importation. To bring these characteristics into focus, competitive energy pathways (pathways employing different energy systems to meet the same consumer demand), need to be developed and evaluated.

Life-Cycle Cost Analysis Methodology

Evaluating the economic impact of various technologies for use in a pathway is not an easy task. Differences in costs, efficiency, fuel consumption, reliability, lifetime of the system, etc. are all factors to be considered. Additionally, different combination of technologies used in the pathway can produce different results in terms of costs, technological performance, and system efficiencies.[4]

In calculating life-cycle cost, the cost of energy resources is a major cost factor. Typically, the cost of energy resources includes the major cost contributors such as initial capital cost, operation and maintenance, fuel cost, and various fixed charges. Less obvious cost contributors such as health care expense, pollution control expense, economic impacts on material and agricultural resources, and other externalities are typically excluded from cost calculations. However, these costs can be substantial and must be taken into account.[5]

Inclusion of externalities into cost calculation can be difficult, but ignoring externalities can have a large impact. Improper accounting for the costs of externalities can lead to improper economic decision making in choosing the right energy resource. Economic efficiency, therefore, can be attained only when the costs of externalities are incorporated into the total cost of energy.[6] The scope of this study did not include the complex considerations associated with internalizing the cost of externalities, which would likely include the monetization of emission estimates, but they may be worth pursuing in follow-on investigations.

For the purposes of this report, we focused on the difference between total consumption benefits and total production costs. When this condition is maximized, economic efficiency is achieved. Differential life-cycle cost criteria can be used to judge whether a considered pathway improves economic efficiency relative to the status quo or to other possible energy investments. It is

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[4] "Energy Pathway Analysis – A Hydrogen Fuel Cycle Framework for System Studies." Badin, J.S., Tagore, S. *International Journal of Hydrogen Energy*, Volume 22, Number 4, April 1997.

[5] Ibid

[6] Ibid

emphasized that our analyses are framed by economic considerations of decision making. This is the point where the pathway analysis methodology outlined in the previous sub-section is combined with the full life-cycle cost analysis methodology.

Deployment of hydrogen as an energy resource can only happen if various technologies used in the new energy production system are compatible and well integrated. Well organized and funded research from the public sector can identify and quantify all the barriers to entry for the hydrogen energy economy. In transitioning to a hydrogen economy, pathway and economic analysis can be employed to identify and anticipate potential issues of technical feasibility, economic impacts and effects, and infrastructure challenges. By conducting this analysis, hydrogen energy applications that have the highest potential to be deployed can easily be identified.[7]

The subsequent paragraphs discuss the economic methodology used to estimate the levelized life-cycle costs per kW or costs per mile-traveled in each step of the pathway.[8]

The product of the present value of the initial capital and the fixed charge rate (FCR) provides an estimate of the required capital investment that must be included in the calculation of the annualized system cost. The equation for the fixed charge rate (FCR) is defined as[9]:

$$\mathrm{FCR} = CRF((1 - tD - X)/(1 - t)) + PTI$$

CRF	Capital Recovery Factor as defined in the next equation
t	Income tax rate
D	Real depreciation factor (present value of depreciation credits)
X	Investment tax credit
PTI	Property taxes and insurance

For the purposes of this study, investment tax credits are zero. A state and federal income tax rate *(t)* of 38% is assumed, while the combined property tax and insurance *(PTI)* is estimated at 2%. As reflected in the fixed charge rate equation, taxes and insurance cost are not multiplied by capital recovery factor (CRF), as they are assumed to be paid with before-tax dollars. Conversely, after-tax dollars are used to pay return on capital with the equation showing that income tax rate and real depreciation factor are multiplied by CRF. The capital recovery factor (CRF) is calculated as[10]:

$$\mathrm{CRF} = k/(1 - (1 + k)^{-n})$$

k	Real annual discount rate (weighted average cost of capital)

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[7] "Energy Pathway Analysis – A Hydrogen Fuel Cycle Framework for System Studies." Badin, J.S., Tagore, S. *International Journal of Hydrogen Energy*, Volume 22, Number 4, April 1997.

[8] "Energy Pathway Analysis" in *Proceedings of the 1994 DOE Hydrogen Program Review*, Badin, J.S., Kervitsky, G., and Mack, S.

[9] "Energy Pathway Analysis – A Hydrogen Fuel Cycle Framework for System Studies." Badin, J.S., Tagore, S. *International Journal of Hydrogen Energy*, Volume 22, Number 4, April 1997.

[10] Ibid

n	The number of years of project life

In this study, the real after-tax discount rate *(k)* of 6.1% is used. In calculating the fixed charge rate, depreciation is represented with a real depreciation factor *(D)*, which represents the present value of allowable depreciation credits over the lifetime of the system. The real depreciation factor is estimated using the modified accelerated capital recovery schedules, established by the IRS for each depreciable project year. The equation for calculating the levelized life-cycle cost (LCC), a measure of the unit process cost per kWh of output is[11,12]:

$$\text{LCC } (\$/\text{kWh}_{out}) = ((I_{pw}\,FCR_o + R_{pw}FCR_r + A_{pw}CRF) / E$$

CRF	Capital recovery factor
FCR	Fixed charge rate
A	Annual and intermittent operating costs, fuel and electricity costs, maintenance, and externalities
I	Investment cost ($)
R	Replacement capital ($)
E	Energy delivered (kWh)
Subscripts	
pw	Present worth
o	Original system
r	Replacement

Each energy pathway analyzed in the preparation of this report includes each step in the process from primary energy extraction or capture through fuel production, storage, transport/delivery, and utilization. By combining the pathway and life-cycle cost methodologies, SENTECH was able to establish a rigorous analytical approach that considered the primary energy resource cost, capital amortization, and conversion efficiencies for each step in the pathways to determine those with the highest value.

Energy resources are consumed to produce products and services through technical processes and the investment of capital. Each technical process is a transformation step that consumes energy, passing on an added cost to the next step. A sequence of these technical processes makes up an energy pathway. Therefore, an energy pathway is a conversion chain linking primary resources to ultimate end-use consumption. Required energy input refers to on-site, available natural energy resources (all cases exclude the extraction process) such as coal, crude oil, and natural gas. Production is the transformation of primary resources to secondary (or intermediate) energy forms such as gasoline, electricity, or hydrogen. Storage represents a set of technologies that accommodate differences in timing of energy service demands and the availability of the energy supply. Transport is the transfer of energy from its primary site to the end-use application. Delivered energy output represents the performance of work or the provision of energy services in the end-use sectors.

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[11] "Energy Pathway Analysis – A Hydrogen Fuel Cycle Framework for System Studies." Badin, J.S., Tagore, S. *International Journal of Hydrogen Energy*, Volume 22, Number 4, April 1997.

[12] The equation and terminology presented is specific to stationary applications. The calculation of the unit process cost per output energy in transportation applications is further converted to the cost per unit of distance traveled, presented as cents/mile.

Important measures of the desirability of candidate energy systems are system capital costs and operating and maintenance (O&M) costs. However, in choosing systems for the future, such market costs should not be the only criteria. In today's society, environmental considerations have grown in importance and are now included in industry and government decision making for many activities. In addition, national security and balance-of-payment issues resulting from imported fuels should be considered. To more accurately analyze energy pathways, these factors should be considered in the pathways themselves.

Unit capital cost estimates must be applied to facility sizes in proportion to the energy flow level at the point where the facility performs its function, and provides a more accurate first approximation of a system's capital investment requirements than estimates made without this approach. Capital costs can be divided into those necessary for energy delivery by the energy supplier and those chosen by the end user. The analyses discussed herewith consider only those capital costs needed to assure a wide availability of hydrogen fuel.

APPENDIX E: Analysis Results

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Baseline Fuel Costs

Gasoline Heat Content	(MBtu/bbl)	5.234
	(gal/bbl)	42
	(MBtu/gal)	0.124619048
Gasoline Price	($/gal)	$1.63
	($/Mbtu)	$13.08
Internal Combustion Engine Efficiency (mi/gal)		20
Fuel Costs	($/mi)	$0.082

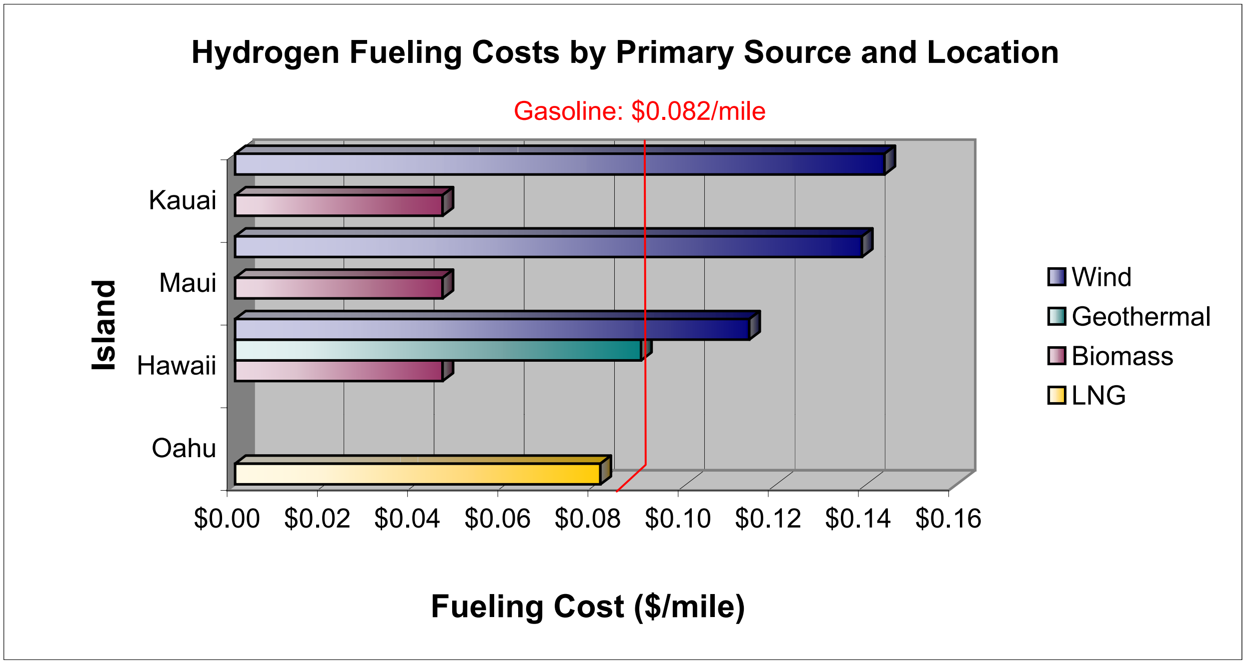
Summary of Results

Island	Energy Source	Converter	Fuel Costs ($/mi)
All	Gasoline	IC Engine	$0.082
Oahu	LNG	Fuel Cell	$0.081
Hawaii	Biomass	Fuel Cell	$0.046
	Geothermal	Fuel Cell	$0.090
	Wind	Fuel Cell	$0.100
Maui	Biomass	Fuel Cell	$0.046
	Wind	Fuel Cell	$0.124
Kauai	Biomass	Fuel Cell	$0.046
	Wind	Fuel Cell	$0.129

Assumptions:

General:

- Retail price of gasoline: $1.63
- Current average fuel efficiency: 20 mi/gal
- Fuel Cell vehicles will be available for the same price as conventional automobiles by the end of the decade.
- Fuel Cell systems will be 2.2 times as efficient as internal combustion engines.
- Each island is an independent, isolated energy economy - transportation of electricity, energy feedstocks, or hydrogen was not considered as options in this study.



Motor Vehicle Usage/Gas consumed by county (1997)

County		Honolulu	Hawaii	Kaui	Maui	Statewide
Registered Vehicles		595,121	118,364	53,904	116,878	884,267
Vehicle Miles Traveled		5,225,200,000	1,161,500,000	570,300,000	1,046,000,000	8,003,000,000
Highway Fuel Used (gallons)						
	Gasoline	262,768,000	61,441,000	23,364,000	52,863,000	400,436,000
	Diesel	19,229,000	5,718,000	1,419,000	3,743,000	30,109,000
	LPG	277,000	16,000	13,000	21,000	327,000
Highway Fuel Used (gallons of gasoline equivalent)		284,302,000	67,794,000	24,947,000	57,030,000	434,073,000
Fuel Used (MBtu)		35,429,444	8,448,424	3,108,871	7,107,024	54,093,764
Estimated Average Vehicle Efficiency (mi/gge)		18.38	17.13	22.86	18.34	18.44
Estimated Average Vehicle Efficiency (mi/MBtu)		147.48	137.48	183.44	147.18	147.95

Fleet Vehicles Data (obtained from DBEDT, data from HES1995)

Cars & Trucks

		Oahu	Hawaii	Kaui	Maui	Statewide	Source
Federal government vehicles							Hawaii Fed. GSA and the First Interim Report of the
	cars	643				643	Federal Fleet Conversion Task Force (August, 1993)
	trucks	1440				1440	Note: tactical military vehicles not included
	TOTAL	2083				2083	
State government vehicles							Department of Accounting and General Services
	cars	865				1468	
	trucks (0-10000)	1065				1685	
	other (bus&truck)	165				321	
	TOTAL	2095				3474	
County government vehicles							Summary of Registered Vehicles (Run date 9/5/92)
	passenger vehicles	980	167	218	481	1846	
	passenger trucks	52	42	67	56	217	
	other	3467	733	131	387	4718	
	TOTAL	4499	942	416	924	6781	
Private Fleets							Automotive Fleet Fact Book, 1992 (Bobit Publishing Co.)
	cars	13362				19232	
	trucks	24856				33516	
	TOTAL	38218				52748	
Rental Cars							Hawaii Automobile Dealer Association Yearbook, 1994 (figures for 1992)
	cars	26742				38491	
	trucks	0				0	
	TOTAL	26742				38491	
TOTAL Cars & Trucks in fleets		73637	% of veh. Oahu:	12.37%		103577	% of total vehicles in state 11.71%
TOTAL Cars & Trucks in fleets excluding rental cars		46895	% of veh. Oahu:	7.88%		65086	% of total vehicles in state 7.36%

Buses

		Statewide	Source
Federal Buses		51	Hawaii GSA (1992 data)
School Buses (Public)		871	MVMA facts and figures '92 (1990 data)
School Buses (Commercial)		695	MVMA facts and figures '92 (1990 data)
TheBus		495	Oahu Transit Services (1992 data)
Other Commercial buses		2391	Hawaii Transportation Association
	TOTAL	4503	

Gasoline conversion factors	5.234	MBtu/bbl
	42	gal/bbl
	0.124619048	MBtu/gal

Hydrogen Pathways for the Island of Hawaii

Potential Market

Registered Vehicles:	118,364 [1]
Ground Transportation Fuel Used (gge)	67,794,000 [1]
Ground Transportation Fuel Used (MBtu)	8,448,424 [1]
Estimated Average Vehicle Efficiency (mi/gge)	17.13 [1]
Estimated Average Vehicle Efficiency (mi/MBtu)	137.4812674

Biomass Gasifier

Resource Availability

Available Land (acres)	799,386 [2]
Yield (dry T/acre)	20 [2]
Annual Production (dry T/year)	15,987,720
Daily Feedstream (Mg/day)	39,728

Production Costs

Annual Production (kg H2)	7469104.5
Annual Production (MBtu H2)	1005266.775
% of total fuel replaced (including FC eff. gains)	23.80%
Annual Production (GJ H2)	1060612.839
Discount Rate	10%
Lifetime (yr)	30

Biomass Gasifier

Plant Size (kg H2/day)	22737 [3]
Operating Capacity	90% [3]
Installed Capital Cost ($)	$53,800,000.00
Annualized Capital Cost ($/yr)	$5,707,063.56
Contribution to Final H2 Cost ($/MBtu)	**$3.36**

Biomass Feedstock Costs

Daily Feedstock Requirements (Mg/day)	314 [3]
Annual Feedstock Requirements (Mg/year)	103149
Feedstock Cost ($/Mg)	46.2 [3]
Annual Cost of Feedstock ($/yr)	$4,765,483.80
Contribution to Final H2 Cost ($/MBtu)	**$4.74**

Totals

Total Annualized Cost ($/yr)	$10,472,547.36
H2 unit cost ($/GJ)	$7.68 [3]
H2 unit cost ($/MBtu)	**$8.10**

Delivery Costs

Cost to distribute ($/MBtu)	**$7.98** [3]
H2 Cost (at refueling station)	**$16.08**

End Use Calculations

Conversion Device	Fuel Cell
Efficiency (mi/gge)	44 [4]
Efficiency (mi/MBtu)	353.1300161
Fuel Cost ($/mi)	**$0.0455**

Geothermal Power

Resource Summary

Existing Geothermal Capacity (MW)	20 [7]
Planned Additions (MW)	30 [7]

Production Costs

		NOTES
replacement goal (% of transportation energy)	10%	
Annual H2 production (MBtu)	422,421	
Annual H2 production (kWh)	123,804,568	
geothermal plant capacity factor	90%	
nominal geothermal generating capacity (MW)	23	
Discount Rate	10%	
Lifetime (yr)	30	

Electrolyzer

plant size (kW in)	23,093	
plant size (kW out)	15703.26838	
plant size (Nm3/day)	184,991	
operating capacity	90%	
capital cost ($)	$9,421,961 [5]	*$600/kW out LHV*
annualized capital cost ($/yr)	$999,474.54	
O&M costs ($/yr)	$1,012,825.66 [5]	*$0.015/$\mathrm{Nm}^3$/yr*
contribution to final H2 price ($/MBtu)	**$4.76**	

Electricity Costs

conversion efficiency	68% [6]
required electricity (kWh/yr)	182,065,541
unit cost of electricity ($/kWh)	$0.044 [7]
total cost of electricity ($/yr)	$8,010,883.81
contribution to final H2 price ($/MBtu)	**$18.96**

Totals

total annual cost ($/yr)	$10,023,184.01
H2 unit cost ($/MBtu)	**$23.73**

Delivery Costs

Cost to distribute ($/MBtu)	**$7.98** [3]
H2 Cost (at refueling station)	**$31.70**

End Use Calculations

Conversion Device	Fuel Cell
Efficiency (mi/gge)	44 [4]
Efficiency (mi/MBtu)	353.1300161
Fuel Cost ($/mi)	**$0.0898**

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[1] Energy, Resources, and Technology Division, Dept. of Business, Economic Development & Tourism, State of Hawaii. 2000. "Hawaii Energy Strategy 2000."

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[7] Global Energy Concepts. 2000. "Update of Selected Cost and Performance Estimates," Energy, Resources, and Technology Division, Dept. of Business, Economic Development & Tourism, State of Hawaii.

Wind Power

Resource Summary

Existing Wind Capacity (MW)	8.8 [7]
Planned Additions (MW)	13 [7]

Production Costs

		NOTES
replacement goal (% of transportation energy)	10%	
Annual H2 production (MBtu)	422,421	
Annual H2 production (kWh)	123,804,568	
Annual H2 production (Nm^3)	41,321,759	
wind turbine capacity factor	33%	
nominal wind generating capacity (MW)	63	
Discount Rate	10%	
Lifetime (yr)	30	
Electrolyzer		
plant size (kW in)	62,981	
plant size (kW out)	42827.09558	
plant size (Nm3/day)	504,521	
operating capacity	90%	
capital cost ($)	$25,696,257 [5]	*$600/kW out LHV*
annualized capital cost ($/yr)	$2,725,839.66	
O&M costs ($/yr)	$619,826.39 [5]	*$0.015/$Nm^3$/yr*
contribution to final H2 price ($/MBtu)	**$7.92**	
Electricity Costs		
conversion efficiency	68% [6]	
required electricity (kWh/yr)	182,065,541	
unit cost of electricity ($/kWh)	$0.045 [7]	
total cost of electricity ($/yr)	$8,192,949.35	
contribution to final H2 price ($/MBtu)	**$19.40**	
Totals		
total annual cost ($/yr)	$11,538,615.40	
H2 unit cost ($/MBtu)	**$27.32**	

Delivery Costs

Cost to distribute ($/MBtu)	**$7.98** [3]
H2 Cost (at refueling station)	**$35.29**

End Use Calculations

Conversion Device	Fuel Cell
Efficiency (mi/gge)	44 [4]
Efficiency (mi/MBtu)	353.1300161
Fuel Cost ($/mi)	**$0.0999**

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Hydrogen Pathways for the Island of Maui

Potential Market

Registered Vehicles:	116,878 [1]
Ground Transportation Fuel Used (gge)	57,030,000 [1]
Ground Transportation Fuel Used (MBtu)	7,107,024 [1]
Estimated Average Vehicle Efficiency (mi/gge)	18.34 [1]
Estimated Average Vehicle Efficiency (mi/MBtu)	147.1783348

Biomass Gasifier

Resource Availability

Available Land (acres)	214982 [2]
Yield (dry T/acre)	20 [2]
Annual Production (dry T/year)	4,299,640
Daily Feedstream (Mg/day)	10,684

Production Costs

	852.6375
Annual Production (kg H2)	7469104.5
Annual Production (MBtu H2)	1005266.775
% of total fuel replaced (taking into account FC effic	28.29%
Annual Production (GJ H2)	1060612.839
Discount Rate	10%
Lifetime (yr)	30

Biomass Gasifier

Plant Size (kg H2/day)	22737 [3]
Operating Capacity	90% [3]
Installed Capital Cost ($)	$53,800,000.00
Annualized Capital Cost ($/yr)	$5,707,063.56
Contribution to Final H2 Cost ($/MBtu)	**$3.36**

Biomass Feedstock Costs

Daily Feedstock Requirements (Mg/day)	314 [3]
Annual Feedstock Requirements (Mg/year)	103149
Feedstock Cost ($/Mg)	46.2 [3]
Annual Cost of Feedstock ($/yr)	$4,765,483.80
Contribution to Final H2 Cost ($/MBtu)	**$4.74**

Totals

Total Annualized Cost ($/yr)	$10,472,547.36
H2 unit cost ($/GJ)	$7.68 [3]
H2 unit cost ($/MBtu)	**$8.10**

Delivery Costs

Cost to distribute ($/MBtu)	**$7.98** [3]
H2 Cost (at refueling station)	**$16.08**

End Use Calculations

Conversion Device	Fuel Cell
Efficiency (mi/gge)	44 [4]
Efficiency (mi/MBtu)	353.1300161
Fuel Cost ($/mi)	**$0.0455**

Wind Power

Resource Summary

Existing Wind Capacity (MW)	0 [7]
Planned Additions (MW)	20 [7]

Production Costs

replacement goal (% of energy used for t	10%
Annual H2 production (MBtu)	355,351
Annual H2 production (kWh)	104,147,484
Annual H2 production (Nm^3)	34,760,892
wind turbine capacity factor	33%
nominal wind generating capacity (MW)	53
Discount Rate	10%
Lifetime (yr)	30

Electrolyzer

plant size (kW in)	52,981	
plant size (kW out)	36027.21865	
plant size (Nm3/day)	424,416	
operating capacity	90%	
capital cost ($)	$21,616,331 [5]	$600/kW out LHV
annualized capital cost ($/yr)	$2,293,044.16	
O&M costs ($/yr)	$521,413.38 [5]	$0.015/Nm3/yr
contribution to final H2 price ($/MBtu)	**$7.92**	

Electricity Costs

conversion efficiency	68% [6]
required electricity (kWh/yr)	153,158,064
unit cost of electricity ($/kWh)	$0.065 [7]
total cost of electricity ($/yr)	$9,955,274.17
contribution to final H2 price ($/MBtu)	**$28.02**

Totals

total annual cost ($/yr)	$12,769,731.72
H2 unit cost ($/MBtu)	**$35.94**

Delivery Costs

Cost to distribute ($/MBtu)	**$7.98** [3]
H2 Cost (at refueling station)	**$43.91**

End Use Calculations

Conversion Device	Fuel Cell
Efficiency (mi/gge)	44 [4]
Efficiency (mi/MBtu)	353.1300161
Fuel Cost ($/mi)	**$0.1243**

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[1] Energy, Resources, and Technology Division, Dept. of Business, Economic Development & Tourism, State of Hawaii. 2000. "Hawaii Energy Strategy 2000."

[2] Parsons Brinckerhoff Quade & Douglas, Inc., 1995. Transportation Energy Strategy: Project #5 of the Hawaii Energy Strategy Development Program. Honolulu: Energy Division, Dept. of Business, Economic Development & Tourism, State of Hawaii.

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Hydrogen Pathways for the Island of Kauai

Potential Market

Registered Vehicles:	53,904 [1]
Ground Transportation Fuel Used (gge)	24,947,000 [1]
Ground Transportation Fuel Used (MBtu)	3,108,871 [1]
Estimated Average Vehicle Efficiency (mi/gge)	22.86 [1]
Estimated Average Vehicle Efficiency (mi/MBtu)	183.4427772

Biomass Gasifier

Resource Availability

Available Land (acres)	107738 [2]
Yield (dry T/acre)	20 [2]
Annual Production (dry T/year)	2,154,760
Daily Feedstream (Mg/day)	5,354

Production Costs

	852.6375
Annual Production (kg H2)	7469104.5
Annual Production (MBtu H2)	1005266.775
% of total fuel replaced (taking into account FC effi	64.67%
Annual Production (GJ H2)	1060612.839
Discount Rate	10%
Lifetime (yr)	30

Biomass Gasifier

Plant Size (kg H2/day)	22737 [3]
Operating Capacity	90% [3]
Installed Capital Cost ($)	$53,800,000.00
Annualized Capital Cost ($/yr)	$5,707,063.56
Contribution to Final H2 Cost ($/MBtu)	**$3.36**

Biomass Feedstock Costs

Daily Feedstock Requirements (Mg/day)	314 [3]
Annual Feedstock Requirements (Mg/year)	103149
Feedstock Cost ($/Mg)	46.2 [3]
Annual Cost of Feedstock ($/yr)	$4,765,483.80
Contribution to Final H2 Cost ($/MBtu)	**$4.74**

Totals

Total Annualized Cost ($/yr)	$10,472,547.36
H2 unit cost ($/GJ)	$7.68 [3]
H2 unit cost ($/MBtu)	**$8.10**

Delivery Costs

Cost to distribute ($/MBtu)	**$7.98** [3]
H2 Cost (at refueling station)	**$16.08**

End Use Calculations

Conversion Device	Fuel Cell
Efficiency (mi/gge)	44 [4]
Efficiency (mi/MBtu)	353.1300161
Fuel Cost ($/mi)	**$0.0455**

Wind Power

Resource Summary

Existing Wind Capacity (MW)	0 [7]
Planned Additions (MW)	0 [7]

Production Costs

	155.9726783
replacement goal (% of energy used for tr	10%
Annual H2 production (MBtu)	155,444
Annual H2 production (kWh)	45,557,904
Annual H2 production (Nm^3)	15,205,681
wind turbine capacity factor	33%
nominal wind generating capacity (MW)	23
Discount Rate	10%
Lifetime (yr)	30

Electrolyzer

plant size (kW in)	23,176	
plant size (kW out)	15759.61816	
plant size (Nm3/day)	185,655	
operating capacity	90%	
capital cost ($)	$9,455,771 [5]	$600/kW out LHV
annualized capital cost ($/yr)	$1,003,061.07	
O&M costs ($/yr)	$228,085.21 [5]	$0.015/Nm3/yr
contribution to final H2 price ($/MBtu)	**$7.92**	

Electricity Costs

conversion efficiency	68% [6]
required electricity (kWh/yr)	66,996,918
unit cost of electricity ($/kWh)	$0.069 [7]
total cost of electricity ($/yr)	$4,622,787.34
contribution to final H2 price ($/MBtu)	**$29.74**

Totals

total annual cost ($/yr)	$5,853,933.62
H2 unit cost ($/MBtu)	**$37.66**

Delivery Costs

Cost to distribute ($/MBtu)	**$7.98** [3]
H2 Cost (at refueling station)	**$45.64**

End Use Calculations

Conversion Device	Fuel Cell
Efficiency (mi/gge)	44 [4]
Efficiency (mi/MBtu)	353.1300161
Fuel Cost ($/mi)	**$0.1292**

References

[1] Energy, Resources, and Technology Division, Dept. of Business, Economic Development & Tourism, State of Hawaii. 2000. "Hawaii Energy Strategy 2000."

[2] Parsons Brinckerhoff Quade & Douglas, Inc., 1995. Transportation Energy Strategy: Project #5 of the Hawaii Energy Strategy Development Program. Honolulu: Energy Division, Dept. of Business, Economic Development & Tourism, State of Hawaii.

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Hydrogen Pathways for the Island of Oahu

Potential Market

***Source: HES2000*[1]**

Registered Vehicles	595,121
Ground Transportation Fuel Used (gge)	284,302,000
Ground Transportation Fuel Used (MBtu)	35,429,444
Estimated Average Vehicle Efficiency (mi/gge)	18.38
Estimated Average Vehicle Efficiency (mi/MBtu)	147.4818496

LNG Feedstock Costs

***Source: The Gas Company IRP*[2]**

Assumptions: Convert existing SNG supply to LNG (3,120,815 MBtu for 1997), purchase LNG on Spot Market for $3.50/MBtu

Annual Natural Gas imports (MBtu/yr)	3120815
% of Transportation fuel displaced	10.54%
Operating Capacity	90%
Facility Size (MBtu/day)	9500.20
Interest Rate	12%
Project lifetime (yrs)	25

LNG Feedstocks

Delivered LNG feedstock cost ($/MBtu)	$3.50

LNG Terminal

capital costs ($)	$113,000,000.00
Unloading Facilities	
Storage	
Regasification Plant	
Send-Out Facilities (pipeline link)	
30 Acres near Barbers Point	
Annualized Capital Costs	$14,407,496.59
Annual O&M Costs ($/yr)	$12,000,000.00
Unit Cost ($/MBtu)	$8.46

TOTAL

Unit Cost ($/MBtu)	$11.96

***Source: East-West Center Report*[3]**

Assumptions: Substitute LNG for every fuel possible (SNG, fuel oil, coal, utility propane, vehicles); purchase LNG in long term contract, import 2.1 mmt/yr (Note: 48.3 MBtu/t LNG)

MBtu/ton LNG	48.3
Annual imports of LNG (tons)	2,100,000
Annual imports of LNG (MBtu)	101,430,000
Interest Rate	12%
Lifetime	20

NG Feedstock		$/MBtu
annual feedstock requirements (MBtu)	116,119,061	
feedstock unit cost ($/MBtu)	$1.15	
annual feedstock costs($/yr)	$133,536,920.44	$1.32
Liquefaction Facility		
Hawaii consumption (mmcf/d)	300	
Supply Facility export capacity (mmcf/d)	1200	
Liquefaction Plant Capital Costs (incl. Storage & port)	$3,200,000,000.00	
Liquefaction Plant O&M Costs ($/yr)	$81,000,000.00	
Hawaii's share: Liquefaction Capital Costs	$800,000,000.00	
Annualized Capital Cost	$107,103,024.03	$1.06
Hawaii's share: Liquefaction O&M ($/yr)	$20,250,000.00	$0.20
Transport		
120,000 m^3 Tanker Cost	$260,000,000.00	
Number of Tankers	6	
Total Tanker Capital Costs	$1,560,000,000.00	
Annualized Capital Cost	$208,850,896.86	$2.06
O&M	$54,772,200.00	$0.54
LNG Terminal		
Facility Size (MBtu/yr)	101,430,000	
Operating Capacity	90%	
Facility Size (MBtu/day)	308767	
Marine Installations	$160,000,000.00	
Storage (163,000 m^3,above ground)	$198,000,000.00	
Regasifier Plant	$182,000,000.00	
Pipes, Cables, etc.	$136,000,000.00	
Land (190 Acres)	$29,000,000.00	
Total Terminal Capital Costs	$705,000,000.00	
Annualized Capital Cost	$94,384,539.93	$0.93
O&M ($/yr)	$33,000,000.00	$0.33
Totals		
Total Annualized Capital Costs ($/yr)	$410,338,460.82	
Total O&M Costs ($/yr)	$108,022,200.00	
Total Feedstock Costs ($/yr)	$133,536,920.44	
Total Annual Costs ($/yr)	$651,897,581.26	
Unit Cost of Natural Gas at Regas plant gate ($/MBtu)	$6.43	

Hydrogen Pathways for the Island of Oahu (page 2)

Source: Andersen et.al.[4]

Assumptions: import ~1000000 tons of LNG/yr

Annual imports of Natural Gas (MBtu)	100,000,000
Annual imports of LNG (tons)	2,123,480
tanker velocity (mi/day)	480
tanker capacity (m3)	135,000
Discount Rate	12%
Lifetime (yr)	20

	short dist., low cap.	short dist., mid cap.	short dist., high cap.	middle	high	*NOTES*
NG Feedstock						
feedstock price ($/MBtu)	$0.50	$0.50	$0.50	0.75	$1.00	
feedstock necessary (MBtu/yr)	112,537,762	112,537,762	112,537,762	114,476,850	117,608,144	
feedstock costs ($/yr)	$56,268,880.85	$56,268,880.85	$56,268,880.85	$85,857,637.31	$117,608,144.36	
Unit Cost ($/MBtu)	$0.56	$0.56	$0.56	$0.86	$1.18	
Liquefaction Facility						
losses	8%	8%	8%	8.50%	9%	*8-9%*
LNG produced (MBtu/yr)	103,534,741	103,534,741	103,534,741	104,746,318	107,023,411	
LNG produced (m3/yr)	5,037,405	5,037,405	5,037,405	5,096,353	5,207,143	
LNG produced (tons/yr)	2,143,576	2,143,576	2,143,576	2,168,661	2,215,806	
capital costs	$643,072,923.97	$1,286,145,847.93	$1,929,218,771.90	$1,301,196,490.84	$1,994,225,056.61	*($300-900 million/1 million metric tons)*
annualized capital costs ($/yr)	$86,093,818.54	$172,187,637.07	$258,281,455.61	$174,202,598.78	$266,984,417.70	
O&M Costs ($/yr)	$63,760,680.41	$111,991,149.71	$160,221,619.01	$113,301,684.44	$165,620,390.95	*$0.15/MBtu processed + 7.5% of Capital Costs*
Unit Cost ($/MBtu)	$1.50	$2.84	$4.19	$2.88	$4.33	
Transport						
source location	Alaska	Alaska	Alaska	Australia	Middle East	
distance (mi)	3000	3000	3000	5000	8000	
round trip travel time (days)	15.9	15.9	15.9	24.2	36.7	*1.7 day turnaround*
number of tankers (135,000 m3)	2	2	2	3	5	*operates 340 days/yr*
Cost per tanker	$260,000,000.00	$260,000,000.00	$260,000,000.00	$260,000,000.00	$260,000,000.00	
total tanker capital costs	$520,000,000.00	$520,000,000.00	$520,000,000.00	$780,000,000.00	$1,300,000,000.00	
annualized capital costs ($/yr)	$69,616,965.62	$69,616,965.62	$69,616,965.62	$104,425,448.43	$174,042,414.05	
O&M Costs ($/yr)	$52,000,000.00	$52,000,000.00	$52,000,000.00	$78,000,000.00	$130,000,000.00	*10% of Capital Costs*
Unit Cost ($/MBtu)	$1.22	$1.22	$1.22	$1.82	$3.04	
losses	0.94%	0.94%	0.94%	2.08%	4.17%	*losses: 0.15-0.25%/day*
LNG received (MBtu)	102,564,103	102,564,103	102,564,103	102,564,103	102,564,103	
LNG received (tons)	2,123,480	2,123,480	2,123,480	2,123,480	2,123,480	
Regasification Plant						*Note: Does not include port facilities*
capital costs	$54,700,000.00	$54,700,000.00	$54,700,000.00	$54,700,000.00	$54,700,000.00	*($0.56/thousand cf/yr = $.547 /MBtu/yr output)*
annualized capital costs ($/yr)	$7,323,169.27	$7,323,169.27	$7,323,169.27	$7,323,169.27	$7,323,169.27	
O&M Costs ($/yr)	$5,470,000.00	$5,470,000.00	$5,470,000.00	$5,470,000.00	$5,470,000.00	*10% of Capital Costs*
Unit Cost ($/MBtu)	$0.13	$0.13	$0.13	$0.13	$0.13	
losses	2.50%	2.50%	2.50%	2.50%	2.50%	
Net Natural Gas imported (MBtu)	100,000,000	100,000,000	100,000,000	100,000,000	100,000,000	
Net Natural Gas imported (MBtu/day)	273,973	273,973	273,973			
Totals						
Unit Cost ($/MBtu)	$3.41	$4.75	$6.09	$5.69	$8.67	
Unit Cost delivered to Regas Plant ($/MBtu)	$3.28	$4.62	$5.96	$5.56	$8.54	
losses	11.14%	11.14%	11.14%	12.65%	14.97%	

Hydrogen Pathways for the Island of Oahu (page 3)

Production Costs

				NOTES
Replacement Goal (% of transportation energy)	10%	10%		
Annual H2 production (MBtu)	1,771,472	1,771,472	5	*assumes HFCV twice as efficient as ICEV*
Annual H2 production (Nm3)	173,287,588	173,287,588		
Discount Rate	10%	10%		
Lifetime (yr)	20	20		

Steam Methane Reformer

plant size (MBtu/day)	5,393	5,393		
plant size (Nm3/day)	527,512	527,512		*LHV*
operating capacity	90%	90%		
capital cost ($)	$31,650,701	$31,650,701	6,7	*\$60/Nm^3/day*
annualized capital cost ($/yr)	$3,717,679.46	$3,717,679.46		
O$M costs (%of capital)	5%	5%		
O&M costs ($/yr)	$1,582,535.05	$1,582,535.05	8	*5% of capital costs*
Contribution to final H2 cost ($/MBtu)	**$2.99**	**$2.99**		

LNG Feedstock Costs

conversion efficiency	68%	68%	8	*LHV*
natural gas feedstock (MBtu/day)	7,930	7,930		
natural gas feedstock (MBtu/yr)	2,605,106	2,605,106		
feedstock unit cost ($/MBtu)	**$11.96**	**$6.43**		
feedstock cost ($/yr)	$31,157,070.29	$16,750,832.94		
Contribution to final H2 cost ($/MBtu)	**$17.59**	**$9.46**		

Totals

total annual cost ($/yr)	$36,457,284.80	$22,051,047.45
Plant-gate H2 unit cost ($/MBtu)	**$20.58**	**$12.45**

Delivery Costs

Cost to distribute ($/MBtu)	**$7.98**	**$7.98**	9
H2 Cost (at refueling station)	**$28.56**	**$20.42**	

End Use Calculations

Conversion Device	Fuel Cell	Fuel Cell	
Efficiency (mi/gge)	44	44	5
Efficiency (mi/MBtu)	353.1300161	353.1300161	
Fuel Cost ($/mi)	**$0.0809**	**$0.0578**	

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[1] Energy, Resources, and Technology Division, Dept. of Business, Economic Development & Tourism, State of Hawaii. 2000. "Hawaii Energy Strategy 2000."

