Analysis of Geothermally Produced Hydrogen on the Big Island of Hawaii: A Roadmap for the Way Forward

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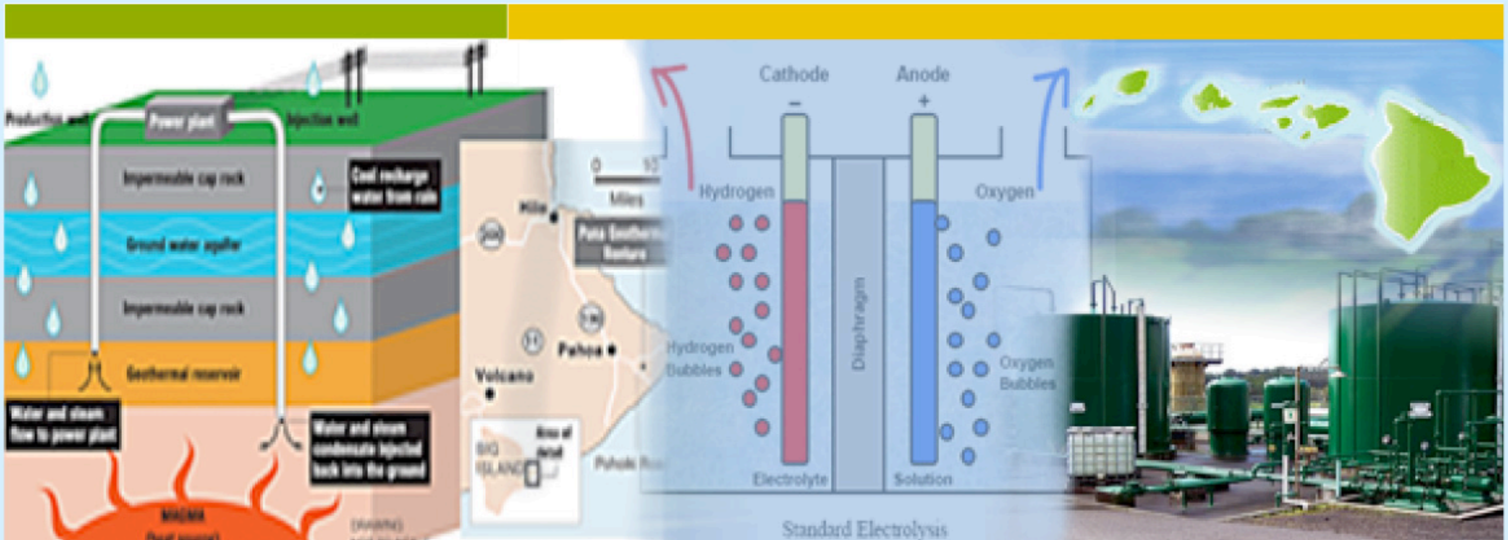

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ANALYSIS OF GEOTHERMALLY PRODUCED HYDROGEN ON THE BIG ISLAND OF HAWAII:

A Roadmap for the Way Forward

September 30, 2008

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The State of Hawaii's extensive reliance on imported oil continues to leave its economy and citizens at risk. This predicament has become painfully obvious in 2008 as oil has spiked to near $150 per barrel,[1] driving electricity prices in Kauai to near $0.50 per kWh[2] and gasoline prices throughout the state to over $4.50 per gallon.[3] The state continues to rely on oil for more than 90% of its energy needs[4] and to generate 78% of its electricity needs;[5] in 2007, more than $7 billion[6] left the Hawaiian economy to pay for its energy imports. Increasing the utilization of Hawaii's vast renewable resources is key to decreasing the demand for imported oil and helping to stabilize the cost of electricity and transportation fuel.

To this end, the potential use of the state's vast geothermal resources to produce renewable hydrogen for transportation purposes has become a topic of increased interest and support. Hawaii's legislature passed SB 2957 CD1 in 2006,[7] which was subsequently signed by Governor Linda Lingle as Act 240. The Act established the *Hawaii Renewable Hydrogen Program* to encourage the achievement of a renewable hydrogen economy. The development of this Roadmap supports the renewable hydrogen goals of the State and the U.S. Department of Energy (DOE) by delineating the optimal initial pathways for the development of a hydrogen energy infrastructure through 2025 based on the geothermal resources of the Big Island of Hawaii.

Hydrogen is viewed as the ultimate sustainable fuel for the United States if it can be made cost-effectively from renewable energy. The Big Island has been specifically identified as a unique and favorable location to test and validate the potential for hydrogen-fueled transportation due to its variety of renewable resources (including geothermal), unique electrical generation system, and economy. The Island's location and characteristics present many challenges and vulnerabilities; however, at the same time, they make the location a potentially ideal test bed, poised to showcase a viable renewable hydrogen economy.

In response to tasks issued by the DOE, State of Hawaii, and Hawaii Natural Energy Institute (HNEI), Sentech, Inc. has analyzed the potential for geothermally produced

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[1] Reuters. 2008. Oil prices briefly spike to record above $147 a barrel. *USA Today,* (July 11), http://www.usatoday.com/money/industries/energy/2008-07-11-oil-friday_N.htm.
[2] Kauai Island Utility Cooperative. 2008. Rate Data Sheet. September 20. http://www.kiuc.coop/pdf/ratedata_2008.pdf.
[3] American Automobile Association. Fuel Gauge Report. http://www.fuelgaugereport.com/HIavg.asp.
[4] State of Hawaii Department of Business, Economic Development & Tourism. 2007. Energy Resources Coordinator's 2007 Annual Report. http://hawaii.gov/dbedt/info/energy/publications/erc07.pdf.
[5] DBEDT. 2007 State of Hawaii Data Book, Table 17.06 (Electricity Generation by Source: 1990 – 2006).
[6] State of Hawaii. Governor Linda Lingle. *Administration Moves Forward on Five-Point Plan for Economic Action.* http://hawaii.gov/gov/economy
[7] State of Hawaii, The Senate, Twenty-Third Legislature, 2006. Senate Bill No. 2957 (CD1): Energy Self-sufficiency. http://www.capitol.hawaii.gov/session2006/bills/SB2957_CD1_.htm.

hydrogen on the Big Island and subsequently developed this Roadmap delineating the most prudent pathways for the development of a hydrogen energy infrastructure based on the geothermal resources on the Big Island of Hawaii through 2025. Results of this analysis indicate that hydrogen *is* a potential transportation fuel for the Big Island of Hawaii; however, a concerted effort by the state's leaders and policy makers will be necessary for hydrogen to become a significant transportation fuel before 2025. The primary conclusions of this report are as follows:

Conclusion 1: Hydrogen transportation fuel can compete with diesel by 2025 only if the electricity to produce hydrogen is available at less than $0.10/kWh and diesel costs exceed $5.30 per gallon. In order to make hydrogen from renewable energy, electricity must be produced from renewable resources and hydrogen must be produced by splitting water using an electrolyzer. Our analysis indicates that the two main cost drivers in this process are the cost of the electricity and the capital cost of the electrolyzer. Our conclusion is that, in order to compete with diesel prices greater than or equal to $5.30 per gallon, the cost of electricity to produce hydrogen must be less than $0.10/kWh.

Conclusion 2: All-electric battery/fuel cell hybrid powertrain vehicles are projected to be the hydrogen vehicles most likely to be available and cost-competitive with internal combustion engine vehicles by 2025. The hydrogen passenger vehicles likely to be available and cost-competitive with internal combustion engine (ICE) vehicles in 2025 will have hybrid electric/fuel cell powertrains. By combining batteries and fuel cells in a hybrid powertrain, vehicle designers can cost-effectively size the energy storage system and fuel cell without sacrificing vehicle performance. A hybrid electric/fuel cell powertrain will offer an extended operating range, which may especially be crucial in early phases of the deployment plan since a limited number of fueling stations may exist on the island.

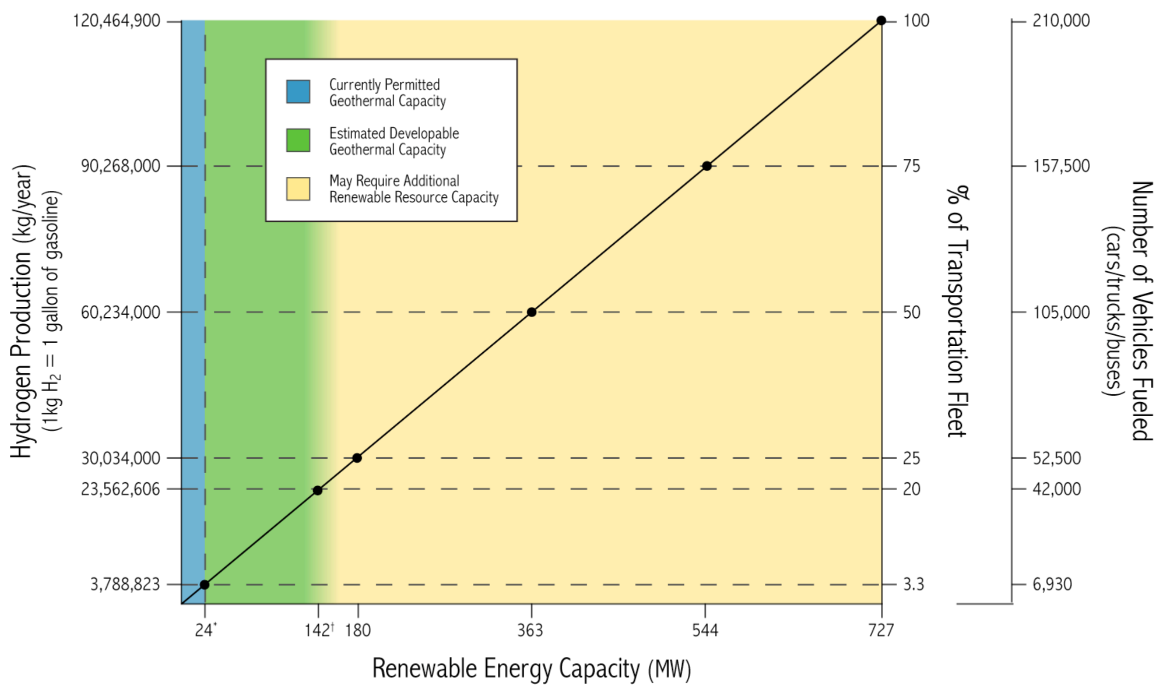
Conclusion 3: Conservative estimates indicate that using 24 MW of the currently permitted 60 MW of geothermal capacity can produce over 10,000 kg of hydrogen per day (approximately 3,800,000 kg/year) – enough to fuel approximately 3.3% of Big Island transportation needs. The analysis also examined the amount of hydrogen that could be made from the potential geothermal energy on the Big Island and whether this hydrogen could fuel some, most, or all of the transportation needs on the island. A number of significant conclusions were reached:

- Only 3.3% of the Big Island's transportation requirements could be served by the currently permitted geothermal power plant, and only if 24 MW of the geothermal capacity was utilized in producing hydrogen.
- 25% of the Big Island transportation needs would require approximately 180 MW of dedicated renewable energy capacity.
- 50% of the Big Island transportation needs would require approximately 363 MW of dedicated renewable energy capacity.
- 75% of the Big Island transportation needs would require approximately 544 MW of dedicated renewable energy capacity.

- 100% of the Big Island transportation needs would require approximately 727 MW of dedicated renewable energy capacity.

Thus, if the State of Hawaii wanted to run all of the Big Island's transportation system on renewably produced hydrogen, it would need to develop more than 700 MW of renewable energy (e.g., geothermal, solar, wind) on the island.

Hydrogen Production Potential on the Big Island



* 24 MW of 60 MW currently permitted geothermal capacity is utilized for H_2 production
† 142 MW of total 180 MW developable capacity is utilized for H_2 production

Conclusion 4: If the State of Hawaii chooses to pursue the renewable hydrogen transportation pathways outlined in this roadmap, an aggressive policy approach will be required. Concerted policy efforts will be necessary to achieve significant expansion of renewable energy on the Big Island, lower-cost electricity to produce a domestic transportation fuel, and incentives to purchase hydrogen-powered vehicles. In addition, these actions must be supported by robust, targeted education and outreach efforts. Major policy considerations must include the following:

- Siting, permitting, and land-use planning to accommodate geothermal and other renewable electricity development on a scale capable of producing hundreds of MWs of renewable electricity
- An electricity policy that will result in alternative fuel-supporting electricity pricing (i.e., a transportation tariff that makes wholesale electricity available to hydrogen producers at less than $0.10/kWh)
- An incentive strategy for early purchasers of hydrogen vehicles and fleet operators.

Based on detailed analysis that was conducted for this report, ***a prudent, three-phased approach to a geothermal hydrogen future for the Big Island is recommended:***

Phase I (2008-2012): Initial Prototype Test and Validation of Infrastructure. This phase will serve two purposes: 1) to allow the hydrogen experts at HNEI to purchase the first hydrogen vehicles and deploy the first hydrogen refueling operation on the Big Island at the Hawaii Volcanoes National Park and 2) to allow the performance and cost validation of these devices to determine whether the state should expand the hydrogen infrastructure on the Big Island. If a more ***progressive*** approach/scenario is followed by decision-makers, infrastructure expansion and increased hydrogen production could begin as early as this phase.

Phase II (2012-2020): Proof-of-Concept Demonstration Period. The second phase would allow for further expansion of hydrogen infrastructure, validation of costs, and evaluation of required policies. This expansion would probably take place by the addition of a refueling station in Kailua-Kona (or further increase in hydrogen production capacity at this station if a ***progressive*** approach/scenario has been followed in Phase I), followed later by one in Hilo, in concert with commitment by partners to the purchase of fleet vehicles. Allowing an eight-year proof-of-concept demonstration period would enable the State of Hawaii to consider the following:

- Consumer acceptance regarding the performance, operation, and cost of hydrogen vehicles
- Availability and prices of necessary hydrogen technology including electrolyzers, refueling stations, and hydrogen vehicles
- Availability and cost of renewable energy to produce a known quantity of hydrogen transportation fuel
- Volatile oil and diesel prices vis-á-vis the cost of policies to pursue the production of hydrogen via domestic renewable resources
- Analysis of costs required to produce renewable energy, expand hydrogen infrastructure, and promote vehicle acquisition sufficiently and progressively enough for hydrogen to become a significant transportation fuel on the Big Island

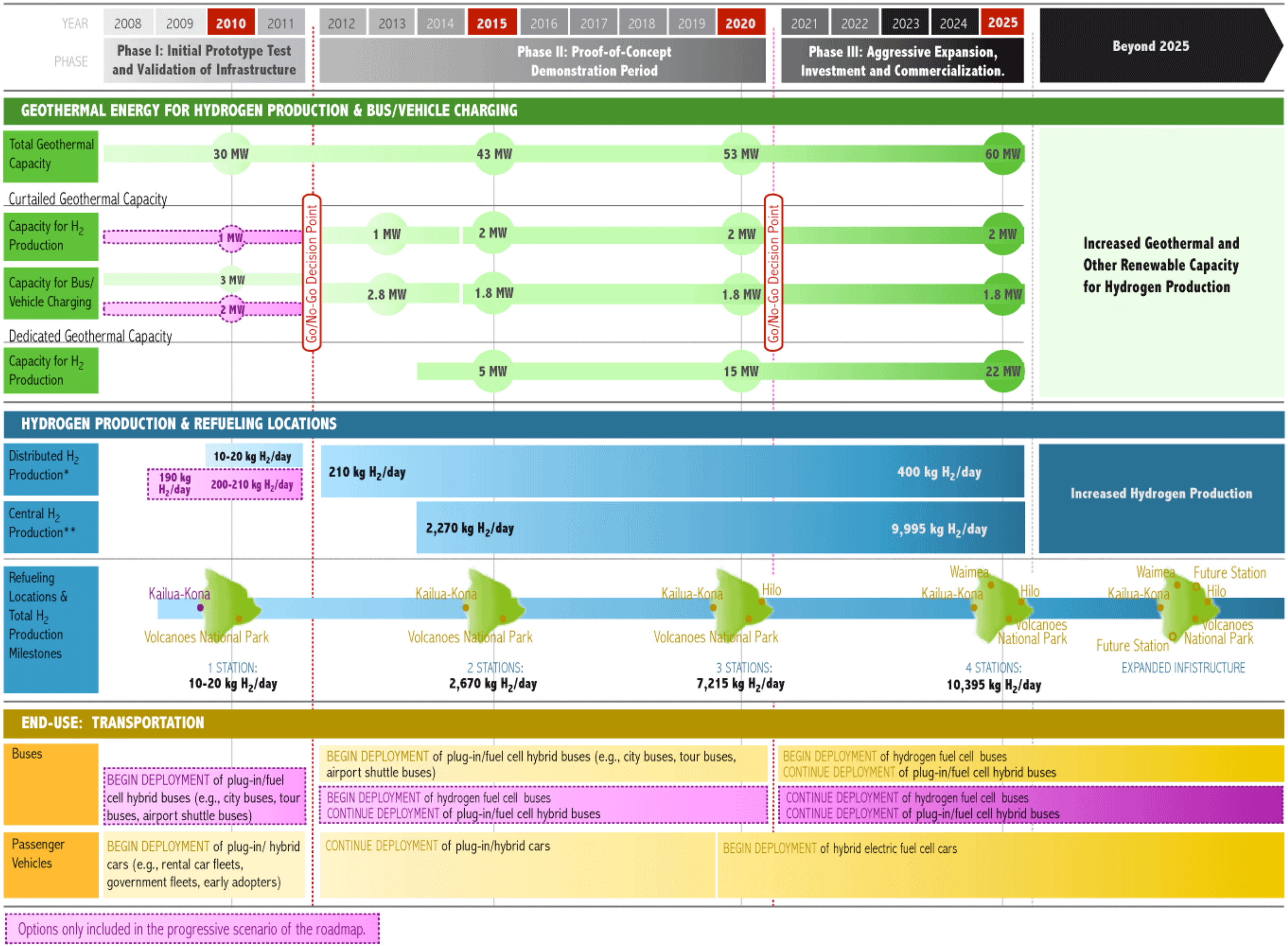
Phase III (2020 and beyond): Aggressive Expansion, Investment and Commercialization. If the results of the Phase II demonstration period indicate that hydrogen transportation investment by the State of Hawaii is prudent, then the policies to actualize such an investment will be implemented during this phase. This period will be marked by growth and development in several areas:

- Expansive development of geothermal and renewable electricity to produce the necessary hydrogen
- Increased refueling infrastructure (including a likely fourth location in Waimea) to accommodate an expanding presence of hydrogen vehicles

- Expansion of both commercial and personal hydrogen vehicle fleets
- Growth of the economic base, including the creation of jobs

The economic challenges resulting from dependence on foreign oil supplies can be ameliorated over time as renewable energy resources are increasingly utilized and a hydrogen economy is developed. The Big Island of Hawaii is poised to showcase the benefits of these changes as recommended policy changes and technology advancements are implemented.

Hawaii Geothermal Hydrogen Roadmap: Recommended Deployment Timeline



* In distributed hydrogen production, electricity is generated at PGV then sent over the grid and is produced onsite at the Kailua-Kona refueling station.

**In central hydrogen production, hydrogen is centrally produced at PGV then delivered to the refueling station via a tube trailer.