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Sensitivity Analysis Summary

Island	Pathway Source	Nominal Fueling Cost	Variable	Input Value	Low/High Estimates	Fueling Costs
Oahu	LNG	$0.081	Feedstock Costs ($/MBtu)	$11.96	$3.50	$0.046
					$13.00	$0.085
			SMR Efficiency (%)	68%	63%	$0.085
					75%	$0.076
			Delivery Costs ($/MBtu)	$7.98	$3.50	$0.068
					$10.82	$0.089
Hawaii	Geothermal	$0.090	Electricity ($/kWh)	$0.044	$0.025	$0.067
					$0.060	$0.109
			Electrolyzer Capital Costs ($)	$600	300	$0.086
					900	$0.093
			Electrolyzer Efficiency (%)	68%	63%	$0.095
					75%	$0.084
			Delivery Costs ($/MBtu)	$7.98	$3.50	$0.077
					$10.82	$0.098
	Wind	$0.114	Electricity ($/kWh)	$0.045	$0.040	$0.108
					$0.060	$0.133
			Capacity Factor (%)	33%	25%	$0.126
					45%	$0.104
			Electrolyzer Capital Costs ($)	$600	$300	$0.105
					$900	$0.123
			Electrolyzer Efficiency (%)	68%	63%	$0.120
					75%	$0.107
			Delivery Costs ($/MBtu)	$7.98	$3.50	$0.102
					$10.82	$0.122
	Biomass	$0.046	Production Costs ($/MBtu)		50%	$0.068
					-50%	$0.023
			Delivery Costs ($/MBtu)	$7.98	$3.50	$0.033
					$10.82	$0.054
Maui	Wind	$0.139	Electricity ($/kWh)	$0.065	0.05	$0.120
					0.085	$0.163
			Capacity Factor (%)	33%	25%	$0.150
					45%	$0.129
			Electrolyzer Capital Costs ($)	$600	300	$0.130
					900	$0.148
			Electrolyzer Efficiency (%)	68%	63%	$0.146
					75%	$0.130
			Delivery Costs ($/MBtu)	$7.98	$3.50	$0.126
					$10.82	$0.147
	Biomass	$0.046	Production Costs ($/MBtu)		50%	$0.068
					-50%	$0.023
			Delivery Costs ($/MBtu)	$7.98	$3.50	$0.033
					$10.82	$0.054
Kauai	Wind	0.114300687	Electricity ($/kWh)	$0.069	0.06	$0.133
					0.08	$0.157
			Capacity Factor (%)	33%	25%	$0.155
					45%	$0.134
			Electrolyzer Capital Costs ($)	$600	300	$0.134
					900	$0.153
			Electrolyzer Efficiency (%)	68%	63%	$0.152
					75%	$0.134
			Delivery Costs ($/MBtu)	$7.98	$3.50	$0.131
					$10.82	$0.152
	Biomass	0.045530539	Production Costs ($/MBtu)		50%	$0.068
					-50%	$0.023
			Delivery Costs ($/MBtu)	$7.98	$3.50	$0.033
					$10.82	$0.054

Sensitivity Analysis: Hydrogen Pathways for the Island of Oahu

Potential Market

Source: HES2000[1]

Registered Vehicles	595,121
Ground Transportation Fuel Used (gge)	284,302,000
Ground Transportation Fuel Used (MBtu)	35,429,444
Estimated Average Vehicle Efficiency (mi/gge)	18.38
Estimated Average Vehicle Efficiency (mi/MBtu)	147.4818496

1. Sensitivity to LNG feedstock cost

												Low	**High**
Annual H2 production (MBtu)	1,771,472	1,771,472	1,771,472	1,771,472	1,771,472	1,771,472	1,771,472	1,771,472	1,771,472	1,771,472	1,771,472	1,771,472	1,771,472
Annual H2 production (Nm3)	173,287,588	173,287,588	173,287,588	173,287,588	173,287,588	173,287,588	173,287,588	173,287,588	173,287,588	173,287,588	173,287,588	173,287,588	173,287,588
Discount Rate	10%	10%	10%	10%	10%	10%	10%	10%	10%	10%	10%	10%	10%
Lifetime (yr)	20	20	20	20	20	20	20	20	20	20	20	20	20
Steam Methane Reformer													
plant size (MBtu/day)	5,393	5,393	5,393	5,393	5,393	5,393	5,393	5,393	5,393	5,393	5,393	5,393	5,393
plant size (Nm3/day)	527,512	527,512	527,512	527,512	527,512	527,512	527,512	527,512	527,512	527,512	527,512	527,512	527,512
operating capacity	90%	90%	90%	90%	90%	90%	90%	90%	90%	90%	90%	90%	90%
capital cost ($)	$31,650,701	$31,650,701	$31,650,701	$31,650,701	$31,650,701	$31,650,701	$31,650,701	$31,650,701	$31,650,701	$31,650,701	$31,650,701	$31,650,701	$31,650,701
annualized capital cost ($/yr)	$3,717,679.46	$3,717,679.46	$3,717,679.46	$3,717,679.46	$3,717,679.46	$3,717,679.46	$3,717,679.46	$3,717,679.46	$3,717,679.46	$3,717,679.46	$3,717,679.46	$3,717,679.46	$3,717,679.46
O$M costs (%of capital)	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%
O&M costs ($/yr)	$1,582,535.05	$1,582,535.05	$1,582,535.05	$1,582,535.05	$1,582,535.05	$1,582,535.05	$1,582,535.05	$1,582,535.05	$1,582,535.05	$1,582,535.05	$1,582,535.05	$1,582,535.05	$1,582,535.05
LNG Feedstock Costs - landed													
conversion efficiency	68%	68%	68%	68%	68%	68%	68%	68%	68%	68%	68%	68%	68%
natural gas feedstock (MBtu/day)	7,930	7,930	7,930	7,930	7,930	7,930	7,930	7,930	7,930	7,930	7,930	7,930	7,930
natural gas feedstock (MBtu/yr)	2,605,106	2,605,106	2,605,106	2,605,106	2,605,106	2,605,106	2,605,106	2,605,106	2,605,106	2,605,106	2,605,106	2,605,106	2,605,106
feedstock unit cost ($/MBtu)	$13.00	$12.00	$11.00	$10.00	$9.00	$8.00	$7.00	$6.00	$5.00	$4.00	$3.00	$3.50	$13.00
feedstock cost ($/yr)	$33,866,380.75	$31,261,274.54	$28,656,168.33	$26,051,062.11	$23,445,955.90	$20,840,849.69	$18,235,743.48	$15,630,637.27	$13,025,531.06	$10,420,424.85	$7,815,318.63	$9,117,871.74	$33,866,380.75
Totals													
total annual cost ($/yr)	$39,166,595.26	$36,561,489.05	$33,956,382.84	$31,351,276.63	$28,746,170.42	$26,141,064.20	$23,535,957.99	$20,930,851.78	$18,325,745.57	$15,720,639.36	$13,115,533.15	$14,418,086.25	$39,166,595.26
H2 unit cost ($/MBtu)	$22.11	$20.64	$19.17	$17.70	$16.23	$14.76	$13.29	$11.82	$10.34	$8.87	$7.40	$8.14	$22.11

Delivery Costs

Cost to distribute ($/MBtu)	$7.98	$7.98	$7.98	$7.98	$7.98	$7.98	$7.98	$7.98	$7.98	$7.98	$7.98	$7.98	$7.98
H2 Cost (at refueling station)	$30.09	$28.61	$27.14	$25.67	$24.20	$22.73	$21.26	$19.79	$18.32	$16.85	$15.38	$16.11	$30.09

End Use Calculations

Conversion Device	Fuel Cell	Fuel Cell	Fuel Cell	Fuel Cell	Fuel Cell	Fuel Cell	Fuel Cell	Fuel Cell	Fuel Cell	Fuel Cell	Fuel Cell	Fuel Cell	Fuel Cell
Efficiency (mi/gge)	44	44	44	44	44	44	44	44	44	44	44	44	44
Efficiency (mi/MBtu)	353.1300161	353.1300161	353.1300161	353.1300161	353.1300161	353.1300161	353.1300161	353.1300161	353.1300161	353.1300161	353.1300161	353.1300161	353.1300161
Fuel Cost ($/mi)	$0.0852	$0.0810	$0.0769	$0.0727	$0.0685	$0.0644	$0.0602	$0.0560	$0.0519	$0.0477	$0.0436	$0.0456	$0.0852

2. Sensitivity to SMR efficiency

									Low	**High**
Annual H2 production (MBtu)	1,771,472	1,771,472	1,771,472	1,771,472	1,771,472	1,771,472	1,771,472	1,771,472	1,771,472	1,771,472
Annual H2 production (Nm3)	173,287,588	173,287,588	173,287,588	173,287,588	173,287,588	173,287,588	173,287,588	173,287,588	173,287,588	173,287,588
Discount Rate	10%	10%	10%	10%	10%	10%	10%	10%	10%	10%
Lifetime (yr)	20	20	20	20	20	20	20	20	20	20
Steam Methane Reformer										
plant size (MBtu/day)	5,393	5,393	5,393	5,393	5,393	5,393	5,393	5,393	5,393	5,393
plant size (Nm3/day)	527,512	527,512	527,512	527,512	527,512	527,512	527,512	527,512	527,512	527,512
operating capacity	90%	90%	90%	90%	90%	90%	90%	90%	90%	90%
capital cost ($)	$31,650,701	$31,650,701	$31,650,701	$31,650,701	$31,650,701	$31,650,701	$31,650,701	$31,650,701	$31,650,701	$31,650,701
annualized capital cost ($/yr)	$3,717,679.46	$3,717,679.46	$3,717,679.46	$3,717,679.46	$3,717,679.46	$3,717,679.46	$3,717,679.46	$3,717,679.46	$3,717,679.46	$3,717,679.46
O$M costs (%of capital)	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%
O&M costs ($/yr)	$1,582,535.05	$1,582,535.05	$1,582,535.05	$1,582,535.05	$1,582,535.05	$1,582,535.05	$1,582,535.05	$1,582,535.05	$1,582,535.05	$1,582,535.05
LNG Feedstock Costs - landed										
conversion efficiency	60%	65%	70%	75%	80%	85%	90%	95%	63%	75%
natural gas feedstock (MBtu/day)	8,988	8,296	7,704	7,190	6,741	6,344	5,992	5,676	8,560	7,190
natural gas feedstock (MBtu/yr)	2,952,454	2,725,342	2,530,675	2,361,963	2,214,340	2,084,085	1,968,302	1,864,708	2,811,861	2,361,963
feedstock unit cost ($/MBtu)	$11.96	$11.96	$11.96	$11.96	$11.96	$11.96	$11.96	$11.96	$11.96	$11.96
feedstock cost ($/yr)	$35,311,346.33	$32,595,088.92	$30,266,868.28	$28,249,077.06	$26,483,509.75	$24,925,656.23	$23,540,897.55	$22,301,902.94	$33,629,853.65	$28,249,077.06
Totals										
total annual cost ($/yr)	$40,611,560.84	$37,895,303.43	$35,567,082.79	$33,549,291.57	$31,783,724.26	$30,225,870.74	$28,841,112.06	$27,602,117.46	$38,930,068.16	$33,549,291.57
H2 unit cost ($/MBtu)	$22.93	$21.39	$20.08	$18.94	$17.94	$17.06	$16.28	$15.58	$21.98	$18.94

Delivery Costs

Cost to distribute ($/MBtu)	$7.98	$7.98	$7.98	$7.98	$7.98	$7.98	$7.98	$7.98	$7.98	$7.98
H2 Cost (at refueling station)	$30.90	$29.37	$28.05	$26.91	$25.92	$25.04	$24.26	$23.56	$29.95	$26.91

End Use Calculations

Conversion Device	Fuel Cell	Fuel Cell	Fuel Cell	Fuel Cell	Fuel Cell	Fuel Cell	Fuel Cell	Fuel Cell	Fuel Cell	Fuel Cell
Efficiency (mi/gge)	44	44	44	44	44	44	44	44	44	44
Efficiency (mi/MBtu)	353.1300161	353.1300161	353.1300161	353.1300161	353.1300161	353.1300161	353.1300161	353.1300161	353.1300161	353.1300161
Fuel Cost ($/mi)	$0.0875	$0.0832	$0.0794	$0.0762	$0.0734	$0.0709	$0.0687	$0.0667	$0.0848	$0.0762

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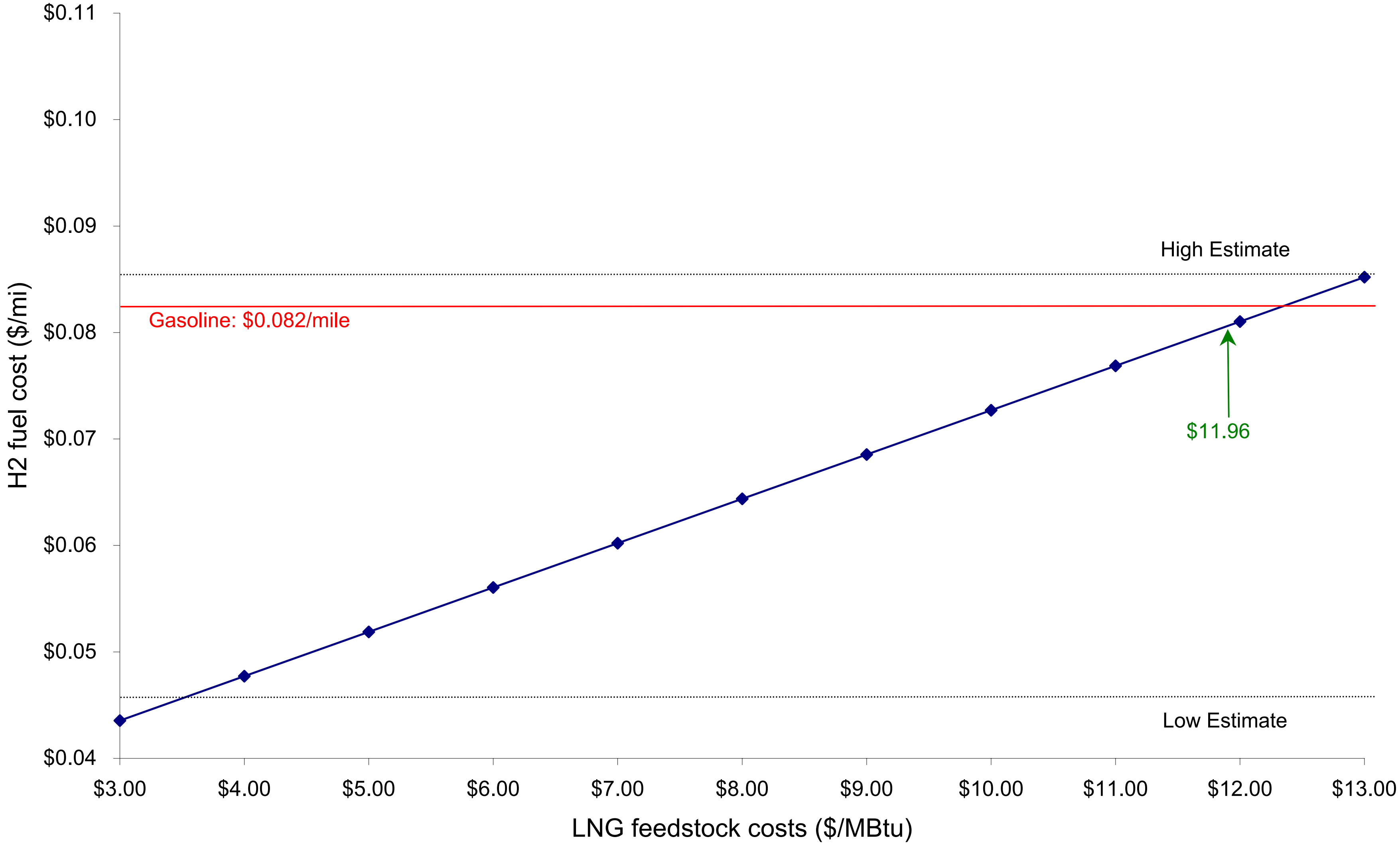

$0.11
$0.10
$0.09
$0.08
$0.07
$0.06
$0.05
$0.04
H2 fuel cost ($/mi)
High Estimate
Gasoline: $0.082/mile
$11.96
Low Estimate
$3.00
$4.00
$5.00
$6.00
$7.00
$8.00
$9.00
$10.00
$11.00
$12.00
$13.00
LNG feedstock costs ($/MBtu)

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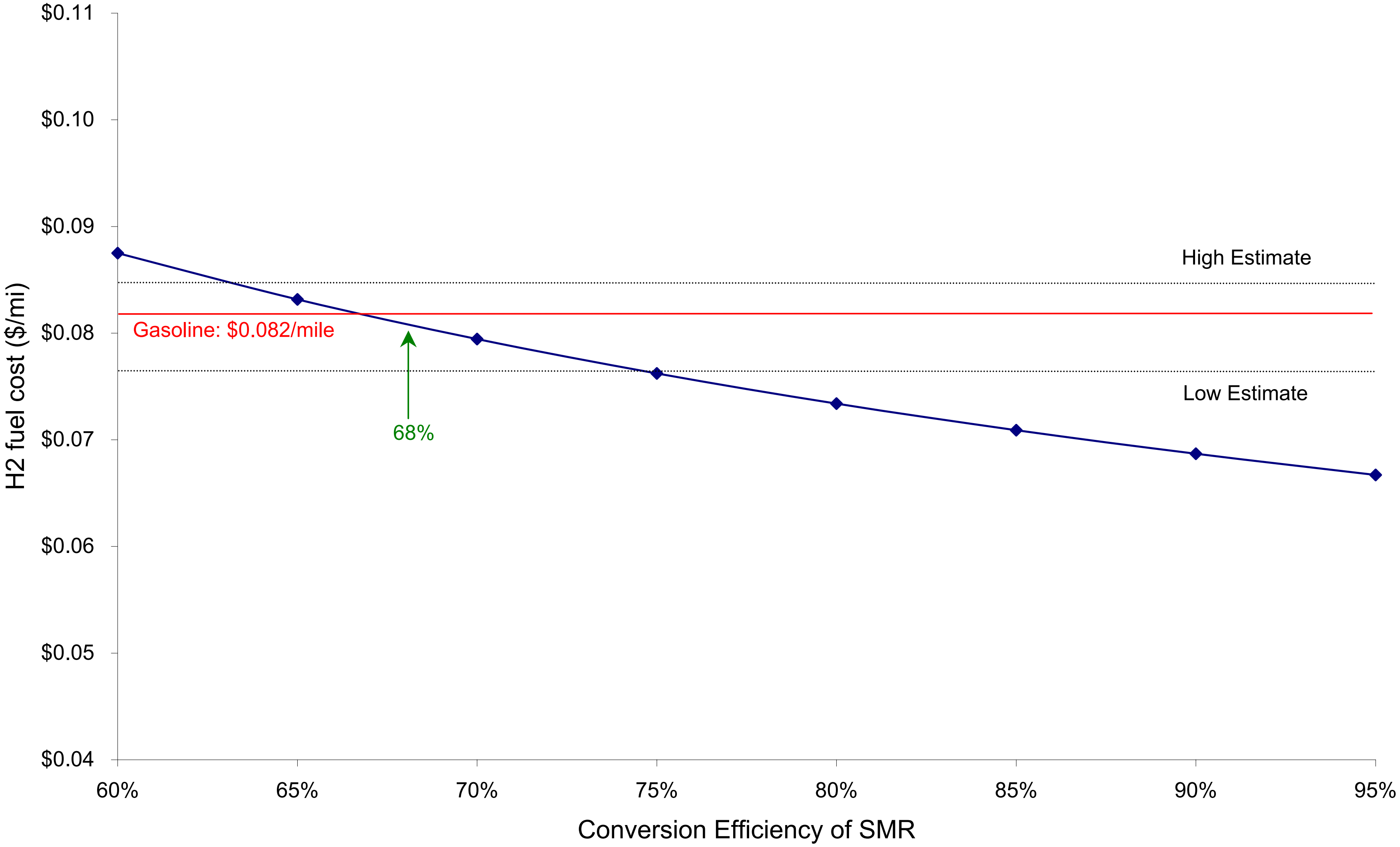
Sensitivity of H2 fuel price to SMR Conversion Efficiency



3. Sensitivity to Delivery Costs

											Low	**High**
Annual H2 production (MBtu)	1,771,472	1,771,472	1,771,472	1,771,472	1,771,472	1,771,472	1,771,472	1,771,472	1,771,472	1,771,472	1,771,472	1,771,472
Annual H2 production (Nm3)	173,287,588	173,287,588	173,287,588	173,287,588	173,287,588	173,287,588	173,287,588	173,287,588	173,287,588	173,287,588	173,287,588	173,287,588
Discount Rate	10%	10%	10%	10%	10%	10%	10%	10%	10%	10%	10%	10%
Lifetime (yr)	20	20	20	20	20	20	20	20	20	20	20	20
Steam Methane Reformer												
plant size (MBtu/day)	5,393	5,393	5,393	5,393	5,393	5,393	5,393	5,393	5,393	5,393	5,393	5,393
plant size (Nm3/day)	527,512	527,512	527,512	527,512	527,512	527,512	527,512	527,512	527,512	527,512	527,512	527,512
operating capacity	90%	90%	90%	90%	90%	90%	90%	90%	90%	90%	90%	90%
capital cost ($)	$31,650,701	$31,650,701	$31,650,701	$31,650,701	$31,650,701	$31,650,701	$31,650,701	$31,650,701	$31,650,701	$31,650,701	$31,650,701	$31,650,701
annualized capital cost ($/yr)	$3,717,679.46	$3,717,679.46	$3,717,679.46	$3,717,679.46	$3,717,679.46	$3,717,679.46	$3,717,679.46	$3,717,679.46	$3,717,679.46	$3,717,679.46	$3,717,679.46	$3,717,679.46
O$M costs (%of capital)	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%
O&M costs ($/yr)	$1,582,535.05	$1,582,535.05	$1,582,535.05	$1,582,535.05	$1,582,535.05	$1,582,535.05	$1,582,535.05	$1,582,535.05	$1,582,535.05	$1,582,535.05	$1,582,535.05	$1,582,535.05
LNG Feedstock Costs - landed												
conversion efficiency	68%	68%	68%	68%	68%	68%	68%	68%	68%	68%	68%	68%
natural gas feedstock (MBtu/day)	7,930	7,930	7,930	7,930	7,930	7,930	7,930	7,930	7,930	7,930	7,930	7,930
natural gas feedstock (MBtu/yr)	2,605,106	2,605,106	2,605,106	2,605,106	2,605,106	2,605,106	2,605,106	2,605,106	2,605,106	2,605,106	2,605,106	2,605,106
feedstock unit cost ($/MBtu)	$11.96	$11.96	$11.96	$11.96	$11.96	$11.96	$11.96	$11.96	$11.96	$11.96	$11.96	$11.96
feedstock cost ($/yr)	$31,157,070.29	$31,157,070.29	$31,157,070.29	$31,157,070.29	$31,157,070.29	$31,157,070.29	$31,157,070.29	$31,157,070.29	$31,157,070.29	$31,157,070.29	$31,157,070.29	$31,157,070.29
Totals												
total annual cost ($/yr)	$36,457,284.80	$36,457,284.80	$36,457,284.80	$36,457,284.80	$36,457,284.80	$36,457,284.80	$36,457,284.80	$36,457,284.80	$36,457,284.80	$36,457,284.80	$36,457,284.80	$36,457,284.80
H2 unit cost ($/MBtu)	$20.58	$20.58	$20.58	$20.58	$20.58	$20.58	$20.58	$20.58	$20.58	$20.58	$20.58	$20.58
Delivery Costs												
Cost to distribute ($/MBtu)	$3.00	$4.00	$5.00	$6.00	$7.00	$8.00	$9.00	$10.00	$11.00	$12.00	$3.50	$10.82
H2 Cost (at refueling station)	$23.58	$24.58	$25.58	$26.58	$27.58	$28.58	$29.58	$30.58	$31.58	$32.58	$24.08	$31.40
End Use Calculations												
Conversion Device	Fuel Cell	Fuel Cell	Fuel Cell	Fuel Cell	Fuel Cell	Fuel Cell	Fuel Cell	Fuel Cell	Fuel Cell	Fuel Cell	Fuel Cell	Fuel Cell
Efficiency (mi/gge)	44	44	44	44	44	44	44	44	44	44	44	44
Efficiency (mi/MBtu)	353.1300161	353.1300161	353.1300161	353.1300161	353.1300161	353.1300161	353.1300161	353.1300161	353.1300161	353.1300161	353.1300161	353.1300161
Fuel Cost ($/mi)	$0.0668	$0.0696	$0.0724	$0.0753	$0.0781	$0.0809	$0.0838	$0.0866	$0.0894	$0.0923	$0.0682	$0.0889

4. Sensitivity to Fuel Cell Efficiency

Annual H2 production (MBtu)	1,771,472	1,771,472	1,771,472	1,771,472	1,771,472	1,771,472	1,771,472	1,771,472	1,771,472	1,771,472
Annual H2 production (Nm3)	173,287,588	173,287,588	173,287,588	173,287,588	173,287,588	173,287,588	173,287,588	173,287,588	173,287,588	173,287,588
Discount Rate	10%	10%	10%	10%	10%	10%	10%	10%	10%	10%
Lifetime (yr)	20	20	20	20	20	20	20	20	20	20
Steam Methane Reformer										
plant size (MBtu/day)	5,393	5,393	5,393	5,393	5,393	5,393	5,393	5,393	5,393	5,393
plant size (Nm3/day)	527,512	527,512	527,512	527,512	527,512	527,512	527,512	527,512	527,512	527,512
operating capacity	90%	90%	90%	90%	90%	90%	90%	90%	90%	90%
capital cost ($)	$31,650,701	$31,650,701	$31,650,701	$31,650,701	$31,650,701	$31,650,701	$31,650,701	$31,650,701	$31,650,701	$31,650,701
annualized capital cost ($/yr)	$3,717,679.46	$3,717,679.46	$3,717,679.46	$3,717,679.46	$3,717,679.46	$3,717,679.46	$3,717,679.46	$3,717,679.46	$3,717,679.46	$3,717,679.46
O$M costs (%of capital)	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%
O&M costs ($/yr)	$1,582,535.05	$1,582,535.05	$1,582,535.05	$1,582,535.05	$1,582,535.05	$1,582,535.05	$1,582,535.05	$1,582,535.05	$1,582,535.05	$1,582,535.05
LNG Feedstock Costs - landed										
conversion efficiency	68%	68%	68%	68%	68%	68%	68%	68%	68%	68%
natural gas feedstock (MBtu/day)	7,930	7,930	7,930	7,930	7,930	7,930	7,930	7,930	7,930	7,930
natural gas feedstock (MBtu/yr)	2,605,106	2,605,106	2,605,106	2,605,106	2,605,106	2,605,106	2,605,106	2,605,106	2,605,106	2,605,106
feedstock unit cost ($/MBtu)	$11.96	$11.96	$11.96	$11.96	$11.96	$11.96	$11.96	$11.96	$11.96	$11.96
feedstock cost ($/yr)	$31,157,070.29	$31,157,070.29	$31,157,070.29	$31,157,070.29	$31,157,070.29	$31,157,070.29	$31,157,070.29	$31,157,070.29	$31,157,070.29	$31,157,070.29
Totals										
total annual cost ($/yr)	$36,457,284.80	$36,457,284.80	$36,457,284.80	$36,457,284.80	$36,457,284.80	$36,457,284.80	$36,457,284.80	$36,457,284.80	$36,457,284.80	$36,457,284.80
H2 unit cost ($/MBtu)	$20.58	$20.58	$20.58	$20.58	$20.58	$20.58	$20.58	$20.58	$20.58	$20.58
Delivery Costs										
Cost to distribute ($/MBtu)	$7.98	$7.98	$7.98	$7.98	$7.98	$7.98	$7.98	$7.98	$7.98	$7.98
H2 Cost (at refueling station)	$28.56	$28.56	$28.56	$28.56	$28.56	$28.56	$28.56	$28.56	$28.56	$28.56
End Use Calculations										
Conversion Device	Fuel Cell	Fuel Cell	Fuel Cell	Fuel Cell	Fuel Cell	Fuel Cell	Fuel Cell	Fuel Cell	Fuel Cell	Fuel Cell
Efficiency (mi/gge)	35	40	45	50	55	60	65	70	75	80
Efficiency (mi/MBtu)	280.8988764	321.0272873	361.1556982	401.2841091	441.4125201	481.540931	521.6693419	561.7977528	601.9261637	642.0545746
Fuel Cost ($/mi)	$0.1017	$0.0890	$0.0791	$0.0712	$0.0647	$0.0593	$0.0547	$0.0508	$0.0474	$0.0445

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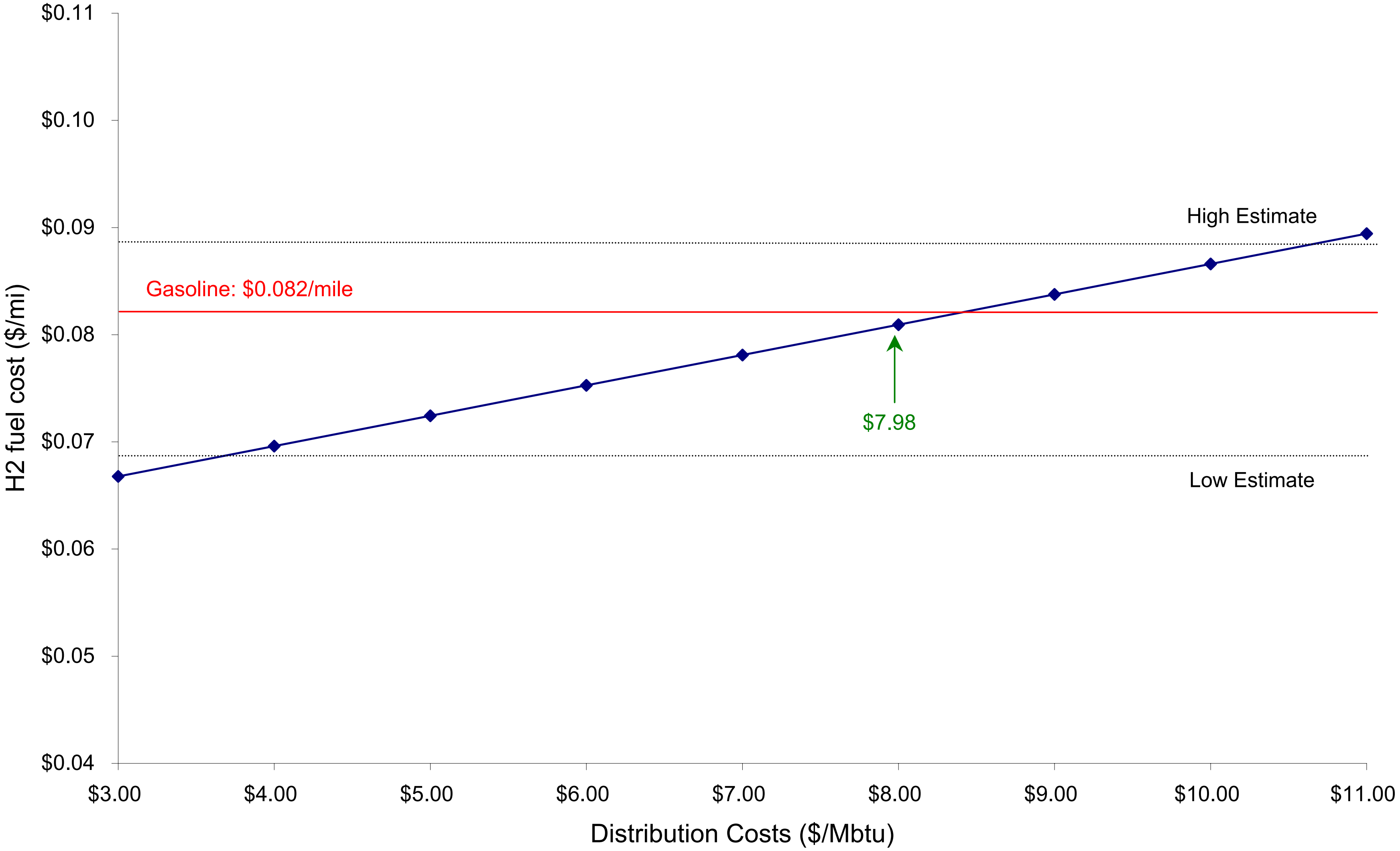
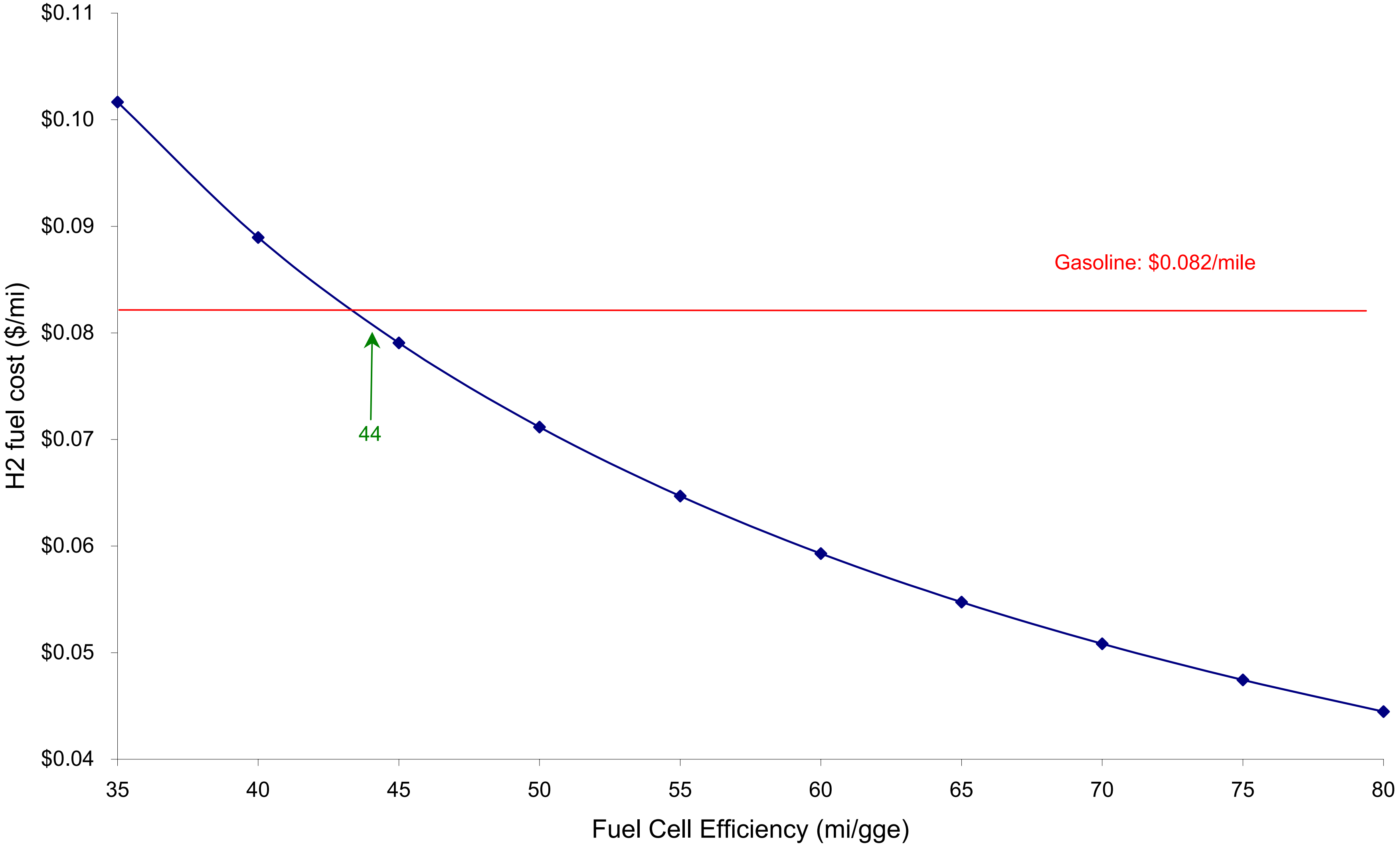
Sensitivity of H2 fuel price to Delivery Costs for LNG



OAHU

Sensitivity of H2 fuel price to Fuel Cell Efficiency for LNG



Hydrogen Pathways for the Island of Hawaii - Geothermal Sensitivity Analyses

Potential Market

Registered Vehicles:	118,364
Ground Transportation Fuel Used (gge)	67,794,000
Ground Transportation Fuel Used (MBtu)	8,448,424
Estimated Average Vehicle Efficiency (mi/gge)	17.13
Estimated Average Vehicle Efficiency (mi/MBtu)	137.4812674

1. Sensitivity to Cost of Geothermal Electricity

Production Costs

									Low	**High**
replacement goal (% of energy used for tranportatio	10%	10%	10%	10%	10%	10%	10%	10%	10%	10%
Annual H2 production (MBtu)	422,421	422,421	422,421	422,421	422,421	422,421	422,421	422,421	422,421	422,421
Annual H2 production (kWh)	123,804,568	123,804,568	123,804,568	123,804,568	123,804,568	123,804,568	123,804,568	123,804,568	123,804,568	123,804,568
geothermal plant capacity factor	90%	90%	90%	90%	90%	90%	90%	90%	90%	90%
nominal geothermal generating capacity (MW)	23	23	23	23	23	23	23	23	23	23
Discount Rate	10%	10%	10%	10%	10%	10%	10%	10%	10%	10%
Lifetime (yr)	30	30	30	30	30	30	30	30	30	30

Electrolyzer

plant size (kW in)	23,093	23,093	23,093	23,093	23,093	23,093	23,093	23,093	23,093	23,093
plant size (kW out)	15703.26838	15703.26838	15703.26838	15703.26838	15703.26838	15703.26838	15703.26838	15703.26838	15703.26838	15703.26838
plant size (Nm3/day)	184,991	184,991	184,991	184,991	184,991	184,991	184,991	184,991	184,991	184,991
operating capacity	90%	90%	90%	90%	90%	90%	90%	90%	90%	90%
capital cost ($)	$9,421,961	$9,421,961	$9,421,961	$9,421,961	$9,421,961	$9,421,961	$9,421,961	$9,421,961	$9,421,961	$9,421,961
annualized capital cost ($/yr)	$999,474.54	$999,474.54	$999,474.54	$999,474.54	$999,474.54	$999,474.54	$999,474.54	$999,474.54	$999,474.54	$999,474.54
O&M costs ($/yr)	$1,012,825.66	$1,012,825.66	$1,012,825.66	$1,012,825.66	$1,012,825.66	$1,012,825.66	$1,012,825.66	$1,012,825.66	$1,012,825.66	$1,012,825.66

Electricity Costs

conversion efficiency	68%	68%	68%	68%	68%	68%	68%	68%	68%	68%
required electricity (kWh/yr)	182,065,541	182,065,541	182,065,541	182,065,541	182,065,541	182,065,541	182,065,541	182,065,541	182,065,541	182,065,541
unit cost of electricity ($/kWh)	$0.025	$0.030	$0.035	$0.040	$0.045	$0.050	$0.055	$0.060	$0.025	$0.060
total cost of electricity ($/yr)	$4,551,638.53	$5,461,966.23	$6,372,293.94	$7,282,621.64	$8,192,949.35	$9,103,277.05	$10,013,604.76	$10,923,932.46	$4,551,638.53	$10,923,932.46

Totals

total annual cost ($/yr)	$6,563,938.73	$7,474,266.44	$8,384,594.14	$9,294,921.85	$10,205,249.55	$11,115,577.26	$12,025,904.96	$12,936,232.67	$6,563,938.73	$12,936,232.67
H2 unit cost ($/MBtu)	$15.54	$17.69	$19.85	$22.00	$24.16	$26.31	$28.47	$30.62	$15.54	$30.62

Delivery Costs

Cost to distribute ($/MBtu)	$7.98	$7.98	$7.98	$7.98	$7.98	$7.98	$7.98	$7.98	$7.98	$7.98
H2 Cost (at refueling station)	$23.51	$25.67	$27.82	$29.98	$32.13	$34.29	$36.44	$38.60	$23.51	$38.60

End Use Calculations

Conversion Device	Fuel Cell	Fuel Cell	Fuel Cell	Fuel Cell	Fuel Cell	Fuel Cell	Fuel Cell	Fuel Cell	Fuel Cell	Fuel Cell
Efficiency (mi/gge)	44	44	44	44	44	44	44	44	44	44
Efficiency (mi/MBtu)	353.1300161	353.1300161	353.1300161	353.1300161	353.1300161	353.1300161	353.1300161	353.1300161	353.1300161	353.1300161
Fuel Cost ($/mi)	$0.0666	$0.0727	$0.0788	$0.0849	$0.0910	$0.0971	$0.1032	$0.1093	$0.0666	$0.1093

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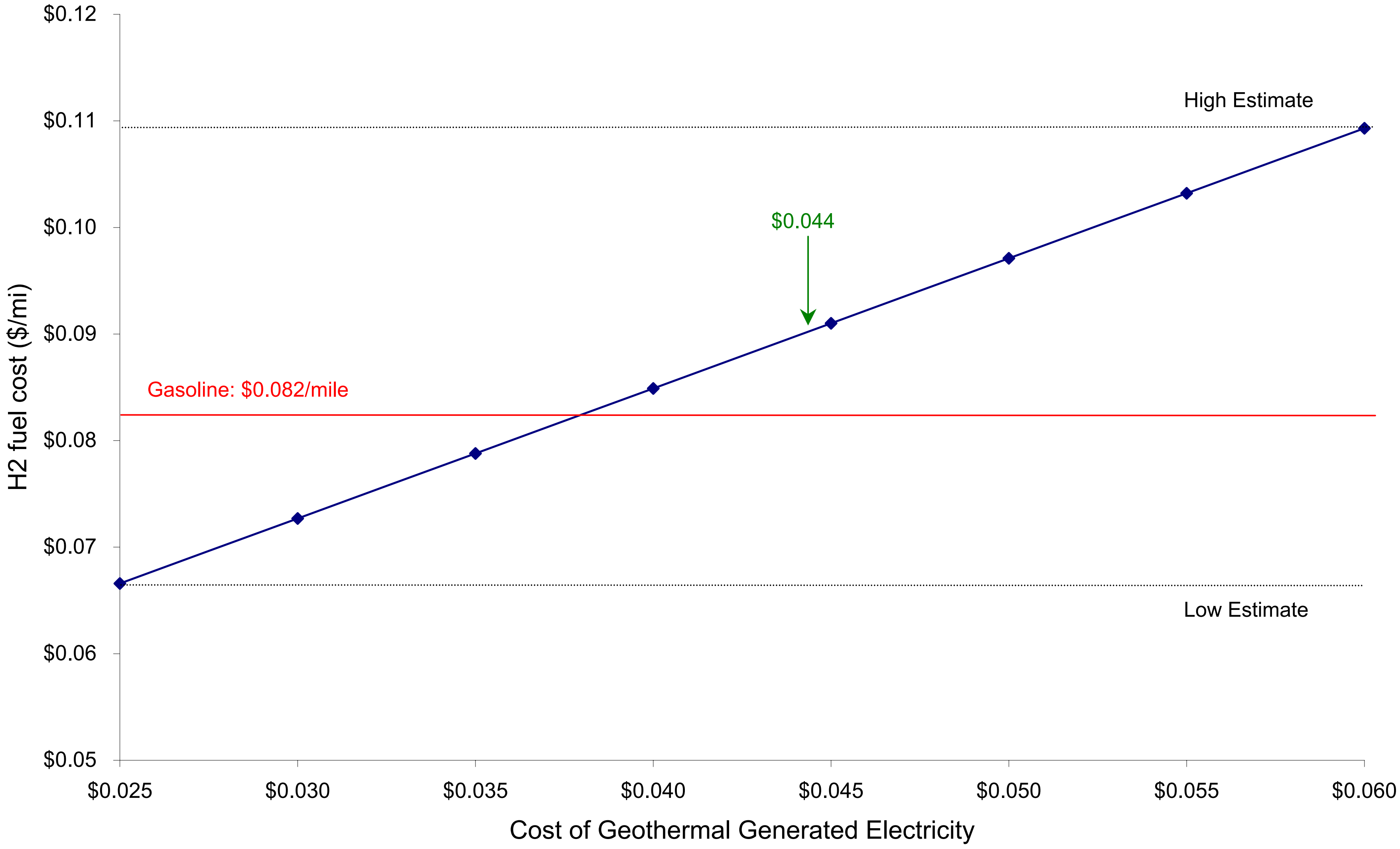
Sensitivity of H2 fuel price to Cost of Geothermal Electricity



2. Sensitivity to Electrolyzer Capital Cost

									Low	**High**
Production Costs										
replacement goal (% of energy used for tranportatio	10%	10%	10%	10%	10%	10%	10%	10%	10%	10%
Annual H2 production (MBtu)	422,421	422,421	422,421	422,421	422,421	422,421	422,421	422,421	422,421	422,421
Annual H2 production (kWh)	123,804,568	123,804,568	123,804,568	123,804,568	123,804,568	123,804,568	123,804,568	123,804,568	123,804,568	123,804,568
geothermal plant capacity factor	90%	90%	90%	90%	90%	90%	90%	90%	90%	90%
nominal geothermal generating capacity (MW)	23	23	23	23	23	23	23	23	23	23
Discount Rate	10%	10%	10%	10%	10%	10%	10%	10%	10%	10%
Lifetime (yr)	30	30	30	30	30	30	30	30	30	30
Electrolyzer										
plant size (kW in)	23,093	23,093	23,093	23,093	23,093	23,093	23,093	23,093	23,093	23,093
plant size (kW out)	15703.26838	15703.26838	15703.26838	15703.26838	15703.26838	15703.26838	15703.26838	15703.26838	15703.26838	15703.26838
plant size (Nm3/day)	184,991	184,991	184,991	184,991	184,991	184,991	184,991	184,991	184,991	184,991
operating capacity	90%	90%	90%	90%	90%	90%	90%	90%	90%	90%
capital cost ($/kW)	$200	$300	$400	$500	$600	$700	$800	$900	$300	$900
annualized capital cost ($/yr)	$333,158.18	$499,737.27	$666,316.36	$832,895.45	$999,474.54	$1,166,053.63	$1,332,632.72	$1,499,211.81	$499,737.27	$1,499,211.81
O&M costs ($/yr)	$1,012,825.66	$1,012,825.66	$1,012,825.66	$1,012,825.66	$1,012,825.66	$1,012,825.66	$1,012,825.66	$1,012,825.66	$1,012,825.66	$1,012,825.66
Electricity Costs										
conversion efficiency	68%	68%	68%	68%	68%	68%	68%	68%	68%	68%
required electricity (kWh/yr)	182,065,541	182,065,541	182,065,541	182,065,541	182,065,541	182,065,541	182,065,541	182,065,541	182,065,541	182,065,541
unit cost of electricity ($/kWh)	$0.044	$0.044	$0.044	$0.044	$0.044	$0.044	$0.044	$0.044	$0.044	$0.044
total cost of electricity ($/yr)	$8,010,883.81	$8,010,883.81	$8,010,883.81	$8,010,883.81	$8,010,883.81	$8,010,883.81	$8,010,883.81	$8,010,883.81	$8,010,883.81	$8,010,883.81
Totals										
total annual cost ($/yr)	$9,356,867.65	$9,523,446.74	$9,690,025.83	$9,856,604.92	$10,023,184.01	$10,189,763.10	$10,356,342.19	$10,522,921.28	$9,523,446.74	$10,522,921.28
H2 unit cost ($/MBtu)	$22.15	$22.54	$22.94	$23.33	$23.73	$24.12	$24.52	$24.91	$22.54	$24.91
Delivery Costs										
Cost to distribute ($/MBtu)	$7.98	$7.98	$7.98	$7.98	$7.98	$7.98	$7.98	$7.98	$7.98	$7.98
H2 Cost (at refueling station)	$30.13	$30.52	$30.92	$31.31	$31.70	$32.10	$32.49	$32.89	$30.52	$32.89
End Use Calculations										
Conversion Device	Fuel Cell	Fuel Cell	Fuel Cell	Fuel Cell	Fuel Cell	Fuel Cell	Fuel Cell	Fuel Cell	Fuel Cell	Fuel Cell
Efficiency (mi/gge)	44	44	44	44	44	44	44	44	44	44
Efficiency (mi/MBtu)	353.1300161	353.1300161	353.1300161	353.1300161	353.1300161	353.1300161	353.1300161	353.1300161	353.1300161	353.1300161
Fuel Cost ($/mi)	$0.0853	$0.0864	$0.0875	$0.0887	$0.0898	$0.0909	$0.0920	$0.0931	$0.0864	$0.0931

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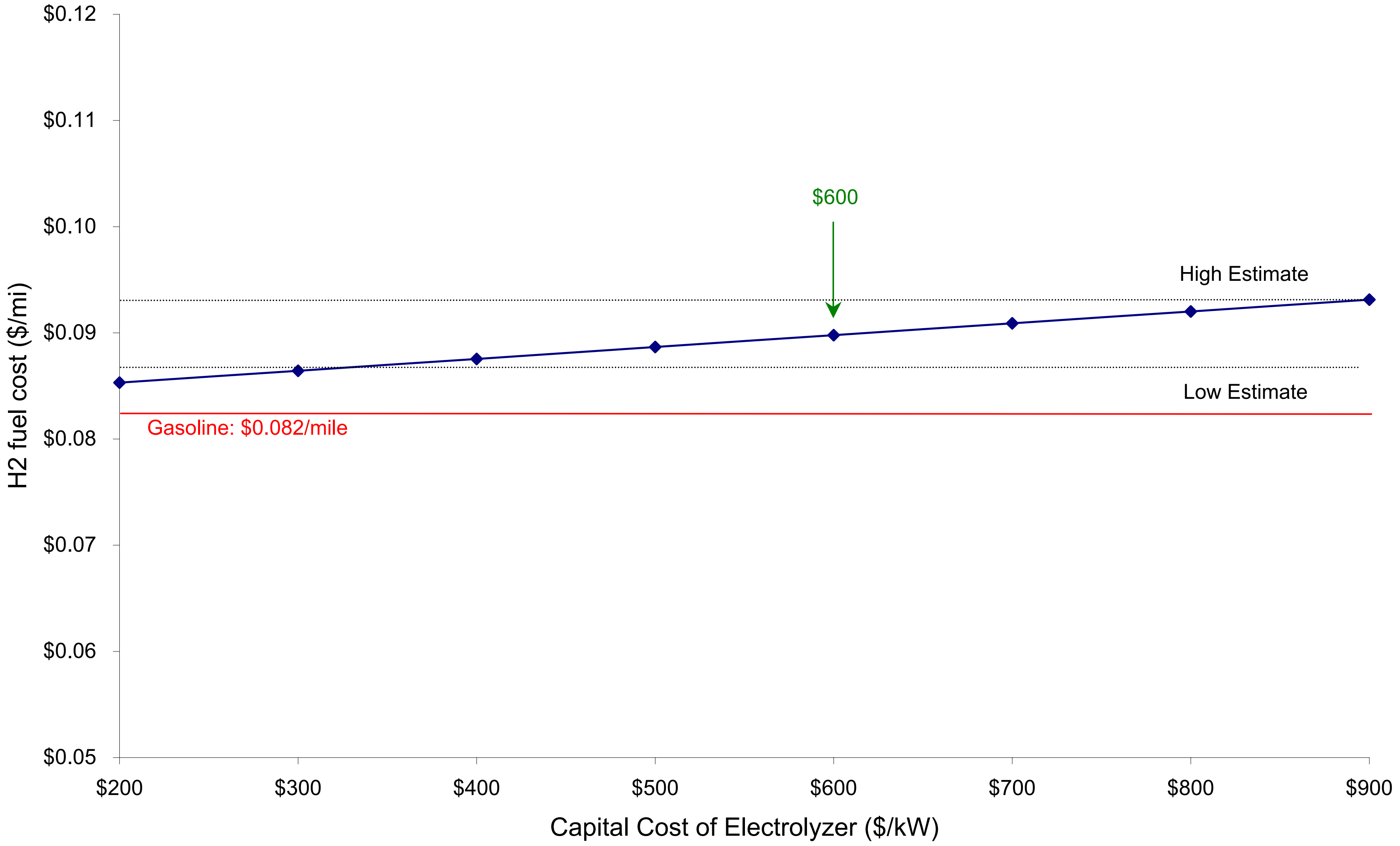
Sensitivity of H2 fuel price to Electolyzer Capital Cost for Geothermal Generation



3. Sensitivity to Electrolyzer Conversion Efficiency

Production Costs									**Low**	**High**
replacement goal (% of energy used for tranportatio	10%	10%	10%	10%	10%	10%	10%	10%	10%	10%
Annual H2 production (MBtu)	422,421	422,421	422,421	422,421	422,421	422,421	422,421	422,421	422,421	422,421
Annual H2 production (kWh)	123,804,568	123,804,568	123,804,568	123,804,568	123,804,568	123,804,568	123,804,568	123,804,568	123,804,568	123,804,568
geothermal plant capacity factor	90%	90%	90%	90%	90%	90%	90%	90%	90%	90%
nominal geothermal generating capacity (MW)	29	26	24	22	21	20	18	17	25	21
Discount Rate	10%	10%	10%	10%	10%	10%	10%	10%	10%	10%
Lifetime (yr)	30	30	30	30	30	30	30	30	30	30
Electrolyzer										
plant size (kW in)	28,551	26,172	24,159	22,433	20,938	19,629	18,474	17,448	24,926	20,938
plant size (kW out)	15703.26838	15703.26838	15703.26838	15703.26838	15703.26838	15703.26838	15703.26838	15703.26838	15703.26838	15703.26838
plant size (Nm3/day)	228,716	209,656	193,529	179,706	167,725	157,242	147,993	139,771	199,673	167,725
operating capacity	90%	90%	90%	90%	90%	90%	90%	90%	90%	90%
capital cost ($)	$9,421,961	$9,421,961	$9,421,961	$9,421,961	$9,421,961	$9,421,961	$9,421,961	$9,421,961	$9,421,961	$9,421,961
annualized capital cost ($/yr)	$999,474.54	$999,474.54	$999,474.54	$999,474.54	$999,474.54	$999,474.54	$999,474.54	$999,474.54	$999,474.54	$999,474.54
O&M costs ($/yr)	$1,252,220.82	$1,147,869.08	$1,059,571.46	$983,887.79	$918,295.27	$860,901.81	$810,260.53	$765,246.06	$1,093,208.65	$918,295.27
Electricity Costs										
conversion efficiency	55%	60%	65%	70%	75%	80%	85%	90%	63%	75%
required electricity (kWh/yr)	225,099,214	206,340,947	190,468,566	176,863,668	165,072,757	154,755,710	145,652,433	137,560,631	196,515,187	165,072,757
unit cost of electricity ($/kWh)	$0.044	$0.044	$0.044	$0.044	$0.044	$0.044	$0.044	$0.044	$0.044	$0.044
total cost of electricity ($/yr)	$9,904,365.43	$9,079,001.65	$8,380,616.90	$7,782,001.41	$7,263,201.32	$6,809,251.24	$6,408,707.04	$6,052,667.76	$8,646,668.24	$7,263,201.32
Totals										
total annual cost ($/yr)	$12,156,060.79	$11,226,345.27	$10,439,662.91	$9,765,363.74	$9,180,971.13	$8,669,627.59	$8,218,442.12	$7,817,388.36	$10,739,351.43	$9,180,971.13
H2 unit cost ($/MBtu)	$28.78	$26.58	$24.71	$23.12	$21.73	$20.52	$19.46	$18.51	$25.42	$21.73
Delivery Costs										
Cost to distribute ($/MBtu)	$7.98	$7.98	$7.98	$7.98	$7.98	$7.98	$7.98	$7.98	$7.98	$7.98
H2 Cost (at refueling station)	$36.75	$34.55	$32.69	$31.09	$29.71	$28.50	$27.43	$26.48	$33.40	$29.71
End Use Calculations										
Conversion Device	Fuel Cell	Fuel Cell	Fuel Cell	Fuel Cell	Fuel Cell	Fuel Cell	Fuel Cell	Fuel Cell	Fuel Cell	Fuel Cell
Efficiency (mi/gge)	44	44	44	44	44	44	44	44	44	44
Efficiency (mi/MBtu)	353.1300161	353.1300161	353.1300161	353.1300161	353.1300161	353.1300161	353.1300161	353.1300161	353.1300161	353.1300161
Fuel Cost ($/mi)	$0.1041	$0.0978	$0.0926	$0.0881	$0.0841	$0.0807	$0.0777	$0.0750	$0.0946	$0.0841

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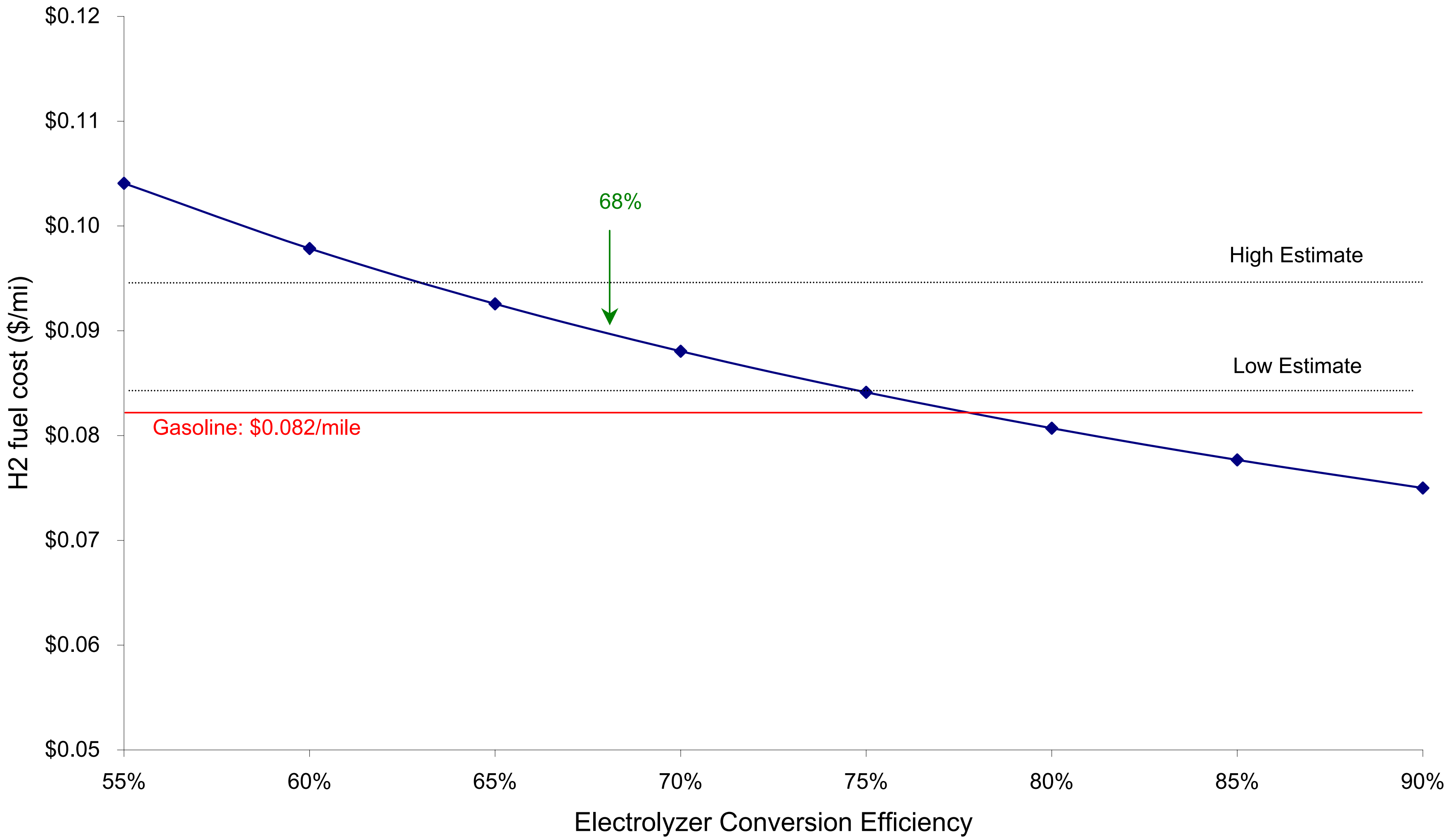
Sensitivity of H2 fuel price to Electolyzer Conversion Efficiency for Geothermal Generation



4. Sensitivity to Delivery Costs

Production Costs										**Low**	**High**
replacement goal (% of energy used for tranportatio	10%	10%	10%	10%	10%	10%	10%	10%	10%	10%	10%
Annual H2 production (MBtu)	422,421	422,421	422,421	422,421	422,421	422,421	422,421	422,421	422,421	422,421	422,421
Annual H2 production (kWh)	123,804,568	123,804,568	123,804,568	123,804,568	123,804,568	123,804,568	123,804,568	123,804,568	123,804,568	123,804,568	123,804,568
geothermal plant capacity factor	90%	90%	90%	90%	90%	90%	90%	90%	90%	90%	90%
nominal geothermal generating capacity (MW)	23	23	23	23	23	23	23	23	23	23	23
Discount Rate	10%	10%	10%	10%	10%	10%	10%	10%	10%	10%	10%
Lifetime (yr)	30	30	30	30	30	30	30	30	30	30	30
Electrolyzer											
plant size (kW in)	23,093	23,093	23,093	23,093	23,093	23,093	23,093	23,093	23,093	23,093	23,093
plant size (kW out)	15703.26838	15703.26838	15703.26838	15703.26838	15703.26838	15703.26838	15703.26838	15703.26838	15703.26838	15703.26838	15703.26838
plant size (Nm3/day)	184,991	184,991	184,991	184,991	184,991	184,991	184,991	184,991	184,991	184,991	184,991
operating capacity	90%	90%	90%	90%	90%	90%	90%	90%	90%	90%	90%
capital cost ($)	$9,421,961	$9,421,961	$9,421,961	$9,421,961	$9,421,961	$9,421,961	$9,421,961	$9,421,961	$9,421,961	$9,421,961	$9,421,961
annualized capital cost ($/yr)	$999,474.54	$999,474.54	$999,474.54	$999,474.54	$999,474.54	$999,474.54	$999,474.54	$999,474.54	$999,474.54	$999,474.54	$999,474.54
O&M costs ($/yr)	$1,012,825.66	$1,012,825.66	$1,012,825.66	$1,012,825.66	$1,012,825.66	$1,012,825.66	$1,012,825.66	$1,012,825.66	$1,012,825.66	$1,012,825.66	$1,012,825.66
Electricity Costs											
conversion efficiency	68%	68%	68%	68%	68%	68%	68%	68%	68%	68%	68%
required electricity (kWh/yr)	182,065,541	182,065,541	182,065,541	182,065,541	182,065,541	182,065,541	182,065,541	182,065,541	182,065,541	182,065,541	182,065,541
unit cost of electricity ($/kWh)	$0.044	$0.044	$0.044	$0.044	$0.044	$0.044	$0.044	$0.044	$0.044	$0.044	$0.044
total cost of electricity ($/yr)	$8,010,883.81	$8,010,883.81	$8,010,883.81	$8,010,883.81	$8,010,883.81	$8,010,883.81	$8,010,883.81	$8,010,883.81	$8,010,883.81	$8,010,883.81	$8,010,883.81
Totals											
total annual cost ($/yr)	$10,023,184.01	$10,023,184.01	$10,023,184.01	$10,023,184.01	$10,023,184.01	$10,023,184.01	$10,023,184.01	$10,023,184.01	$10,023,184.01	$10,023,184.01	$10,023,184.01
H2 unit cost ($/MBtu)	$23.73	$23.73	$23.73	$23.73	$23.73	$23.73	$23.73	$23.73	$23.73	$23.73	$23.73
Delivery Costs											
Cost to distribute ($/MBtu)	$3.00	$4.00	$5.00	$6.00	$7.00	$8.00	$9.00	$10.00	$11.00	$3.50	$10.82
H2 Cost (at refueling station)	$26.73	$27.73	$28.73	$29.73	$30.73	$31.73	$32.73	$33.73	$34.73	$27.23	$34.55
End Use Calculations											
Conversion Device	Fuel Cell	Fuel Cell	Fuel Cell	Fuel Cell	Fuel Cell	Fuel Cell	Fuel Cell	Fuel Cell	Fuel Cell	Fuel Cell	Fuel Cell
Efficiency (mi/gge)	44	44	44	44	44	44	44	44	44	44	44
Efficiency (mi/MBtu)	353.1300161	353.1300161	353.1300161	353.1300161	353.1300161	353.1300161	353.1300161	353.1300161	353.1300161	353.1300161	353.1300161
Fuel Cost ($/mi)	$0.0757	$0.0785	$0.0814	$0.0842	$0.0870	$0.0898	$0.0927	$0.0955	$0.0983	$0.0771	$0.0978