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1. Introduction

1.1 Purpose of the Roadmap

The State of Hawaii's extensive reliance on imported oil continues to leave its economy and citizens at risk. This predicament has become painfully obvious in 2008 as oil has spiked to near $150 per barrel,[8] driving electricity prices in Kauai to near $0.50 per kWh[9] and gasoline prices throughout the state to over $4.50 per gallon.[10] The state continues to rely on oil for more than 90% of its energy needs[11] and to generate 78% of its electricity needs;[12] in 2007, more than $7 billion[13] left the Hawaiian economy to pay for its energy imports. Increasing the utilization of Hawaii's vast renewable resources is key to decreasing the demand for imported oil and helping to stabilize the cost of electricity and transportation fuel. More information on the State of Hawaii's economy and energy use can be found in Appendix A.

To this end, the potential use of the state's vast geothermal resources to produce renewable hydrogen for transportation purposes has become a topic of increased interest and support. Hawaii's legislature passed SB 2957 CD1 in 2006,[14] which was subsequently signed by Governor Linda Lingle as Act 240. The Act established the *Hawaii Renewable Hydrogen Program* to encourage the achievement of a renewable hydrogen economy. The development of this Roadmap supports the renewable hydrogen goals of the State and the U.S. Department of Energy (DOE) by delineating the optimal initial pathways for the development of a hydrogen energy infrastructure through 2025 based on the geothermal resources of the Big Island of Hawaii.

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[8] Reuters. 2008. Oil prices briefly spike to record above $147 a barrel. *USA Today*, (July 11), http://www.usatoday.com/money/industries/energy/2008-07-11-oil-friday_N.htm.
[9] Kauai Islanc Utility Cooperative. 2008. Rate Data Sheet. September 20. http://www.kiuc.coop/pdf/ratedata_2008.pdf.
[10] American Automobile Association. Fuel Gauge Report. http://www.fuelgaugereport.com/HIavg.asp.
[11] State of Hawaii Department of Business, Economic Development & Tourism. 2007. Energy Resources Coordinator's 2007 Annual Report. http://hawaii.gov/dbedt/info/energy/publications/erc07.pdf.
[12] DBEDT. 2007 State of Hawaii Data Book, Table 17.06 (Electricity Generation by Source: 1990 – 2006).
[13] State of Hawaii. Governor Linda Lingle. *Administration Moves Forward on Five-Point Plan for Economic Action.* http://hawaii.gov/gov/economy
[14] State of Hawaii, The Senate, Twenty-Third Legislature, 2006. Senate Bill No. 2957 (CD1): Energy Self-sufficiency. http://www.capitol.hawaii.gov/session2006/bills/SB2957_CD1_.htm.

hydrogen on the Big Island and subsequently developed this Roadmap delineating the most prudent pathways for the development of a hydrogen energy infrastructure based on the geothermal resources on the Big Island of Hawaii through 2025. Beginning with a snapshot of the Island's current energy situation, this report presents a phased deployment plan to realize a sustainable transportation system for the Big Island.

1.2 Summary of Previous Work

This Roadmap builds on the findings of the June 2006 study[15] entitled *Economic Assessment of Hydrogen Generation for Transportation Applications using Geothermal Energy on the Island of Hawaii* prepared by Sentech, Inc. for DOE. The 2006 study investigated the utilization of curtailed geothermal energy (capacity that may otherwise be lost) for potential hydrogen production. Scenarios of likely curtailment of current and potential geothermal capacities were explored and resulting hydrogen generation was investigated. Results concluded that the use of *only* curtailed geothermal electricity generation for hydrogen production is insufficient to fuel a substantial portion of the Big Island's vehicle fleet.

1.3 Approach

As previous analysis has highlighted, the authors of this report acknowledge that the full potential for use of the Big Island's geothermal resources for the production of hydrogen far exceeds the use of only curtailed geothermal energy. Therefore, a range of geothermal capacities beyond curtailment was investigated in this study to demonstrate how much hydrogen production is attainable at certain capacity levels and what this means for the Island's transportation system. By considering a range of hydrogen production options, the state can align its vision of a hydrogen economy on the Big Island with the most appropriate level of geothermal development. A deployment plan has been constructed to provide guidance on developing a geothermal hydrogen infrastructure. For each phase of the deployment plan, a number of factors were investigated:

- The resource development required to achieve a given capacity for hydrogen production, including any plant expansion or new development
- The resulting hydrogen production pathways and quantities
- The anticipated percentage of passenger vehicles that can be fueled from the available hydrogen
- Other considerations (e.g., siting, permitting, new infrastructure needs, etc.)

This Roadmap relies on a customized, techno-economic Geothermal Hydrogen for Hawaii (GH3) modeling tool and many of the assumptions developed in the 2006 report. However, many technical data (e.g., hydrogen production system component costs and technology specifications) have been updated for use in this analysis. Additional factors (e.g., Hawaii-specific land, water, labor costs; by-product potential; and geothermal capacity and development) that must be considered to implement this Roadmap have also been researched and incorporated. Furthermore, the structure and calculation methodology of the GH3 model have been adjusted to use real-world technology data and projections as opposed to relying solely on theoretical modeling.

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[15] Liu, et al. 2006. *Economic Assessment of Hydrogen Generation for Transportation Applications Using Geothermal Energy on the Island of Hawaii.* Sentech, Inc., for the U.S. Department of Energy. June 1.

2. The Big Island's Current Energy Situation

2.1. Geothermal Resources/Capacity

The Big Island is larger than all the other Hawaiian Islands combined; it is the youngest formation in the Hawaiian archipelago and is still growing due to volcanic activity. Resource assessments have confirmed that the Big Island possesses a significant geothermal resource that has been used for the commercial production of electricity since mid-1993. With the state's commitment to renewable hydrogen, there is increased interest in the use of geothermal resources for the creation of a geothermal-based hydrogen economy on the Big Island. This study examines three different levels of geothermal energy for hydrogen production: 1) a curtailed portion of existing and near-term capacity on the island, 2) a dedicated portion of the up to 60 MW capacity that Puna Geothermal Venture (PGV) will be permitted to generate, and 3) the island's total "developable" geothermal recovery as defined by GeothermEx, Inc.[16] in its most recent geothermal resource assessment.

In 2005, GeothermEx identified seven geothermal resource areas on the Hawaiian Islands – five of which are on the Big Island (See Figure 2-1). However, only three out of the five resource locations on the Big Island were used by GeothermEx in its analysis of electrical generation potential: the lower Kilauea East Rift Zone (KERZ), Hualalai (northeast of Kailua-Kona), and Mauna Loa Southwest Rift Zone (near South Point).[17] Table 2-1 summarizes the general characteristics of each site.

Significantly, the lower KERZ is the site of the current Puna Geothermal Venture (PGV) plant. PGV is currently Hawaii's only commercial geothermal operation, generating clean, base-load power by utilizing the island's high-temperature resources. The PGV facility is located about 21 miles south of Hilo on 30 acres of a 500-acre plot. It currently has a generation capacity of 30 MW and is permitted to expand to up to 60 MW. While PGV has no immediate plans to increase its capacity to this amount, intentions to install an 8 MW, bottoming cycle unit currently exist. PGV was fully acquired by Ormat Technologies, Inc. in April 2004. Electricity generation from PGV saves Hawaii Electric Light Company (HELCO) over 144,000 barrels of annual imported oil while serving 30,000 residents and visitors of the Big Island.[18] PGV and HELCO have an existing contract that allows HELCO to curtail up to 8 MW of PGV's 30 MW generation capacity for 10 off-peak hours daily.[19]

The results of the GeothermEx study indicated that all the five sites on the Big Island result in an estimated total minimum capacity of 488 MW and a most likely capacity of 1,396 MW of geothermal resource potential. The lower KERZ region (shown in Figure 2-

[16] GeothermEx, Inc. 2005. *Assessment of Energy Reserves and Costs of Geothermal Resources in Hawaii*. For the State of Hawaii, Department of Business, Economic Development and Tourism. September 30.

[17] Per GeothermEx, "The Lower Kilauea Southwest Rift Zone and the Mauna Loa Northeast Rift Zone are not included in the forecast, because they are subject to the same constraint on east-to-west transmission as the Lower KERZ, which is assumed to have priority."

[18] Puna Geothermal Venture Hawaii. http://www.punageothermalventure.com.

[19] GeothermEx, Inc. 2005. *Assessment of Energy Reserves and Costs of Geothermal Resources in Hawaii*. For the State of Hawaii, Department of Business, Economic Development and Tourism. September 30.

2) alone has a minimum resource capacity of 181 MW and a likely capacity of 438 MW.[20]

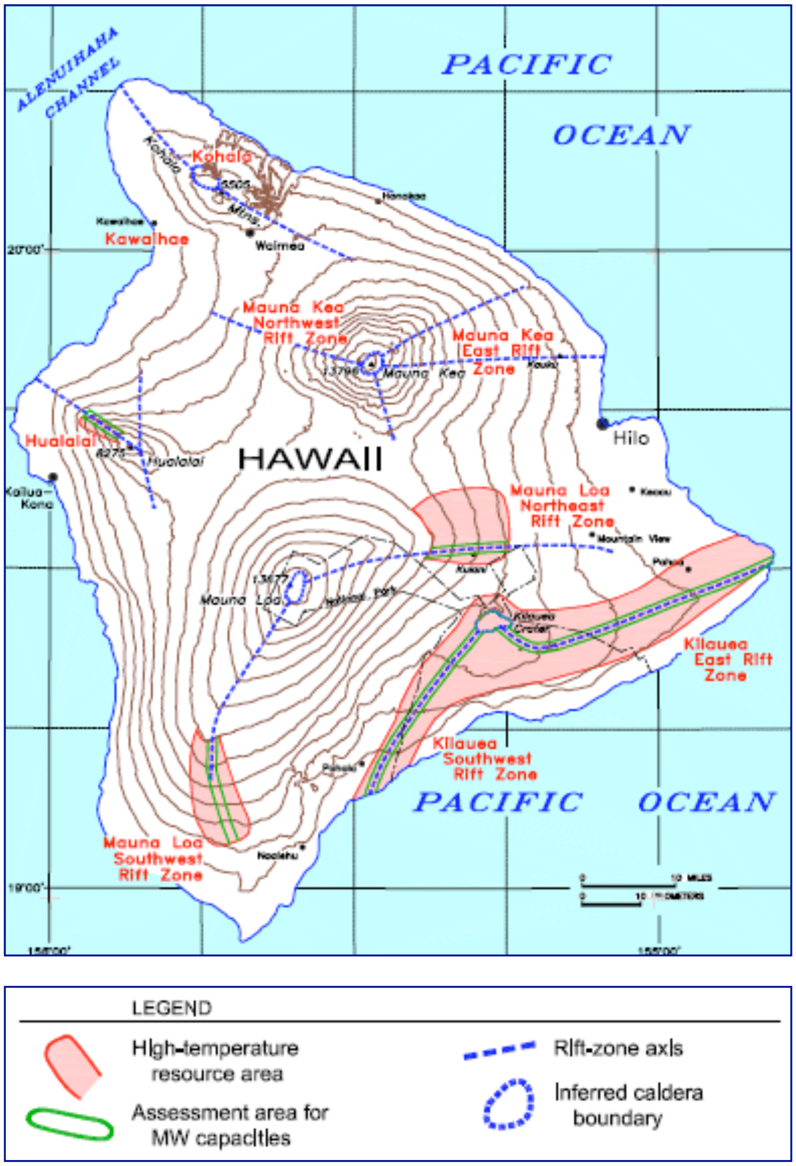

Figure 2-1. Geothermal Resource Areas on the Big Island.[21]

Table B-1 in Appendix B details the GeothermEx forecast of electrical generation capacity development for the three sites investigated through the year 2025. For the lower KERZ region alone, it is projected that a (base case) geothermal generation capacity of 82 MW is developable by 2025. Upside scenarios indicate that the lower

[20] *Ibid.*
[21] *Ibid.*

KERZ region could be developed up to 95 MW and that all three regions investigated could be developed up to 180 MW by 2025.

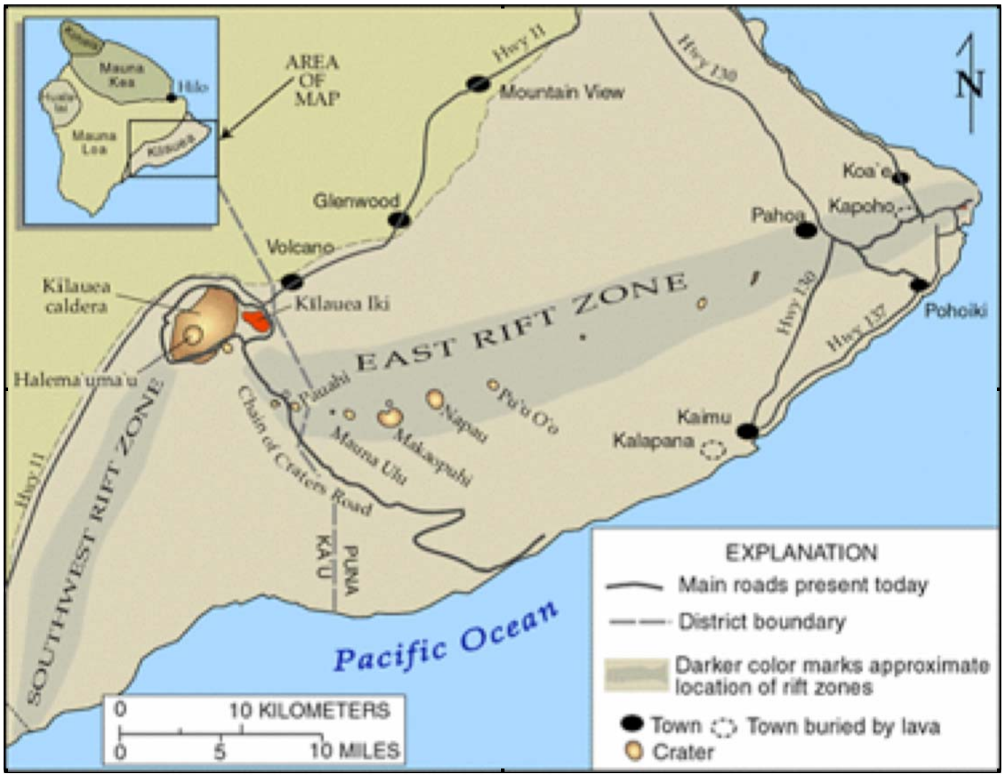

Figure 2-2. Kilauea East Rift Zone on the Big Island.

Table 2-1. Site Characteristics of developable geothermal resources (upside case) on the Big Island.22

CHARACTERISTICS	LOWER KERZ (PUNA)	HUALALAI	MAUNA LOA SOUTHWEST
Reservoir Temperature	580 to 650°F	257 to 500°F	400 to 650°F
Reservoir Area	5.75 to 11.50 sq. miles	2.5 to 5.0 sq. miles	5.75 to 11.50 sq. miles
Reservoir Thickness	6,350 feet	1,800 to 4,800 feet	2,400 to 5,400 feet
Mean Recovery	438 MW (non-excluded zone)	25 MW	125 MW
Recovery Efficiency	n/a	0.53%	0.69%
Developable Recovery by 2025	95 MW	25 MW	60 MW

[22] *Ibid.*

2.2 Electricity Generation

HELCO owns and operates 39% of the electricity generation on the Big Island.[23] The remainder of the island's electricity generation capacity is provided by independent power producers (IPPs). Annual peak demand growth on the Big Island is estimated at 2.3 % through 2010 and 1.5% from 2011 to 2025.[24] As shown in Figure 2-3, approximately 70% of the Big Island's electricity generation needs are supplied by oil while about 30% is generated by renewable resources.[25] Besides the approximately 18% geothermal electricity provided by PGV, the island's other renewable energy sources include two new wind farms located on the northernmost tip (Upolu Point) and the southernmost tip (South Point) of the island and two major hydroelectric plants near Hilo, on the eastern shore.

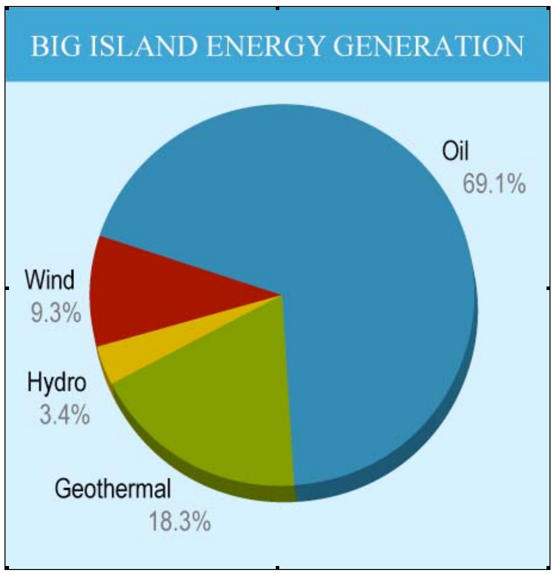

Figure 2-3. Big Island electricity generation resource breakdown based on kWh produced (2007).[26]

2.3 Energy Costs

The State of Hawaii's reliance on imported fossil fuels for almost 90%[27] of its primary energy needs has left Hawaii vulnerable to supply disruptions and uncertain energy prices. Currently, the state has the highest electricity rates in the nation, and gasoline prices are among the highest as well. Figure 2-4 compares U.S. mainland gasoline and residential electricity prices with those in the State of Hawaii.[28] Over the one-year period

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[23] HECO. 2007. Hawaiian Electric Company 2007 Corporate Sustainability Report. www.heco.com/vcmcontent/StaticFiles/pdf/Sustainable_AR_vflr.pdf.

[24] Hawaii Electric Light Company, Inc. 2007. Integrated Resource Plan 2007-2026. May 31.

[25] HECO. 2007. Hawaiian Electric Company 2007 Corporate Sustainability Report. www.heco.com/vcmcontent/StaticFiles/pdf/Sustainable_AR_vflr.pdf.

[26] *Ibid.*

[27] State of Hawaii Department of Business, Economic Development & Tourism. 2007. Energy Resources Coordinator's 2007 Annual Report. http://hawaii.gov/dbedt/info/energy/publications/erc07.pdf.

[28] American Automobile Association. Fuel Gauge Report. http://www.fuelgaugereport.com/HIavg.asp. (accessed August 15, 2008); and Energy Information Administration. Electricity: Current and Historical Monthly Retail Sales, Revenues, and Average Retail Price by Sector.

shown in Figure 2-3, Hawaii residents paid on average 13.4%, or \$0.39 per gallon, higher than the national average for gasoline. For electricity, Hawaii residents consistently paid more than double (in some cases, nearly triple) the national average. While overall U.S. residential electricity prices have remained within a \$0.03/kWh range since 1990, Hawaii residents have endured a staggering increase of nearly \$0.20/kWh over the same time period.[29] Furthermore, residential electricity rates on the Big Island are historically higher than most other islands with an average rate of over \$0.30/kWh.[30] Increased utilization of Hawaii's renewable resources may help to decrease the demand for imported oil and stabilize the cost of electricity in the longer term.

Figure 2-4. Relative prices of gasoline and residential electricity in the State of Hawaii and the U.S.

2.4 Constraints

Unique aspects of the Big Island present geothermal developers with several uncommon issues. The volcanic terrain alone has largely determined where residents have settled and how they commute across the island; this may indirectly affect the placement of hydrogen production sites and fuel transportation strategies. Geothermal development in the heart of the nation's only rain forest also raises environmental and cultural concerns.