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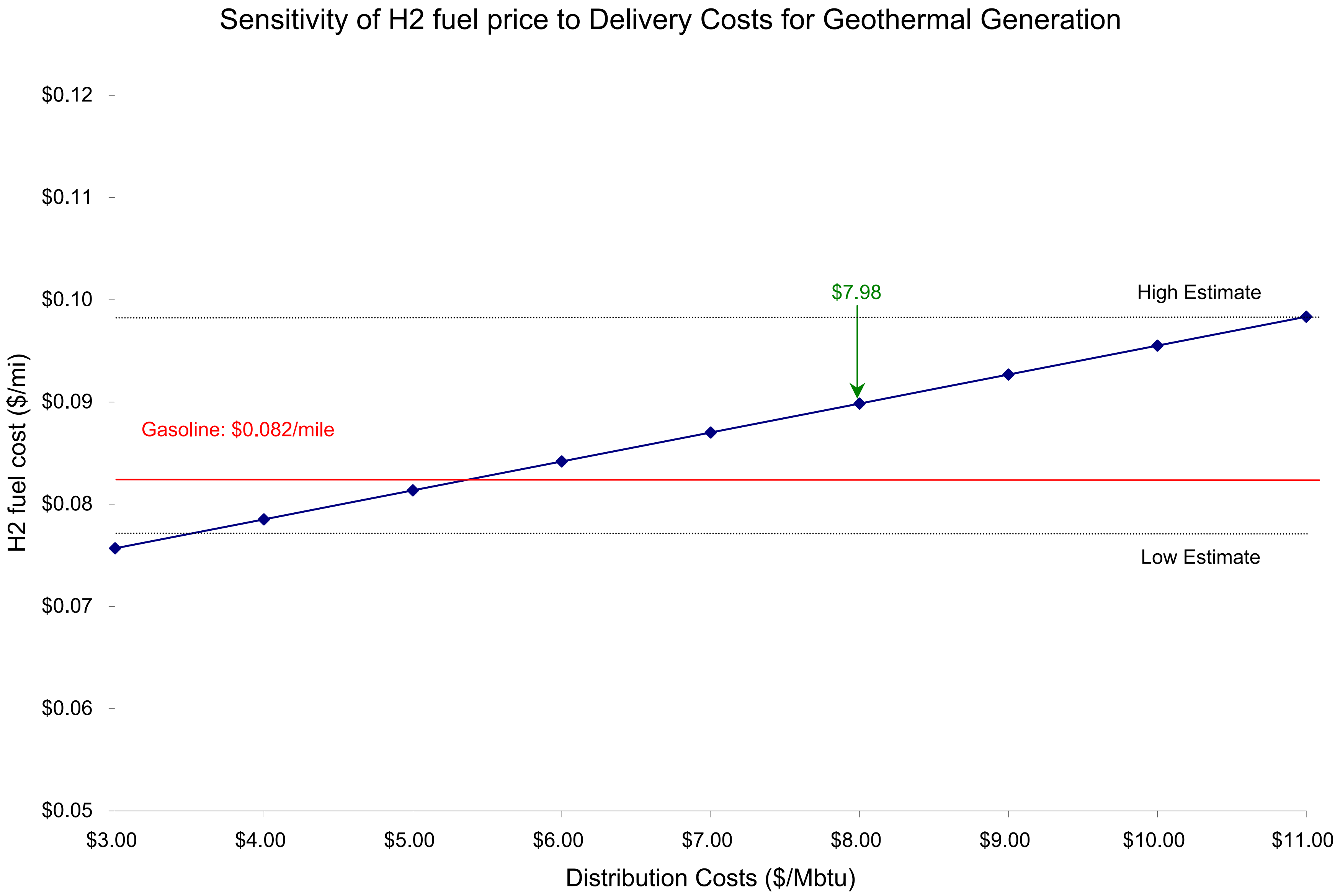

Sensitivity of H2 fuel price to Delivery Costs for Geothermal Generation
$0.12
$0.11
$0.10
$0.09
$0.08
$0.07
$0.06
$0.05
H2 fuel cost ($/mi)
$7.98
High Estimate
Gasoline: $0.082/mile
Low Estimate
$3.00
$4.00
$5.00
$6.00
$7.00
$8.00
$9.00
$10.00
$11.00
Distribution Costs ($/Mbtu)

5. Sensitivity to Fuel Cell Efficiency

Production Costs

replacement goal (% of energy used for tranportatio	10%	10%	10%	10%	10%	10%	10%	10%	10%	10%
Annual H2 production (MBtu)	422,421	422,421	422,421	422,421	422,421	422,421	422,421	422,421	422,421	422,421
Annual H2 production (kWh)	123,804,568	123,804,568	123,804,568	123,804,568	123,804,568	123,804,568	123,804,568	123,804,568	123,804,568	123,804,568
geothermal plant capacity factor	90%	90%	90%	90%	90%	90%	90%	90%	90%	90%
nominal geothermal generating capacity (MW)	23	23	23	23	23	23	23	23	23	23
Discount Rate	10%	10%	10%	10%	10%	10%	10%	10%	10%	10%
Lifetime (yr)	30	30	30	30	30	30	30	30	30	30

Electrolyzer

plant size (kW in)	23,093	23,093	23,093	23,093	23,093	23,093	23,093	23,093	23,093	23,093
plant size (kW out)	15703.26838	15703.26838	15703.26838	15703.26838	15703.26838	15703.26838	15703.26838	15703.26838	15703.26838	15703.26838
plant size (Nm3/day)	184,991	184,991	184,991	184,991	184,991	184,991	184,991	184,991	184,991	184,991
operating capacity	90%	90%	90%	90%	90%	90%	90%	90%	90%	90%
capital cost ($)	$9,421,961	$9,421,961	$9,421,961	$9,421,961	$9,421,961	$9,421,961	$9,421,961	$9,421,961	$9,421,961	$9,421,961
annualized capital cost ($/yr)	$999,474.54	$999,474.54	$999,474.54	$999,474.54	$999,474.54	$999,474.54	$999,474.54	$999,474.54	$999,474.54	$999,474.54
O&M costs ($/yr)	$1,012,825.66	$1,012,825.66	$1,012,825.66	$1,012,825.66	$1,012,825.66	$1,012,825.66	$1,012,825.66	$1,012,825.66	$1,012,825.66	$1,012,825.66

Electricity Costs

conversion efficiency	68%	68%	68%	68%	68%	68%	68%	68%	68%	68%
required electricity (kWh/yr)	182,065,541	182,065,541	182,065,541	182,065,541	182,065,541	182,065,541	182,065,541	182,065,541	182,065,541	182,065,541
unit cost of electricity ($/kWh)	$0.044	$0.044	$0.044	$0.044	$0.044	$0.044	$0.044	$0.044	$0.044	$0.044
total cost of electricity ($/yr)	$8,010,883.81	$8,010,883.81	$8,010,883.81	$8,010,883.81	$8,010,883.81	$8,010,883.81	$8,010,883.81	$8,010,883.81	$8,010,883.81	$8,010,883.81

Totals

total annual cost ($/yr)	$10,023,184.01	$10,023,184.01	$10,023,184.01	$10,023,184.01	$10,023,184.01	$10,023,184.01	$10,023,184.01	$10,023,184.01	$10,023,184.01	$10,023,184.01
H2 unit cost ($/MBtu)	$23.73	$23.73	$23.73	$23.73	$23.73	$23.73	$23.73	$23.73	$23.73	$23.73

Delivery Costs

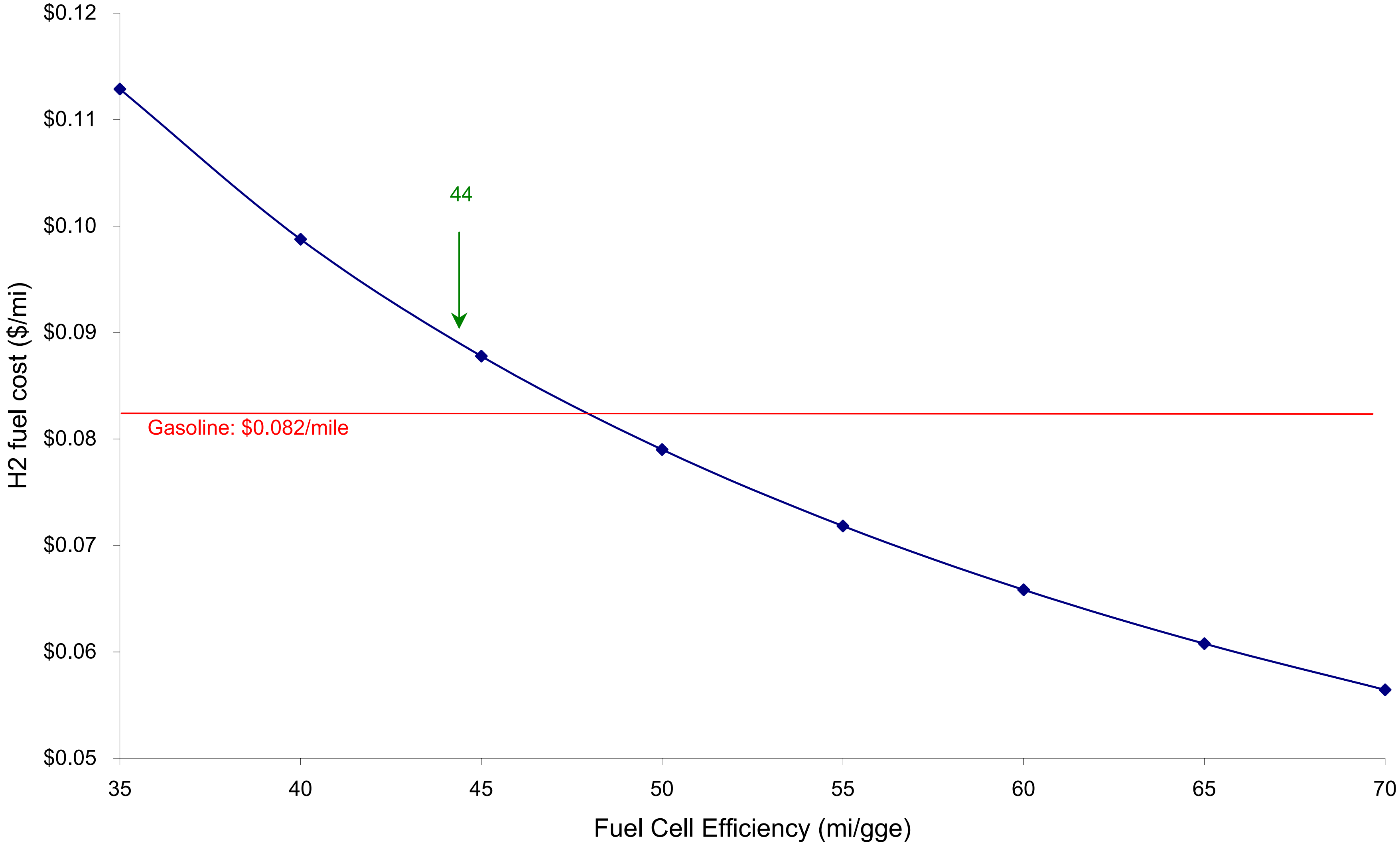
Cost to distribute ($/MBtu)	$7.98	$7.98	$7.98	$7.98	$7.98	$7.98	$7.98	$7.98	$7.98	$7.98
H2 Cost (at refueling station)	$31.70	$31.70	$31.70	$31.70	$31.70	$31.70	$31.70	$31.70	$31.70	$31.70

End Use Calculations

Conversion Device	Fuel Cell	Fuel Cell	Fuel Cell	Fuel Cell	Fuel Cell	Fuel Cell	Fuel Cell	Fuel Cell	Fuel Cell	Fuel Cell
Efficiency (mi/gge)	35	40	45	50	55	60	65	70	75	80
Efficiency (mi/MBtu)	280.8988764	321.0272873	361.1556982	401.2841091	441.4125201	481.540931	521.6693419	561.7977528	601.9261637	642.0545746
Fuel Cost ($/mi)	$0.1129	$0.0988	$0.0878	$0.0790	$0.0718	$0.0658	$0.0608	$0.0564	$0.0527	$0.0494

HAWAII

Sensitivity of H2 fuel price to Fuel Cell Efficiency for Geothermal Generation



Hydrogen Pathways for the Island of Hawaii - Wind Sensitivity Analyses

Potential Market

Registered Vehicles:	118,364
Ground Transportation Fuel Used (gge)	67,794,000
Ground Transportation Fuel Used (MBtu)	8,448,424
Estimated Average Vehicle Efficiency (mi/gge)	17.13
Estimated Average Vehicle Efficiency (mi/MBtu)	137.4812674

1. Sensitivity to Cost of Electricity from Wind

Production Costs

									Low	High
replacement goal (% of energy used for tranportatic	10%	10%	10%	10%	10%	10%	10%	10%	10%	10%
Annual H2 production (MBtu)	422,421	422,421	422,421	422,421	422,421	422,421	422,421	422,421	422,421	422,421
Annual H2 production (kWh)	123,804,568	123,804,568	123,804,568	123,804,568	123,804,568	123,804,568	123,804,568	123,804,568	123,804,568	123,804,568
wind turbine capacity factor	33%	33%	33%	33%	33%	33%	33%	33%	33%	33%
nominal wind generating capacity (MW)	63	63	63	63	63	63	63	63	63	63
Discount Rate	10%	10%	10%	10%	10%	10%	10%	10%	10%	10%
Lifetime (yr)	30	30	30	30	30	30	30	30	30	30
Electrolyzer										
plant size (kW in)	62,981	62,981	62,981	62,981	62,981	62,981	62,981	62,981	62,981	62,981
plant size (kW out)	42827.09558	42827.09558	42827.09558	42827.09558	42827.09558	42827.09558	42827.09558	42827.09558	42827.09558	42827.09558
plant size (Nm3/day)	504,521	504,521	504,521	504,521	504,521	504,521	504,521	504,521	504,521	504,521
operating capacity	90%	90%	90%	90%	90%	90%	90%	90%	90%	90%
capital cost ($)	$25,696,257	$25,696,257	$25,696,257	$25,696,257	$25,696,257	$25,696,257	$25,696,257	$25,696,257	$25,696,257	$25,696,257
annualized capital cost ($/yr)	$2,725,839.66	$2,725,839.66	$2,725,839.66	$2,725,839.66	$2,725,839.66	$2,725,839.66	$2,725,839.66	$2,725,839.66	$2,725,839.66	$2,725,839.66
O&M costs ($/yr)	$2,762,251.81	$2,762,251.81	$2,762,251.81	$2,762,251.81	$2,762,251.81	$2,762,251.81	$2,762,251.81	$2,762,251.81	$2,762,251.81	$2,762,251.81
Electricity Costs										
conversion efficiency	68%	68%	68%	68%	68%	68%	68%	68%	68%	68%
required electricity (kWh/yr)	182,065,541	182,065,541	182,065,541	182,065,541	182,065,541	182,065,541	182,065,541	182,065,541	182,065,541	182,065,541
unit cost of electricity ($/kWh)	$0.030	$0.035	$0.040	$0.045	$0.050	$0.055	$0.060	$0.065	$0.040	$0.060
total cost of electricity ($/yr)	$5,461,966.23	$6,372,293.94	$7,282,621.64	$8,192,949.35	$9,103,277.05	$10,013,604.76	$10,923,932.46	$11,834,260.17	$7,282,621.64	$10,923,932.46
Totals										
total annual cost ($/yr)	$10,950,057.70	$11,860,385.41	$12,770,713.11	$13,681,040.82	$14,591,368.52	$15,501,696.23	$16,412,023.93	$17,322,351.64	$12,770,713.11	$16,412,023.93
H2 unit cost ($/MBtu)	$25.92	$28.08	$30.23	$32.39	$34.54	$36.70	$38.85	$41.01	$30.23	$38.85

Delivery Costs

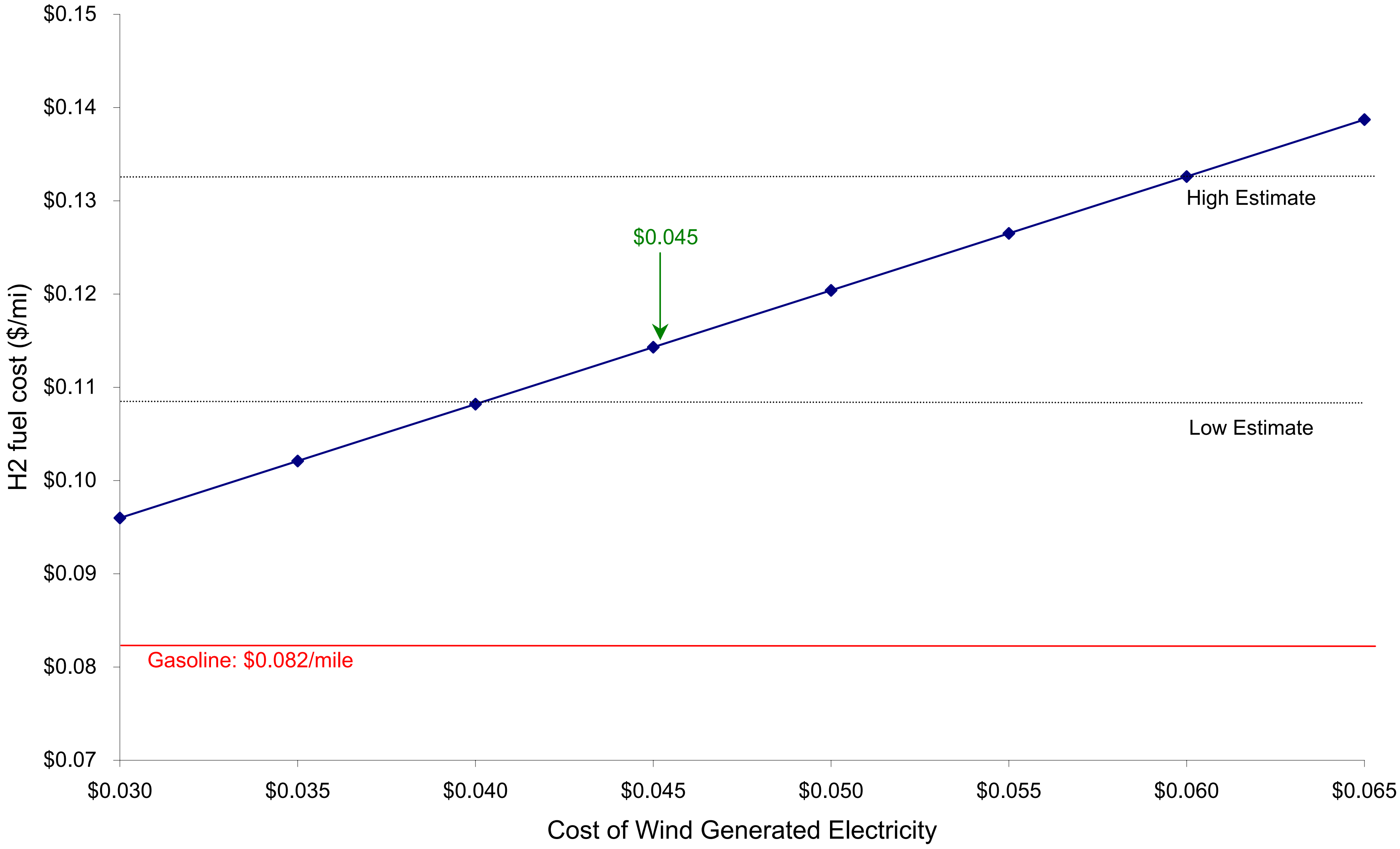
Cost to distribute ($/MBtu)	$7.98	$7.98	$7.98	$7.98	$7.98	$7.98	$7.98	$7.98	$7.98	$7.98
H2 Cost (at refueling station)	$33.90	$36.05	$38.21	$40.36	$42.52	$44.67	$46.83	$48.98	$38.21	$46.83

End Use Calculations

Conversion Device	Fuel Cell	Fuel Cell	Fuel Cell	Fuel Cell	Fuel Cell	Fuel Cell	Fuel Cell	Fuel Cell	Fuel Cell	Fuel Cell
Efficiency (mi/gge)	44	44	44	44	44	44	44	44	44	44
Efficiency (mi/MBtu)	353.1300161	353.1300161	353.1300161	353.1300161	353.1300161	353.1300161	353.1300161	353.1300161	353.1300161	353.1300161
Fuel Cost ($/mi)	$0.0960	$0.1021	$0.1082	$0.1143	$0.1204	$0.1265	$0.1326	$0.1387	$0.1082	$0.1326

HAWAII

Sensitivity of H2 fuel price to Cost of Electricity from Wind



2. Sensitivity to Wind Turbine Capacity Factor

Production Costs

									Low	**High**
replacement goal (% of energy used for tranportatic	10%	10%	10%	10%	10%	10%	10%	10%	10%	10%
Annual H2 production (MBtu)	422,421	422,421	422,421	422,421	422,421	422,421	422,421	422,421	422,421	422,421
Annual H2 production (kWh)	123,804,568	123,804,568	123,804,568	123,804,568	123,804,568	123,804,568	123,804,568	123,804,568	123,804,568	123,804,568
wind turbine capacity factor	20%	25%	30%	35%	40%	45%	50%	55%	25%	45%
nominal wind generating capacity (MW)	104	83	69	59	52	46	42	38	83	46
Discount Rate	10%	10%	10%	10%	10%	10%	10%	10%	10%	10%
Lifetime (yr)	30	30	30	30	30	30	30	30	30	30

Electrolyzer

plant size (kW in)	103,919	83,135	69,279	59,382	51,959	46,186	41,567	37,789	83,135	46,186
plant size (kW out)	70664.70771	56531.76617	47109.80514	40379.83298	35332.35386	31406.53676	28265.88308	25696.25735	56531.76617	31406.53676
plant size (Nm3/day)	832,459	665,968	554,973	475,691	416,230	369,982	332,984	302,713	665,968	369,982
operating capacity	90%	90%	90%	90%	90%	90%	90%	90%	90%	90%
capital cost ($)	$42,398,825	$33,919,060	$28,265,883	$24,227,900	$21,199,412	$18,843,922	$16,959,530	$15,417,754	$33,919,060	$18,843,922
annualized capital cost ($/yr)	$4,497,635.44	$3,598,108.35	$2,998,423.63	$2,570,077.40	$2,248,817.72	$1,998,949.09	$1,799,054.18	$1,635,503.80	$3,598,108.35	$1,998,949.09
O&M costs ($/yr)	$4,557,715.48	$3,646,172.38	$3,038,476.99	$2,604,408.85	$2,278,857.74	$2,025,651.32	$1,823,086.19	$1,657,351.08	$3,646,172.38	$2,025,651.32

Electricity Costs

conversion efficiency	68%	68%	68%	68%	68%	68%	68%	68%	68%	68%
required electricity (kWh/yr)	182,065,541	182,065,541	182,065,541	182,065,541	182,065,541	182,065,541	182,065,541	182,065,541	182,065,541	182,065,541
unit cost of electricity ($/kWh)	$0.045	$0.045	$0.045	$0.045	$0.045	$0.045	$0.045	$0.045	$0.045	$0.045
total cost of electricity ($/yr)	$8,192,949.35	$8,192,949.35	$8,192,949.35	$8,192,949.35	$8,192,949.35	$8,192,949.35	$8,192,949.35	$8,192,949.35	$8,192,949.35	$8,192,949.35

Totals

total annual cost ($/yr)	$17,248,300.27	$15,437,230.09	$14,229,849.96	$13,367,435.59	$12,720,624.81	$12,217,549.76	$11,815,089.72	$11,485,804.23	$15,437,230.09	$12,217,549.76
H2 unit cost ($/MBtu)	$40.83	$36.54	$33.69	$31.64	$30.11	$28.92	$27.97	$27.19	$36.54	$28.92

Delivery Costs

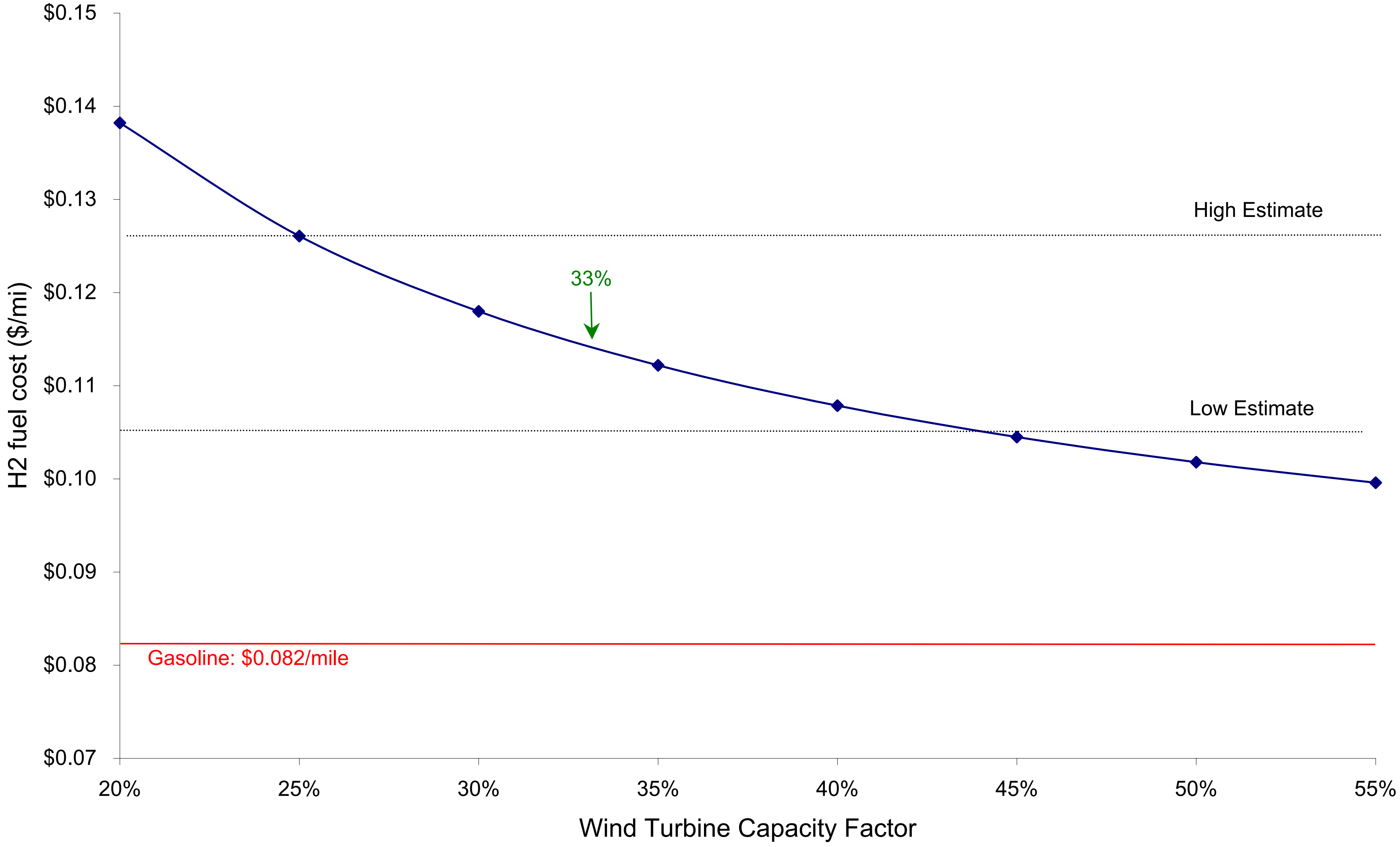
Cost to distribute ($/MBtu)	$7.98	$7.98	$7.98	$7.98	$7.98	$7.98	$7.98	$7.98	$7.98	$7.98
H2 Cost (at refueling station)	$48.81	$44.52	$41.66	$39.62	$38.09	$36.90	$35.95	$35.17	$44.52	$36.90

End Use Calculations

Conversion Device	Fuel Cell	Fuel Cell	Fuel Cell	Fuel Cell	Fuel Cell	Fuel Cell	Fuel Cell	Fuel Cell	Fuel Cell	Fuel Cell
Efficiency (mi/gge)	44	44	44	44	44	44	44	44	44	44
Efficiency (mi/MBtu)	353.1300161	353.1300161	353.1300161	353.1300161	353.1300161	353.1300161	353.1300161	353.1300161	353.1300161	353.1300161
Fuel Cost ($/mi)	$0.1382	$0.1261	$0.1180	$0.1122	$0.1079	$0.1045	$0.1018	$0.0996	$0.1261	$0.1045

HAWAII

Sensitivity of H2 fuel price to Wind Turbine Capacity Factor



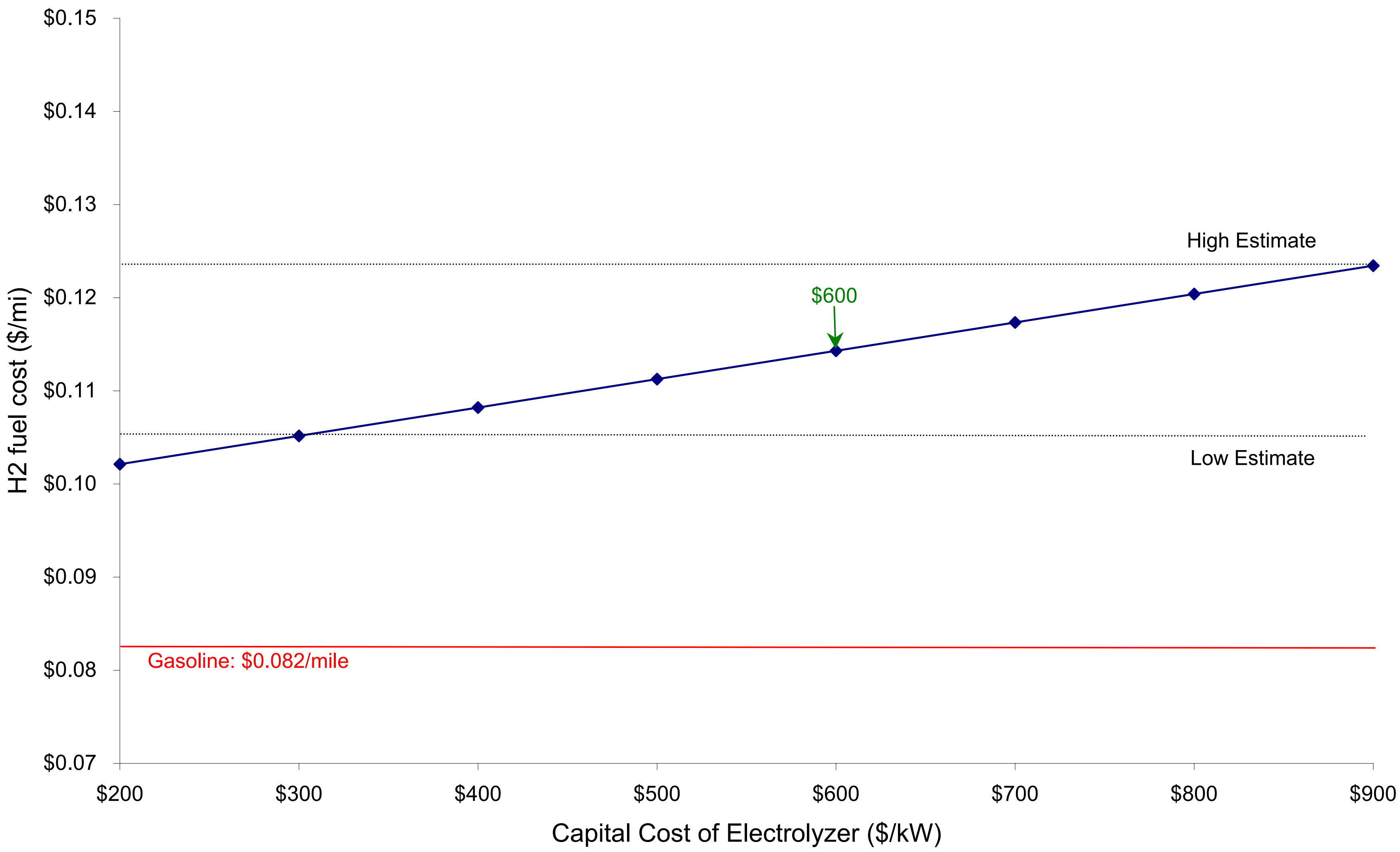
3. Sensitivity to Electrolyzer Capital Cost