2.4.1 Population Distribution and Trends

The Big Island is composed of nine districts with two concentrated population centers, one on the western side of the island and the other on the eastern side. More rapid population and energy demand growth are occurring on the western side, around Kailua-Kona, including several high-end resorts along the Kohala Coast. Meanwhile, the major power generators are located on the eastern side around Hilo and Pahoa (the location of the PGV facility). As a result, it has been estimated that 85% of generating capacity originates on the eastern side of the island, while 60% of demand is on the western side

[29] *Ibid.*
[30] Hawaiian Electric Company. *Average Electric Rates for Hawaiian Electric Co., Maui Electric Co. and Hawaii Electric Light Co.* (Does not include energy cost adjustment clause.)

of the island.[31] Latest census reports show that population increases on the Big Island are outpacing the rest of the state, with a 14.7% increase since 2000. If current trends continue, the total population for this decade is expected to grow by 37,500 residents.[32] Likewise, transportation fuel demand (and, consequently, hydrogen demand) is expected to grow in certain regions as new residents purchase and register new vehicles. For more detailed information on the island's population trends, see Appendix C.

2.4.2. Transportation System and Trends

Due to the unique volcanic terrain of the Big Island, the Hawaii Belt Road encircles the island and must accommodate much of the island's traffic since cross-island routes (e.g., Saddle Road) are not suitable for everyday commutes. Vehicle density is the highest in the populated areas of Hilo and Kailua-Kona. Roughly 175,000 motor vehicles are currently registered on the island resulting in a demand of over 95 million gallons of "highway use" fuel in 2006 -- the second highest county demand behind Oahu. Passenger vehicles alone account for over 135,000 vehicles on the Big Island (Figure 2-5).

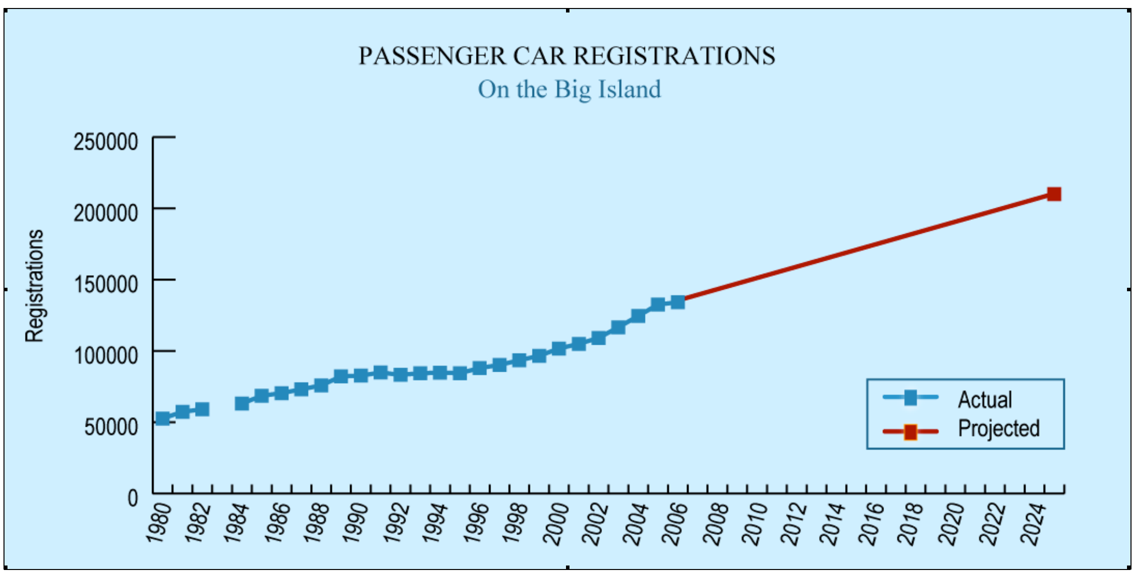

Figure 2-5. Trend of passenger car registrations on the Big Island.[33]

In addition to motor vehicles, the Big Island operates a mass transit system of approximately 20 "Hele-On" buses with service in Kailua-Kona and Hilo areas and all

[31] Hawaiian Electric Company, Inc. and Sentech, Inc. 2004. HELCO Operational Issues Bulk Energy Storage. For the U.S. Department of Energy and the State of Hawaii, Department of Business, Economic Development and Tourism. October.

[32] Hawaii Health Guide. 2007. Despite Earthquakes and Lava and Vog, Census Shows Big Island Population Increasing Fastest in State of Hawaii.
http://www.hawaiihealthguide.com/healthtalk/display.htm?id=549

[33] Department of Research and Development. County of Hawaii Data Book. Table 14.6 – Passenger Vehicles Registered, Hawaii County: 1980 to 2006.

major towns in between.[34] Private shuttle and tour bus companies also have a strong presence on the Big Island, providing airport shuttle service, scenic tours of Volcanoes National Park, and Grand Circle tours. For more detailed information about the island's transportation system and trends, see Appendix D.

2.4.3. Cultural and Environmental Concerns

When planning or deploying potential geothermal projects on the Big Island, the culture, traditions, and beliefs of native Hawaiians must be considered. While development within Hawaii can be controversial, geothermal development on the Big Island has historically proven to be a culturally sensitive issue.[35] Other concerns related to geothermal development may include such environmental considerations as air emissions, liquid effluent, noise, visual aesthetics, and physical disturbances during construction. Its impact on the Big Island's tropical rain forest has also raised environmentalists' concerns regarding the protection of Hawaii's endemic flora and fauna. For these reasons, extensive education and outreach must be included in planning for any expanded geothermal development.

2.5 Existing Policies

With regard to renewable energy policies, Hawaii is a progressive state with renewable portfolio standards, alternative fuels standards, and generous incentives available to businesses that promote increased renewable energy use and/or decreased oil imports. For example, the $10 million Hydrogen Investment Capital Special Fund provides seed capital for the private sector and cost share for Federal projects for research, development, testing, and implementation of hydrogen activities.[36] A business investment tax credit has also been made available to entrepreneurs seeking funding for high-technology business investments, including qualified hydrogen-related ventures.[37]

The State of Hawaii also has a Renewable Portfolio Standard (RPS) which requires an escalating percentage of electricity sales from renewable resources and electrical energy savings measures -- 10% in 2010, 15% in 2015, and 20% in 2020. Including electrical energy savings from renewable displacement (e.g., solar water heating) and energy efficiency technologies, HELCO reported that it had achieved an RPS percentage of 39.8% at the close of 2007.[38] For more information about these and other policies and incentives, see Appendix E.

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[34] County of Hawaii Department of Research and Development. County of Hawaii Data Book. Table 14.12 – Hele-On Bus Service for Hawaii County: 1985 to 1999.
[35] Sacred Land Film Project. http://www.sacredland.org/historical_sites_pages/wao_kele.html.
[36] Hydrogen Energy Plan and Fund. Hawaii Incentives and Laws. Alternative Fuels & Advanced Vehicles Data Center. Office of Energy Efficiency and Renewable Energy. U.S. Department of Energy.
[37] Business Investment Tax Credit. Hawaii Incentives and Laws. Alternative Fuels & Advanced Vehicles Data Center. Office of Energy Efficiency and Renewable Energy. U.S. Department of Energy.
[38] HECO, HELCO, and MECO. 2007. 2007 Renewable Portfolio Standard Status Report. http://www.heco.com/vcmcontent/StaticFiles/pdf/2007_RPs_Report-to-PUC_draft_080530_Final.pdf.

3. Roadmap

Current economic, environmental, and societal conditions on both a local and global scale have raised the level of interest in greater use of geothermal energy for the creation of a renewable hydrogen economy for the Big Island of Hawaii. This Roadmap aims to present existing and future opportunities for utilizing the significant geothermal resource base and other renewables on the Big Island.

3.1 Analyses Supporting Roadmap Development

As previously mentioned, an enhanced version of the GH3 model[39] was tailored to be more specific to Hawaii for use in this Roadmap and deployment plan for the Big Island. This tool was specifically used to accomplish the following analytical tasks:

- To estimate hydrogen infrastructure component costs, life-cycle hydrogen costs (on a dollars per kilogram of hydrogen basis), and relative contributions of cost components for a kilogram of hydrogen produced
- To run sensitivity analyses on different factors (such as capital costs, geothermal resource quantity, financial incentives, etc.) to determine which had the greatest effect on overall costs
- To project the number of vehicles capable of being fueled in a given deployment strategy and the gallons of diesel fuel displaced by that deployment strategy

Electricity rates proved to be a major contributor to the overall hydrogen cost. Based on efficiencies of 3.5 miles/gallon[40] for diesel buses and 5.28 miles/kg H_2[41] for fuel cell buses, the cost of hydrogen would have to be less than or equal to \$8.00/kg H_2 for a plug-in hybrid electric fuel cell bus to have a similar \$/mile value as that of a diesel bus at \$5.30/gallon diesel. Therefore, an electricity cost of slightly less than \$0.10/kWh would be needed to produce and deliver central gaseous hydrogen that is cost-competitive (Figure 3-1). Similarly, distributed gaseous production of hydrogen would require an electricity cost of \$0.11/kWh to produce hydrogen utilizing the grid, as indicated in the initial stages of this Roadmap. Figure 3-2 demonstrates the projected cost of hydrogen between now and 2025. Detailed calculations and results from the analyses are presented in Appendix F.

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[39] Liu, et al. 2006. *Economic Assessment of Hydrogen Generation for Transportation Applications Using Geothermal Energy on the Island of Hawaii*. Sentech, Inc., for the U.S. Department of Energy. June 1.
[40] Green Car Congress (http://www.greencarcongress.com/2005/01/gasolineelectri.html) and BAE Systems (http://www.baesystems.com/Newsroom/NewsReleases/2001/press_261020013.html).
[41] As these values differ according to many factors, such as driving conditions, a conservative assumption based on various fleet demonstration results and DOE estimates was made.

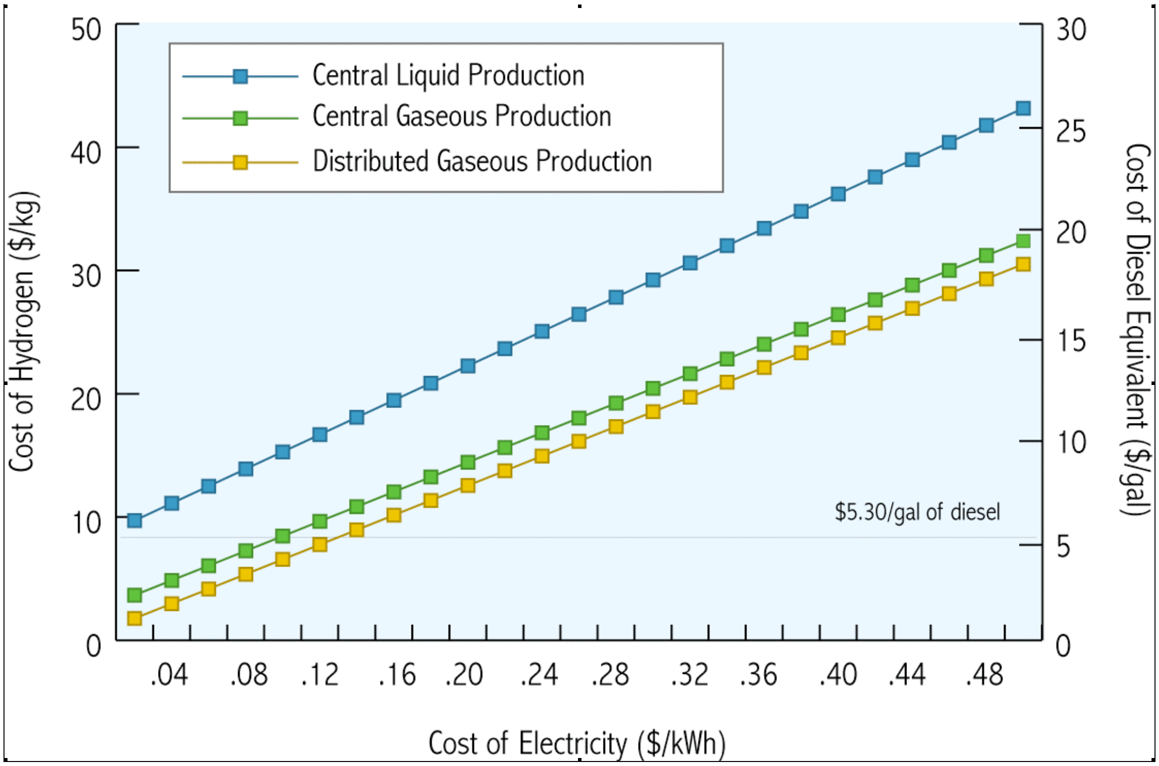

Figure 3-1: The effect of electricity cost on hydrogen cost.

With equal electricity rates, it is seen that distributed gaseous production has the lowest $/kg of the three cases. This is because there are no delivery costs associated with distributed production. However, due to transmission and distribution (T&D) costs, the electricity rates for distributed production will be higher than those for central production. Central liquid production includes extra capital costs and electricity consumption (as well as delivery costs), which is why the costs increase at a faster rate than those of distributed gaseous or central gaseous. Based on quotes from the utilities, it is likely that electricity for distributed production could be obtained at $0.26/kWh[42] and the rate for the two central production cases could be $0.15/kWh.[43] At these electricity rates, central gaseous production is the most economical followed by distributed production.

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[42] HELCO "Schedule P – Large Power Use Business" rate; http://www.heco.com.
[43] Personal communication with Michael Kaleikini, PGV Plant Manager.

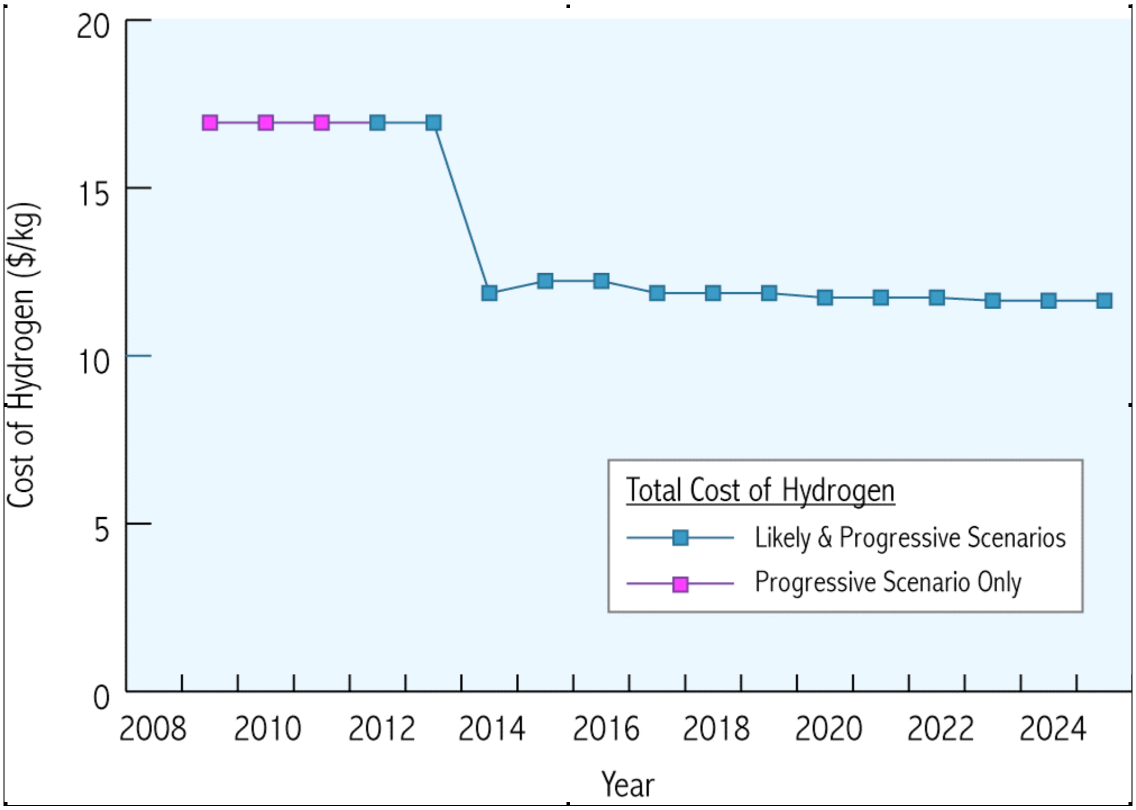

Figure 3-2: Anticipated cost of hydrogen from initial deployment through 2025.

Figure 3-2 shows the estimated cost of hydrogen for a given year. The initial costs are based on distributed gaseous production with an electricity rate of $0.26/kWh. The sharp descent in year 2014 marks the first 5 MW addition of dedicated geothermal electricity capacity for central gaseous hydrogen production. The subsequent, minor rise in 2015 can be attributed to increased distributed gaseous production from 190 kg/day to 380kg/day. Because this hydrogen is more expensive to produce, it slightly raises the overall hydrogen cost/kg. Dedicated geothermal capacity additions occur in 2017, 2020, and 2023, and it can be seen in the figure that each addition causes a decrease in overall hydrogen price. The reason for these drops is economies of scale coupled with a lower production price for central gaseous hydrogen production (at the given $/kWh).

3.2 Primary End-Use Application

Several end-use applications for hydrogen on the Big Island were initially explored for this Roadmap. Stationary fuels cells were first considered for peak-shaving applications, but they were found to only be appropriate for emergency power or non-grid connected applications because of the high energy losses during conversion. Calculations show a nearly 50% of energy loss when converting electricity to hydrogen and back to electricity.[44]

[44] This calculation uses 52.3 kWh/kg of hydrogen and an 85% efficiency value for stationary fuel cells with cogeneration. *Sources:* Fuel Cells 2000 (http://www.fuelcells.org/basics/benefits.html) and Plug Power

Transportation applications appeared to be the most economically viable pathway for this Roadmap, presenting a sufficient market size and higher level of visibility while effectively utilizing the geothermal resources on the Big Island. This market also presents logical steps for maturation, beginning with demonstrations, transitioning to small fleets, and then potentially entering the private vehicle market.

A recognized strategy for near-term market entry of hydrogen-fueled vehicles is targeting fleet operators (e.g., municipal bus fleets, government fleets, corporate fleets, and airport shuttles). By introducing these vehicles in fleets, consumer acceptance increases due to high visibility/awareness and demonstrations of their technological viability. Hydrogen vehicles have been demonstrated in the State of Hawaii. Hawaii's first fuel cell vehicle in operation was a 30-foot crew shuttle bus at Hickam Air Force Base delivered in 2004. This was shortly followed by the state's first hydrogen generation and dispensing station on the base in 2006.[45] The partnership between HNEI and Hawaii Volcanoes National Park to introduce a small fleet of hydrogen plug-in shuttle buses at the Park in the near future will serve as the "seed" of the deployment pathway suggested in this Roadmap.[46]

The hydrogen vehicles likely to be available and cost-competitive with internal combustion engine (ICE) vehicles by 2025 will have a hybrid electric fuel cell powertrain. By combining batteries and fuel cells in a hybrid powertrain, vehicle designers can cost effectively size the energy storage system and fuel cell without sacrificing vehicle performance. A hybrid electric fuel cell powertrain will offer an extended operating range, which may be crucial in especially early phases of the deployment plan as a limited number of fueling stations may exist on the island. Since the passenger vehicle market will likely develop in the later phases of this Roadmap, rental car fleets may be a logical target for these vehicles. Aside from fleets, as with any new technology, there will be early adopters – sustainability-minded individuals who are enthusiastic about being among the first to evaluate these new developments and willing to pay for the experience.

Since a thriving hydrogen economy on the Big Island is a long term goal, alternative technologies, such the "plug-in" versions of cars and buses, are likely to be complementary or transitional technologies. Vehicles designed in this format would provide greater flexibility of fuel choices since the vehicle could be charged with curtailed geothermal electricity during off-peak hours. In the initial years of the suggested Roadmap timeline, plug-in versions of gasoline ICE cars may be used by early adopters or car rental agency fleets, which will reduce their petroleum use and serve as the initial steps towards a sustainable transportation future. Purchase costs for plug-in

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presentation on International Stationary Fuel Cell Demonstration (http://www1.eere.energy.gov/hydrogenandfuelcells/pdfs/new_fc_vogel_plugpower.pdf).

[45] DOE Hydrogen, Fuel Cells and Infrastructure Technologies Program; Technology Validation - Hickam Air Force Base; http://www.eere.energy.gov/hydrogenadnfuelcells/tech_validation/hickam_airforce.html.

[46] R. Rocheleau and M. Ewan. 2008. Hawaii Hydrogen Center for Development and Deployment of Distributed Energy Systems. DOE 2008 Annual Merit Review Presentation. June 10. http://www.hydrogen.energy.gov/pdfs/review08/tv_8_rocheleau.pdf.

hybrid autos are expected to be $40K in 2010 and $27K in 2020-2025.[47] Operating cost is highly dependent on liquid fuel and electricity prices.

The dual powertrain would likely be designed with a small fuel cell that operates at peak performance in sustained mode while a battery compensates for peak and fluctuating loads. The plug-in hybrid electric fuel cell version of the Chevrolet Volt is anticipated for production within the next decade and may be a likely candidate for personal transportation on the Big Island by 2025. An estimated purchase cost for this vehicle has not yet been released.[48]

Plug-in/fuel cell hybrid buses, on the other hand, could offer fuel flexibility while the hydrogen infrastructure is developing, as is described further in section 3.4. Purchase costs for these buses are currently in the $2.2M range.[49] Some manufacturers have a near-term target of $1.5M and expect the costs to go down to approximately $800K-$900K in the next four years.[50]

3.3 Hydrogen Potential for Transportation Sector

The amount of hydrogen production required to fuel the Big Island's transportation needs was calculated, with hydrogen-fueled vehicles comprising 0-100% of the entire fleet. Figure 3-3 compares the megawatts of electricity necessary to meet certain percentages of the Big Island's transportation fuel needs. Although fuel cell vehicles currently have greater fuel efficiency than their petroleum counterparts, this analysis is based on 1 kg of hydrogen replacing 1 gallon of petroleum fuel. The total fuel use is based on the 2025 projection that was calculated based on the historical fuel use trends of the island (see Figure F-4 in Appendix F).

[47] Oak Ridge National Laboratory, Sentech, Inc., General Electric, and Electric Power Research Institute. To be released. Phase 1, Task 4 - Interim Report – DRAFT. (The vehicle cost numbers are in 2008 dollars.)
[48] "GM Says Goodbye to Oil and Hello to Hydrogen." GM-Volt website. June 11, 2008.
[49] Personal communication with Leslie Eudy of the National Renewable Energy Laboratory (NREL).
[50] Personal Communication with Dale Hill of Proterra.

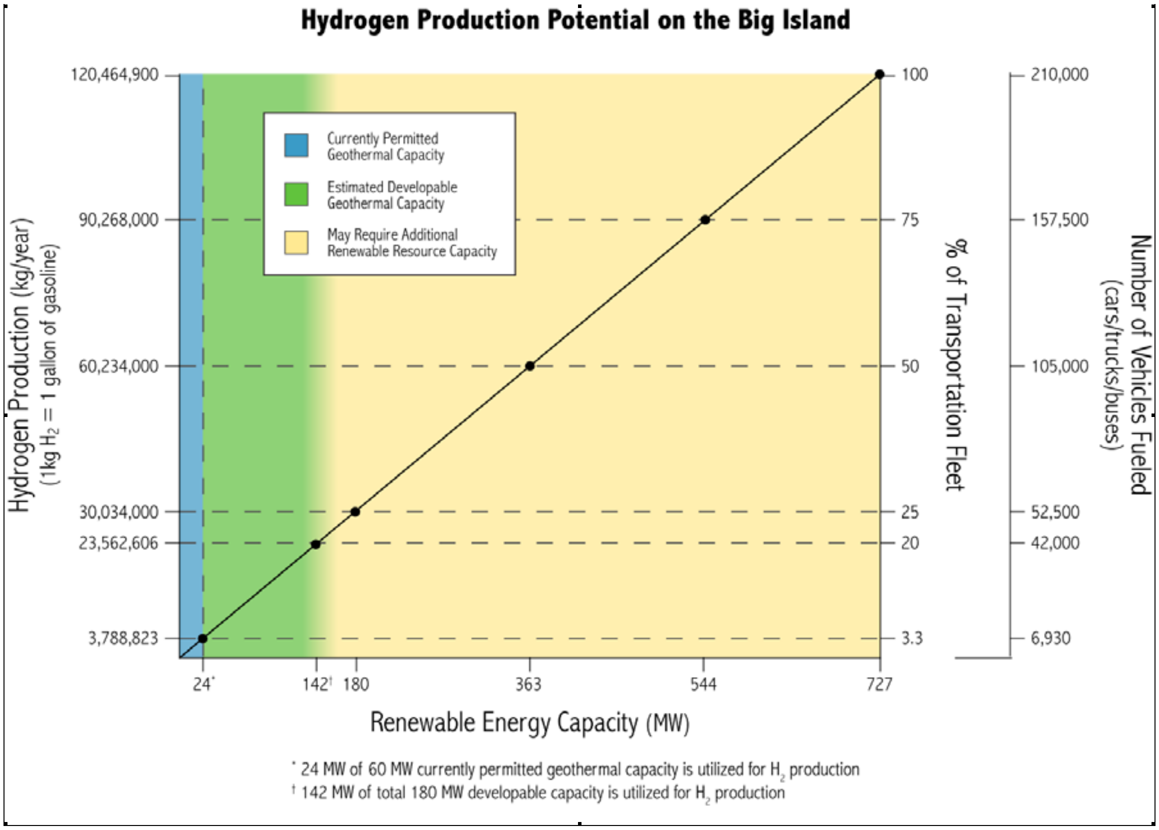

Figure 3-3: Capacity required to meet the Big Island's transportation needs. *This figure indicates that, at best, current developable geothermal capacity could only provide enough hydrogen to provide ~20% of the Big Island transportation needs. More than 700 MW of renewable electricity to produce hydrogen will be required if hydrogen is to provide 100% of the Big Island's transportation needs.*

As shown in Figure 3-3, only **3.3%** of the Big Island's transportation needs can be met if 24 MW of geothermal capacity was utilized (assuming PGV expands to 60 MW of capacity).[51] Roughly **20%** of the projected transportation needs could potentially be fueled in the unlikely case that the entire island's "developable" recovery (180 MW, see Appendix B) was utilized and 142 MW of this capacity was dedicated to hydrogen production. Beyond this, other sources of renewable energy (e.g., wind, solar) or advancements in geothermal recovery techniques would likely be needed to supplement additional hydrogen fuel production. To learn more about alternative sources of renewable energy available on the Big Island, see Appendix G.

The renewable energy capacities required to fuel other significant portions of the Big Island's transportation needs with hydrogen are as follows:

[51] As detailed in further sections of this report, of the total 24 MW, 22 MW is dedicated hydrogen production, with hydrogen being produced 24 hrs/day and 2 MW is hydrogen produced from curtailed geothermal capacity (10 hrs/day). Yearly hydrogen production for 24 MW, indicated in Figure 3-3, reflects these considerations. All other yearly hydrogen production numbers in Figure 3-3 are based on the assumption of 24 hrs/day hydrogen production.

- Only 3.3% of the Big Island's transportation requirements could be served from the currently permitted geothermal power plant, and only if 24 MW of the geothermal capacity was utilized to producing hydrogen.
- 25% of the Big Island transportation needs would require approximately 180 MW of dedicated renewable energy capacity.
- 50% of the Big Island transportation needs would require approximately 363 MW of dedicated renewable energy capacity.
- 75% of the Big Island transportation needs would require approximately 544 MW of dedicated renewable energy capacity.
- 100% of the Big Island transportation needs would require approximately 727 MW of dedicated renewable energy capacity.[52]

This would be followed by *dedicated* hydrogen production, which is envisioned as geothermal capacity being fed into electrolyzers located at the geothermal facility on a 24-hour basis to generate hydrogen.

3.4 Roadmap Deployment Phases

The results of the analysis were indicative of the renewable energy quantities, hydrogen production and delivery infrastructure, and hydrogen vehicle acquisition that would be required to have a significant impact on the Big Island's transportation system and to subsequently reduce the State of Hawaii's need to rely on oil as a transportation fuel. This analysis pointed to indications of ***what*** is needed, but not ***how*** to get there.

Recommendations of ***how*** to get there were developed in a phased approach – a roadmap that describes what will be required over the next fifteen years to achieve a significant impact. This roadmap outlines a ***prudent approach to a geothermal hydrogen future for the Big Island and includes three phases*** that are detailed in the following sections.

The Roadmap phases described below illustrate a possible, or likely, pathway for a geothermal hydrogen infrastructure for transportation on the Big Island of Hawaii. The State, private sector investors, and other partners will determine the pace at which this pathway will be traveled. Throughout the descriptions of the phases and on the related timeline sections shown, a more ***progressive*** approach/scenario and its results are explained, to provide decision makers with a view of how infrastructure development may start earlier and what possibilities may exist if they commit to this more capital intensive and assertive approach. The phase descriptions state the objectives, provide some more detail on the approach taken, and then focus on specific components of the timeline to portray how resource utilization, infrastructure development, and end-use may be carried out.

[52] Required capacities calculated by extrapolating Big Island fuel usage trend (DBEDT. 2007. 2007 State of Hawaii Databook. Table 18.17.) to 2025, and determining equivalent hydrogen volume.

3.4.1 *Phase I (2008 – 2012): Initial Prototype Test and Validation of Infrastructure*

Objectives. This initial phase will serve two main purposes: 1) to allow the hydrogen experts at HNEI to purchase the first hydrogen vehicles and deploy the first hydrogen refueling operation on the Big Island at the Hawaii Volcanoes National Park (HAVO) and 2) to allow validation of technology performance and costs of these vehicles and infrastructure components to determine whether the State of Hawaii should expand hydrogen infrastructure on the Big Island. If a more ***progressive*** approach/scenario is followed by decision-makers, increased infrastructure and hydrogen production could begin as early as this phase.

Approach. The HNEI, located at the University of Hawaii, has ongoing efforts to install the initial hydrogen fueling infrastructure on the Big Island at HAVO with funding provided from the U.S. Department of Interior (DOI) and DOE, in conjunction with the "Climate Friendly Parks" initiative by the National Park Service (NPS). Federal financial support will be matched with state cost-sharing from the State of Hawaii through the Hydrogen Investment Capital Special Fund. This initial infrastructure development will be supported by HAVO Visitor Center staff and park ranger interpreters on shuttle buses. They will educate the public on these advanced technologies and engage the millions of visitors[53] to the park, cultivating interest and visibility for the development of the Big Island's hydrogen infrastructure.[54]

Resource Utilization. At this initial timeframe, the island's existing geothermal facility, PGV, will be operating at 30 MW capacity.

- ***Geothermal Capacity for Demonstration Site.*** Approximately 1,700 kWh/day of geothermal electricity will be used at the HAVO demonstration site for both hydrogen generation and bus charging. Of this total, 700-1,400 kWh will be utilized to produce hydrogen onsite via electrolyzers located there and 300-1,000 kWh will be available for charging the buses on the demonstration site.
- ***Curtailed Geothermal Capacity.*** In addition to the HAVO demonstration, the PGV facility's curtailment rate of 10% during 10 off-peak hours will provide 3 MW of curtailed geothermal capacity which may be used for passenger vehicle charging on the Island during off-peak hours. If a more ***progressive*** approach is followed, 1 MW of this total 3 MW curtailed capacity may be used for hydrogen production, while the remaining 2 MW would be available for vehicle charging.

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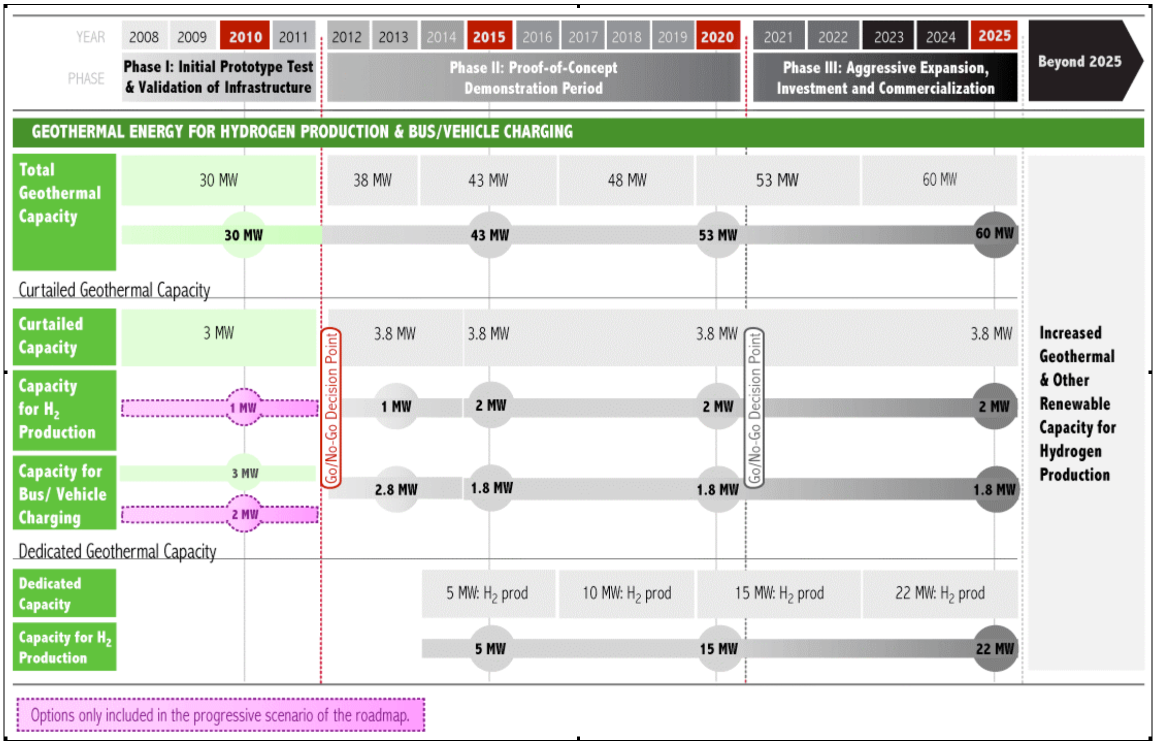
[53] Close to 1.5 million people visited HAVO in 2007. *Source:* DBEDT 2007 Data Book, Table 7.44: "National Parks: 1992 to 2007."

[54] R. Rocheleau and M. Ewan. 2008. Hawaii Hydrogen Center for Development and Deployment of Distributed Energy Systems. DOE Hydrogen Program Annual Merit Review presentation. July 10.

Key Milestones.

In 2010, **700-1,400 kWh** geothermal capacity will be available for hydrogen production at the HAVO site.

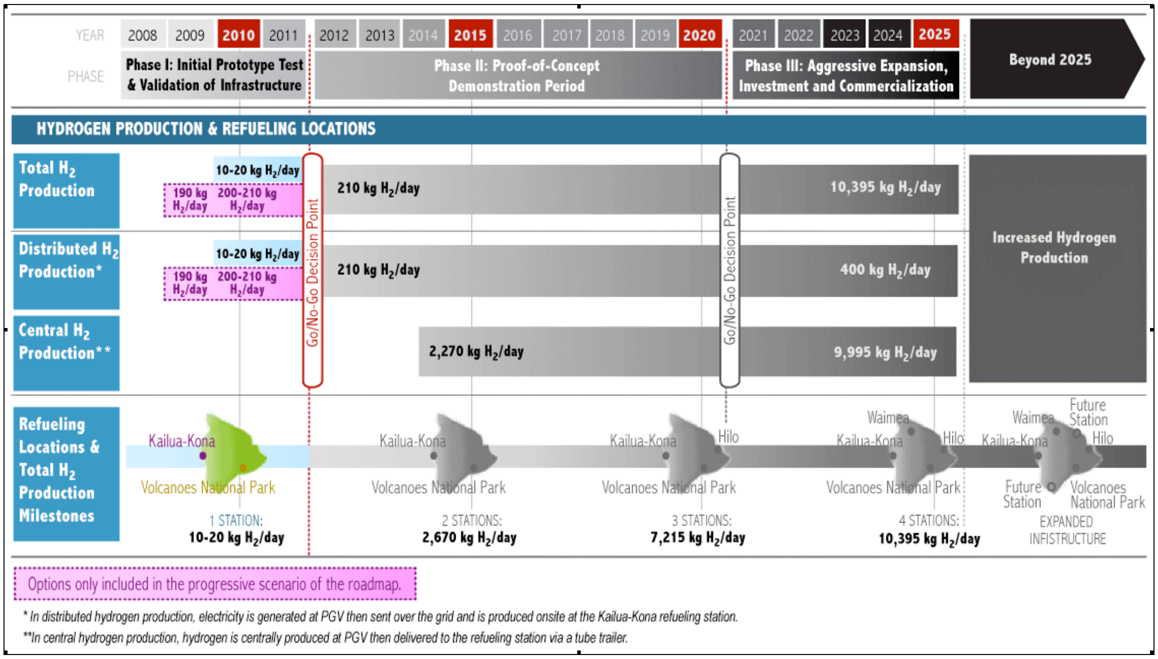
Additionally, **300-1,000 kWh** geothermal capacity will be available for bus charging at the HAVO site and **3 MW** curtailed geothermal capacity (**2 MW** if a **progressive** approach is followed) will be available on the Island for vehicle charging (during 10 off-peak hours).



Infrastructure. Hydrogen production (at a rate of 10-20 kg/day) and refueling will be begin in 2010 to be carried out at the Department of Defense's (DOD) Kilauea Military Camp located on HAVO grounds, making use of the geothermal electricity sent over the grid. If a more ***progressive*** approach is followed, hydrogen production may start earlier, in 2009, with 1 MW (of the 3 MW curtailed) geothermal electricity being sent over the grid to Kailua-Kona area, to generate 190 kg H_2/day onsite at the National Energy Laboratory of Hawaii Authority (NELHA) or the Kona airport.

Key Milestones.

In 2010, total hydrogen produced will reach **10-20 kg H_2/day**, available at **HAVO**. If a more progressive approach is followed, **190 kg H_2/day** will also be available at **Kailua-Kona** at this point, providing a **total of 200-210 kg H_2/day**.