Production Costs

									Low	High
replacement goal (% of energy used for tranportatic	10%	10%	10%	10%	10%	10%	10%	10%	10%	10%
Annual H2 production (MBtu)	422,421	422,421	422,421	422,421	422,421	422,421	422,421	422,421	422,421	422,421
Annual H2 production (kWh)	123,804,568	123,804,568	123,804,568	123,804,568	123,804,568	123,804,568	123,804,568	123,804,568	123,804,568	123,804,568
wind turbine capacity factor	33%	33%	33%	33%	33%	33%	33%	33%	33%	33%
nominal wind generating capacity (MW)	63	63	63	63	63	63	63	63	63	63
Discount Rate	10%	10%	10%	10%	10%	10%	10%	10%	10%	10%
Lifetime (yr)	30	30	30	30	30	30	30	30	30	30
Electrolyzer										
plant size (kW in)	62,981	62,981	62,981	62,981	62,981	62,981	62,981	62,981	62,981	62,981
plant size (kW out)	42827.09558	42827.09558	42827.09558	42827.09558	42827.09558	42827.09558	42827.09558	42827.09558	42827.09558	42827.09558
plant size (Nm3/day)	504,521	504,521	504,521	504,521	504,521	504,521	504,521	504,521	504,521	504,521
operating capacity	90%	90%	90%	90%	90%	90%	90%	90%	90%	90%
capital cost ($/kW)	$200	$300	$400	$500	$600	$700	$800	$900	$300	$900
annualized capital cost ($/yr)	$908,613.22	$1,362,919.83	$1,817,226.44	$2,271,533.05	$2,725,839.66	$3,180,146.27	$3,634,452.88	$4,088,759.49	$1,362,919.83	$4,088,759.49
O&M costs ($/yr)	$2,762,251.81	$2,762,251.81	$2,762,251.81	$2,762,251.81	$2,762,251.81	$2,762,251.81	$2,762,251.81	$2,762,251.81	$2,762,251.81	$2,762,251.81
Electricity Costs										
conversion efficiency	68%	68%	68%	68%	68%	68%	68%	68%	68%	68%
required electricity (kWh/yr)	182,065,541	182,065,541	182,065,541	182,065,541	182,065,541	182,065,541	182,065,541	182,065,541	182,065,541	182,065,541
unit cost of electricity ($/kWh)	$0.045	$0.045	$0.045	$0.045	$0.045	$0.045	$0.045	$0.045	$0.045	$0.045
total cost of electricity ($/yr)	$8,192,949.35	$8,192,949.35	$8,192,949.35	$8,192,949.35	$8,192,949.35	$8,192,949.35	$8,192,949.35	$8,192,949.35	$8,192,949.35	$8,192,949.35
Totals										
total annual cost ($/yr)	$11,863,814.37	$12,318,120.98	$12,772,427.59	$13,226,734.21	$13,681,040.82	$14,135,347.43	$14,589,654.04	$15,043,960.65	$12,318,120.98	$15,043,960.65
H2 unit cost ($/MBtu)	$28.09	$29.16	$30.24	$31.31	$32.39	$33.46	$34.54	$35.61	$29.16	$35.61
Delivery Costs										
Cost to distribute ($/MBtu)	$7.98	$7.98	$7.98	$7.98	$7.98	$7.98	$7.98	$7.98	$7.98	$7.98
H2 Cost (at refueling station)	$36.06	$37.14	$38.21	$39.29	$40.36	$41.44	$42.51	$43.59	$37.14	$43.59
End Use Calculations										
Conversion Device	Fuel Cell	Fuel Cell	Fuel Cell	Fuel Cell	Fuel Cell	Fuel Cell	Fuel Cell	Fuel Cell	Fuel Cell	Fuel Cell
Efficiency (mi/gge)	44	44	44	44	44	44	44	44	44	44
Efficiency (mi/MBtu)	353.1300161	353.1300161	353.1300161	353.1300161	353.1300161	353.1300161	353.1300161	353.1300161	353.1300161	353.1300161
Fuel Cost ($/mi)	$0.1021	$0.1052	$0.1082	$0.1113	$0.1143	$0.1173	$0.1204	$0.1234	$0.1052	$0.1234

HAWAII

Sensitivity of H2 fuel price to Electrolyzer Capital Cost for Wind Generation



4. Sensitivity to Electrolyzer Conversion Efficiency

Production Costs

									Low	High
replacement goal (% of energy used for tranportatic	10%	10%	10%	10%	10%	10%	10%	10%	10%	10%
Annual H2 production (MBtu)	422,421	422,421	422,421	422,421	422,421	422,421	422,421	422,421	422,421	422,421
Annual H2 production (kWh)	123,804,568	123,804,568	123,804,568	123,804,568	123,804,568	123,804,568	123,804,568	123,804,568	123,804,568	123,804,568
wind turbine capacity factor	33%	33%	33%	33%	33%	33%	33%	33%	33%	33%
nominal wind generating capacity (MW)	78	71	66	61	57	54	50	48	68	57
Discount Rate	10%	10%	10%	10%	10%	10%	10%	10%	10%	10%
Lifetime (yr)	30	30	30	30	30	30	30	30	30	30
Electrolyzer										
plant size (kW in)	77,867	71,378	65,888	61,182	57,103	53,534	50,385	47,586	67,980	57,103
plant size (kW out)	42827.09558	42827.09558	42827.09558	42827.09558	42827.09558	42827.09558	42827.09558	42827.09558	42827.09558	42827.09558
plant size (Nm3/day)	623,771	571,790	527,806	490,106	457,432	428,843	403,617	381,194	544,562	457,432
operating capacity	90%	90%	90%	90%	90%	90%	90%	90%	90%	90%
capital cost ($)	$25,696,257	$25,696,257	$25,696,257	$25,696,257	$25,696,257	$25,696,257	$25,696,257	$25,696,257	$25,696,257	$25,696,257
annualized capital cost ($/yr)	$2,725,839.66	$2,725,839.66	$2,725,839.66	$2,725,839.66	$2,725,839.66	$2,725,839.66	$2,725,839.66	$2,725,839.66	$2,725,839.66	$2,725,839.66
O&M costs ($/yr)	$3,415,147.69	$3,130,552.05	$2,889,740.35	$2,683,330.33	$2,504,441.64	$2,347,914.04	$2,209,801.44	$2,087,034.70	$2,981,478.14	$2,504,441.64
Electricity Costs										
conversion efficiency	55%	60%	65%	70%	75%	80%	85%	90%	63%	75%
required electricity (kWh/yr)	225,099,214	206,340,947	190,468,566	176,863,668	165,072,757	154,755,710	145,652,433	137,560,631	196,515,187	165,072,757
unit cost of electricity ($/kWh)	$0.045	$0.045	$0.045	$0.045	$0.045	$0.045	$0.045	$0.045	$0.045	$0.045
total cost of electricity ($/yr)	$10,129,464.65	$9,285,342.59	$8,571,085.47	$7,958,865.08	$7,428,274.07	$6,964,006.95	$6,554,359.48	$6,190,228.40	$8,843,183.42	$7,428,274.07
Totals										
total annual cost ($/yr)	$16,270,452.00	$15,141,734.30	$14,186,665.48	$13,368,035.07	$12,658,555.37	$12,037,760.64	$11,490,000.59	$11,003,102.76	$14,550,501.22	$12,658,555.37
H2 unit cost ($/MBtu)	$38.52	$35.85	$33.58	$31.65	$29.97	$28.50	$27.20	$26.05	$34.45	$29.97

Delivery Costs

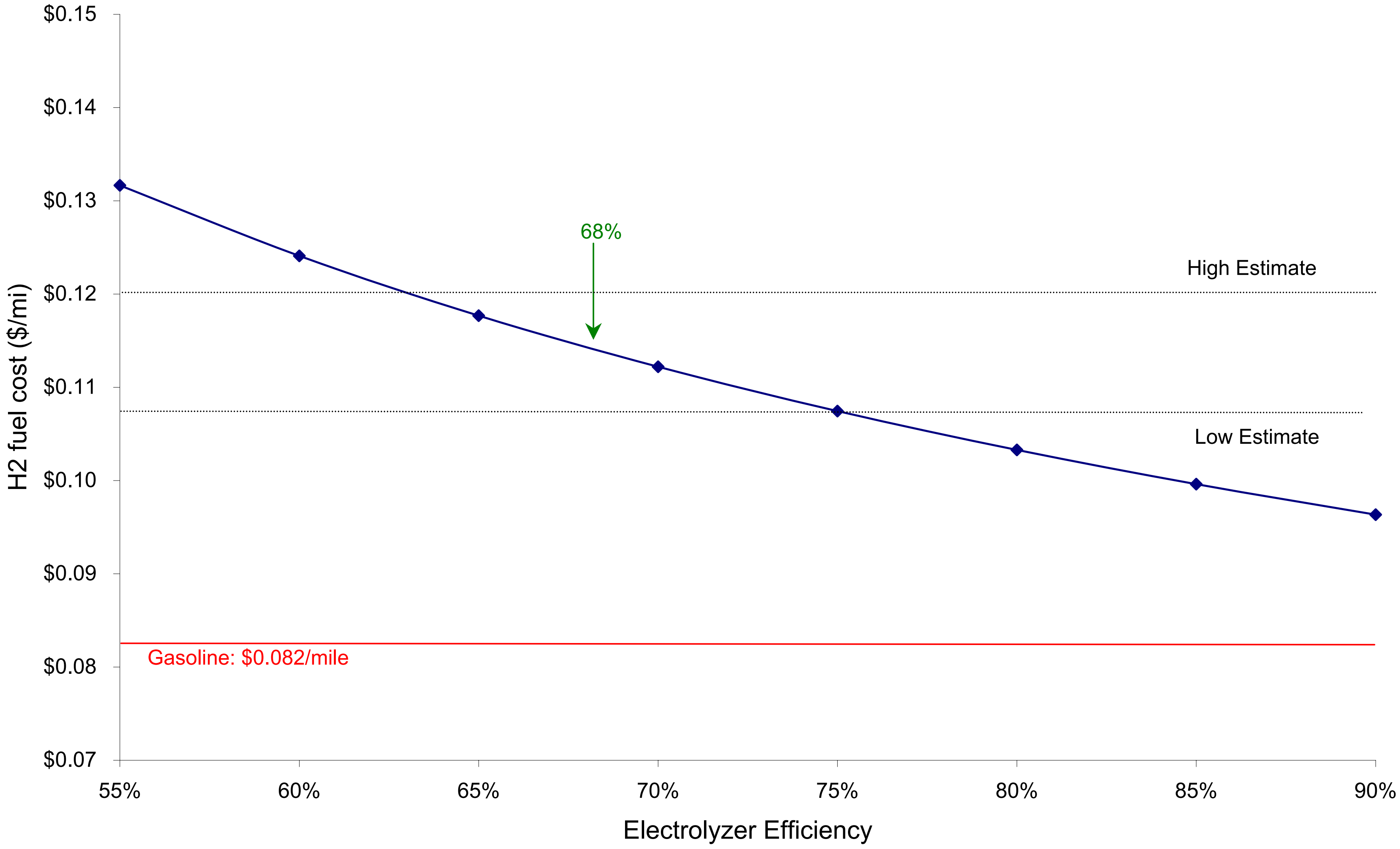
Cost to distribute ($/MBtu)	$7.98	$7.98	$7.98	$7.98	$7.98	$7.98	$7.98	$7.98	$7.98	$7.98
H2 Cost (at refueling station)	$46.49	$43.82	$41.56	$39.62	$37.94	$36.47	$35.18	$34.02	$42.42	$37.94

End Use Calculations

Conversion Device	Fuel Cell	Fuel Cell	Fuel Cell	Fuel Cell	Fuel Cell	Fuel Cell	Fuel Cell	Fuel Cell	Fuel Cell	Fuel Cell
Efficiency (mi/gge)	44	44	44	44	44	44	44	44	44	44
Efficiency (mi/MBtu)	353.1300161	353.1300161	353.1300161	353.1300161	353.1300161	353.1300161	353.1300161	353.1300161	353.1300161	353.1300161
Fuel Cost ($/mi)	$0.1317	$0.1241	$0.1177	$0.1122	$0.1074	$0.1033	$0.0996	$0.0963	$0.1201	$0.1074

HAWAII

Sensitivity of H2 fuel price to Electrolyzer Conversion Efficiency for Wind Generation



5. Sensitivity to Delivery Costs

Production Costs

										Low	High
replacement goal (% of energy used for tranportatic	10%	10%	10%	10%	10%	10%	10%	10%	10%	10%	10%
Annual H2 production (MBtu)	422,421	422,421	422,421	422,421	422,421	422,421	422,421	422,421	422,421	422,421	422,421
Annual H2 production (kWh)	123,804,568	123,804,568	123,804,568	123,804,568	123,804,568	123,804,568	123,804,568	123,804,568	123,804,568	123,804,568	123,804,568
wind turbine capacity factor	33%	33%	33%	33%	33%	33%	33%	33%	33%	33%	33%
nominal wind generating capacity (MW)	63	63	63	63	63	63	63	63	63	63	63
Discount Rate	10%	10%	10%	10%	10%	10%	10%	10%	10%	10%	10%
Lifetime (yr)	30	30	30	30	30	30	30	30	30	30	30
Electrolyzer											
plant size (kW in)	62,981	62,981	62,981	62,981	62,981	62,981	62,981	62,981	62,981	62,981	62,981
plant size (kW out)	42827.09558	42827.09558	42827.09558	42827.09558	42827.09558	42827.09558	42827.09558	42827.09558	42827.09558	42827.09558	42827.09558
plant size (Nm3/day)	504,521	504,521	504,521	504,521	504,521	504,521	504,521	504,521	504,521	504,521	504,521
operating capacity	90%	90%	90%	90%	90%	90%	90%	90%	90%	90%	90%
capital cost ($)	$25,696,257	$25,696,257	$25,696,257	$25,696,257	$25,696,257	$25,696,257	$25,696,257	$25,696,257	$25,696,257	$25,696,257	$25,696,257
annualized capital cost ($/yr)	$2,725,839.66	$2,725,839.66	$2,725,839.66	$2,725,839.66	$2,725,839.66	$2,725,839.66	$2,725,839.66	$2,725,839.66	$2,725,839.66	$2,725,839.66	$2,725,839.66
O&M costs ($/yr)	$2,762,251.81	$2,762,251.81	$2,762,251.81	$2,762,251.81	$2,762,251.81	$2,762,251.81	$2,762,251.81	$2,762,251.81	$2,762,251.81	$2,762,251.81	$2,762,251.81
Electricity Costs											
conversion efficiency	68%	68%	68%	68%	68%	68%	68%	68%	68%	68%	68%
required electricity (kWh/yr)	182,065,541	182,065,541	182,065,541	182,065,541	182,065,541	182,065,541	182,065,541	182,065,541	182,065,541	182,065,541	182,065,541
unit cost of electricity ($/kWh)	$0.045	$0.045	$0.045	$0.045	$0.045	$0.045	$0.045	$0.045	$0.045	$0.045	$0.045
total cost of electricity ($/yr)	$8,192,949.35	$8,192,949.35	$8,192,949.35	$8,192,949.35	$8,192,949.35	$8,192,949.35	$8,192,949.35	$8,192,949.35	$8,192,949.35	$8,192,949.35	$8,192,949.35
Totals											
total annual cost ($/yr)	$13,681,040.82	$13,681,040.82	$13,681,040.82	$13,681,040.82	$13,681,040.82	$13,681,040.82	$13,681,040.82	$13,681,040.82	$13,681,040.82	$13,681,040.82	$13,681,040.82
H2 unit cost ($/MBtu)	$32.39	$32.39	$32.39	$32.39	$32.39	$32.39	$32.39	$32.39	$32.39	$32.39	$32.39

Delivery Costs

Cost to distribute ($/MBtu)	$3.00	$4.00	$5.00	$6.00	$7.00	$8.00	$9.00	$10.00	$11.00	$3.50	$10.82
H2 Cost (at refueling station)	$35.39	$36.39	$37.39	$38.39	$39.39	$40.39	$41.39	$42.39	$43.39	$35.89	$43.21

End Use Calculations

Conversion Device	Fuel Cell	Fuel Cell	Fuel Cell	Fuel Cell	Fuel Cell	Fuel Cell	Fuel Cell	Fuel Cell	Fuel Cell	Fuel Cell	Fuel Cell
Efficiency (mi/gge)	44	44	44	44	44	44	44	44	44	44	44
Efficiency (mi/MBtu)	353.1300161	353.1300161	353.1300161	353.1300161	353.1300161	353.1300161	353.1300161	353.1300161	353.1300161	353.1300161	353.1300161
Fuel Cost ($/mi)	$0.1002	$0.1030	$0.1059	$0.1087	$0.1115	$0.1144	$0.1172	$0.1200	$0.1229	$0.1016	$0.1224

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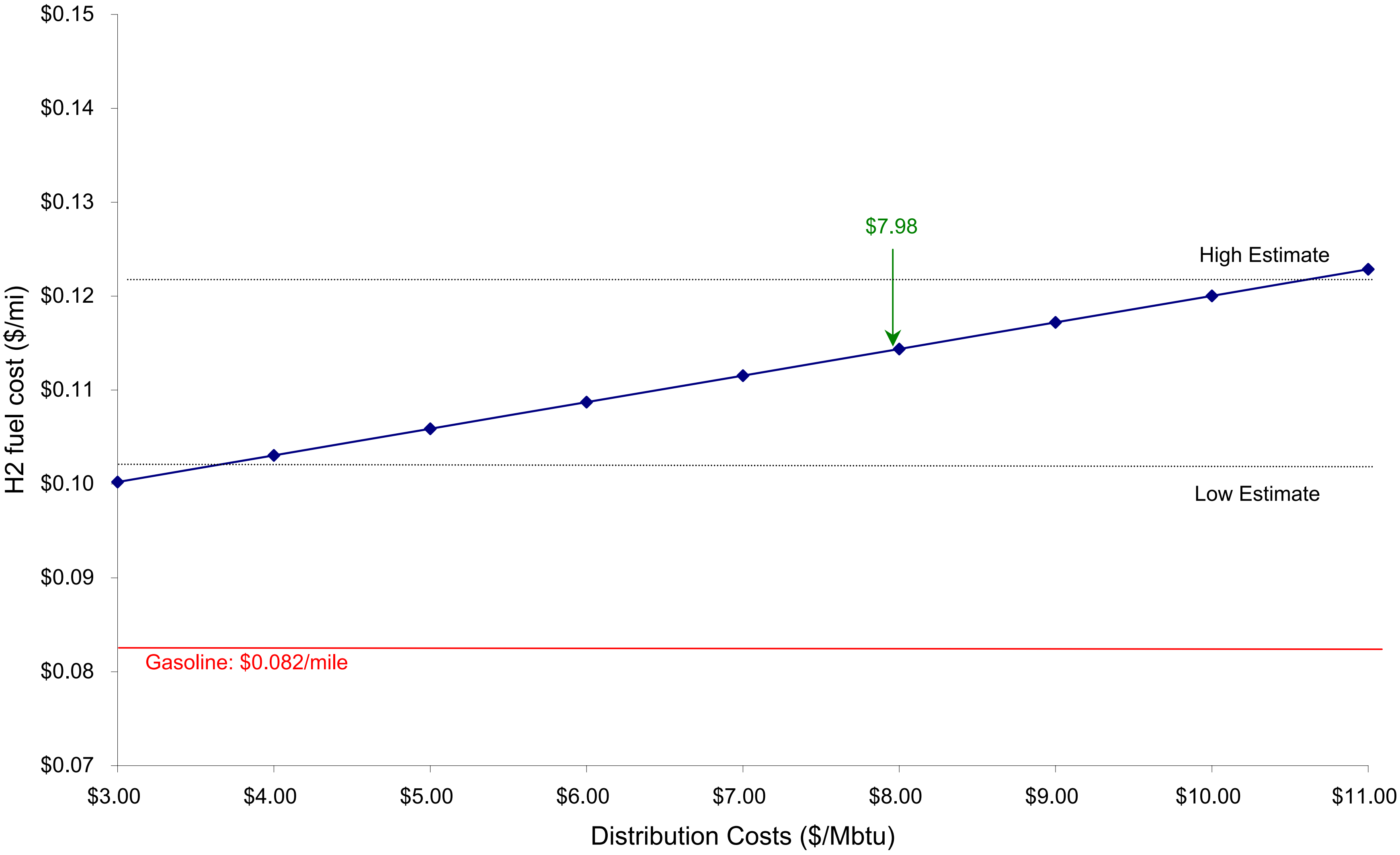
Sensitivity of H2 fuel price to Delivery Costs for Wind Generation



6. Sensitivity to Fuel Cell Efficiency

Production Costs

replacement goal (% of energy used for tranportatic	10%	10%	10%	10%	10%	10%	10%	10%	10%	10%
Annual H2 production (MBtu)	422,421	422,421	422,421	422,421	422,421	422,421	422,421	422,421	422,421	422,421
Annual H2 production (kWh)	123,804,568	123,804,568	123,804,568	123,804,568	123,804,568	123,804,568	123,804,568	123,804,568	123,804,568	123,804,568
wind turbine capacity factor	33%	33%	33%	33%	33%	33%	33%	33%	33%	33%
nominal wind generating capacity (MW)	63	63	63	63	63	63	63	63	63	63
Discount Rate	10%	10%	10%	10%	10%	10%	10%	10%	10%	10%
Lifetime (yr)	30	30	30	30	30	30	30	30	30	30

Electrolyzer

plant size (kW in)	62,981	62,981	62,981	62,981	62,981	62,981	62,981	62,981	62,981	62,981
plant size (kW out)	42827.09558	42827.09558	42827.09558	42827.09558	42827.09558	42827.09558	42827.09558	42827.09558	42827.09558	42827.09558
plant size (Nm3/day)	504,521	504,521	504,521	504,521	504,521	504,521	504,521	504,521	504,521	504,521
operating capacity	90%	90%	90%	90%	90%	90%	90%	90%	90%	90%
capital cost ($)	$25,696,257	$25,696,257	$25,696,257	$25,696,257	$25,696,257	$25,696,257	$25,696,257	$25,696,257	$25,696,257	$25,696,257
annualized capital cost ($/yr)	$2,725,839.66	$2,725,839.66	$2,725,839.66	$2,725,839.66	$2,725,839.66	$2,725,839.66	$2,725,839.66	$2,725,839.66	$2,725,839.66	$2,725,839.66
O&M costs ($/yr)	$2,762,251.81	$2,762,251.81	$2,762,251.81	$2,762,251.81	$2,762,251.81	$2,762,251.81	$2,762,251.81	$2,762,251.81	$2,762,251.81	$2,762,251.81

Electricity Costs

conversion efficiency	68%	68%	68%	68%	68%	68%	68%	68%	68%	68%
required electricity (kWh/yr)	182,065,541	182,065,541	182,065,541	182,065,541	182,065,541	182,065,541	182,065,541	182,065,541	182,065,541	182,065,541
unit cost of electricity ($/kWh)	$0.045	$0.045	$0.045	$0.045	$0.045	$0.045	$0.045	$0.045	$0.045	$0.045
total cost of electricity ($/yr)	$8,192,949.35	$8,192,949.35	$8,192,949.35	$8,192,949.35	$8,192,949.35	$8,192,949.35	$8,192,949.35	$8,192,949.35	$8,192,949.35	$8,192,949.35

Totals

total annual cost ($/yr)	$13,681,040.82	$13,681,040.82	$13,681,040.82	$13,681,040.82	$13,681,040.82	$13,681,040.82	$13,681,040.82	$13,681,040.82	$13,681,040.82	$13,681,040.82
H2 unit cost ($/MBtu)	$32.39	$32.39	$32.39	$32.39	$32.39	$32.39	$32.39	$32.39	$32.39	$32.39

Delivery Costs

Cost to distribute ($/MBtu)	$7.98	$7.98	$7.98	$7.98	$7.98	$7.98	$7.98	$7.98	$7.98	$7.98
H2 Cost (at refueling station)	$40.36	$40.36	$40.36	$40.36	$40.36	$40.36	$40.36	$40.36	$40.36	$40.36

End Use Calculations

Conversion Device	Fuel Cell	Fuel Cell	Fuel Cell	Fuel Cell	Fuel Cell	Fuel Cell	Fuel Cell	Fuel Cell	Fuel Cell	Fuel Cell
Efficiency (mi/gge)	35	40	45	50	55	60	65	70	75	80
Efficiency (mi/MBtu)	280.8988764	321.0272873	361.1556982	401.2841091	441.4125201	481.540931	521.6693419	561.7977528	601.9261637	642.0545746
Fuel Cost ($/mi)	$0.1437	$0.1257	$0.1118	$0.1006	$0.0914	$0.0838	$0.0774	$0.0718	$0.0671	$0.0629

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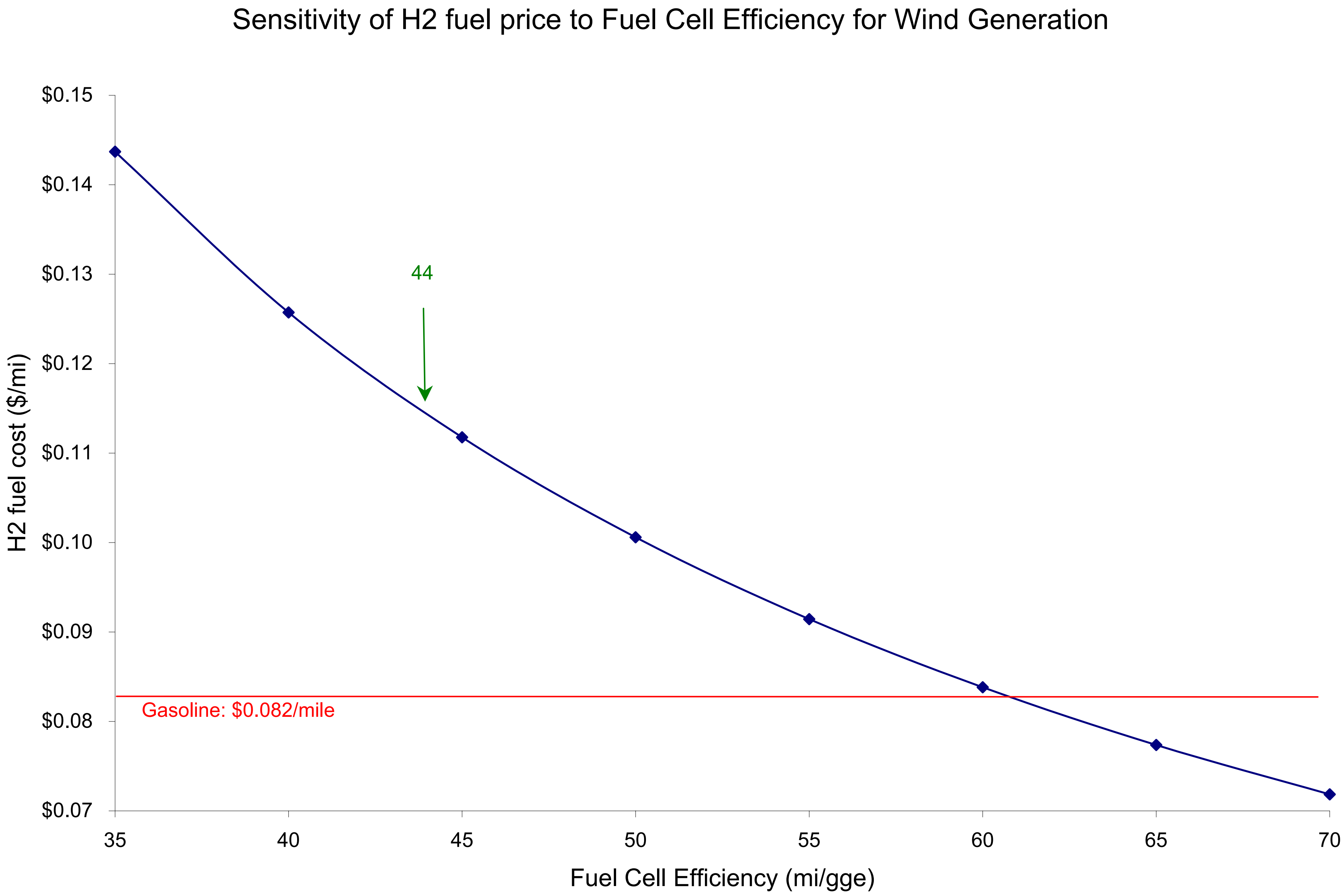
Sensitivity of H2 fuel price to Fuel Cell Efficiency for Wind Generation
H2 fuel cost ($/mi)
$0.15
$0.14
$0.13
$0.12
$0.11
$0.10
$0.09
$0.08
$0.07
44
Gasoline: $0.082/mile
35
40
45
50
55
60
65
70
Fuel Cell Efficiency (mi/gge)

Hydrogen Pathways for the Island of Hawaii

Potential Market

Registered Vehicles:	118,364
Ground Transportation Fuel Used (gge)	67,794,000
Ground Transportation Fuel Used (MBtu)	8,448,424
Estimated Average Vehicle Efficiency (mi/gge)	17.13
Estimated Average Vehicle Efficiency (mi/MBtu)	137.4812674

Biomass Gasifier

1. Sensitivity to Delivery Costs

										Low	**High**
Annual Production (kg H2)	7469104.5	7469104.5	7469104.5	7469104.5	7469104.5	7469104.5	7469104.5	7469104.5	7469104.5	7469104.5	7469104.5
Annual Production (MBtu H2)	1005266.775	1005266.775	1005266.775	1005266.775	1005266.775	1005266.775	1005266.775	1005266.775	1005266.775	1005266.775	1005266.775
% of total fuel replaced (taking into account FC effic	23.80%	23.80%	23.80%	23.80%	23.80%	23.80%	23.80%	23.80%	23.80%	23.80%	23.80%
Annual Production (GJ H2)	1060612.839	1060612.839	1060612.839	1060612.839	1060612.839	1060612.839	1060612.839	1060612.839	1060612.839	1060612.839	1060612.839
Discount Rate	10%	10%	10%	10%	10%	10%	10%	10%	10%	10%	10%
Lifetime (yr)	30	30	30	30	30	30	30	30	30	30	30
Biomass Gasifier											
Plant Size (kg H2/day)	22737	22737	22737	22737	22737	22737	22737	22737	22737	22737	22737
Operating Capacity	90%	90%	90%	90%	90%	90%	90%	90%	90%	90%	90%
Installed Capital Cost ($)	$53,800,000.00	$53,800,000.00	$53,800,000.00	$53,800,000.00	$53,800,000.00	$53,800,000.00	$53,800,000.00	$53,800,000.00	$53,800,000.00	$53,800,000.00	$53,800,000.00
Annualized Capital Cost ($/yr)	$5,707,063.56	$5,707,063.56	$5,707,063.56	$5,707,063.56	$5,707,063.56	$5,707,063.56	$5,707,063.56	$5,707,063.56	$5,707,063.56	$5,707,063.56	$5,707,063.56
Biomass Feedstock Costs											
Daily Feedstock Requirements (Mg/day)	314	314	314	314	314	314	314	314	314	314	314
Annual Feedstock Requirements (Mg/year)	103149	103149	103149	103149	103149	103149	103149	103149	103149	103149	103149
Feedstock Cost ($/Mg)	46.2	46.2	46.2	46.2	46.2	46.2	46.2	46.2	46.2	46.2	46.2
Annual Cost of Feedstock ($/yr)	$4,765,483.80	$4,765,483.80	$4,765,483.80	$4,765,483.80	$4,765,483.80	$4,765,483.80	$4,765,483.80	$4,765,483.80	$4,765,483.80	$4,765,483.80	$4,765,483.80
Totals											
Total Annualized Cost ($/yr)	$10,472,547.36	$10,472,547.36	$10,472,547.36	$10,472,547.36	$10,472,547.36	$10,472,547.36	$10,472,547.36	$10,472,547.36	$10,472,547.36	$10,472,547.36	$10,472,547.36
H2 unit cost ($/GJ)	$7.68	$7.68	$7.68	$7.68	$7.68	$7.68	$7.68	$7.68	$7.68	$7.68	$7.68
H2 unit cost ($/MBtu)	$8.10	$8.10	$8.10	$8.10	$8.10	$8.10	$8.10	$8.10	$8.10	$8.10	$8.10
Delivery Costs											
Cost to distribute ($/MBtu)	$3.00	$4.00	$5.00	$6.00	$7.00	$8.00	$9.00	$10.00	$11.00	$3.50	$10.82
H2 Cost (at refueling station)	$11.10	$12.10	$13.10	$14.10	$15.10	$16.10	$17.10	$18.10	$19.10	$11.61	$18.93
End Use Calculations											
Conversion Device	Fuel Cell	Fuel Cell	Fuel Cell	Fuel Cell	Fuel Cell	Fuel Cell	Fuel Cell	Fuel Cell	Fuel Cell	Fuel Cell	Fuel Cell
Efficiency (mi/gge)	44	44	44	44	44	44	44	44	44	44	44
Efficiency (mi/MBtu)	353.1300161	353.1300161	353.1300161	353.1300161	353.1300161	353.1300161	353.1300161	353.1300161	353.1300161	353.1300161	353.1300161
Fuel Cost ($/mi)	$0.0314	$0.0343	$0.0371	$0.0399	$0.0428	$0.0456	$0.0484	$0.0513	$0.0541	$0.0329	$0.0536

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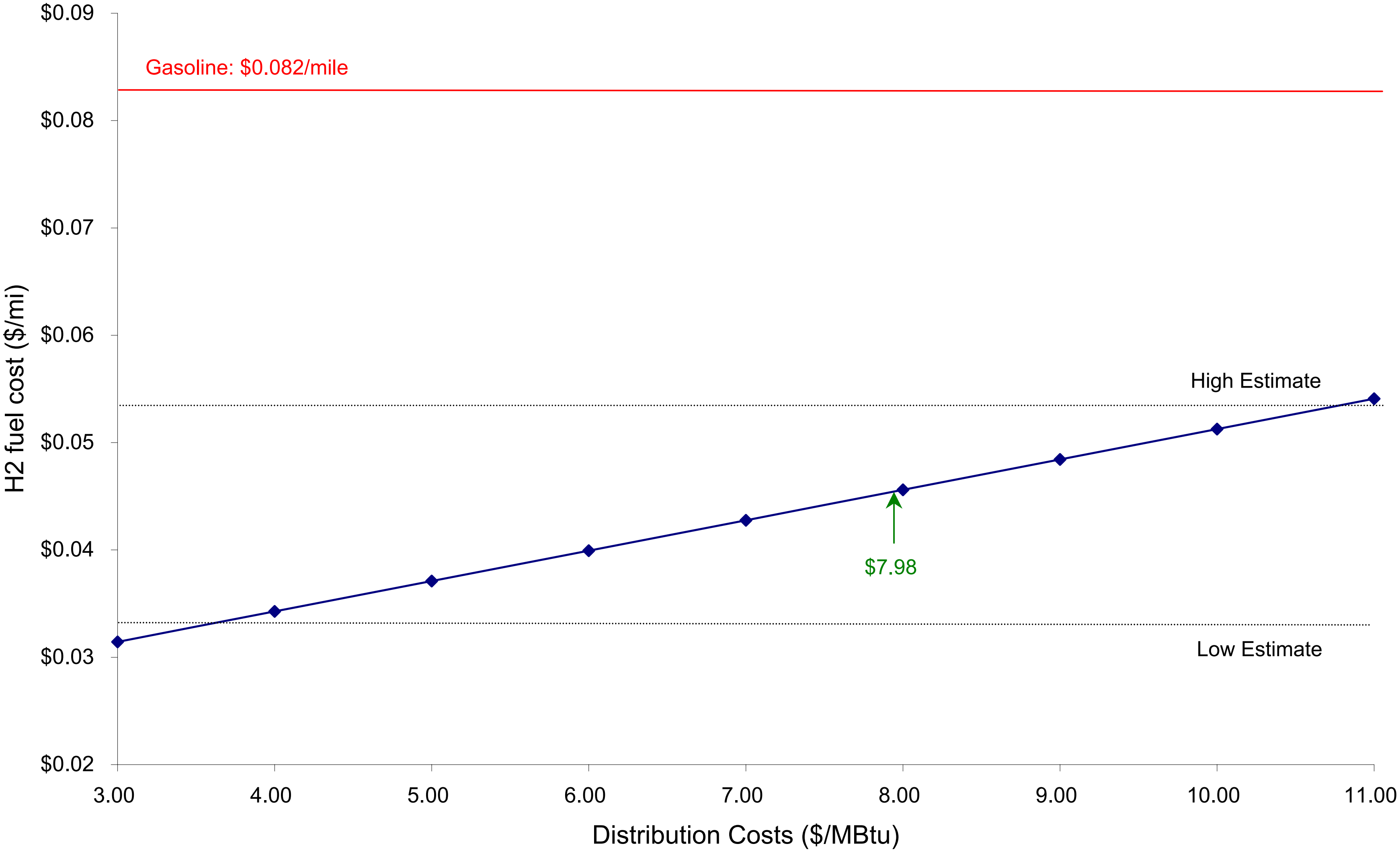
Sensitivity of H2 fuel price to Delivery Costs for Biomass Gasification



2. Sensitivity to Fuel Cell Efficiency

Annual Production (kg H2)	7469104.5	7469104.5	7469104.5	7469104.5	7469104.5	7469104.5	7469104.5	7469104.5	7469104.5	7469104.5
Annual Production (MBtu H2)	1005266.775	1005266.775	1005266.775	1005266.775	1005266.775	1005266.775	1005266.775	1005266.775	1005266.775	1005266.775
% of total fuel replaced (taking into account FC effic	23.80%	23.80%	23.80%	23.80%	23.80%	23.80%	23.80%	23.80%	23.80%	23.80%
Annual Production (GJ H2)	1060612.839	1060612.839	1060612.839	1060612.839	1060612.839	1060612.839	1060612.839	1060612.839	1060612.839	1060612.839
Discount Rate	10%	10%	10%	10%	10%	10%	10%	10%	10%	10%
Lifetime (yr)	30	30	30	30	30	30	30	30	30	30

Biomass Gasifier

Plant Size (kg H2/day)	22737	22737	22737	22737	22737	22737	22737	22737	22737	22737
Operating Capacity	90%	90%	90%	90%	90%	90%	90%	90%	90%	90%
Installed Capital Cost ($)	$53,800,000.00	$53,800,000.00	$53,800,000.00	$53,800,000.00	$53,800,000.00	$53,800,000.00	$53,800,000.00	$53,800,000.00	$53,800,000.00	$53,800,000.00
Annualized Capital Cost ($/yr)	$5,707,063.56	$5,707,063.56	$5,707,063.56	$5,707,063.56	$5,707,063.56	$5,707,063.56	$5,707,063.56	$5,707,063.56	$5,707,063.56	$5,707,063.56

Biomass Feedstock Costs

Daily Feedstock Requirements (Mg/day)	314	314	314	314	314	314	314	314	314	314
Annual Feedstock Requirements (Mg/year)	103149	103149	103149	103149	103149	103149	103149	103149	103149	103149
Feedstock Cost ($/Mg)	46.2	46.2	46.2	46.2	46.2	46.2	46.2	46.2	46.2	46.2
Annual Cost of Feedstock ($/yr)	$4,765,483.80	$4,765,483.80	$4,765,483.80	$4,765,483.80	$4,765,483.80	$4,765,483.80	$4,765,483.80	$4,765,483.80	$4,765,483.80	$4,765,483.80

Totals

Total Annualized Cost ($/yr)	$10,472,547.36	$10,472,547.36	$10,472,547.36	$10,472,547.36	$10,472,547.36	$10,472,547.36	$10,472,547.36	$10,472,547.36	$10,472,547.36	$10,472,547.36
H2 unit cost ($/GJ)	$7.68	$7.68	$7.68	$7.68	$7.68	$7.68	$7.68	$7.68	$7.68	$7.68
H2 unit cost ($/MBtu)	$8.10	$8.10	$8.10	$8.10	$8.10	$8.10	$8.10	$8.10	$8.10	$8.10

Delivery Costs

Cost to distribute ($/MBtu)	$7.98	$7.98	$7.98	$7.98	$7.98	$7.98	$7.98	$7.98	$7.98	$7.98
H2 Cost (at refueling station)	$16.08	$16.08	$16.08	$16.08	$16.08	$16.08	$16.08	$16.08	$16.08	$16.08

End Use Calculations

Conversion Device	Fuel Cell	Fuel Cell	Fuel Cell	Fuel Cell	Fuel Cell	Fuel Cell	Fuel Cell	Fuel Cell	Fuel Cell	Fuel Cell
Efficiency (mi/gge)	35	40	45	50	55	60	65	70	75	80
Efficiency (mi/MBtu)	280.8988764	321.0272873	361.1556982	401.2841091	441.4125201	481.540931	521.6693419	561.7977528	601.9261637	642.0545746
Fuel Cost ($/mi)	$0.0572	$0.0501	$0.0445	$0.0401	$0.0364	$0.0334	$0.0308	$0.0286	$0.0267	$0.0250

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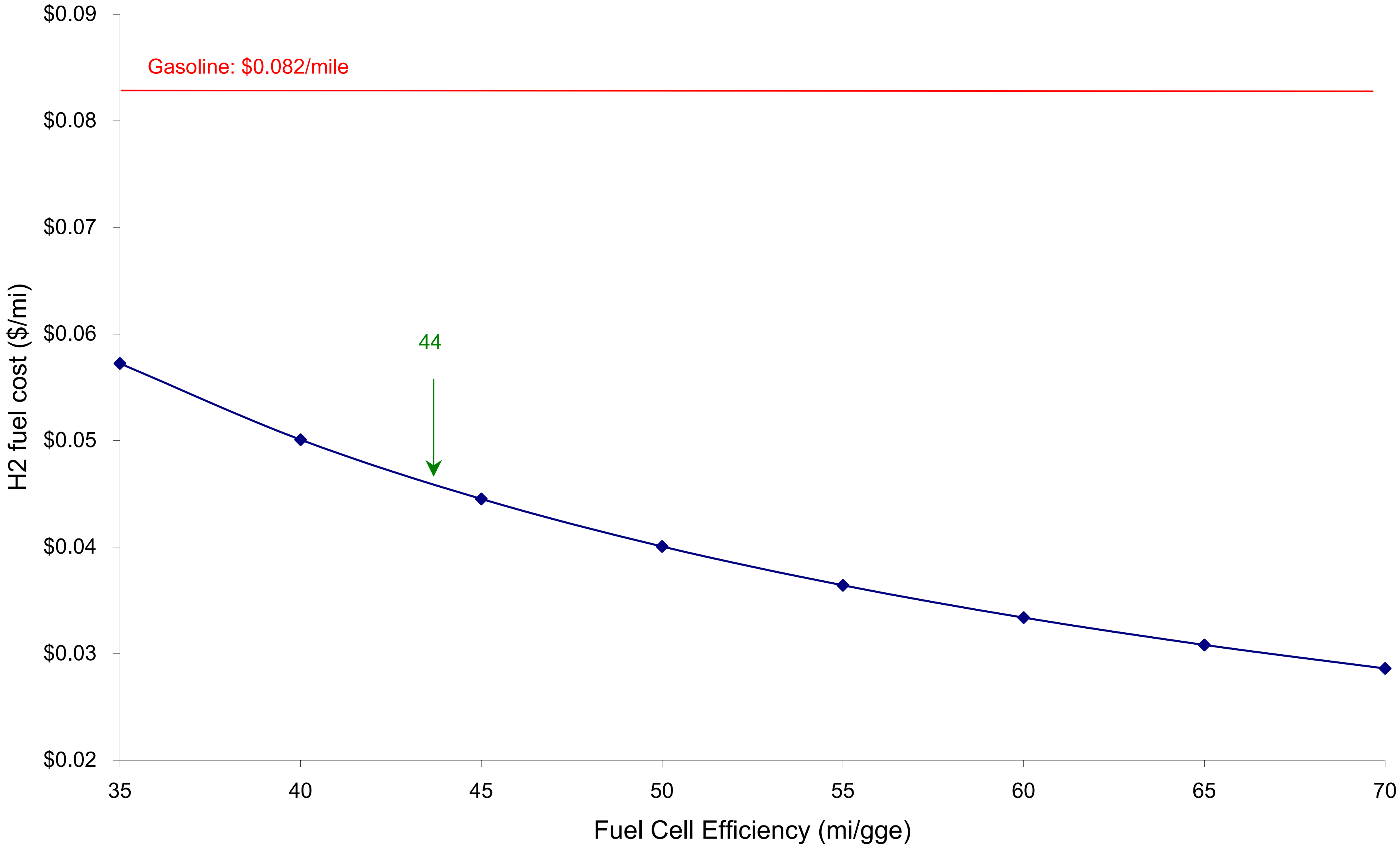
Sensitivity of H2 fuel price to Fuel Cell Efficiency for Biomass Gasification



Hydrogen Pathways for the Island of Maui - Wind Sensitivity Analyses

Potential Market

Registered Vehicles:	116,878
Ground Transportation Fuel Used (gge)	57,030,000
Ground Transportation Fuel Used (MBtu)	7,107,024
Estimated Average Vehicle Efficiency (mi/gge)	18.34
Estimated Average Vehicle Efficiency (mi/MBtu)	147.1783348

1. Sensitivity to Cost of Electricity from Wind

Production Costs

									Low	High
replacement goal (% of energy used for tranportatic	10%	10%	10%	10%	10%	10%	10%	10%	10%	10%
Annual H2 production (MBtu)	355,351	355,351	355,351	355,351	355,351	355,351	355,351	355,351	355,351	355,351
Annual H2 production (kWh)	104,147,484	104,147,484	104,147,484	104,147,484	104,147,484	104,147,484	104,147,484	104,147,484	104,147,484	104,147,484
wind turbine capacity factor	33%	33%	33%	33%	33%	33%	33%	33%	33%	33%
nominal wind generating capacity (MW)	53	53	53	53	53	53	53	53	53	53
Discount Rate	10%	10%	10%	10%	10%	10%	10%	10%	10%	10%
Lifetime (yr)	30	30	30	30	30	30	30	30	30	30
Electrolyzer										
plant size (kW in)	52,981	52,981	52,981	52,981	52,981	52,981	52,981	52,981	52,981	52,981
plant size (kW out)	36027.21865	36027.21865	36027.21865	36027.21865	36027.21865	36027.21865	36027.21865	36027.21865	36027.21865	36027.21865
plant size (Nm3/day)	424,416	424,416	424,416	424,416	424,416	424,416	424,416	424,416	424,416	424,416
operating capacity	90%	90%	90%	90%	90%	90%	90%	90%	90%	90%
capital cost ($)	$21,616,331	$21,616,331	$21,616,331	$21,616,331	$21,616,331	$21,616,331	$21,616,331	$21,616,331	$21,616,331	$21,616,331
annualized capital cost ($/yr)	$2,293,044.16	$2,293,044.16	$2,293,044.16	$2,293,044.16	$2,293,044.16	$2,293,044.16	$2,293,044.16	$2,293,044.16	$2,293,044.16	$2,293,044.16
O&M costs ($/yr)	$2,323,674.96	$2,323,674.96	$2,323,674.96	$2,323,674.96	$2,323,674.96	$2,323,674.96	$2,323,674.96	$2,323,674.96	$2,323,674.96	$2,323,674.96
Electricity Costs										
conversion efficiency	68%	68%	68%	68%	68%	68%	68%	68%	68%	68%
required electricity (kWh/yr)	153,158,064	153,158,064	153,158,064	153,158,064	153,158,064	153,158,064	153,158,064	153,158,064	153,158,064	153,158,064
unit cost of electricity ($/kWh)	$0.050	$0.055	$0.060	$0.065	$0.070	$0.075	$0.080	$0.085	$0.050	$0.085
total cost of electricity ($/yr)	$7,657,903.21	$8,423,693.53	$9,189,483.85	$9,955,274.17	$10,721,064.50	$11,486,854.82	$12,252,645.14	$13,018,435.46	$7,657,903.21	$13,018,435.46
Totals										
total annual cost ($/yr)	$12,274,622.34	$13,040,412.66	$13,806,202.98	$14,571,993.30	$15,337,783.62	$16,103,573.94	$16,869,364.26	$17,635,154.59	$12,274,622.34	$17,635,154.59
H2 unit cost ($/MBtu)	$34.54	$36.70	$38.85	$41.01	$43.16	$45.32	$47.47	$49.63	$34.54	$49.63

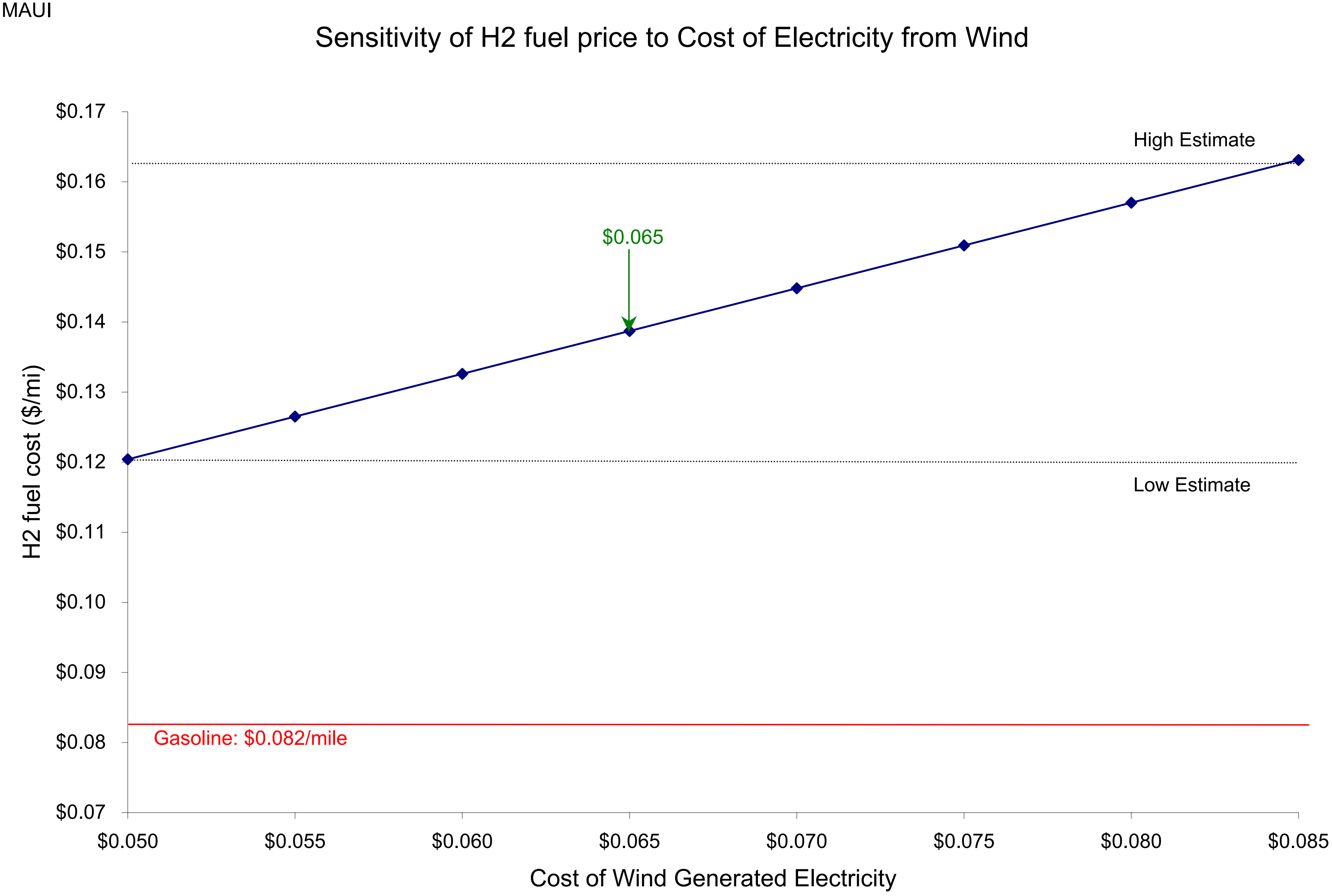
Delivery Costs

Cost to distribute ($/MBtu)	$7.98	$7.98	$7.98	$7.98	$7.98	$7.98	$7.98	$7.98	$7.98	$7.98
H2 Cost (at refueling station)	$42.52	$44.67	$46.83	$48.98	$51.14	$53.29	$55.45	$57.60	$42.52	$57.60

End Use Calculations

Conversion Device	Fuel Cell	Fuel Cell	Fuel Cell	Fuel Cell	Fuel Cell	Fuel Cell	Fuel Cell	Fuel Cell	Fuel Cell	Fuel Cell
Efficiency (mi/gge)	44	44	44	44	44	44	44	44	44	44
Efficiency (mi/MBtu)	353.1300161	353.1300161	353.1300161	353.1300161	353.1300161	353.1300161	353.1300161	353.1300161	353.1300161	353.1300161
Fuel Cost ($/mi)	$0.1204	$0.1265	$0.1326	$0.1387	$0.1448	$0.1509	$0.1570	$0.1631	$0.1204	$0.1631

MAUI

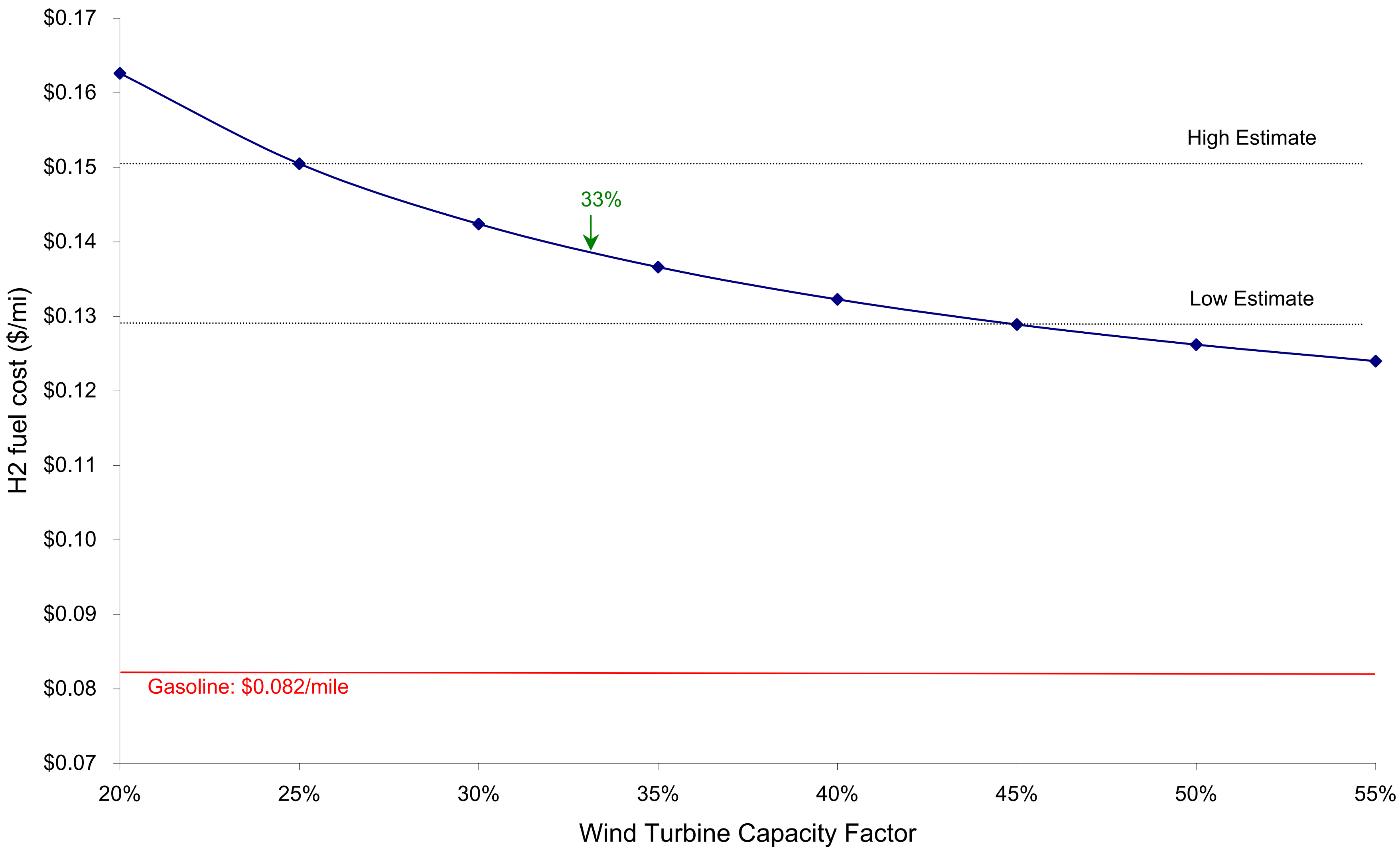

Sensitivity of H2 fuel price to Cost of Electricity from Wind
H2 fuel cost ($/mi)
$0.17
$0.16
$0.15
$0.14
$0.13
$0.12
$0.11
$0.10
$0.09
$0.08
$0.07
High Estimate
$0.065
Low Estimate
Gasoline: $0.082/mile
$0.050
$0.055
$0.060
$0.065
$0.070
$0.075
$0.080
$0.085
Cost of Wind Generated Electricity

2. Sensitivity to Wind Turbine Capacity Factor

									Low	High
Production Costs										
replacement goal (% of energy used for tranportatic	10%	10%	10%	10%	10%	10%	10%	10%	10%	10%
Annual H2 production (MBtu)	355,351	355,351	355,351	355,351	355,351	355,351	355,351	355,351	355,351	355,351
Annual H2 production (kWh)	104,147,484	104,147,484	104,147,484	104,147,484	104,147,484	104,147,484	104,147,484	104,147,484	104,147,484	104,147,484
wind turbine capacity factor	20%	25%	30%	35%	40%	45%	50%	55%	25%	45%
nominal wind generating capacity (MW)	87	70	58	50	44	39	35	32	70	39
Discount Rate	10%	10%	10%	10%	10%	10%	10%	10%	10%	10%
Lifetime (yr)	30	30	30	30	30	30	30	30	30	30
Electrolyzer										
plant size (kW in)	87,419	69,935	58,279	49,954	43,709	38,853	34,968	31,789	69,935	38,853
plant size (kW out)	59444.91077	47555.92862	39629.94051	33968.52044	29722.45539	26419.96034	23777.96431	21616.33119	47555.92862	26419.96034
plant size (Nm3/day)	700,286	560,228	466,857	400,163	350,143	311,238	280,114	254,649	560,228	311,238
operating capacity	90%	90%	90%	90%	90%	90%	90%	90%	90%	90%
capital cost ($)	$35,666,946	$28,533,557	$23,777,964	$20,381,112	$17,833,473	$15,851,976	$14,266,779	$12,969,799	$28,533,557	$15,851,976
annualized capital cost ($/yr)	$3,783,522.87	$3,026,818.29	$2,522,348.58	$2,162,013.07	$1,891,761.43	$1,681,565.72	$1,513,409.15	$1,375,826.50	$3,026,818.29	$1,681,565.72
O&M costs ($/yr)	$3,834,063.69	$3,067,250.95	$2,556,042.46	$2,190,893.54	$1,917,031.85	$1,704,028.31	$1,533,625.48	$1,394,204.98	$3,067,250.95	$1,704,028.31
Electricity Costs										
conversion efficiency	68%	68%	68%	68%	68%	68%	68%	68%	68%	68%
required electricity (kWh/yr)	153,158,064	153,158,064	153,158,064	153,158,064	153,158,064	153,158,064	153,158,064	153,158,064	153,158,064	153,158,064
unit cost of electricity ($/kWh)	$0.065	$0.065	$0.065	$0.065	$0.065	$0.065	$0.065	$0.065	$0.065	$0.065
total cost of electricity ($/yr)	$9,955,274.17	$9,955,274.17	$9,955,274.17	$9,955,274.17	$9,955,274.17	$9,955,274.17	$9,955,274.17	$9,955,274.17	$9,955,274.17	$9,955,274.17
Totals										
total annual cost ($/yr)	$17,572,860.73	$16,049,343.42	$15,033,665.21	$14,308,180.78	$13,764,067.45	$13,340,868.20	$13,002,308.80	$12,725,305.65	$16,049,343.42	$13,340,868.20
H2 unit cost ($/MBtu)	$49.45	$45.16	$42.31	$40.26	$38.73	$37.54	$36.59	$35.81	$45.16	$37.54
Delivery Costs										
Cost to distribute ($/MBtu)	$7.98	$7.98	$7.98	$7.98	$7.98	$7.98	$7.98	$7.98	$7.98	$7.98
H2 Cost (at refueling station)	$57.43	$53.14	$50.28	$48.24	$46.71	$45.52	$44.57	$43.79	$53.14	$45.52
End Use Calculations										
Conversion Device	Fuel Cell	Fuel Cell	Fuel Cell	Fuel Cell	Fuel Cell	Fuel Cell	Fuel Cell	Fuel Cell	Fuel Cell	Fuel Cell
Efficiency (mi/gge)	44	44	44	44	44	44	44	44	44	44
Efficiency (mi/MBtu)	353.1300161	353.1300161	353.1300161	353.1300161	353.1300161	353.1300161	353.1300161	353.1300161	353.1300161	353.1300161
Fuel Cost ($/mi)	$0.1626	$0.1505	$0.1424	$0.1366	$0.1323	$0.1289	$0.1262	$0.1240	$0.1505	$0.1289

MAUI

Sensitivity of H2 fuel price to Wind Turbine Capacity Factor



3. Sensitivity to Electrolyzer Capital Cost

Production Costs

									Low	High
replacement goal (% of energy used for tranportatic	10%	10%	10%	10%	10%	10%	10%	10%	10%	10%
Annual H2 production (MBtu)	355,351	355,351	355,351	355,351	355,351	355,351	355,351	355,351	355,351	355,351
Annual H2 production (kWh)	104,147,484	104,147,484	104,147,484	104,147,484	104,147,484	104,147,484	104,147,484	104,147,484	104,147,484	104,147,484
wind turbine capacity factor	33%	33%	33%	33%	33%	33%	33%	33%	33%	33%
nominal wind generating capacity (MW)	53	53	53	53	53	53	53	53	53	53
Discount Rate	10%	10%	10%	10%	10%	10%	10%	10%	10%	10%
Lifetime (yr)	30	30	30	30	30	30	30	30	30	30
Electrolyzer										
plant size (kW in)	52,981	52,981	52,981	52,981	52,981	52,981	52,981	52,981	52,981	52,981
plant size (kW out)	36027.21865	36027.21865	36027.21865	36027.21865	36027.21865	36027.21865	36027.21865	36027.21865	36027.21865	36027.21865
plant size (Nm3/day)	424,416	424,416	424,416	424,416	424,416	424,416	424,416	424,416	424,416	424,416
operating capacity	90%	90%	90%	90%	90%	90%	90%	90%	90%	90%
capital cost ($/kW)	$200	$300	$400	$500	$600	$700	$800	$900	$300	$900
annualized capital cost ($/yr)	$764,348.05	$1,146,522.08	$1,528,696.11	$1,910,870.14	$2,293,044.16	$2,675,218.19	$3,057,392.22	$3,439,566.24	$1,146,522.08	$3,439,566.24
O&M costs ($/yr)	$2,323,674.96	$2,323,674.96	$2,323,674.96	$2,323,674.96	$2,323,674.96	$2,323,674.96	$2,323,674.96	$2,323,674.96	$2,323,674.96	$2,323,674.96
Electricity Costs										
conversion efficiency	68%	68%	68%	68%	68%	68%	68%	68%	68%	68%
required electricity (kWh/yr)	153,158,064	153,158,064	153,158,064	153,158,064	153,158,064	153,158,064	153,158,064	153,158,064	153,158,064	153,158,064
unit cost of electricity ($/kWh)	$0.065	$0.065	$0.065	$0.065	$0.065	$0.065	$0.065	$0.065	$0.065	$0.065
total cost of electricity ($/yr)	$9,955,274.17	$9,955,274.17	$9,955,274.17	$9,955,274.17	$9,955,274.17	$9,955,274.17	$9,955,274.17	$9,955,274.17	$9,955,274.17	$9,955,274.17
Totals										
total annual cost ($/yr)	$13,043,297.19	$13,425,471.22	$13,807,645.25	$14,189,819.27	$14,571,993.30	$14,954,167.33	$15,336,341.36	$15,718,515.38	$13,425,471.22	$15,718,515.38
H2 unit cost ($/MBtu)	$36.71	$37.78	$38.86	$39.93	$41.01	$42.08	$43.16	$44.23	$37.78	$44.23

Delivery Costs

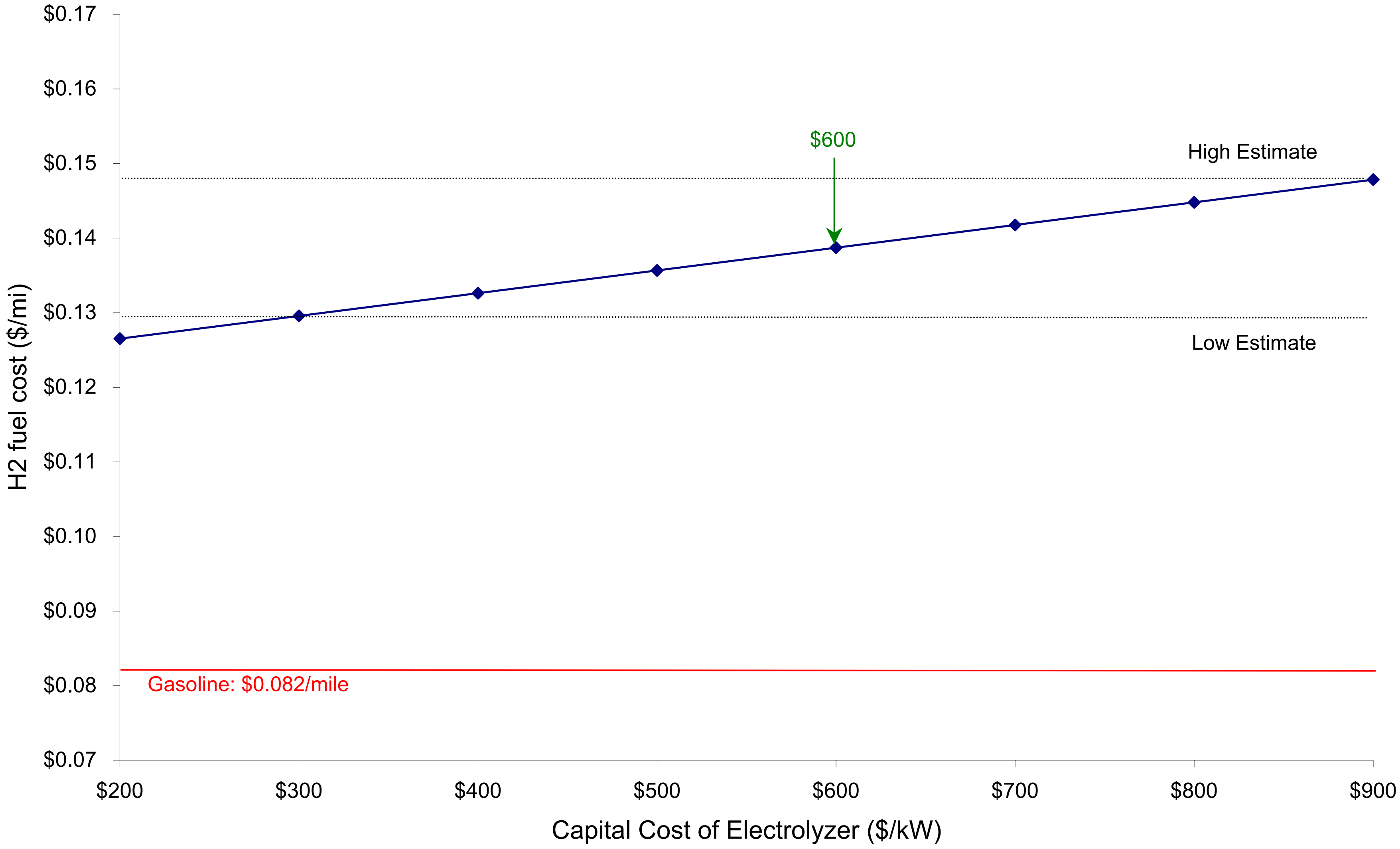
Cost to distribute ($/MBtu)	$7.98	$7.98	$7.98	$7.98	$7.98	$7.98	$7.98	$7.98	$7.98	$7.98
H2 Cost (at refueling station)	$44.68	$45.76	$46.83	$47.91	$48.98	$50.06	$51.13	$52.21	$45.76	$52.21

End Use Calculations

Conversion Device	Fuel Cell	Fuel Cell	Fuel Cell	Fuel Cell	Fuel Cell	Fuel Cell	Fuel Cell	Fuel Cell	Fuel Cell	Fuel Cell
Efficiency (mi/gge)	44	44	44	44	44	44	44	44	44	44
Efficiency (mi/MBtu)	353.1300161	353.1300161	353.1300161	353.1300161	353.1300161	353.1300161	353.1300161	353.1300161	353.1300161	353.1300161
Fuel Cost ($/mi)	$0.1265	$0.1296	$0.1326	$0.1357	$0.1387	$0.1418	$0.1448	$0.1478	$0.1296	$0.1478