End-use. This phase will include procurement of two to five battery-dominant, hydrogen ICE plug-in hybrid shuttle buses[55] by HNEI, each with 24-person capacity. The maximum energy available on these buses will be 129 kWh, with 54 kWh available from the battery (200 ampere hours and 80 percent discharge rate) and 75 kWh available from onboard hydrogen storage (at 5,000 psi pressure, holding 5 kg H_2). These buses will have a duty cycle of at least 8 hr/day, 7 day/week operation and will have two routes (see Figure 3-4): around Crater Rim Drive (two to five trips per day) and down the Chain of Craters Road and back (one to three trips per day). Thus, they will transport 72-120 passengers per bus per day.[56] Additionally, plug-in hybrid passenger vehicles (of rental car fleets, government fleets or early adopters) may be charged throughout the island during 10 off-peak hours, utilizing the 3 MW curtailed geothermal electricity available. If a more ***progressive*** approach is followed, a transportation partnership between vehicle OEMs, rental car and airport fleets and the state may be formed to introduce a small fleet (possibly consisting of 3-10 vehicles) of plug-in fuel cell hybrid buses to make use of both the hydrogen introduced earlier in the Kailua-Kona area and charging through the available curtailed geothermal capacity.

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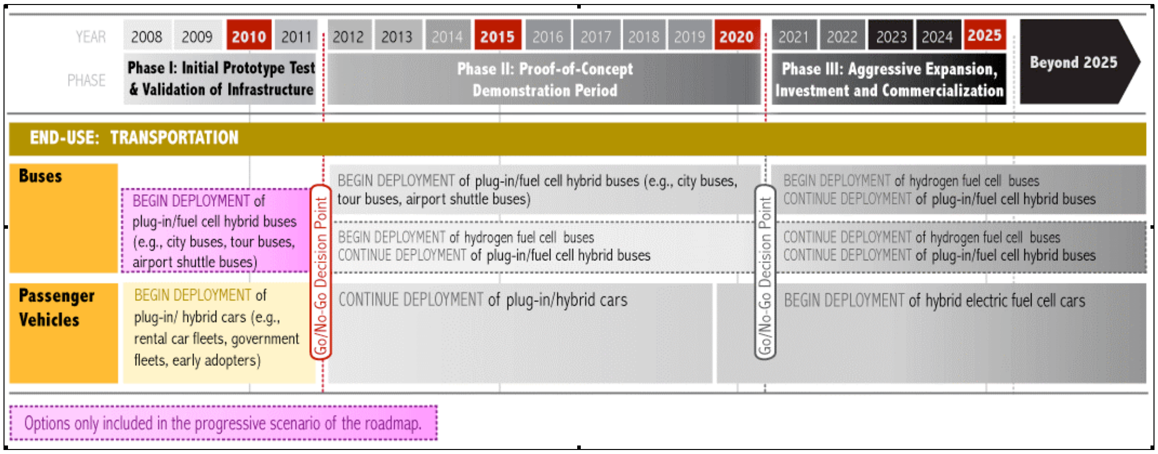
[55] Due to the high sulfur levels experienced at the HAVO site and the susceptibility of fuel cells to sulfur, hydrogen ICE buses, instead of hydrogen fuel cell buses, have been planned for the HAVO demonstration. Fuel cell buses will play a role in the overall Roadmap, but OEM partners need to take the necessary precautions (such as installing sulfur traps), recognizing the unique characteristics of the Big Island.

[56] Personal communication with Mitch Ewan, Hydrogen Systems Program Manager at HNEI.

Decision Point. By mid-2011, based on cost and performance of the technology, a recommendation may be made to the State of Hawaii regarding the feasibility of Phase II hydrogen infrastructure expansion.

Key Milestones.

In 2010, **up to five** battery-dominant, **hydrogen ICE plug-in hybrid shuttle buses** will be operating at the **HAVO** demonstration site. Additionally, plug-in hybrid passenger vehicles will make use of off-peak curtailed geothermal electricity for charging. If a more **progressive** approach is used, **plug-in fuel cell hybrid bus fleets** may also operate in the Kailua-Kona area.



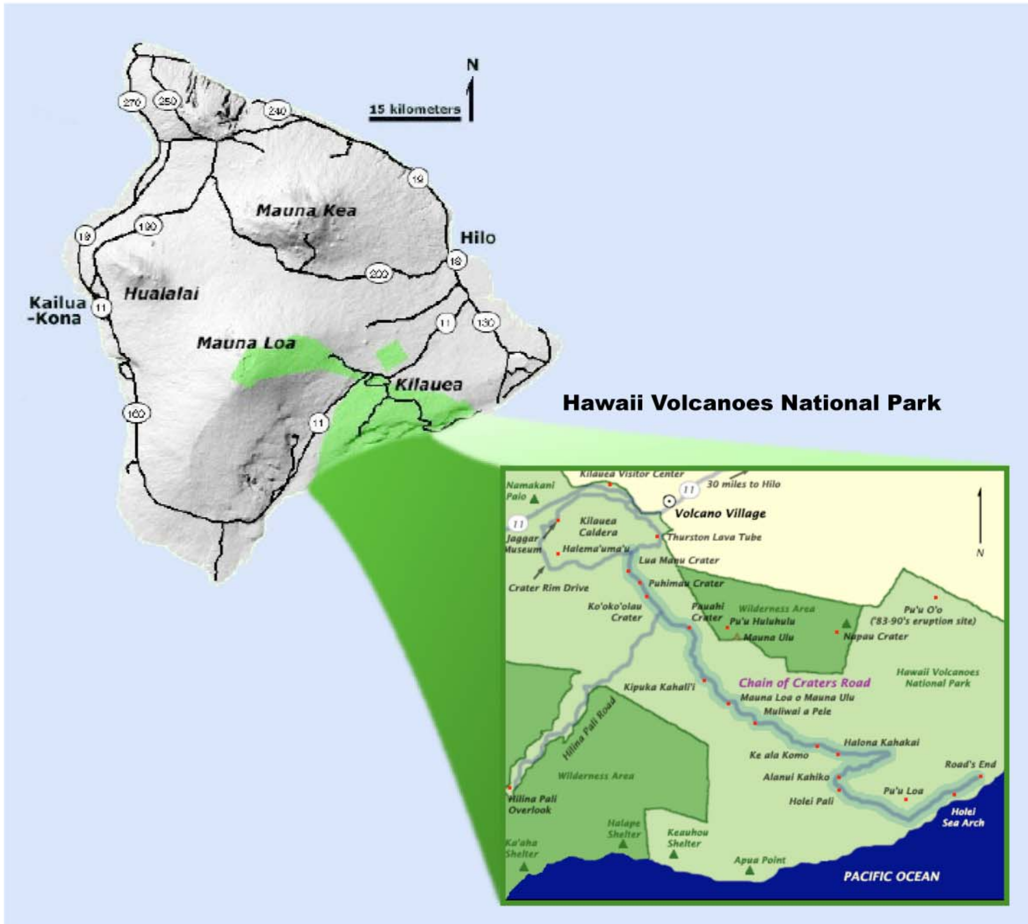


Figure 3-4: Crater Rim Drive and Chain of Craters Road, to be utilized by demo buses in Phase I of the Roadmap.

3.4.2 Phase II (2012 – 2020): Proof-of-Concept Demonstration Period

Objectives. The Phase II objectives would be twofold: 1) to allow for the commercial introduction of a modest hydrogen fleet in order to truly assess the cost and performance of hydrogen fuel and transportation in commercial operation and 2) to assess the public policy cost (and hold a public policy debate) to determine whether to move aggressively toward an expansion of hydrogen as a transportation fuel on the Big Island and throughout the state.

Approach. This expansion would probably take place by adding a refueling station in Kailua-Kona (or by increasing hydrogen production capacity at this station if a ***progressive*** approach/scenario has been followed in Phase I), and then later adding one in Hilo in concert with commitment by partners to the purchase of fleet vehicles. Allowing an eight-year, proof-of-concept demonstration period would enable the State of Hawaii to consider the following factors:

- Consumer acceptance regarding the performance, operation, and cost of hydrogen vehicles
- Availability and prices of necessary hydrogen technology including electrolyzers, refueling stations, and hydrogen vehicles
- Availability and cost of renewable energy to produce a known quantity of hydrogen transportation fuel
- Oil and diesel prices, and the risk of continuing to rely on these volatile fuels vis-à-vis the cost of policies to pursue the domestic production and use of hydrogen
- Analysis of costs to required to produce renewable energy, expand hydrogen infrastructure, and promote vehicle acquisition sufficiently and progressively enough for hydrogen to become a significant transportation fuel on the Big Island

Resource Utilization. By 2012, the PGV facility is expected to have an increased operational capacity of 38 MW:[57]

- ***Curtailed Geothermal Capacity.*** The curtailment rate is expected to remain at 10% during 10 off-peak hours,[58] providing 3.8 MW of curtailed geothermal capacity. Part of this capacity (2.8 MW) will be utilized to generate hydrogen while the rest of the capacity will be available during off-peak hours to be used for vehicle charging.
- ***Dedicated Geothermal Capacity.*** Starting from the year 2014, dedicated geothermal capacity will gradually be added (5 MW every three years) to eventually reach PGV's permitted 60 MW total capacity.

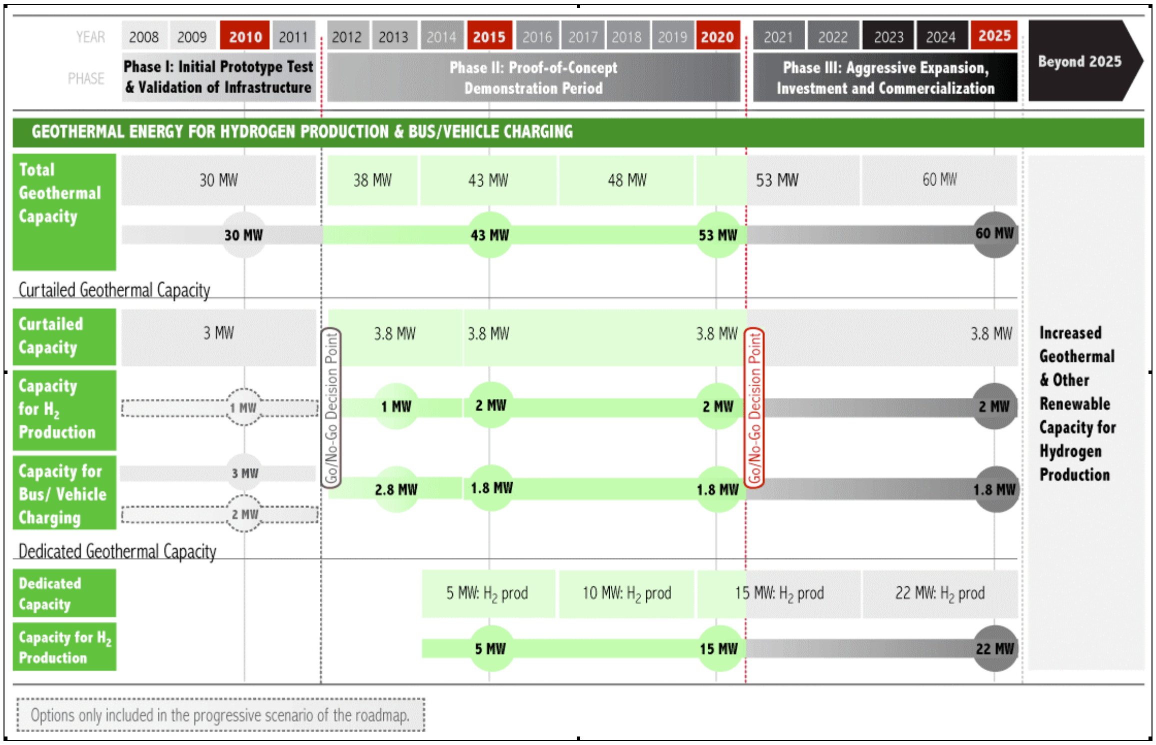
[57] At this time, PGV has negotiations ongoing with HELCO to install a bottoming-cycle unit, increasing its overall capacity to 38 MW. PGV officials have indicated that they expect this extra 8 MW capacity to be operational after approximately 18 months from receiving an amended Power Purchase Agreement (PPA) from HELCO. The amended PPA is expected sometime between the first quarter of 2009 to the second quarter of 2009. This means that this extra capacity could be available *as early as* the latter few months of 2010, but is assumed to be online in 2012 for the purposes of this Roadmap.

[58] The amended PPA that will enable the extra 8 MW capacity is expected to follow different terms than what is in place currently for the 30 MW base load power. HELCO could regulate PGV's output to range from 27 MW to 38 MW, depending on needs. As the terms are currently uncertain as to what the future curtailment levels will be, this Roadmap assumes the same 10% curtailment rate throughout the roadmap planning period, providing 3.8 MW curtailed capacity for hydrogen production and vehicle charging.

Key Milestones.

In 2015, **2 MW curtailed** and **5 MW dedicated** geothermal capacity will be available for hydrogen production. Additionally, **1.8 MW curtailed** geothermal capacity will be available for vehicle charging.

In 2020, **2 MW curtailed** and **15 MW dedicated** geothermal capacity will be available for hydrogen production. Additionally, **1.8 MW curtailed** geothermal capacity will be available for vehicle charging.



Infrastructure. This phase will involve the expansion of hydrogen fueling infrastructure to Kona (or further increase in hydrogen production capacity at this station if a progressive approach/scenario has been followed in Phase I and Hilo). The growth of hydrogen generation capacity will be gradual, with only a portion of the curtailed geothermal capacity being used initially; this capacity will be increased over time, with dedicated capacity being added in several years.

- ***Distributed Hydrogen Production.*** In the initial two years of this phase, 1 MW of the 3.8 MW curtailed capacity will be used for hydrogen production by sending geothermal electricity over the grid to produce hydrogen onsite at a refueling location in Kailua-Kona,[59] with one electrolyzer generating 190 kg H_2/day. (If a more ***progressive*** approach is followed, this capacity will have already been in

[59] Most Island tourists fly in and out of Kona International Airport. Aircraft operations at the Kona airport were 1.5 times that at the Hilo airport in 2007 (*Source:* DBEDT 2007 Data Book; Table 18.31: Aircraft Operations for Specified Airport: 1991 to 2007.) Kona also provides access to a greater majority of resorts, shops, and other tourist interests on the Island and is expected to experience greater population increases. Therefore, Kona is envisioned as a logical first step in infrastructure expansion.

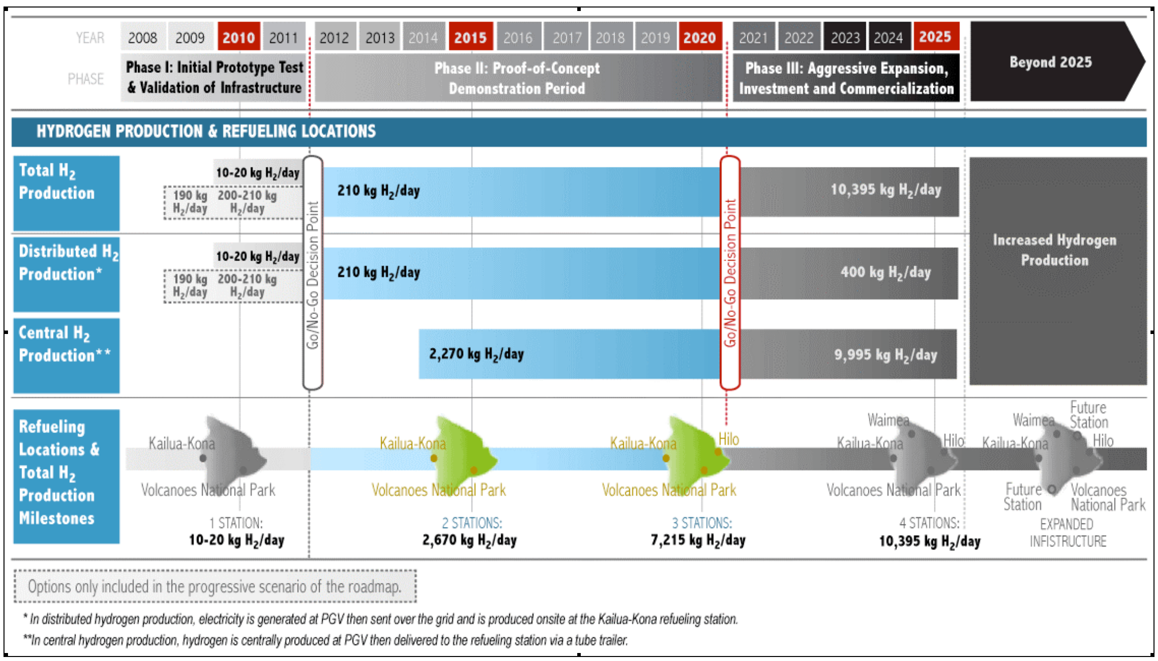
place since 2009.) In 2015, this curtailed geothermal capacity will be ramped-up to 2 MW, enabling the same electrolyzer at Kona to provide 380 kg H_2/day.

- ***Central Hydrogen Production.*** To ramp-up hydrogen capacity, in 2014, the total geothermal capacity at the PGV facility will be expanded by 5 MW, all of which will be dedicated to hydrogen production. Electrolyzers will be located onsite at the geothermal facility and the generated hydrogen will be sent to Kona via compressed gas tube trailers. The ramp-up of hydrogen production will continue, with total dedicated geothermal capacity reaching 10 MW in 2017 and 15 MW in 2020. To accommodate this increased hydrogen capacity, infrastructure will be expanded to include another refueling site at Hilo.
- ***Geothermal Capacity for Vehicle Charging.*** Initially, of the 3.8 MW curtailed geothermal capacity available during this period, 2.8 MW will be available during off-peak hours for vehicle charging. In 2015, when more of the curtailed capacity is utilized for hydrogen production, the amount available for vehicle charging will be reduced to 1.8 MW.

Key Milestones.

In 2015, total hydrogen produced will reach **2,670 kg H_2/day**, available at **2 refueling sites (HAVO and Kona)**.

In 2020, total hydrogen production will reach **7,215 kg H_2/day**, available at **2 refueling sites (HAVO, Kona and Hilo)**.

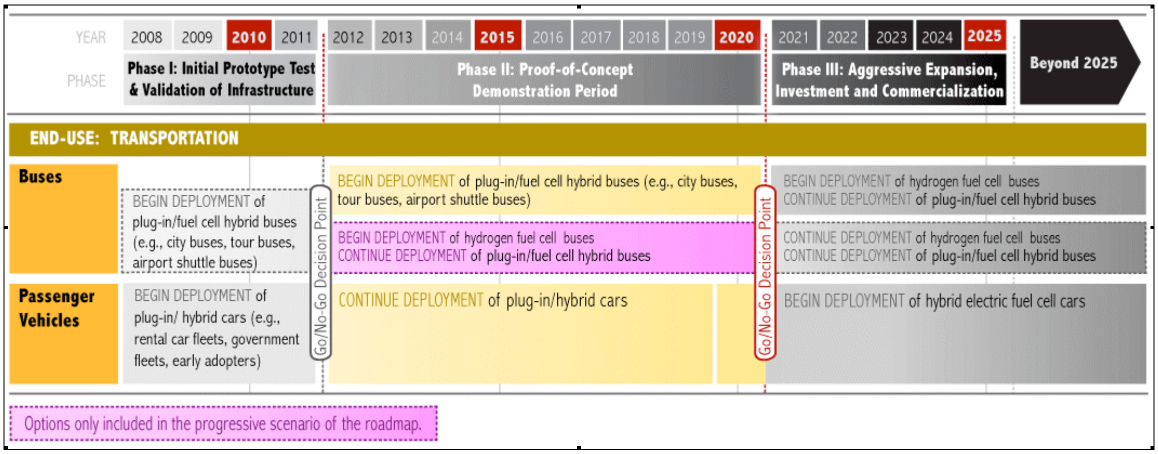


End-use.

Plug-in hybrid passenger vehicles (of rental car fleets, government fleets or early adopters) may continue to be charged throughout the island during 10 off-peak hours, utilizing the curtailed geothermal electricity available. A transportation partnership between vehicle OEMs, rental car fleets, airport fleets, and the State may be formed to introduce a small fleet (possibly 3-10 vehicles) of plug-in fuel cell hybrid buses to make use of the hydrogen capacity in the Kailua-Kona area (possibly at NELHA or the Kona airport) and charging through the available curtailed geothermal capacity. If a more ***progressive*** approach is followed, hydrogen fuel cell buses may also be introduced at this phase.

Key Milestones.

In 2015, **plug-in hybrid passenger vehicles** will make use of off-peak curtailed geothermal electricity for charging and **plug-in fuel cell hybrid bus fleets** will operate in the **Kailua-Kona** area. If a more **progressive** approach is followed, in 2020, **hydrogen fuel cell bus fleets** may be introduced.



Decision Point. If the results of the Phase II demonstration period indicate that hydrogen transportation investment by the State of Hawaii is prudent, then the policies to actualize such an investment will be implemented during Phase III.

3.4.3 Phase III (2020 and beyond): Aggressive Expansion, Investment and Commercialization

Objectives. This period will be marked by growth and development in several areas:

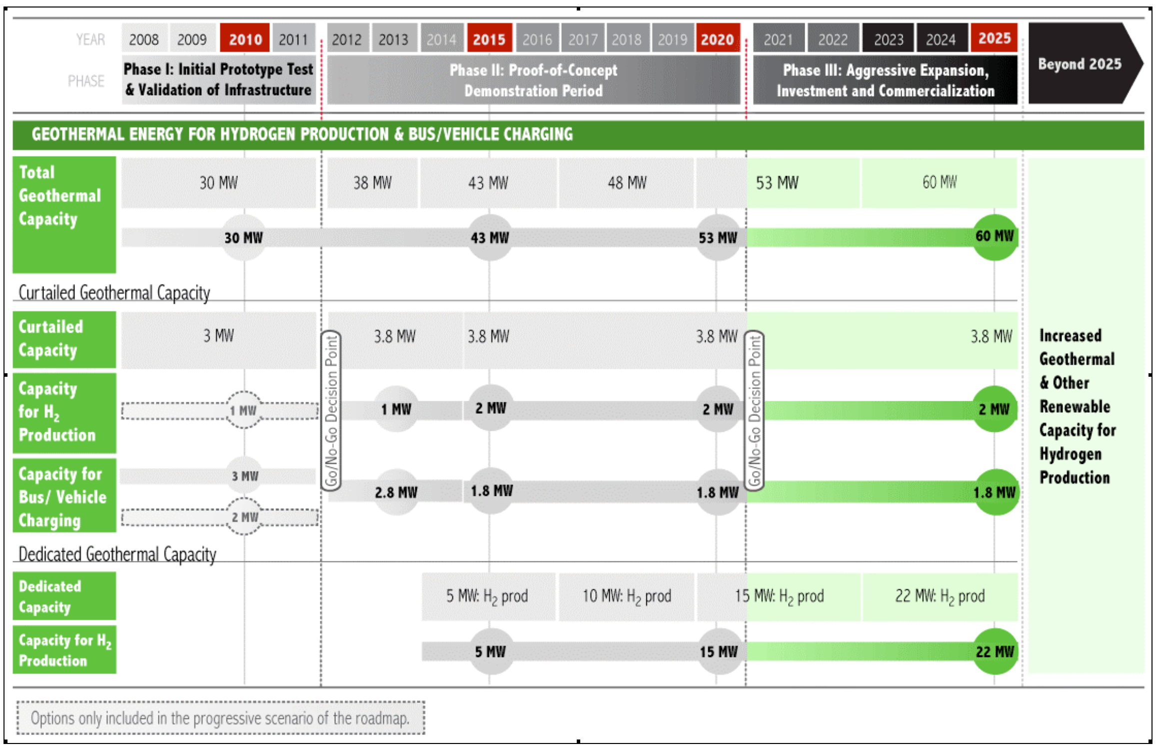
- Expansive development of geothermal and renewable electricity to produce the necessary hydrogen
- Increased refueling infrastructure (including a likely fourth location in Waimea) to accommodate an expanding presence of hydrogen vehicles
- Expanding fleets of both commercial and personal hydrogen vehicles
- Growth of the economic base, including the creation of jobs concomitant with such an expansion

Approach. If the State and its hydrogen partners are committed to a set progressive energy policies that promote renewable energy and hydrogen production, and if billions of dollars of capital investment for the renewable electricity and hydrogen infrastructure are made available, then a rapid deployment of hydrogen vehicles will occur in Phase III.

Resource Utilization. From 2020 to 2025, the strategy of gradually deploying dedicated geothermal capacity while maintaining curtailed capacity will be continued. By 2025, the total geothermal capacity reached will be the permitted 60 MW. Of this capacity, 22 MW will be deployed to generate dedicated hydrogen, while 2 MW of curtailed hydrogen will still be available for distributed hydrogen production. Additionally, 1.8 MW of curtailed geothermal capacity will be available for vehicle charging during off-peak hours. Beyond 2025, however, several hundred MWs from geothermal, wind, and solar power plants will be required, with many being dedicated for the production of hydrogen as transportation fuel.

Key Milestones.

By 2025, **2 MW curtailed** and **22 MW dedicated** geothermal capacity will be available for hydrogen production. Additionally, **1.8 MW curtailed** geothermal capacity will be available for vehicle charging.



Infrastructure. Total hydrogen produced will reach 10,395 kg H_2/day, and fueling will be expanded to Waimea. Beyond 2025, the state may choose to further utilize the geothermal reserves of the Big Island, as well as other renewable resources, to reach a full-scale hydrogen economy for the transportation sector. Based on GeothermEx's forecast of developable geothermal reserves on the Big Island (see Table B-1 in Appendix B), the Lower KERZ area has a base (lower) case of being developed up to 82 MW, and an upside case of being developed up to 95 MW.[60] This provides the next level

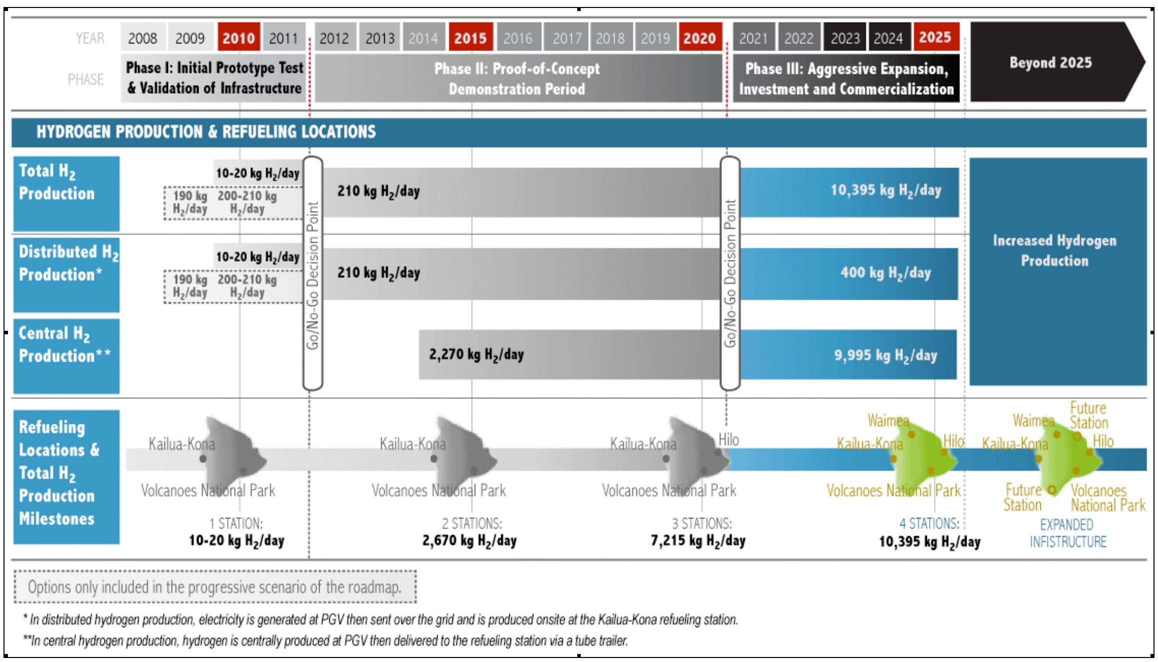
[60] GeothermEx, Inc. 2005. *Assessment of Energy Reserves and Costs of Geothermal Resources in Hawaii.* For the State of Hawaii, Department of Business, Economic Development and Tourism. September 30.

of opportunity for the realization of a geothermal hydrogen economy, while a developable capacity totaling 180 MW for the three main geothermal reserve areas of the Big Island supplies further resources.

Due to the Big Island's unique volcanic terrain, the road infrastructure is constrained to the perimeter of the island, requiring the placement of refueling stations to follow the same pattern. As described in the suggested roadmap outlined in this report, the western, eastern, and northern parts of the island will each have at least one refueling station to cover the major population areas and sections of the island by 2025. The next logical placements would be on the southern part of the island (around Naalehu) and on the northeastern part of the island (Hamakua coast). Once all major areas are covered by at least one station, other stations are expected to emerge at mid-points as the hydrogen economy on the island expands.

Key Milestones.

By 2025, total hydrogen produced will reach **10,395 kg H_2/day**, available at **4 refueling sites (HAVO, Kona, Hilo and Waimea)**.

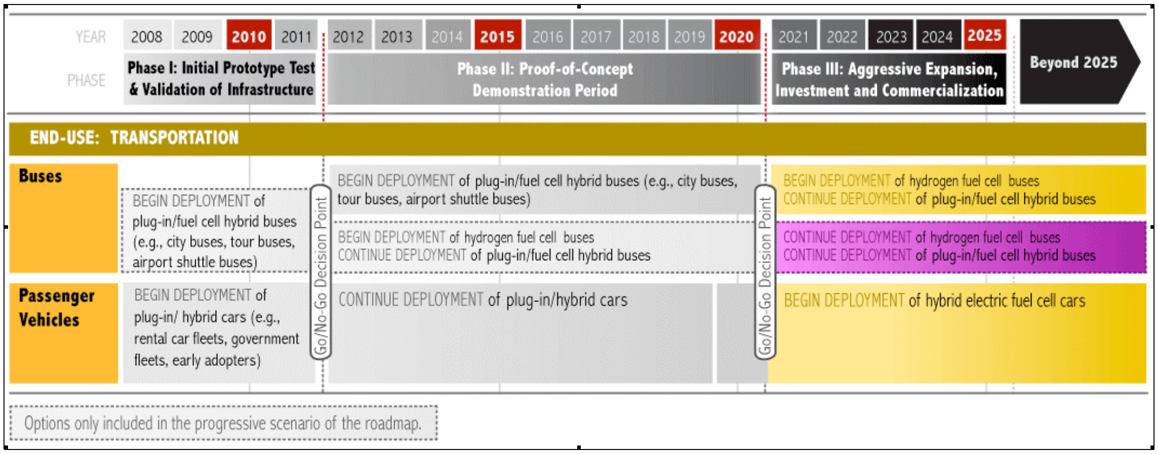


End-use.

While plug-in hybrid passenger vehicles may continue to be charged via curtailed geothermal electricity throughout the island during 10 off-peak hours, the deployment of hybrid electric fuel cell cars will also begin. Previously formed transportation partnerships may be expanded to include more plug-in fuel cell hybrid buses and to begin the deployment of hydrogen fuel cell buses. This increase in transportation demand will be met by the expanded infrastructure of four hydrogen refueling sites. Car and bus charging through the available curtailed geothermal capacity will continue.

Key Milestones.

By 2025, a variety of vehicles – plug-in hybrid cars; hybrid electric fuel cell cars; plug-in/fuel cell hybrid buses and hydrogen fuel cell buses – will be running on hydrogen dispensed at four refueling stations.



3.5 Potential Partners and Their Roles

The implementation of the Roadmap will require an extensive array of stakeholders working in concert toward a common hydrogen deployment vision. These stakeholders range from policymakers to energy providers to hydrogen researchers. A summary of stakeholders is provided below with a more extensive list presented in Appendix H.

Federal Government Support: Several Federal agencies have committed funding or shown interest in hydrogen projects in Hawaii including DOE, U.S. Department of Transportation (DOT), DOI/ NPS, and DOD. These agencies could also participate in demonstrations, policy construction, and location siting. In addition, each could act as a source of information, expertise and funding.

State of Hawaii Organizations: A number of state organizations will be needed to provide leadership, policy infrastructure, technical expertise, and financing for implementation of this Roadmap. A few of these organizations are highlighted below:

- ***The State of Hawaii Legislature*** must provide the leadership, policy framework, and state financing to move the state toward the use of hydrogen as a transportation fuel
- ***County and local government*** must support the local codes and standards, siting and permitting policies, and public outreach needed to promote the development of renewable energy and installation of hydrogen infrastructure
- ***State agencies*** will need to implement any policies passed by the state legislature regarding energy and land-use policy. Thus, organizations such as the Department of Business, Economic Development and Tourism (DBEDT) and the Department of Land and Natural Resources, and the Hawaii Department of Transportation (Airports Division) will be instrumental in many aspects of the Roadmap implementation.

- ***The University of Hawaii/Hawaii Natural Energy Institute*** staff provides renewable and hydrogen technical expertise within the State of Hawaii and will serve as project managers in implementing key projects identified in Phase I;
- ***Hawaii Center for Advanced Transportation Technologies (HCATT)*** provides expertise on alternatively fueled transportation and is responsible for converting vehicles and managing fleets of electric and hydrogen vehicles.

Geothermal and Renewable Electricity Developers and Providers: Producing the amount of hydrogen necessary will require hundreds of MWs of geothermal and renewable electricity to be developed and delivered to the appropriate hydrogen production infrastructure.

- ***Renewable energy developers*** are the likely developers of geothermal, solar, and wind power plants. They must acquire land rights, establish power purchase agreements, obtain financing, and deliver electricity to hydrogen production customers.
- ***Hawaii Electric Light Company***, the Big Island's electric utility**,** will be a key partner in providing renewable electricity, transmitting electricity throughout the island, and working with partners to develop electricity tariff structures that can provide off-peak electricity for transportation.

Hydrogen Production and Refueling Infrastructure Providers: Technology manufacturers and infrastructure providers must put devices into place that produce, distribute, and dispense hydrogen.

- ***Electrolyzers*** are the key technology to produce hydrogen from electricity and water. There are only a few manufacturers in the world that manufacture these devices at the size and scale necessary for implementing this roadmap, and they must be engaged early in the process as key partners.
- ***Storage tanks and refueling stations*** are critical components since hydrogen is produced off-peak (at night) and must be stored before being becoming available to cars and buses requiring fuel. There are a few industrial gas companies that have expertise in designing and installing hydrogen refueling infrastructure.

Hydrogen and Hybrid Vehicle Providers and Users: Hydrogen-fueled automobiles are likely to be more expensive than internal combustion vehicles when introduced, especially during the early phases of this Roadmap. Thus, manufacturers and purchasers of automobiles will be key stakeholders.

- ***Original equipment manufacturers (OEMs)*** are critical to provide the supply of hydrogen transportation vehicles that will be required. Relevant OEMs include GM, Ford, Chrysler in the United States; Toyota, Nissan, Mazda, others in Japan; and others in South Korea, China, or India.
- ***Fleet transportation operators*** represent an opportunity for early market entry. Specific fleets of interest include the County of Hawaii Mass Transit (Hele-On buses), airport shuttles (e.g., SpeediShuttle), Ali'i Shuttle, Hawaii Volcanoes

National Park shuttles, and private transportation companies like Polynesian Adventure Tours/Gray Line Hawaii and Roberts Hawaii.

- ***Auto rental companies*** provide large fleets of vehicles and represent yet another outstanding market entry opportunity. For example, Hertz has distinguied itself as a technology leader by deploying the first three Toyota Prius hydrogen hybrid vehicles as part of its rental fleet in Iceland.[61]

3.6 State and/or County Policy Path

The hydrogen-related policies and financial incentives currently in place in the State of Hawaii will help initiate the necessary business and infrastructure growth; however, additional, larger incentives will likely be needed in the future, depending on the state's desired level of expansion. Concerted policy efforts will be necessary to achieve significant expansion of renewable energy on the Big Island, lower-cost electricity to produce a domestic transportation fuel, and incentives to purchase hydrogen-powered vehicles. In addition, these actions must be supported by robust, targeted education and outreach efforts. Major policy considerations must include the following:

- Siting, permitting, and land-use planning to accommodate geothermal and other renewable electricity development on a scale to produce hundreds of MWs of renewable electricity
- An electricity policy that will result in alternative-fuel-supporting electricity pricing (i.e., a transportation tariff that makes wholesale electricity available to hydrogen producers at less than $0.10/kWh)
- An incentive strategy for early purchasers of hydrogen vehicles and fleet operators.

3.7 Education and Outreach

Educating Hawaii residents, industry leaders, and public policy makers about the benefits of hydrogen is a vital element of a statewide adoption process. Targeted education and outreach programs to increase broad-based understanding and acceptance for hydrogen applications could foster increased support for important policy changes. Many state agencies already operate outreach programs that educate the general public about renewable projects currently taking place on the Big Island. Public and private organizations can further increase statewide awareness and acceptance of hydrogen by participating in public relations and media campaigns, renewable energy partnerships, hydrogen demonstration projects, and Hawaii's education system. In addition to the potential project partners, some of the cooperating groups and supporters listed in Appendix H may choose to participate in these education and outreach efforts.

Beyond these state-specific stakeholders, the Island's 28,000 daily tourists[62] may share their experiences with this new technology upon returning home, thereby cultivating globally shared understanding, learning, and support. The Big Island's tourism industry

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[61] Inter Press Service News Agency. 2008. Iceland: Filling Up on Hydrogen. http://ipsnews.net/news.asp?idnews=43704.

[62] DBEDT. 2007. 2007 State of Hawaii Databook. Table 7.06: Average Daily Visitor Census, by County and Island: 2006 and 2007.

clearly provides an opportunity to effectively represent hydrogen as a clean, secure, and safe energy carrier to a widespread audience.

3.8 Economic Impacts

Increased hydrogen usage can offer a means to reduce imported fuels. As hydrogen produced from geothermal energy becomes increasingly used as a transportation fuel, the $7 billion[63] that the State of Hawaii currently spends for its imported oil is likely to decline over time. Other benefits of hydrogen implementation, in addition to reduced oil use, are summarized in Appendix I.