MAUI

Sensitivity of H2 fuel price to Electrolyzer Capital Cost for Wind Generation



4. Sensitivity to Electrolyzer Conversion Efficiency

Production Costs

									Low	**High**
replacement goal (% of energy used for tranportatic	10%	10%	10%	10%	10%	10%	10%	10%	10%	10%
Annual H2 production (MBtu)	355,351	355,351	355,351	355,351	355,351	355,351	355,351	355,351	355,351	355,351
Annual H2 production (kWh)	104,147,484	104,147,484	104,147,484	104,147,484	104,147,484	104,147,484	104,147,484	104,147,484	104,147,484	104,147,484
wind turbine capacity factor	33%	33%	33%	33%	33%	33%	33%	33%	33%	33%
nominal wind generating capacity (MW)	66	60	55	51	48	45	42	40	57	48
Discount Rate	10%	10%	10%	10%	10%	10%	10%	10%	10%	10%
Lifetime (yr)	30	30	30	30	30	30	30	30	30	30
Electrolyzer										
plant size (kW in)	65,504	60,045	55,426	51,467	48,036	45,034	42,385	40,030	57,186	48,036
plant size (kW out)	36027.21865	36027.21865	36027.21865	36027.21865	36027.21865	36027.21865	36027.21865	36027.21865	36027.21865	36027.21865
plant size (Nm3/day)	524,732	481,004	444,004	412,289	384,803	360,753	339,532	320,670	458,099	384,803
operating capacity	90%	90%	90%	90%	90%	90%	90%	90%	90%	90%
capital cost ($)	$21,616,331	$21,616,331	$21,616,331	$21,616,331	$21,616,331	$21,616,331	$21,616,331	$21,616,331	$21,616,331	$21,616,331
annualized capital cost ($/yr)	$2,293,044.16	$2,293,044.16	$2,293,044.16	$2,293,044.16	$2,293,044.16	$2,293,044.16	$2,293,044.16	$2,293,044.16	$2,293,044.16	$2,293,044.16
O&M costs ($/yr)	$2,872,907.23	$2,633,498.29	$2,430,921.50	$2,257,284.25	$2,106,798.63	$1,975,123.72	$1,858,939.97	$1,755,665.53	$2,508,093.61	$2,106,798.63
Electricity Costs										
conversion efficiency	55%	60%	65%	70%	75%	80%	85%	90%	63%	75%
required electricity (kWh/yr)	189,359,061	173,579,139	160,226,898	148,782,120	138,863,312	130,184,355	122,526,451	115,719,426	165,313,466	138,863,312
unit cost of electricity ($/kWh)	$0.065	$0.065	$0.065	$0.065	$0.065	$0.065	$0.065	$0.065	$0.065	$0.065
total cost of electricity ($/yr)	$12,308,338.98	$11,282,644.06	$10,414,748.37	$9,670,837.77	$9,026,115.25	$8,461,983.05	$7,964,219.34	$7,521,762.71	$10,745,375.30	$9,026,115.25
Totals										
total annual cost ($/yr)	$17,474,290.37	$16,209,186.52	$15,138,714.03	$14,221,166.18	$13,425,958.05	$12,730,150.93	$12,116,203.47	$11,570,472.40	$15,546,513.07	$13,425,958.05
H2 unit cost ($/MBtu)	$49.17	$45.61	$42.60	$40.02	$37.78	$35.82	$34.10	$32.56	$43.75	$37.78

Delivery Costs

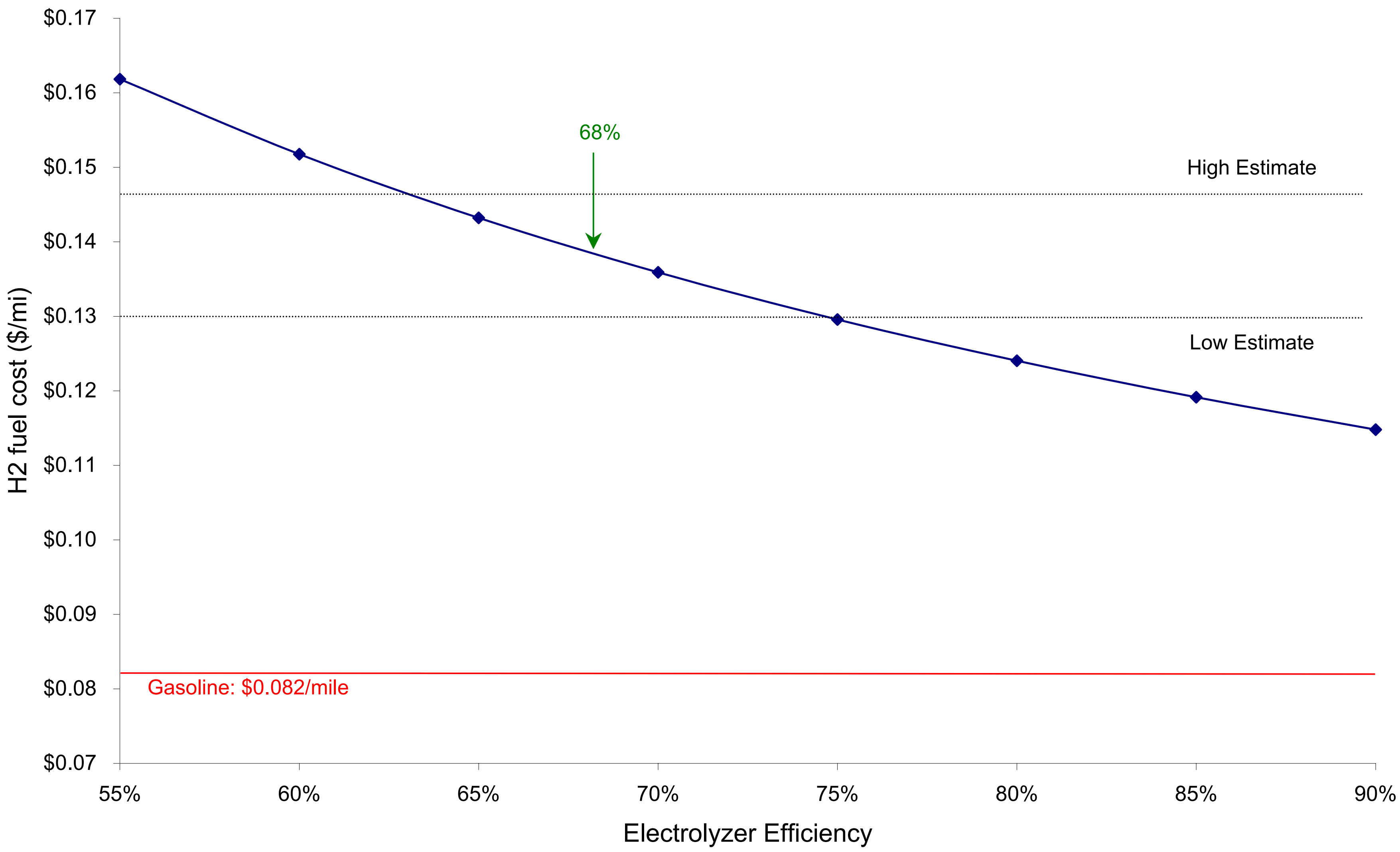
Cost to distribute ($/MBtu)	$7.98	$7.98	$7.98	$7.98	$7.98	$7.98	$7.98	$7.98	$7.98	$7.98
H2 Cost (at refueling station)	$57.15	$53.59	$50.58	$48.00	$45.76	$43.80	$42.07	$40.54	$51.73	$45.76

End Use Calculations

Conversion Device	Fuel Cell	Fuel Cell	Fuel Cell	Fuel Cell	Fuel Cell	Fuel Cell	Fuel Cell	Fuel Cell	Fuel Cell	Fuel Cell
Efficiency (mi/gge)	44	44	44	44	44	44	44	44	44	44
Efficiency (mi/MBtu)	353.1300161	353.1300161	353.1300161	353.1300161	353.1300161	353.1300161	353.1300161	353.1300161	353.1300161	353.1300161
Fuel Cost ($/mi)	$0.1618	$0.1518	$0.1432	$0.1359	$0.1296	$0.1240	$0.1191	$0.1148	$0.1465	$0.1296

MAUI

Sensitivity of H2 fuel price to Electrolyzer Conversion Efficiency for Wind Generation



5. Sensitivity to Delivery Costs

Production Costs

										Low	High
replacement goal (% of energy used for tranportatic	10%	10%	10%	10%	10%	10%	10%	10%	10%	10%	10%
Annual H2 production (MBtu)	355,351	355,351	355,351	355,351	355,351	355,351	355,351	355,351	355,351	355,351	355,351
Annual H2 production (kWh)	104,147,484	104,147,484	104,147,484	104,147,484	104,147,484	104,147,484	104,147,484	104,147,484	104,147,484	104,147,484	104,147,484
wind turbine capacity factor	33%	33%	33%	33%	33%	33%	33%	33%	33%	33%	33%
nominal wind generating capacity (MW)	53	53	53	53	53	53	53	53	53	53	53
Discount Rate	10%	10%	10%	10%	10%	10%	10%	10%	10%	10%	10%
Lifetime (yr)	30	30	30	30	30	30	30	30	30	30	30
Electrolyzer											
plant size (kW in)	52,981	52,981	52,981	52,981	52,981	52,981	52,981	52,981	52,981	52,981	52,981
plant size (kW out)	36027.21865	36027.21865	36027.21865	36027.21865	36027.21865	36027.21865	36027.21865	36027.21865	36027.21865	36027.21865	36027.21865
plant size (Nm3/day)	424,416	424,416	424,416	424,416	424,416	424,416	424,416	424,416	424,416	424,416	424,416
operating capacity	90%	90%	90%	90%	90%	90%	90%	90%	90%	90%	90%
capital cost ($)	$21,616,331	$21,616,331	$21,616,331	$21,616,331	$21,616,331	$21,616,331	$21,616,331	$21,616,331	$21,616,331	$21,616,331	$21,616,331
annualized capital cost ($/yr)	$2,293,044.16	$2,293,044.16	$2,293,044.16	$2,293,044.16	$2,293,044.16	$2,293,044.16	$2,293,044.16	$2,293,044.16	$2,293,044.16	$2,293,044.16	$2,293,044.16
O&M costs ($/yr)	$2,323,674.96	$2,323,674.96	$2,323,674.96	$2,323,674.96	$2,323,674.96	$2,323,674.96	$2,323,674.96	$2,323,674.96	$2,323,674.96	$2,323,674.96	$2,323,674.96
Electricity Costs											
conversion efficiency	68%	68%	68%	68%	68%	68%	68%	68%	68%	68%	68%
required electricity (kWh/yr)	153,158,064	153,158,064	153,158,064	153,158,064	153,158,064	153,158,064	153,158,064	153,158,064	153,158,064	153,158,064	153,158,064
unit cost of electricity ($/kWh)	$0.065	$0.065	$0.065	$0.065	$0.065	$0.065	$0.065	$0.065	$0.065	$0.065	$0.065
total cost of electricity ($/yr)	$9,955,274.17	$9,955,274.17	$9,955,274.17	$9,955,274.17	$9,955,274.17	$9,955,274.17	$9,955,274.17	$9,955,274.17	$9,955,274.17	$9,955,274.17	$9,955,274.17
Totals											
total annual cost ($/yr)	$14,571,993.30	$14,571,993.30	$14,571,993.30	$14,571,993.30	$14,571,993.30	$14,571,993.30	$14,571,993.30	$14,571,993.30	$14,571,993.30	$14,571,993.30	$14,571,993.30
H2 unit cost ($/MBtu)	$41.01	$41.01	$41.01	$41.01	$41.01	$41.01	$41.01	$41.01	$41.01	$41.01	$41.01

Delivery Costs

Cost to distribute ($/MBtu)	$3.00	$4.00	$5.00	$6.00	$7.00	$8.00	$9.00	$10.00	$11.00	$3.50	$10.82
H2 Cost (at refueling station)	$44.01	$45.01	$46.01	$47.01	$48.01	$49.01	$50.01	$51.01	$52.01	$44.51	$51.83

End Use Calculations

Conversion Device	Fuel Cell	Fuel Cell	Fuel Cell	Fuel Cell	Fuel Cell	Fuel Cell	Fuel Cell	Fuel Cell	Fuel Cell	Fuel Cell	Fuel Cell
Efficiency (mi/gge)	44	44	44	44	44	44	44	44	44	44	44
Efficiency (mi/MBtu)	353.1300161	353.1300161	353.1300161	353.1300161	353.1300161	353.1300161	353.1300161	353.1300161	353.1300161	353.1300161	353.1300161
Fuel Cost ($/mi)	$0.1246	$0.1275	$0.1303	$0.1331	$0.1359	$0.1388	$0.1416	$0.1444	$0.1473	$0.1260	$0.1468

MAUI


Sensitivity of H2 fuel price to Delivery Costs for Wind Generation
H2 fuel cost ($/mi)
$0.17
$0.16
$0.15
$0.14
$0.13
$0.12
$0.11
$0.10
$0.09
$0.08
$0.07
$3.00
$4.00
$5.00
$6.00
$7.00
$8.00
$9.00
$10.00
$11.00
Distribution Costs ($/Mbtu)
$7.98
High Estimate
Low Estimate
Gasoline: $0.082/mile

6. Sensitivity to Fuel Cell Efficiency

Production Costs

replacement goal (% of energy used for tranportatic	10%	10%	10%	10%	10%	10%	10%	10%	10%	10%
Annual H2 production (MBtu)	355,351	355,351	355,351	355,351	355,351	355,351	355,351	355,351	355,351	355,351
Annual H2 production (kWh)	104,147,484	104,147,484	104,147,484	104,147,484	104,147,484	104,147,484	104,147,484	104,147,484	104,147,484	104,147,484
wind turbine capacity factor	33%	33%	33%	33%	33%	33%	33%	33%	33%	33%
nominal wind generating capacity (MW)	53	53	53	53	53	53	53	53	53	53
Discount Rate	10%	10%	10%	10%	10%	10%	10%	10%	10%	10%
Lifetime (yr)	30	30	30	30	30	30	30	30	30	30
Electrolyzer										
plant size (kW in)	52,981	52,981	52,981	52,981	52,981	52,981	52,981	52,981	52,981	52,981
plant size (kW out)	36027.21865	36027.21865	36027.21865	36027.21865	36027.21865	36027.21865	36027.21865	36027.21865	36027.21865	36027.21865
plant size (Nm3/day)	424,416	424,416	424,416	424,416	424,416	424,416	424,416	424,416	424,416	424,416
operating capacity	90%	90%	90%	90%	90%	90%	90%	90%	90%	90%
capital cost ($)	$21,616,331	$21,616,331	$21,616,331	$21,616,331	$21,616,331	$21,616,331	$21,616,331	$21,616,331	$21,616,331	$21,616,331
annualized capital cost ($/yr)	$2,293,044.16	$2,293,044.16	$2,293,044.16	$2,293,044.16	$2,293,044.16	$2,293,044.16	$2,293,044.16	$2,293,044.16	$2,293,044.16	$2,293,044.16
O&M costs ($/yr)	$2,323,674.96	$2,323,674.96	$2,323,674.96	$2,323,674.96	$2,323,674.96	$2,323,674.96	$2,323,674.96	$2,323,674.96	$2,323,674.96	$2,323,674.96
Electricity Costs										
conversion efficiency	68%	68%	68%	68%	68%	68%	68%	68%	68%	68%
required electricity (kWh/yr)	153,158,064	153,158,064	153,158,064	153,158,064	153,158,064	153,158,064	153,158,064	153,158,064	153,158,064	153,158,064
unit cost of electricity ($/kWh)	$0.065	$0.065	$0.065	$0.065	$0.065	$0.065	$0.065	$0.065	$0.065	$0.065
total cost of electricity ($/yr)	$9,955,274.17	$9,955,274.17	$9,955,274.17	$9,955,274.17	$9,955,274.17	$9,955,274.17	$9,955,274.17	$9,955,274.17	$9,955,274.17	$9,955,274.17
Totals										
total annual cost ($/yr)	$14,571,993.30	$14,571,993.30	$14,571,993.30	$14,571,993.30	$14,571,993.30	$14,571,993.30	$14,571,993.30	$14,571,993.30	$14,571,993.30	$14,571,993.30
H2 unit cost ($/MBtu)	$41.01	$41.01	$41.01	$41.01	$41.01	$41.01	$41.01	$41.01	$41.01	$41.01

Delivery Costs

Cost to distribute ($/MBtu)	$7.98	$7.98	$7.98	$7.98	$7.98	$7.98	$7.98	$7.98	$7.98	$7.98
H2 Cost (at refueling station)	$48.98	$48.98	$48.98	$48.98	$48.98	$48.98	$48.98	$48.98	$48.98	$48.98

End Use Calculations

Conversion Device	Fuel Cell	Fuel Cell	Fuel Cell	Fuel Cell	Fuel Cell	Fuel Cell	Fuel Cell	Fuel Cell	Fuel Cell	Fuel Cell
Efficiency (mi/gge)	35	40	45	50	55	60	65	70	75	80
Efficiency (mi/MBtu)	280.8988764	321.0272873	361.1556982	401.2841091	441.4125201	481.540931	521.6693419	561.7977528	601.9261637	642.0545746
Fuel Cost ($/mi)	$0.1744	$0.1526	$0.1356	$0.1221	$0.1110	$0.1017	$0.0939	$0.0872	$0.0814	$0.0763

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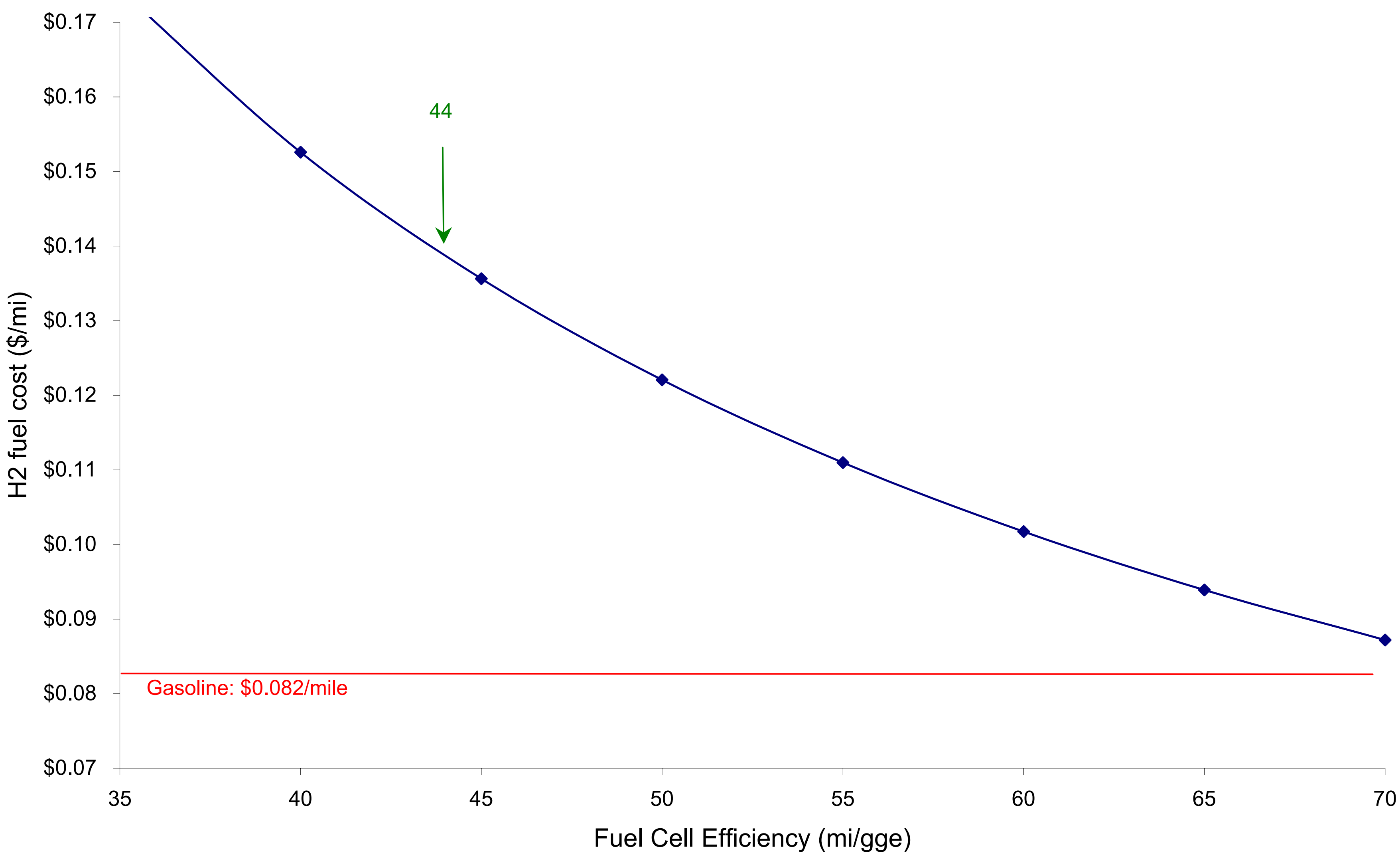
Sensitivity of H2 fuel price to Fuel Cell Efficiency for Wind Generation



Hydrogen Pathways for the Island of Kauai - Wind Sensitivity Analyses

Potential Market

Registered Vehicles:	53,904
Ground Transportation Fuel Used (gge)	24,947,000
Ground Transportation Fuel Used (MBtu)	3,108,871
Estimated Average Vehicle Efficiency (mi/gge)	22.86
Estimated Average Vehicle Efficiency (mi/MBtu)	183.4427772

1. Sensitivity to Cost of Electricity from Wind

Production Costs

									Low	**High**
replacement goal (% of energy used for tranportatic	10%	10%	10%	10%	10%	10%	10%	10%	10%	10%
Annual H2 production (MBtu)	155,444	155,444	155,444	155,444	155,444	155,444	155,444	155,444	155,444	155,444
Annual H2 production (kWh)	45,557,904	45,557,904	45,557,904	45,557,904	45,557,904	45,557,904	45,557,904	45,557,904	45,557,904	45,557,904
wind turbine capacity factor	33%	33%	33%	33%	33%	33%	33%	33%	33%	33%
nominal wind generating capacity (MW)	23	23	23	23	23	23	23	23	23	23
Discount Rate	10%	10%	10%	10%	10%	10%	10%	10%	10%	10%
Lifetime (yr)	30	30	30	30	30	30	30	30	30	30
Electrolyzer										
plant size (kW in)	23,176	23,176	23,176	23,176	23,176	23,176	23,176	23,176	23,176	23,176
plant size (kW out)	15759.61816	15759.61816	15759.61816	15759.61816	15759.61816	15759.61816	15759.61816	15759.61816	15759.61816	15759.61816
plant size (Nm3/day)	185,655	185,655	185,655	185,655	185,655	185,655	185,655	185,655	185,655	185,655
operating capacity	90%	90%	90%	90%	90%	90%	90%	90%	90%	90%
capital cost ($)	$9,455,771	$9,455,771	$9,455,771	$9,455,771	$9,455,771	$9,455,771	$9,455,771	$9,455,771	$9,455,771	$9,455,771
annualized capital cost ($/yr)	$1,003,061.07	$1,003,061.07	$1,003,061.07	$1,003,061.07	$1,003,061.07	$1,003,061.07	$1,003,061.07	$1,003,061.07	$1,003,061.07	$1,003,061.07
O&M costs ($/yr)	$1,016,460.10	$1,016,460.10	$1,016,460.10	$1,016,460.10	$1,016,460.10	$1,016,460.10	$1,016,460.10	$1,016,460.10	$1,016,460.10	$1,016,460.10
Electricity Costs										
conversion efficiency	68%	68%	68%	68%	68%	68%	68%	68%	68%	68%
required electricity (kWh/yr)	66,996,918	66,996,918	66,996,918	66,996,918	66,996,918	66,996,918	66,996,918	66,996,918	66,996,918	66,996,918
unit cost of electricity ($/kWh)	$0.050	$0.055	$0.060	$0.065	$0.070	$0.075	$0.080	$0.085	$0.060	$0.080
total cost of electricity ($/yr)	$3,349,845.90	$3,684,830.48	$4,019,815.07	$4,354,799.66	$4,689,784.25	$5,024,768.84	$5,359,753.43	$5,694,738.02	$4,019,815.07	$5,359,753.43
Totals										
total annual cost ($/yr)	$5,369,367.06	$5,704,351.65	$6,039,336.24	$6,374,320.83	$6,709,305.42	$7,044,290.01	$7,379,274.60	$7,714,259.19	$6,039,336.24	$7,379,274.60
H2 unit cost ($/MBtu)	$34.54	$36.70	$38.85	$41.01	$43.16	$45.32	$47.47	$49.63	$38.85	$47.47
Delivery Costs										
Cost to distribute ($/MBtu)	$7.98	$7.98	$7.98	$7.98	$7.98	$7.98	$7.98	$7.98	$7.98	$7.98
H2 Cost (at refueling station)	$42.52	$44.67	$46.83	$48.98	$51.14	$53.29	$55.45	$57.60	$46.83	$55.45
End Use Calculations										
Conversion Device	Fuel Cell	Fuel Cell	Fuel Cell	Fuel Cell	Fuel Cell	Fuel Cell	Fuel Cell	Fuel Cell	Fuel Cell	Fuel Cell
Efficiency (mi/gge)	44	44	44	44	44	44	44	44	44	44
Efficiency (mi/MBtu)	353.1300161	353.1300161	353.1300161	353.1300161	353.1300161	353.1300161	353.1300161	353.1300161	353.1300161	353.1300161
Fuel Cost ($/mi)	$0.1204	$0.1265	$0.1326	$0.1387	$0.1448	$0.1509	$0.1570	$0.1631	$0.1326	$0.1570

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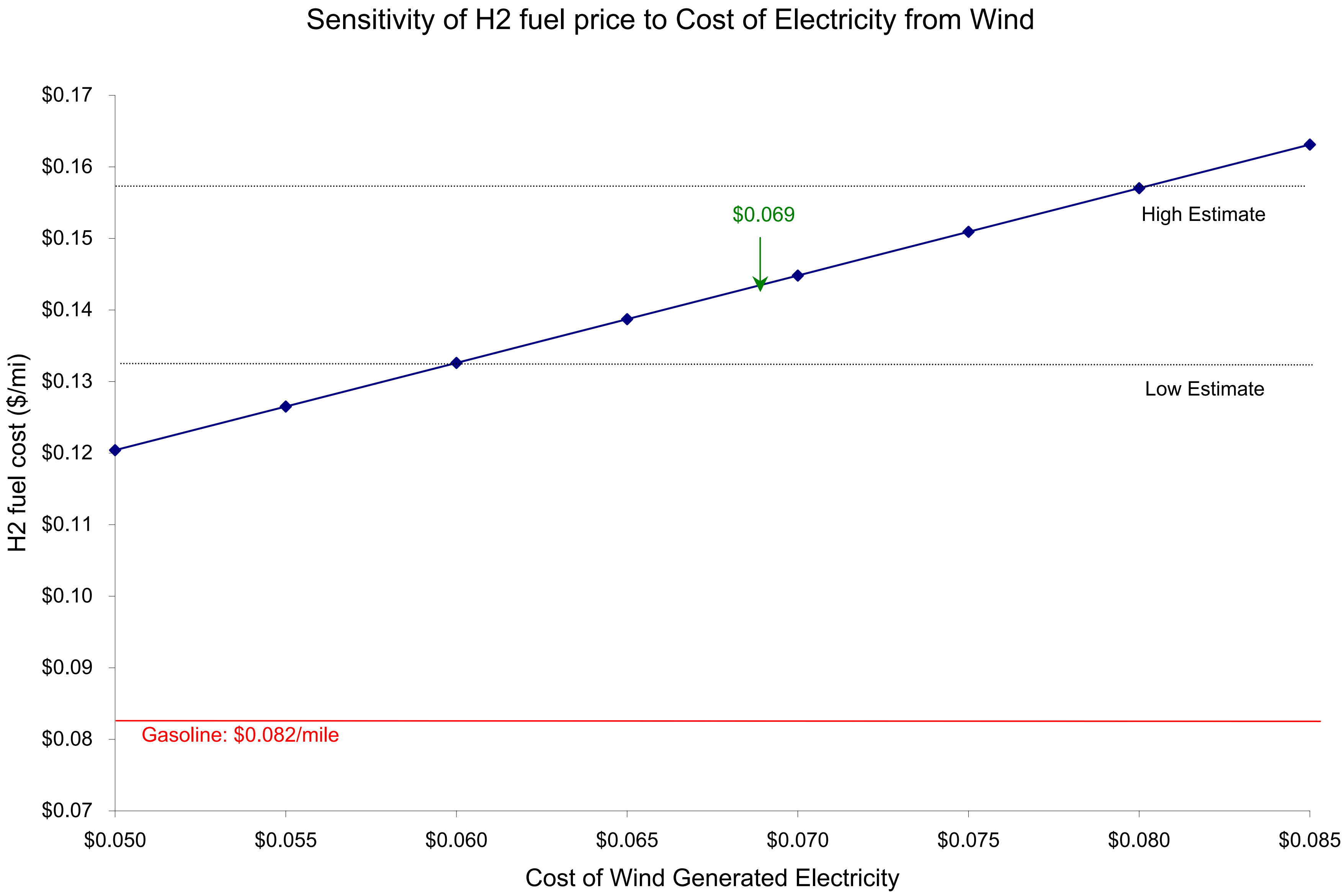
Sensitivity of H2 fuel price to Cost of Electricity from Wind
H2 fuel cost ($/mi)
$0.17
$0.16
$0.15
$0.14
$0.13
$0.12
$0.11
$0.10
$0.09
$0.08
$0.07
$0.069
High Estimate
Low Estimate
Gasoline: $0.082/mile
$0.050
$0.055
$0.060
$0.065
$0.070
$0.075
$0.080
$0.085
Cost of Wind Generated Electricity

2. Sensitivity to Wind Turbine Capacity Factor

Production Costs

									Low	High
replacement goal (% of energy used for tranportatic	10%	10%	10%	10%	10%	10%	10%	10%	10%	10%
Annual H2 production (MBtu)	155,444	155,444	155,444	155,444	155,444	155,444	155,444	155,444	155,444	155,444
Annual H2 production (kWh)	45,557,904	45,557,904	45,557,904	45,557,904	45,557,904	45,557,904	45,557,904	45,557,904	45,557,904	45,557,904
wind turbine capacity factor	20%	25%	30%	35%	40%	45%	50%	55%	25%	45%
nominal wind generating capacity (MW)	38	31	25	22	19	17	15	14	31	17
Discount Rate	10%	10%	10%	10%	10%	10%	10%	10%	10%	10%
Lifetime (yr)	30	30	30	30	30	30	30	30	30	30
Electrolyzer										
plant size (kW in)	38,240	30,592	25,493	21,852	19,120	16,996	15,296	13,906	30,592	16,996
plant size (kW out)	26003.36996	20802.69597	17335.57998	14859.06855	13001.68498	11557.05332	10401.34799	9455.770896	20802.69597	11557.05332
plant size (Nm3/day)	306,330	245,064	204,220	175,046	153,165	136,147	122,532	111,393	245,064	136,147
operating capacity	90%	90%	90%	90%	90%	90%	90%	90%	90%	90%
capital cost ($)	$15,602,022	$12,481,618	$10,401,348	$8,915,441	$7,801,011	$6,934,232	$6,240,809	$5,673,463	$12,481,618	$6,934,232
annualized capital cost ($/yr)	$1,655,050.76	$1,324,040.61	$1,103,367.18	$945,743.29	$827,525.38	$735,578.12	$662,020.31	$601,836.64	$1,324,040.61	$735,578.12
O&M costs ($/yr)	$1,677,159.16	$1,341,727.33	$1,118,106.11	$958,376.66	$838,579.58	$745,404.07	$670,863.66	$609,876.06	$1,341,727.33	$745,404.07
Electricity Costs										
conversion efficiency	68%	68%	68%	68%	68%	68%	68%	68%	68%	68%
required electricity (kWh/yr)	66,996,918	66,996,918	66,996,918	66,996,918	66,996,918	66,996,918	66,996,918	66,996,918	66,996,918	66,996,918
unit cost of electricity ($/kWh)	$0.069	$0.069	$0.069	$0.069	$0.069	$0.069	$0.069	$0.069	$0.069	$0.069
total cost of electricity ($/yr)	$4,622,787.34	$4,622,787.34	$4,622,787.34	$4,622,787.34	$4,622,787.34	$4,622,787.34	$4,622,787.34	$4,622,787.34	$4,622,787.34	$4,622,787.34
Totals										
total annual cost ($/yr)	$7,954,997.26	$7,288,555.27	$6,844,260.62	$6,526,907.29	$6,288,892.30	$6,103,769.52	$5,955,671.30	$5,834,500.03	$7,288,555.27	$6,103,769.52
H2 unit cost ($/MBtu)	$51.18	$46.89	$44.03	$41.99	$40.46	$39.27	$38.31	$37.53	$46.89	$39.27
Delivery Costs										
Cost to distribute ($/MBtu)	$7.98	$7.98	$7.98	$7.98	$7.98	$7.98	$7.98	$7.98	$7.98	$7.98
H2 Cost (at refueling station)	$59.15	$54.86	$52.01	$49.96	$48.43	$47.24	$46.29	$45.51	$54.86	$47.24
End Use Calculations										
Conversion Device	Fuel Cell	Fuel Cell	Fuel Cell	Fuel Cell	Fuel Cell	Fuel Cell	Fuel Cell	Fuel Cell	Fuel Cell	Fuel Cell
Efficiency (mi/gge)	44	44	44	44	44	44	44	44	44	44
Efficiency (mi/MBtu)	353.1300161	353.1300161	353.1300161	353.1300161	353.1300161	353.1300161	353.1300161	353.1300161	353.1300161	353.1300161
Fuel Cost ($/mi)	$0.1675	$0.1554	$0.1473	$0.1415	$0.1372	$0.1338	$0.1311	$0.1289	$0.1554	$0.1338