[63] State of Hawaii. Governor Linda Lingle. *Administration Moves Forward on Five-Point Plan for Economic Action.* http://hawaii.gov/gov/economy

4. Conclusions

The analysis conducted for this report indicates that hydrogen *is* a potential transportation fuel for the Big Island of Hawaii; however, a concerted effort by the state's leaders and policy makers will be necessary for hydrogen to become a significant transportation fuel before 2025. The primary conclusions of this report are as follows:

Conclusion 1: Hydrogen transportation fuel can compete with diesel by 2025 only if the electricity to produce hydrogen is available at less than $0.10/kWh and diesel exceeds $5.30 per gallon. In order to make hydrogen from renewable energy, electricity must be produced from renewable resources and hydrogen must be produced by splitting water using an electrolyzer. Our analysis indicated that the two main cost drivers in this process are the cost of the electricity and the capital cost of the electrolyzer. Our conclusion is that, in order to compete with diesel prices greater than or equal to $5.30 per gallon, the cost of electricity to produce hydrogen must be less than $0.10/kWh.

Conclusion 2: All-electric battery/fuel cell hybrid powertrain vehicles are projected to be the hydrogen vehicles most likely to be available and cost-competitive with internal combustion engine vehicles by 2025. The hydrogen passenger vehicles likely to be available and cost-competitive with ICE vehicles in 2025 will have hybrid electric/fuel cell powertrains. By combining batteries and fuel cells in a hybrid powertrain, vehicle designers can cost-effectively size the energy storage system and fuel cell without sacrificing vehicle performance. A hybrid electric/fuel cell powertrain will offer an extended operating range, which may especially be crucial in early phases of the deployment plan since a limited number of fueling stations may exist on the island.

Conclusion 3: Conservative estimates indicate that using 24 MW of the currently permitted 60 MW of geothermal capacity can produce over 10,000 kg of hydrogen per day (approximately 3,800,000 kg/year) – enough to fuel approximately 3.3% of Big Island transportation needs. The analysis also examined the amount of hydrogen that could be made from the potential geothermal energy on the Big Island and whether this hydrogen could fuel some, most, or all of the transportation needs on the island. A number of significant conclusions were reached:

- Only 3.3% of the Big Island's transportation requirements could be served by the currently permitted geothermal power plant, and only if 24 MW of the geothermal capacity was utilized in producing hydrogen.
- 25% of the Big Island transportation needs would require approximately 180 MW of dedicated renewable energy capacity.
- 50% of the Big Island transportation needs would require approximately 363 MW of dedicated renewable energy capacity.
- 75% of the Big Island transportation needs would require approximately 544 MW of dedicated renewable energy capacity.
- 100% of the Big Island transportation needs would require approximately 727 MW of dedicated renewable energy capacity.

Thus, if the State of Hawaii wanted to run all of the Big Island's transportation system on renewably produced hydrogen, it would need to develop more than 700 MW of renewable energy (e.g., geothermal, solar, wind) on the island.

Conclusion 4: If the State of Hawaii chooses to pursue the renewable hydrogen transportation pathways outlined in this roadmap, an aggressive policy approach will be required. Concerted policy efforts will be necessary to achieve significant expansion of renewable energy on the Big Island, lower-cost electricity to produce a domestic transportation fuel, and incentives to purchase hydrogen-powered vehicles. In addition, these actions must be supported by robust, targeted education and outreach efforts. Major policy considerations must include the following:

- Siting, permitting, and land-use planning to accommodate geothermal and other renewable electricity development on a scale to produce hundreds of MWs of renewable electricity
- An electricity policy that will result in alternative-fuel-supporting electricity pricing (i.e., a transportation tariff that makes wholesale electricity available to hydrogen producers at less than $0.10/kWh)
- An incentive strategy for early purchasers of hydrogen vehicles and fleet operators.

Based on the detailed analysis that was conducted for this report, ***a prudent, three-phased approach to a geothermal hydrogen future for the Big Island is recommended:***

> ***Phase I (2008-2012): Initial Prototype Test and Validation of Infrastructure.*** This phase will serve two purposes: 1) to allow the hydrogen experts at HNEI to purchase the first hydrogen vehicles and deploy the first hydrogen refueling operation on the Big Island at the Hawaii Volcanoes National Park and 2) to allow the performance and cost validation of these devices to determine whether the state should expand the hydrogen infrastructure on the Big Island. If a more ***progressive*** approach/scenario is followed by decision-makers, infrastructure expansion and increased hydrogen production could begin as early as this phase.
>
> ***Phase II (2012-2020): Proof-of-Concept Demonstration Period.*** The second phase would allow for further expansion of hydrogen infrastructure, validation of costs, and evaluation of required policies. This expansion would probably take place by the addition of a refueling station in Kailua-Kona (or further increase in hydrogen production capacity at this station if a *progressive* approach/scenario has been followed in Phase I), followed later by one in Hilo, in concert with commitment by partners to the purchase of fleet vehicles. Allowing an eight-year proof-of-concept demonstration period would enable the State of Hawaii to consider the following:
>
> - Consumer acceptance regarding the performance, operation, and cost of hydrogen vehicles

- Availability and prices of necessary hydrogen technology including electrolyzers, refueling stations, and hydrogen vehicles
- Availability and cost of renewable energy to produce a known quantity of hydrogen transportation fuel
- Volatile oil and diesel prices vis-á-vis the cost of policies to pursue the production of hydrogen via domestic renewable resources
- Analysis of costs to required to produce renewable energy, expand hydrogen infrastructure, and promote vehicle acquisition sufficiently and progressively enough for hydrogen to become a significant transportation fuel on the Big Island

Phase III (2020 and beyond): Aggressive Expansion, Investment and Commercialization. If the results of the Phase II demonstration period indicate that hydrogen transportation investment by the State of Hawaii is prudent, then the policies to actualize such an investment will be implemented during this phase. This period will be marked by growth and development in several areas:

- Expansive development of geothermal and renewable electricity to produce the necessary hydrogen
- Increased refueling infrastructure (including a likely fourth location in Waimea) to accommodate an expanding presence of hydrogen vehicles
- Expansion of both commercial and personal hydrogen vehicle fleets
- Growth of the economic base, including the creation of jobs

The economic challenges resulting from dependence on foreign oil supplies can be ameliorated over time as renewable energy resources are increasingly utilized and a hydrogen economy is developed. The Big Island of Hawaii is poised to showcase the benefits of these changes as recommended policy changes and technology advancements are implemented.

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APPENDICES

APPENDIX A: ENERGY PICTURE OF THE STATE OF HAWAII
APPENDIX B: FORECASTED GEOTHERMAL RESOURCE BASE ON THE BIG ISLAND OF HAWAII
APPENDIX C: POPULATION DISTRIBUTION AND TRENDS
APPENDIX D: TRANSPORTATION SYSTEM AND TRENDS
APPENDIX E: CONSTRUCTIVE POLICIES
APPENDIX F: DETAILS OF ANALYSES
APPENDIX G: POSSIBLE FUTURE INTEGRATION OF OTHER RENEWABLES
APPENDIX H: OTHER POTENTIAL PARTNERS, COOPERATING GROUPS AND SUPPORTERS
APPENDIX I: ECONOMIC IMPACTS

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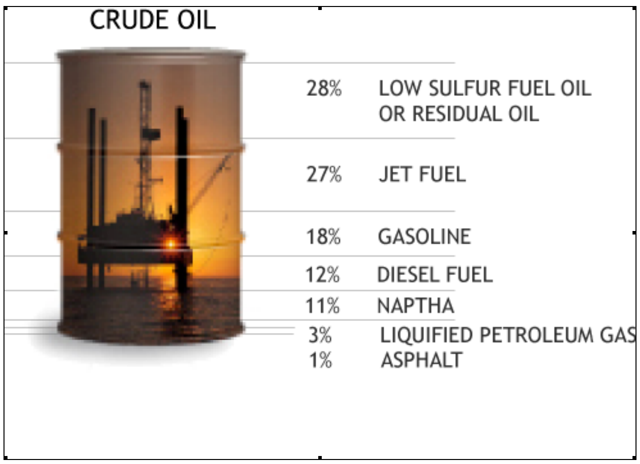
Appendix A: Energy Picture of the State of Hawaii

As shown in Figure A-1, imported crude oil is refined to produce a variety of petroleum-based fuels that are utilized for transportation, electricity generation, and various commercial and industrial applications. The transportation sector's high relative consumption is due in large part to use by the military and commercial air transport. Petroleum is also the primary energy source for electricity generation in the State of Hawaii at approximately 78% (the nation's highest), followed by coal-fired generation with 14%, and renewable energy systems with 8%.[64]



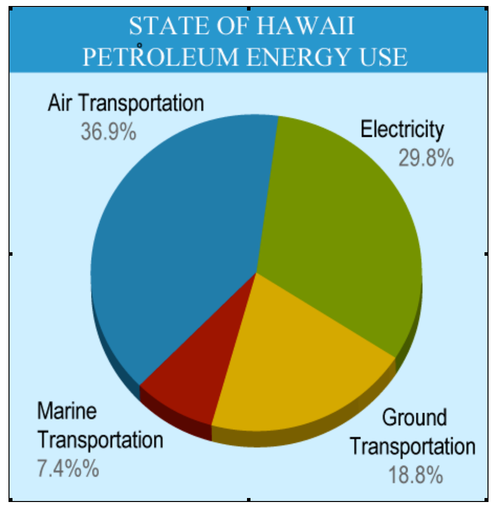


Figure A-1. Petroleum is refined for a number of uses in the State of Hawaii.[65]

Hawaii has a statewide generating capacity exceeding 2,400 MW.[66] It has a traditional regulated market for electric power; however, unlike the continental United States, each island has an isolated stand-alone grid. This presents Hawaii with a number of unique challenges. Each island must independently rely on its own generation sources, including renewable resources, and imported fuels to meet its energy needs.

Together, Hawaiian Electric Company, Inc. (HECO) and its subsidiaries, Maui Electric Company, Ltd. (MECO), and Hawaii Electric Light Company, Inc. (HELCO), provide electricity to 95% of the state's 1.2 million residents on the islands of Oahu, Maui, Big Island, Lanai, and Molokai.[67] The Kauai Island Utility Cooperative provides electricity for the island of Kauai. The three HECO utilities purchase a portion of electricity through independent power producers (IPPs), including waste, hydro, and biomass combustion. In the future, under Hawaii's Renewable Portfolio Standards statute, these

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[64] DBEDT. 2007. 2007 State of Hawaii Data Book. Table 17.06: Electricity Generation by Source: 1990 – 2006.

[65] HECO. Fuel oil use in Hawaii. (Factsheet).

[66] Hawaii Renewable Electricity Profile (2006). Energy Information Administration. Release Date: May 2008.

[67] HECO. About Us. http://www.heco.com/portal/site/heco/menuitem.20516707928314340b4c0610c510b1ca/?vgnextoid=613df2b154da9010VgnVCM10000053011bacRCRD&vgnextfmt=default.

utilities are anticipated to utilize more renewable energy, accounting for much of the renewable energy used in Hawaii including wind, geothermal, municipal solid waste. Figure A-2 displays the locations of both traditional and renewable energy production in Hawaii and the amount of electricity from the various fuel sources. Figure A-3 provides the breakdown of renewable electricity generation in Hawaii relative to oil and coal generation.

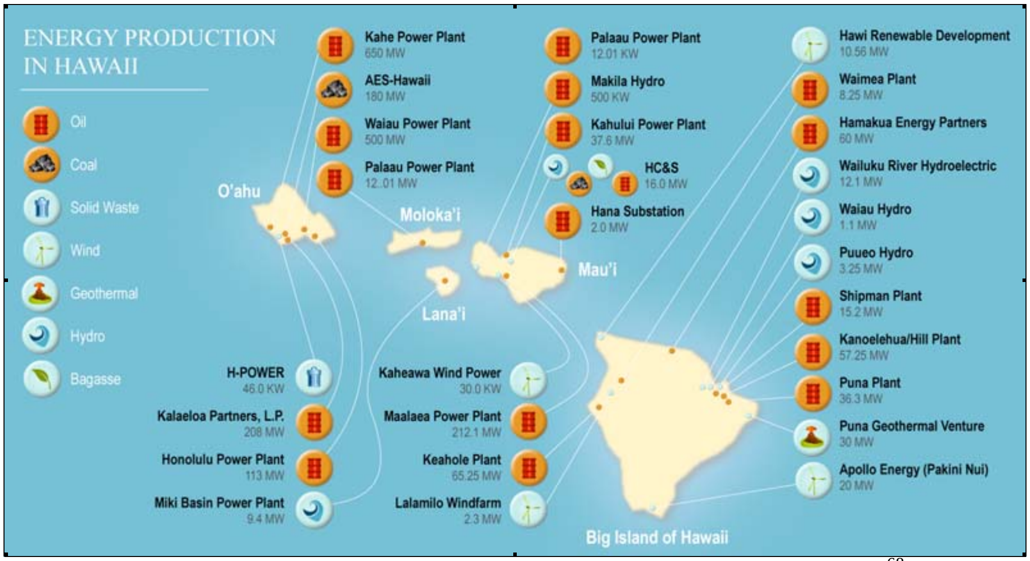

Figure A-2. Electricity generation portfolio for the State of Hawaii.[68]

Renewable Electricity Generation in Hawaii (Gigawatt hours)	
Biofuel	1.43
Biomass	57.47
Geothermal	229.89
Hydro	14.73
Solid Waste	328.31
Wind	241.54
Total	873.37

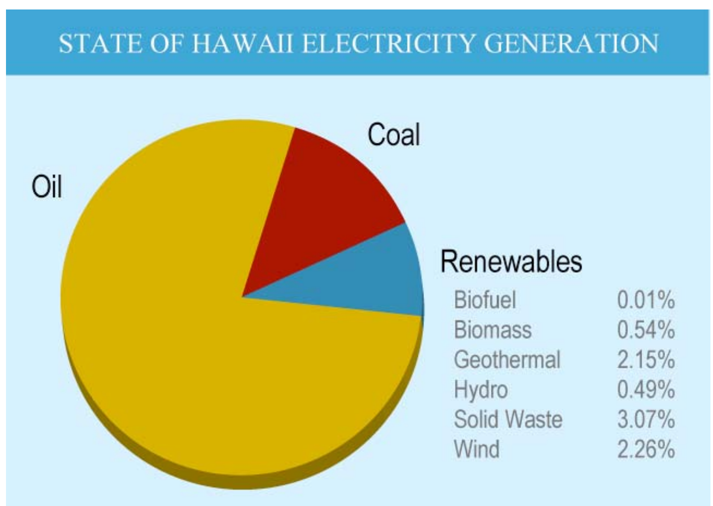

Figure A-3. Renewable and non-renewable energy production in Hawaii (as of 12/31/07; does not include Kauai).[69]

[68] HECO. 2007. Hawaiian Electric Company 2007 Corporate Sustainability Report. www.heco.com/vcmcontent/StaticFiles/pdf/Sustainable_AR_vflr.pdf.

Appendix B: Forecasted Geothermal Resource Base on the Big Island of Hawaii

Table B-1. GeothermEx Forecast of Developable Generation Capacity from Geothermal Resources on the Big Island of Hawaii.[70]

	BASE CASE	UPSIDE CASE			
YEAR	LOWER KERZ (NET MW)	LOWER KERZ (NET MW)	HUALALAI (NET MW)	MAUNA LOA SW RIFT ZONE (NET MW)	TOTAL FOR ISLAND OF HAWAII (NET MW)
2005	30	30			30
2006	38	40			40
2007	38	40			40
2008	38	40	0		40
2009	46	50	5	0	55
2010	46	50	5	10	65
2011	46	50	5	10	65
2012	54	60	10	10	80
2013	54	60	10	20	90
2014	54	60	10	20	90
2015	62	70	15	20	105
2016	62	70	15	30	115
2017	62	70	15	30	115
2018	70	80	20	30	130
2019	70	80	20	40	140
2020	70	80	20	40	140
2021	70	90	25	40	155
2022	78	90	25	50	165
2023	78	90	25	50	165
2024	78	95	25	50	170
2025	82	95	25	60	180

[69] HECO. 2007. Hawaiian Electric Company 2007 Corporate Sustainability Report. www.heco.com/vcmcontent/StaticFiles/pdf/Sustainable_AR_vflr.pdf.
[70] GeothermEx, Inc. 2005. Assessment of Energy Reserves and Costs of Geothermal Resources in Hawaii.

Appendix C: Population Distribution and Trends

As illustrated in Figure C-1, the Big Island has nine districts and two concentrated population centers, one on the west side of the island and one on the east. More rapid population and energy demand growth is occurring on the western side of the Big Island including the area around Kailua-Kona and several high-end resorts along the Kohala Coast. However, the major power generators reside on the eastern side of the Island, around Hilo and Pahoa (the location of the Puna Geothermal Venture [PGV] facility). It has been estimated that 85% of generating capacity originates on the eastern side of the island, while 60%of the demand resides in the western side of the island.[71]

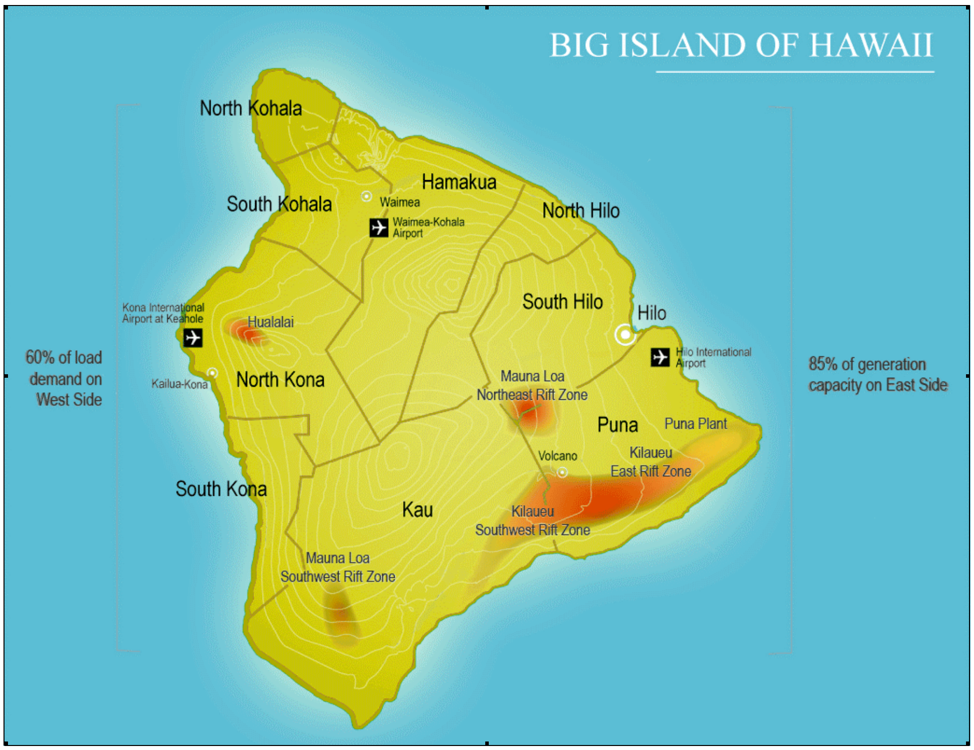

Figure C-1. Big Island districts and imbalance between load demand and generation capacity.