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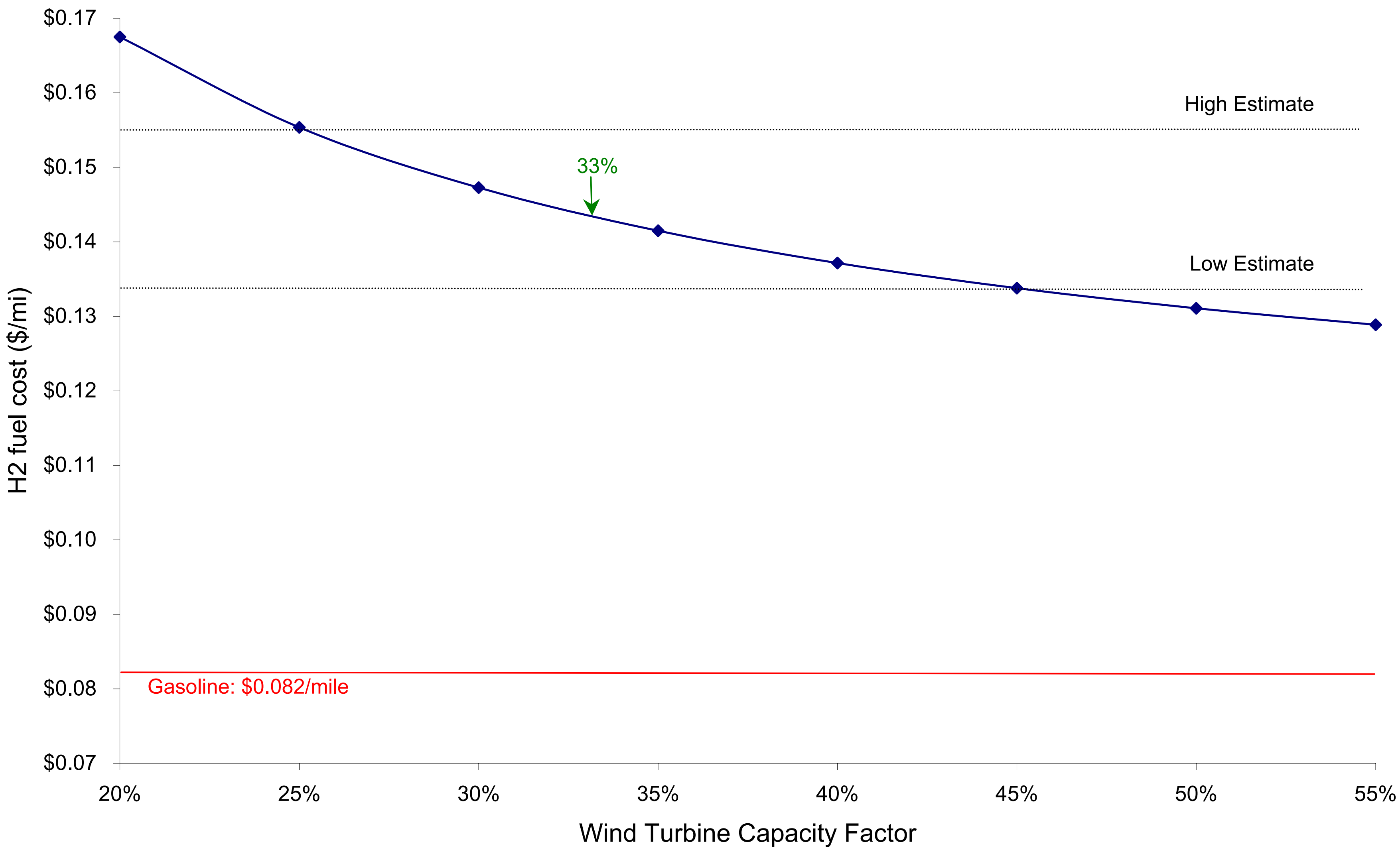
Sensitivity of H2 fuel price to Wind Turbine Capacity Factor



3. Sensitivity to Electrolyzer Capital Cost

Production Costs

									Low	High
replacement goal (% of energy used for tranportatic	10%	10%	10%	10%	10%	10%	10%	10%	10%	10%
Annual H2 production (MBtu)	155,444	155,444	155,444	155,444	155,444	155,444	155,444	155,444	155,444	155,444
Annual H2 production (kWh)	45,557,904	45,557,904	45,557,904	45,557,904	45,557,904	45,557,904	45,557,904	45,557,904	45,557,904	45,557,904
wind turbine capacity factor	33%	33%	33%	33%	33%	33%	33%	33%	33%	33%
nominal wind generating capacity (MW)	23	23	23	23	23	23	23	23	23	23
Discount Rate	10%	10%	10%	10%	10%	10%	10%	10%	10%	10%
Lifetime (yr)	30	30	30	30	30	30	30	30	30	30
Electrolyzer										
plant size (kW in)	23,176	23,176	23,176	23,176	23,176	23,176	23,176	23,176	23,176	23,176
plant size (kW out)	15759.61816	15759.61816	15759.61816	15759.61816	15759.61816	15759.61816	15759.61816	15759.61816	15759.61816	15759.61816
plant size (Nm3/day)	185,655	185,655	185,655	185,655	185,655	185,655	185,655	185,655	185,655	185,655
operating capacity	90%	90%	90%	90%	90%	90%	90%	90%	90%	90%
capital cost ($/kW)	$200	$300	$400	$500	$600	$700	$800	$900	$300	$900
annualized capital cost ($/yr)	$334,353.69	$501,530.53	$668,707.38	$835,884.22	$1,003,061.07	$1,170,237.91	$1,337,414.76	$1,504,591.60	$501,530.53	$1,504,591.60
O&M costs ($/yr)	$1,016,460.10	$1,016,460.10	$1,016,460.10	$1,016,460.10	$1,016,460.10	$1,016,460.10	$1,016,460.10	$1,016,460.10	$1,016,460.10	$1,016,460.10
Electricity Costs										
conversion efficiency	68%	68%	68%	68%	68%	68%	68%	68%	68%	68%
required electricity (kWh/yr)	66,996,918	66,996,918	66,996,918	66,996,918	66,996,918	66,996,918	66,996,918	66,996,918	66,996,918	66,996,918
unit cost of electricity ($/kWh)	$0.069	$0.069	$0.069	$0.069	$0.069	$0.069	$0.069	$0.069	$0.069	$0.069
total cost of electricity ($/yr)	$4,622,787.34	$4,622,787.34	$4,622,787.34	$4,622,787.34	$4,622,787.34	$4,622,787.34	$4,622,787.34	$4,622,787.34	$4,622,787.34	$4,622,787.34
Totals										
total annual cost ($/yr)	$5,973,601.12	$6,140,777.97	$6,307,954.81	$6,475,131.66	$6,642,308.50	$6,809,485.35	$6,976,662.19	$7,143,839.03	$6,140,777.97	$7,143,839.03
H2 unit cost ($/MBtu)	$38.43	$39.50	$40.58	$41.66	$42.73	$43.81	$44.88	$45.96	$39.50	$45.96

Delivery Costs

Cost to distribute ($/MBtu)	$7.98	$7.98	$7.98	$7.98	$7.98	$7.98	$7.98	$7.98	$7.98	$7.98
H2 Cost (at refueling station)	$46.41	$47.48	$48.56	$49.63	$50.71	$51.78	$52.86	$53.93	$47.48	$53.93

End Use Calculations

Conversion Device	Fuel Cell	Fuel Cell	Fuel Cell	Fuel Cell	Fuel Cell	Fuel Cell	Fuel Cell	Fuel Cell	Fuel Cell	Fuel Cell
Efficiency (mi/gge)	44	44	44	44	44	44	44	44	44	44
Efficiency (mi/MBtu)	353.1300161	353.1300161	353.1300161	353.1300161	353.1300161	353.1300161	353.1300161	353.1300161	353.1300161	353.1300161
Fuel Cost ($/mi)	$0.1314	$0.1345	$0.1375	$0.1405	$0.1436	$0.1466	$0.1497	$0.1527	$0.1345	$0.1527

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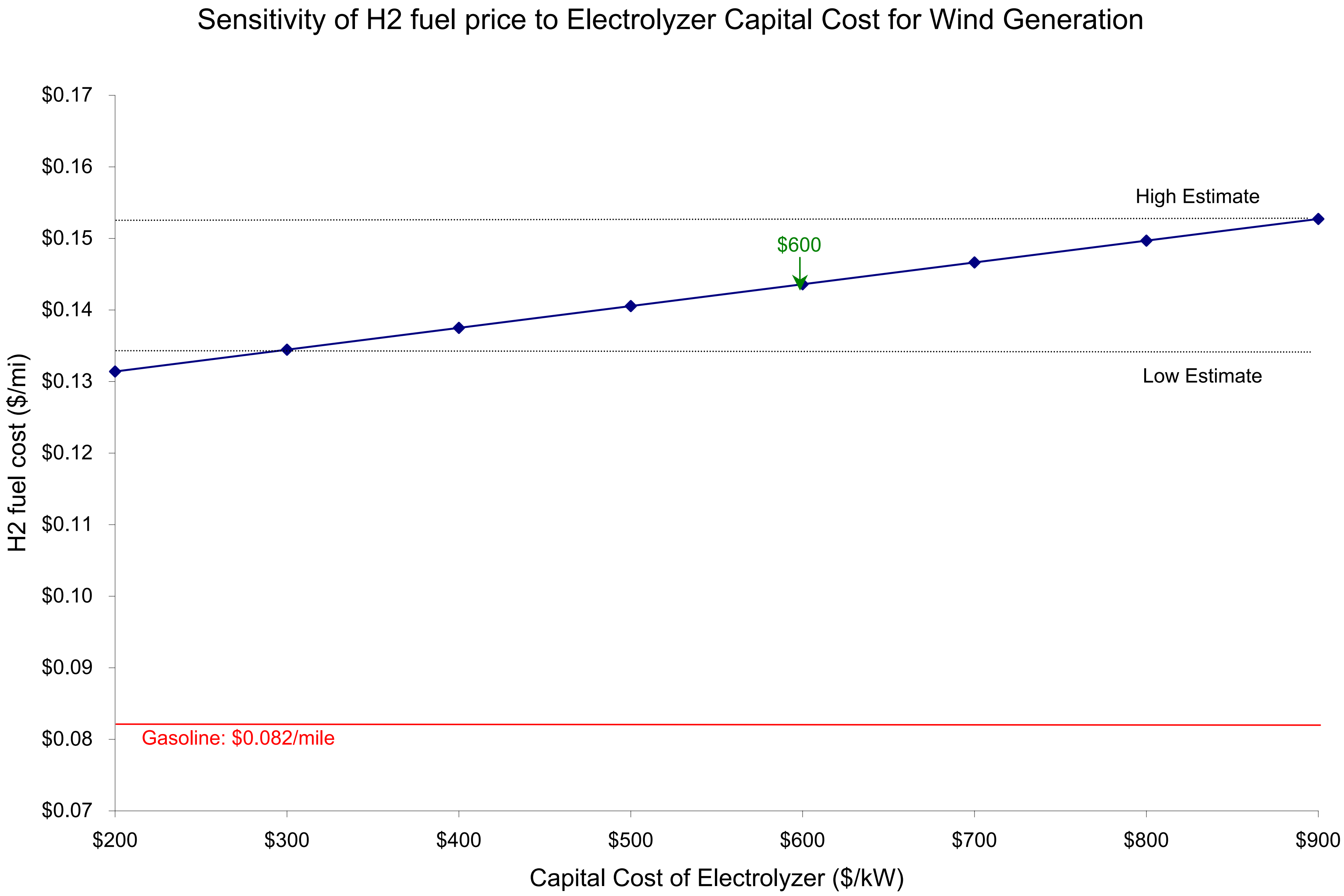
Sensitivity of H2 fuel price to Electrolyzer Capital Cost for Wind Generation
H2 fuel cost ($/mi)
$0.17
$0.16
$0.15
$0.14
$0.13
$0.12
$0.11
$0.10
$0.09
$0.08
$0.07
High Estimate
$600
Low Estimate
Gasoline: $0.082/mile
$200
$300
$400
$500
$600
$700
$800
$900
Capital Cost of Electrolyzer ($/kW)

4. Sensitivity to Electrolyzer Conversion Efficiency

Production Costs

									Low	High
replacement goal (% of energy used for tranportatic	10%	10%	10%	10%	10%	10%	10%	10%	10%	10%
Annual H2 production (MBtu)	155,444	155,444	155,444	155,444	155,444	155,444	155,444	155,444	155,444	155,444
Annual H2 production (kWh)	45,557,904	45,557,904	45,557,904	45,557,904	45,557,904	45,557,904	45,557,904	45,557,904	45,557,904	45,557,904
wind turbine capacity factor	33%	33%	33%	33%	33%	33%	33%	33%	33%	33%
nominal wind generating capacity (MW)	29	26	24	23	21	20	19	18	25	21
Discount Rate	10%	10%	10%	10%	10%	10%	10%	10%	10%	10%
Lifetime (yr)	30	30	30	30	30	30	30	30	30	30
Electrolyzer										
plant size (kW in)	28,654	26,266	24,246	22,514	21,013	19,700	18,541	17,511	25,015	21,013
plant size (kW out)	15759.61816	15759.61816	15759.61816	15759.61816	15759.61816	15759.61816	15759.61816	15759.61816	15759.61816	15759.61816
plant size (Nm3/day)	229,537	210,409	194,223	180,350	168,327	157,807	148,524	140,273	200,389	168,327
operating capacity	90%	90%	90%	90%	90%	90%	90%	90%	90%	90%
capital cost ($)	$9,455,771	$9,455,771	$9,455,771	$9,455,771	$9,455,771	$9,455,771	$9,455,771	$9,455,771	$9,455,771	$9,455,771
annualized capital cost ($/yr)	$1,003,061.07	$1,003,061.07	$1,003,061.07	$1,003,061.07	$1,003,061.07	$1,003,061.07	$1,003,061.07	$1,003,061.07	$1,003,061.07	$1,003,061.07
O&M costs ($/yr)	$1,256,714.30	$1,151,988.11	$1,063,373.64	$987,418.38	$921,590.49	$863,991.08	$813,168.08	$767,992.07	$1,097,131.53	$921,590.49
Electricity Costs										
conversion efficiency	55%	60%	65%	70%	75%	80%	85%	90%	63%	75%
required electricity (kWh/yr)	82,832,553	75,929,840	70,089,083	65,082,720	60,743,872	56,947,380	53,597,534	50,619,894	72,314,134	60,743,872
unit cost of electricity ($/kWh)	$0.069	$0.069	$0.069	$0.069	$0.069	$0.069	$0.069	$0.069	$0.069	$0.069
total cost of electricity ($/yr)	$5,715,446.16	$5,239,158.98	$4,836,146.75	$4,490,707.70	$4,191,327.18	$3,929,369.24	$3,698,229.87	$3,492,772.65	$4,989,675.22	$4,191,327.18
Totals										
total annual cost ($/yr)	$7,975,221.53	$7,394,208.16	$6,902,581.46	$6,481,187.15	$6,115,978.74	$5,796,421.39	$5,514,459.01	$5,263,825.79	$7,089,867.82	$6,115,978.74
H2 unit cost ($/MBtu)	$51.31	$47.57	$44.41	$41.69	$39.35	$37.29	$35.48	$33.86	$45.61	$39.35

Delivery Costs

Cost to distribute ($/MBtu)	$7.98	$7.98	$7.98	$7.98	$7.98	$7.98	$7.98	$7.98	$7.98	$7.98
H2 Cost (at refueling station)	$59.28	$55.54	$52.38	$49.67	$47.32	$45.27	$43.45	$41.84	$53.59	$47.32

End Use Calculations

Conversion Device	Fuel Cell	Fuel Cell	Fuel Cell	Fuel Cell	Fuel Cell	Fuel Cell	Fuel Cell	Fuel Cell	Fuel Cell	Fuel Cell
Efficiency (mi/gge)	44	44	44	44	44	44	44	44	44	44
Efficiency (mi/MBtu)	353.1300161	353.1300161	353.1300161	353.1300161	353.1300161	353.1300161	353.1300161	353.1300161	353.1300161	353.1300161
Fuel Cost ($/mi)	$0.1679	$0.1573	$0.1483	$0.1407	$0.1340	$0.1282	$0.1230	$0.1185	$0.1517	$0.1340

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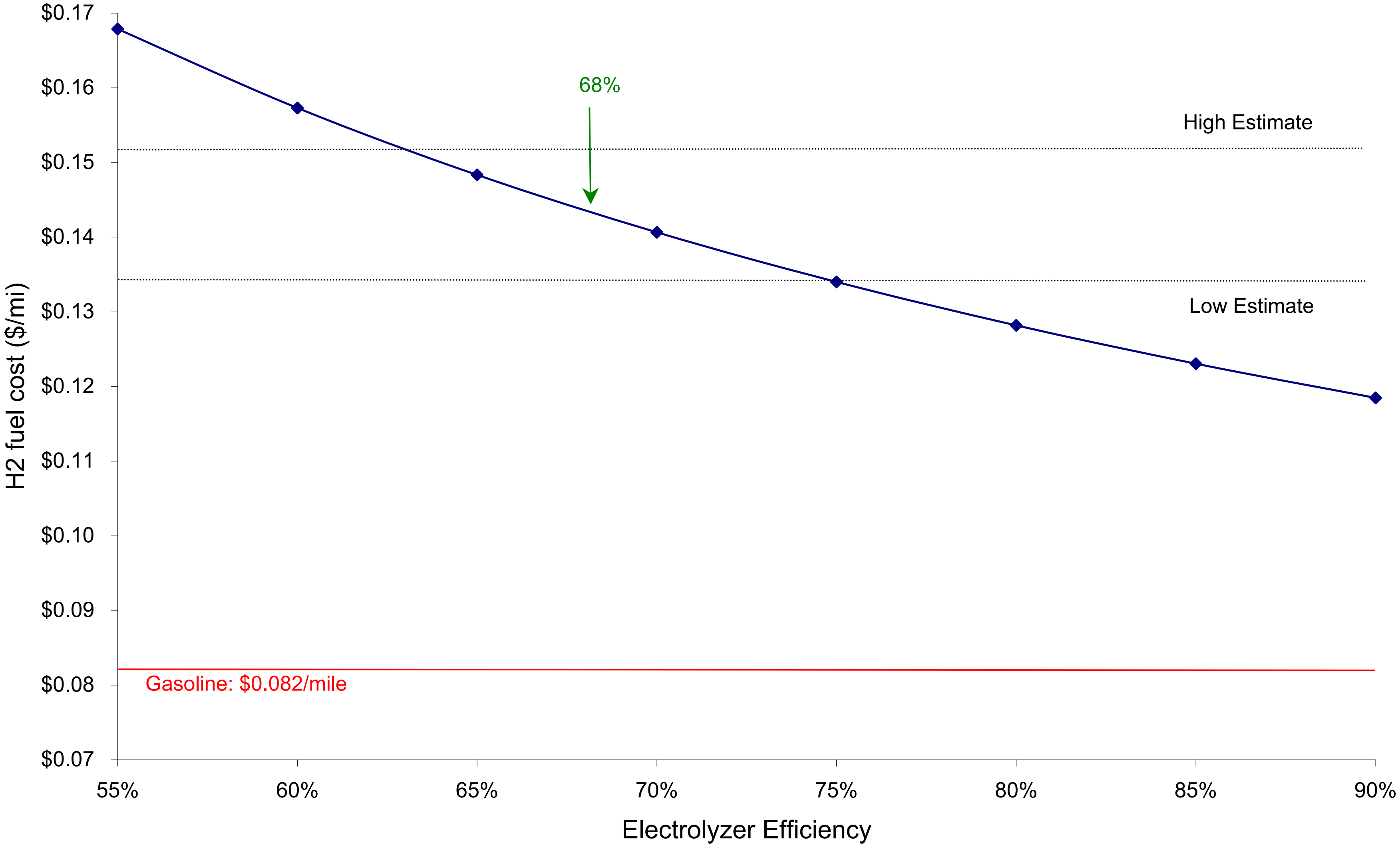
Sensitivity of H2 fuel price to Electrolyzer Conversion Efficiency for Wind Generation



5. Sensitivity to Delivery Costs

Production Costs

										Low	High
replacement goal (% of energy used for tranportatic	10%	10%	10%	10%	10%	10%	10%	10%	10%	10%	10%
Annual H2 production (MBtu)	155,444	155,444	155,444	155,444	155,444	155,444	155,444	155,444	155,444	155,444	155,444
Annual H2 production (kWh)	45,557,904	45,557,904	45,557,904	45,557,904	45,557,904	45,557,904	45,557,904	45,557,904	45,557,904	45,557,904	45,557,904
wind turbine capacity factor	33%	33%	33%	33%	33%	33%	33%	33%	33%	33%	33%
nominal wind generating capacity (MW)	23	23	23	23	23	23	23	23	23	23	23
Discount Rate	10%	10%	10%	10%	10%	10%	10%	10%	10%	10%	10%
Lifetime (yr)	30	30	30	30	30	30	30	30	30	30	30
Electrolyzer											
plant size (kW in)	23,176	23,176	23,176	23,176	23,176	23,176	23,176	23,176	23,176	23,176	23,176
plant size (kW out)	15759.61816	15759.61816	15759.61816	15759.61816	15759.61816	15759.61816	15759.61816	15759.61816	15759.61816	15759.61816	15759.61816
plant size (Nm3/day)	185,655	185,655	185,655	185,655	185,655	185,655	185,655	185,655	185,655	185,655	185,655
operating capacity	90%	90%	90%	90%	90%	90%	90%	90%	90%	90%	90%
capital cost ($)	$9,455,771	$9,455,771	$9,455,771	$9,455,771	$9,455,771	$9,455,771	$9,455,771	$9,455,771	$9,455,771	$9,455,771	$9,455,771
annualized capital cost ($/yr)	$1,003,061.07	$1,003,061.07	$1,003,061.07	$1,003,061.07	$1,003,061.07	$1,003,061.07	$1,003,061.07	$1,003,061.07	$1,003,061.07	$1,003,061.07	$1,003,061.07
O&M costs ($/yr)	$1,016,460.10	$1,016,460.10	$1,016,460.10	$1,016,460.10	$1,016,460.10	$1,016,460.10	$1,016,460.10	$1,016,460.10	$1,016,460.10	$1,016,460.10	$1,016,460.10
Electricity Costs											
conversion efficiency	68%	68%	68%	68%	68%	68%	68%	68%	68%	68%	68%
required electricity (kWh/yr)	66,996,918	66,996,918	66,996,918	66,996,918	66,996,918	66,996,918	66,996,918	66,996,918	66,996,918	66,996,918	66,996,918
unit cost of electricity ($/kWh)	$0.069	$0.069	$0.069	$0.069	$0.069	$0.069	$0.069	$0.069	$0.069	$0.069	$0.069
total cost of electricity ($/yr)	$4,622,787.34	$4,622,787.34	$4,622,787.34	$4,622,787.34	$4,622,787.34	$4,622,787.34	$4,622,787.34	$4,622,787.34	$4,622,787.34	$4,622,787.34	$4,622,787.34
Totals											
total annual cost ($/yr)	$6,642,308.50	$6,642,308.50	$6,642,308.50	$6,642,308.50	$6,642,308.50	$6,642,308.50	$6,642,308.50	$6,642,308.50	$6,642,308.50	$6,642,308.50	$6,642,308.50
H2 unit cost ($/MBtu)	$42.73	$42.73	$42.73	$42.73	$42.73	$42.73	$42.73	$42.73	$42.73	$42.73	$42.73

Delivery Costs

Cost to distribute ($/MBtu)	$3.00	$4.00	$5.00	$6.00	$7.00	$8.00	$9.00	$10.00	$11.00	$3.50	$10.82
H2 Cost (at refueling station)	$45.73	$46.73	$47.73	$48.73	$49.73	$50.73	$51.73	$52.73	$53.73	$46.23	$53.56

End Use Calculations

Conversion Device	Fuel Cell	Fuel Cell	Fuel Cell	Fuel Cell	Fuel Cell	Fuel Cell	Fuel Cell	Fuel Cell	Fuel Cell	Fuel Cell	Fuel Cell
Efficiency (mi/gge)	44	44	44	44	44	44	44	44	44	44	44
Efficiency (mi/MBtu)	353.1300161	353.1300161	353.1300161	353.1300161	353.1300161	353.1300161	353.1300161	353.1300161	353.1300161	353.1300161	353.1300161
Fuel Cost ($/mi)	$0.1295	$0.1323	$0.1352	$0.1380	$0.1408	$0.1437	$0.1465	$0.1493	$0.1522	$0.1309	$0.1517

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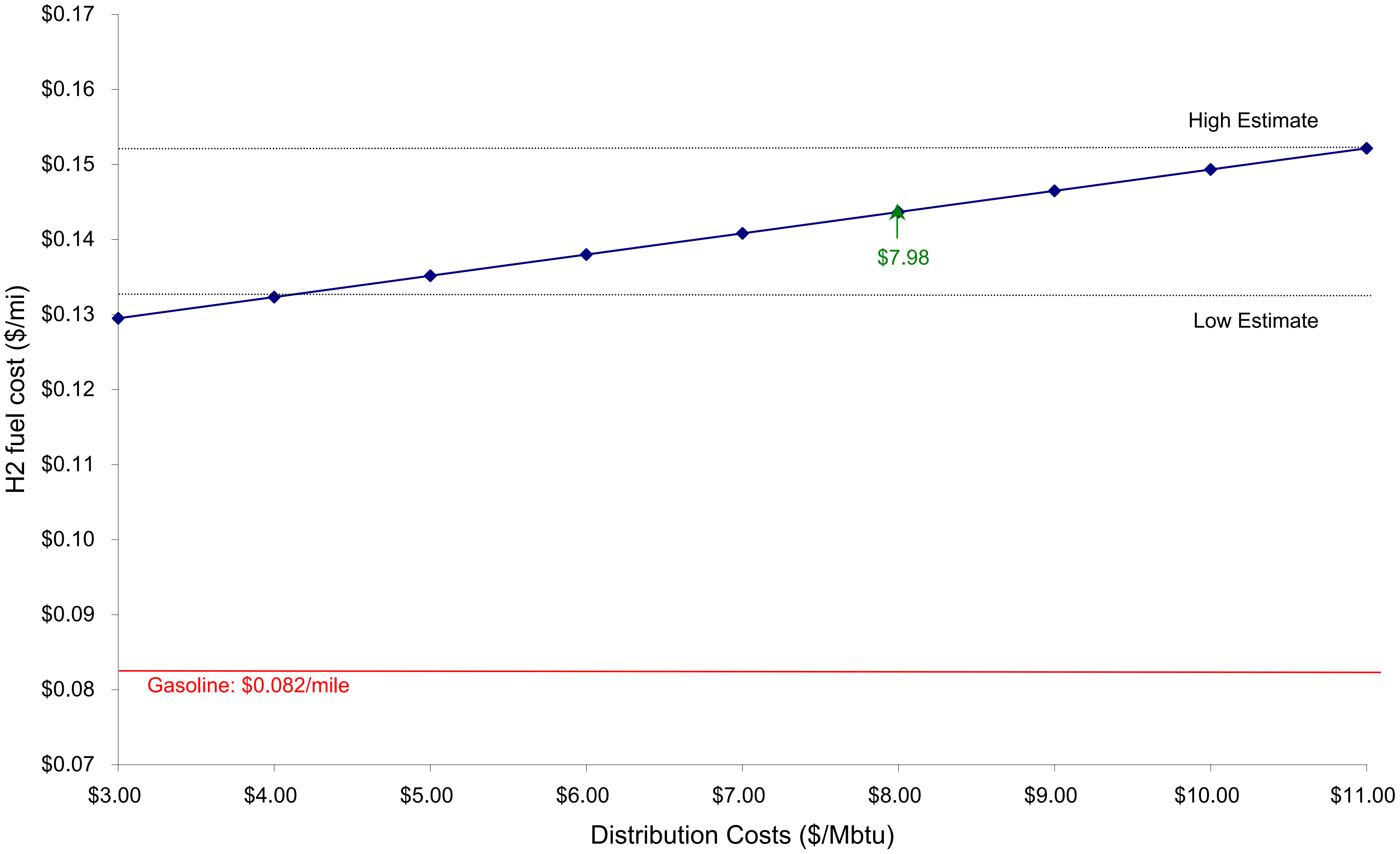
Sensitivity of H2 fuel price to Delivery Costs for Wind Generation



6. Sensitivity to Fuel Cell Efficiency

Production Costs

replacement goal (% of energy used for tranportatic	10%	10%	10%	10%	10%	10%	10%	10%	10%	10%
Annual H2 production (MBtu)	155,444	155,444	155,444	155,444	155,444	155,444	155,444	155,444	155,444	155,444
Annual H2 production (kWh)	45,557,904	45,557,904	45,557,904	45,557,904	45,557,904	45,557,904	45,557,904	45,557,904	45,557,904	45,557,904
wind turbine capacity factor	33%	33%	33%	33%	33%	33%	33%	33%	33%	33%
nominal wind generating capacity (MW)	23	23	23	23	23	23	23	23	23	23
Discount Rate	10%	10%	10%	10%	10%	10%	10%	10%	10%	10%
Lifetime (yr)	30	30	30	30	30	30	30	30	30	30
Electrolyzer										
plant size (kW in)	23,176	23,176	23,176	23,176	23,176	23,176	23,176	23,176	23,176	23,176
plant size (kW out)	15759.61816	15759.61816	15759.61816	15759.61816	15759.61816	15759.61816	15759.61816	15759.61816	15759.61816	15759.61816
plant size (Nm3/day)	185,655	185,655	185,655	185,655	185,655	185,655	185,655	185,655	185,655	185,655
operating capacity	90%	90%	90%	90%	90%	90%	90%	90%	90%	90%
capital cost ($)	$9,455,771	$9,455,771	$9,455,771	$9,455,771	$9,455,771	$9,455,771	$9,455,771	$9,455,771	$9,455,771	$9,455,771
annualized capital cost ($/yr)	$1,003,061.07	$1,003,061.07	$1,003,061.07	$1,003,061.07	$1,003,061.07	$1,003,061.07	$1,003,061.07	$1,003,061.07	$1,003,061.07	$1,003,061.07
O&M costs ($/yr)	$1,016,460.10	$1,016,460.10	$1,016,460.10	$1,016,460.10	$1,016,460.10	$1,016,460.10	$1,016,460.10	$1,016,460.10	$1,016,460.10	$1,016,460.10
Electricity Costs										
conversion efficiency	68%	68%	68%	68%	68%	68%	68%	68%	68%	68%
required electricity (kWh/yr)	66,996,918	66,996,918	66,996,918	66,996,918	66,996,918	66,996,918	66,996,918	66,996,918	66,996,918	66,996,918
unit cost of electricity ($/kWh)	$0.069	$0.069	$0.069	$0.069	$0.069	$0.069	$0.069	$0.069	$0.069	$0.069
total cost of electricity ($/yr)	$4,622,787.34	$4,622,787.34	$4,622,787.34	$4,622,787.34	$4,622,787.34	$4,622,787.34	$4,622,787.34	$4,622,787.34	$4,622,787.34	$4,622,787.34
Totals										
total annual cost ($/yr)	$6,642,308.50	$6,642,308.50	$6,642,308.50	$6,642,308.50	$6,642,308.50	$6,642,308.50	$6,642,308.50	$6,642,308.50	$6,642,308.50	$6,642,308.50
H2 unit cost ($/MBtu)	$42.73	$42.73	$42.73	$42.73	$42.73	$42.73	$42.73	$42.73	$42.73	$42.73

Delivery Costs

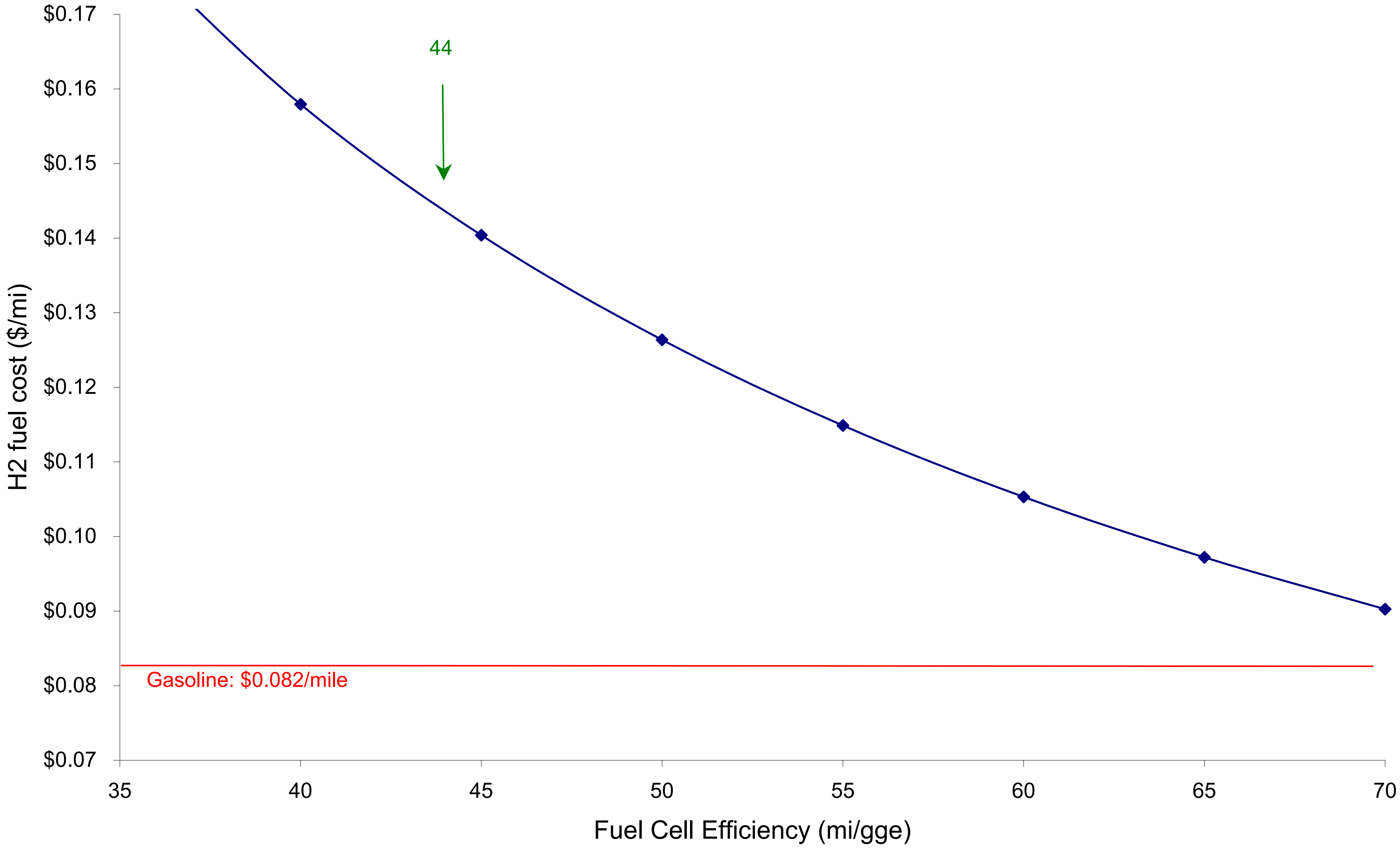
Cost to distribute ($/MBtu)	$7.98	$7.98	$7.98	$7.98	$7.98	$7.98	$7.98	$7.98	$7.98	$7.98
H2 Cost (at refueling station)	$50.71	$50.71	$50.71	$50.71	$50.71	$50.71	$50.71	$50.71	$50.71	$50.71

End Use Calculations

Conversion Device	Fuel Cell	Fuel Cell	Fuel Cell	Fuel Cell	Fuel Cell	Fuel Cell	Fuel Cell	Fuel Cell	Fuel Cell	Fuel Cell
Efficiency (mi/gge)	35	40	45	50	55	60	65	70	75	80
Efficiency (mi/MBtu)	280.8988764	321.0272873	361.1556982	401.2841091	441.4125201	481.540931	521.6693419	561.7977528	601.9261637	642.0545746
Fuel Cost ($/mi)	$0.1805	$0.1580	$0.1404	$0.1264	$0.1149	$0.1053	$0.0972	$0.0903	$0.0842	$0.0790

KAUAI

Sensitivity of H2 fuel price to Fuel Cell Efficiency for Wind Generation



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APPENDIX G: References

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