[71] Hawaiian Electric company, Inc. and Sentech, Inc. 2004. HELCO Operational Issues Bulk Energy Storage. For the U.S. Department of Energy and the State of Hawaii, Department of Business, Economic Development and Tourism. October.

Table C-1. Projection of Resident Population by District, Hawaii County: 2000 to 2025.

DISTRICT	2000	2005	2010	2015	2020	2025
TOTAL	148,677	159,907	176,938	195,965	217,718	241,700
Puna	31,335	36,351	42,591	49,801	58,246	67,600
South Hilo	47,386	46,273	47,477	48,614	49,791	50,900
North Hilo	1,720	1,643	1,720	1,798	1,879	2,000
Hamakua	6,108	6,196	6,561	6,933	7,328	7,700
North Kohala	6,038	6,622	7,917	9,446	11,273	13,400
South Kohala	13,131	15,659	18,184	21,072	24,426	28,000
North Kona	28,543	30,467	34,024	37,922	42,275	47,300
South Kona	8,589	10,253	11,414	12,681	14,092	15,700
Kau	5,827	6,443	7,050	7,698	8,408	9,100

Source (Years 2000-2020): Hawaii County. County of Hawai`i General Plan 2005 (Amended December 2006 by Ord. No. 06-153). Website: http://www.co.hawaii.hi.us/la/gp/toc.html. Source (Year 2025): Extrapolation of previous source.

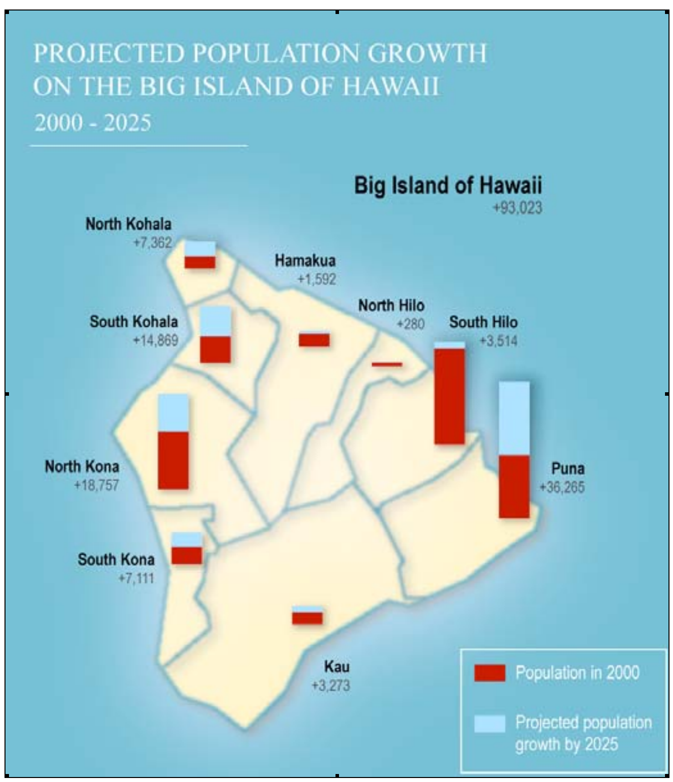

Figure C-2. Population trends on the Big Island.

Latest census reports show that the Big Island's population increases are outpacing growth in the rest of the state, with a 14.7% increase since 2000. The Big Island has grown by approximately 28,000 people each decade, starting with the 1970s. If current trends continue, the total population is expected to increase by 37,500 residents during this decade. [72]

According to an analysis by the State of Hawaii's Department of Business, Economic Development and Tourism,, most of the state's population growth is due to births and immigrants from other countries. In addition, about 2,922 people move to the Big Island from other islands and the mainland every year. [73]

[72] "Despite Earthquakes and Lava and Vog, Census Shows Big Island Population Increasing Fastest in State of Hawaii." Hawaii Health Guide. March 22, 2007. http://www.hawaiihealthguide.com/healthtalk/display.htm?id=549
[73] *Ibid.*

Appendix D: Transportation System and Trends

Road Infrastructure
The unique volcanic terrain of the Big Island forces most traffic to run along the perimeter of the island on the Hawaii Belt. Only one cross-island road, Saddle Road (Hwy 130), runs through the center of the island between the Mauna Kea and Mauna Loa summits. Figure D-1 shows the major highways, which have the following routes:

- **Highway 11** runs along the southern half of the island perimeter from Hilo to Kailua-Kona and runs through the Volcanoes National Park.
- **Highway 19** runs along the northern half of the island perimeter from Hilo to Kailua-Kona and passes through Honokae and Waimea. It is the quickest route from Kailua-Kona to Hilo/Puna.
- **Highway 130** runs from Puna/Pahoa through Hilo, and then turns into Saddle Road, which goes cross-island to Waimea. It also passes through Pohakula Military Reservation.
- **Highway 190** runs from Kailua-Kona to Waimea.
- **Highways 270 and 250** comprise a small loop from Waimea up to northernmost tip (Hawi).

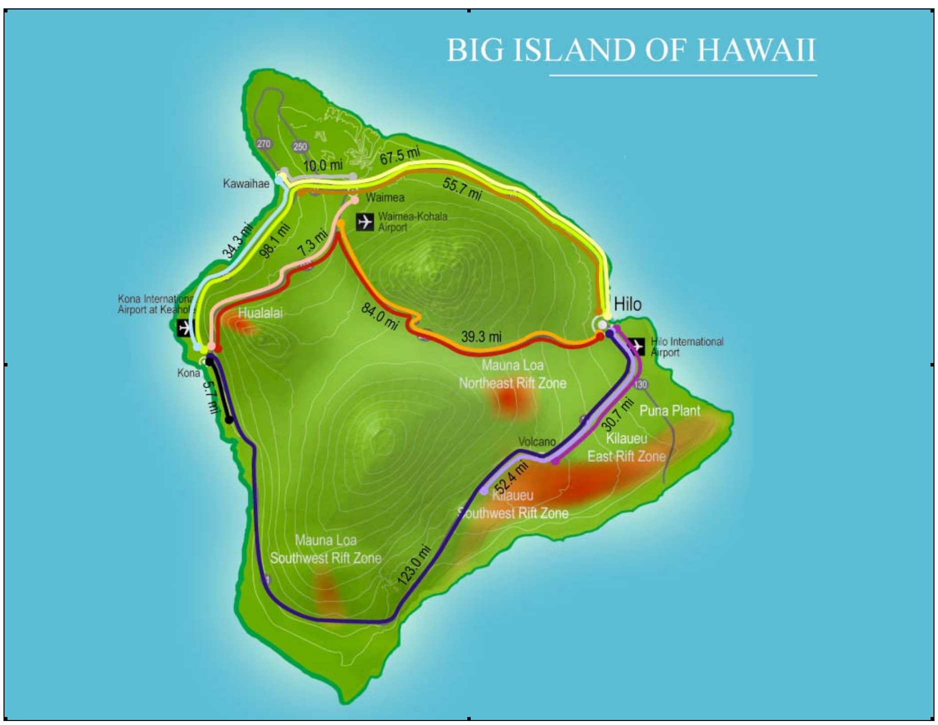

Figure D-1. Major highways on the Big Island.

Table D-1 lists the distances between some of the areas/towns of interest. The colors correspond with the route colors in the map above.

Table D-1. Highway Distances, Hawaii County.[74]

ROUTE	COLOR KEY	STATUTE MILES
Hilo – Mauna Kea summit		39.3
Hilo – Mauna Loa summit		52.4
Hilo – Volcano House		30.7
Hilo – Kailua-Kona, via Naalehu		123.0
Hilo – Kailua-Kona, via Saddle Road		84.0
Hilo – Kailua,-Kona via Hamakua		98.1
Hilo – Waimea, via Hamakua		55.7
Hilo – Kawaihae, via Hamakua		67.5
Waimea – Kawaihae		10.0
Kawaihae – Kailua-Kona		34.3
Kailua-Kona – Keahole Airport		7.3
Kailua-Kona – Keauhou		5.7

Passenger Vehicles

Over 176,000 motor vehicles (approximately 135,500 of which are passenger vehicles) are registered on the Big Island.[75] As a result, the County of Hawaii had a demand of over 95 million gallons of "highway use" fuel (gasoline, diesel oil and butane gas) in 2006, which was the second highest county demand behind Honolulu.[76]

Based on the population trends depicted in Table D-2, passenger vehicles were also delineated according to districts on the Big Island. The overall trend is shown in Figure D-2.

[74] Hawaii State Department of Business, Economic & Development. http://www.hawaii.gov/dbedt/.
[75] DBEDT. 2007. 2007 State of Hawaii Data Book. Table 18.08: Vehicle Registration, By Type of Vehicle, By County: 2007.
[76] DBEDT. 2007. 2007 State of Hawaii Data Book. Table 18.17: Motor Vehicle Fuel Consumption and Vehicle, 1990 to 2006, and by County, 2005 and 2006.

Table D-2. Projection of Passenger Vehicles by District, Hawaii County: 2000 to 2025.[77]

DISTRICT	2000	2005	2010	2015	2020	2025
Total	**101,761**	**132,620**	**150,000**	**170,000**	**190,000**	**210,000**
Puna	21,451	30,145	36,100	43,200	50,800	59,500
South Hilo	32,431	38,380	40,200	42,100	43,500	44,200
North Hilo	1,180	1,366	1,500	1,600	1,600	1,800
Hamakua	4,182	5,132	5,600	6,000	6,400	6,800
North Kohala	4,131	5,490	6,700	8,200	9,900	11,800
South Kohala	8,985	12,983	15,400	18,300	21,300	24,700
North Kona	19,538	25,264	28,800	32,900	36,900	41,500
South Kona	5,872	8,501	9,700	11,000	12,300	13,800
Kau	3,989	5,345	6,000	6,700	7,300	8,000

Buses

- **Mass Transit.** The Island of Hawaii's mass transit system is comprised of approximately 20 Hele-On buses.[78] The Hele-On Bus provides transportation within the Kona and Hilo areas and has stops at perimeter towns between these two population areas including Waimea, Volcanoes National Park, and Pahoa. Averaging approximately 40,000 annual miles driven (comparable to Oahu's mass transit)[79] at 3.5 mpg[80] (5 days per week), the diesel demand for the entire fleet (assuming all are in service) is approximately 225,000 gallons per year.
- **Island Shuttles.** The Big Island has one major airport shuttle known as the SpeediShuttle, with shuttle buses that have a capacity of 9 to 12 people.[81] SpeediShuttle is a privately-owned, Hawaii-based company with 38 vehicles providing ground transportation shuttle service on the Big Island, Maui, Oahu, and Kauai. The company is a strong supporter of renewable fuels with a fleet of Mercedes Benz passenger shuttles that run on B100 (100% recycled vegetable oil), a carbon-neutral fuel. Furthermore, the company uses local suppliers of B100 to minimize the fleet's carbon footprint. Another popular island shuttle is the Ali'i Shuttle, which offers transportation from Kailua-Kona to Keauhou via Ali'i Drive, a common shopping destination.

[77] Source ("Totals" for Years 2000-2005): Passenger Vehicles Registered, Hawaii County: 1980 to 2006. Source (Years 2010-2025): Vehicle locations distributed according to population densities listed in Table 3.
[78] Department of Research and Development. County of Hawaii Data Book. Table 14.12 Hele-On Bus Service for Hawaii County: 1985 to 1999.
[79] DBEDT. 2007. 2007 State of Hawaii Data Book. Table 18.25: Public Transit, for Oahu: 1993 to 2007.
[80] Industry average.
[81] Speedishuttle website. http://www.speedishuttle.com/.

- **Tour Buses.** Two major tour bus companies serve the Big Island. Roberts Hawaii has a fleet of over 1,000 vehicles (approximately 25% of bus transportation market on Hawaii) and also operates most of the school buses.[82] Polynesian Adventure Tours/Grey Line Hawaii has a fleet of about 140 buses on four islands.[83] Both companies offer a Grand Circle Tour around the island's perimeter and a Volcanoes National Park Tour.
- **Hawaii Volcanoes National Park Buses.** Currently, a small demonstration of hydrogen buses (conducted by HNEI) is near deployment at the Hawaii Volcanoes National Park, the state's biggest tourist attraction. These buses will transport visitors around Crater Rim Drive and down Chain of Craters Road. Other than this demonstration, the Park does not have an official transportation system for its visitors.[84]

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[82] Roberts Hawaii website. http://robertshawaii.com/.
[83] Polynesian Adventure Tours website. http://robertshawaii.com/.
[84] Hawaii Natural Energy Institute. 2008. Hawaii Hydrogen Center for Development and Deployment of Distributed Energy Systems. June 10.

Appendix E: Constructive Policies

Hawaii is a progressive state with relatively high standards and generous incentives available to businesses that promote increased renewable energy use (including hydrogen and geothermal) and decreased oil imports. Selected noteworthy existing policies and regulations are described below.

State Laws, Regulations and Initiatives

- **Alternative Fuels Promotion.** A Memorandum of Understanding (MOU) between the State of Hawaii and the U.S. Department of Energy (DOE) was signed in January 2008, establishing the Hawaii Clean Energy Initiative. The MOU documents the collaboration intended to transform Hawaii's energy systems to meet up to 70% of the state's future energy needs with clean energy sources by 2030. The following specific goals of the initiative were cited: "[to] transition to a clean energy-dominated economy; demonstrate and foster innovation in the use of clean energy, including alternative fuels; create opportunities for the widespread distribution of clean energy benefits; establish an open learning model for other states and entities to adopt; and build a workforce with cross-cutting skills to support a clean energy economy in the state." [85]
- **Alternative Fuel Development Support.** The State of Hawaii is tasked with supporting alternative fuels development, potentially including hydrogen created via geothermal electricity. The State is also responsible for supporting the attainment of a statewide alternative fuels standard. The alternative fuels standard will be as follows: 10% of highway fuel use to be provided by alternative fuels by 2010, 15% by 2015, and 20% by 2020. [86]

Financial Incentives

Hawaii Renewable Hydrogen Program & Investment Capital Special Fund.[87] Act 240 was signed into law in 2006. This legislation established the Renewable Hydrogen Program in the Department of Business, Economic Development and Tourism (DBEDT) in order to manage the state's transition to a renewable hydrogen economy. An amount of $10 million was appropriated for the Hydrogen Investment Capital Special Fund to provide seed capital for private sector and cost share for Federal projects for research, development, testing, and implementation pursuant to the Hawaii Renewable Hydrogen Program. According to the legislation, the Hawaii Renewable Hydrogen Program "shall design, implement, and administer activities that include:

  - Strategic partnerships for research, development, testing, and deployment of renewable hydrogen technologies;

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[85] "Hawaii Hydrogen Laws and Incentives." Alternative Fuels & Advanced Vehicles Data Center. Office of Energy Efficiency and Renewable Energy. U.S. Department of Energy. (Directed from Database of State Incentives for Renewables & Efficiency (DSIRE) website.)

[86] *Ibid.*

[87] *Ibid.*

- Engineering and economic evaluations of Hawaii's potential for renewable hydrogen use and near-term project opportunities for the State's renewable energy resources;
- Electric grid reliability and security projects that will enable the integration of a substantial increase of electricity from renewable energy resources on the Island of Hawaii;
- Hydrogen demonstration projects, including infrastructure for the production, storage, and refueling of hydrogen vehicles;
- A statewide hydrogen economy public education and outreach plan focusing on the Island of Hawaii, to be developed in coordination with Hawaii's public education institutions;
- Promotion of Hawaii's renewable hydrogen resources to potential partners and investors;
- A plan, for implementation during 2007 to 2010, to more fully deploy hydrogen technologies and infrastructure capable of supporting the Island of Hawaii's energy needs, including: expanded installation of hydrogen production facilities; development of integrated energy systems, including hydrogen vehicles; construction of additional hydrogen refueling stations; and promotion of building design and construction that fully incorporates clean energy assets, including reliance on hydrogen-fueled energy generation;
- A plan, for implementation during the years of 2010 to 2020, to transition the Island of Hawaii to a hydrogen-fueled economy and to extend the application of the plan throughout the state; and
- Evaluation of policy recommendations to: encourage the adoption of hydrogen-fueled vehicles; continually fund the Hydrogen Investment Capital Special Fund; and support investment in hydrogen infrastructure, including production, storage, and dispensing facilities."[88]

- **Business Investment Tax Credit.**[89] Entrepreneurs seeking to make high-technology business investments, including hydrogen-related ventures, are eligible for tax credits applicable during the initial year of investment and the following four years. To be considered a "qualified high technology business," three conditions must be met: over 50% of the activities must be qualified research; 75% of the qualified research must be conducted in Hawaii; and over 75% of the income must originate from qualified research (e.g., from products sold, manufactured or produced in the state or from services performed in the State). "Qualified research" includes any research related to non-fossil fuel energy-related technology. As shown in Table E-1, the tax credit (that expires on December 31, 2010) is calculated on a percent basis of total investment for that year, up to the listed maximums.

[88] *Ibid.*
[89] *Ibid.*

Table E-1. Terms of the Business Investment Tax Credit.

Year	Tax Credit (percent of investment made)	Maximum Value of Credit
Year of Investment	35%	$700,000
1st Year Following Investment	25%	$500,000
2nd Year Following Investment	20%	$400,000
3rd Year Following Investment	10%	$200,000
4th Year Following Investment	10%	$200,000

In the event that the tax credit exceeds the taxpayer's income tax liability for any of the five applicable years, the remainder of the tax credit may be credited towards subsequent years until exhausted.

Appendix F: Details of Analyses

Geothermal Hydrogen Hawaii (GH3) Model

In order to illuminate optimized pathway(s), analyses were conducted prior to proposing a roadmap of geothermal energy-based hydrogen infrastructure for the Big Island. Information was collected relating to factors such as the geothermal resource base, current and projected costs of components of a hydrogen infrastructure, and technology characteristics. These specific data were then incorporated into the Geothermal Hydrogen for Hawaii (GH3) model to obtain results on the potential price of hydrogen and to perform sensitivity analyses on several factors and their relative effects. The following sections describe the model's structure (including its inputs, outputs, assumptions, and calculations) and results. Additionally, assumptions tables are provided to show details about the data behind the results graphs, and the electrolyzer specification table exhibits details obtained from the manufacturers of some of the system components. These tables are located at the end of this appendix.

Model Structure

The GH3 model has two components: (1) a state-of-the-art component and (2) a theoretical component. The state-of-the-art component uses values for equipment that is currently available or near-term. The theoretical component of the model is only used to estimate values for equipment that was not quoted by the manufacturer: the compressor and liquefier.

Based on this structure, the model analyzes hydrogen production cost for three production and delivery pathways (See Figure F-1 below for pathway schematics.):

1. **Central Gaseous Pathway.** Hydrogen is produced via electrolysis, compressed, and stored at the geothermal plant site. It is then delivered via pressurized tube trucks to refueling stations for dispensing.

2. **Central Liquefied Pathway.** Hydrogen is produced via electrolysis, liquefied, and stored at the geothermal plant site. It is then delivered in liquid form via cryogenic tankers to refueling stations for dispensing.

3. **Forecourt Gaseous Pathway.** Hydrogen is produced in a distributed fashion via electrolysis using grid electricity (equivalent to the geothermal electricity production) at refueling stations. It is then compressed, stored, and dispensed at these refueling stations.

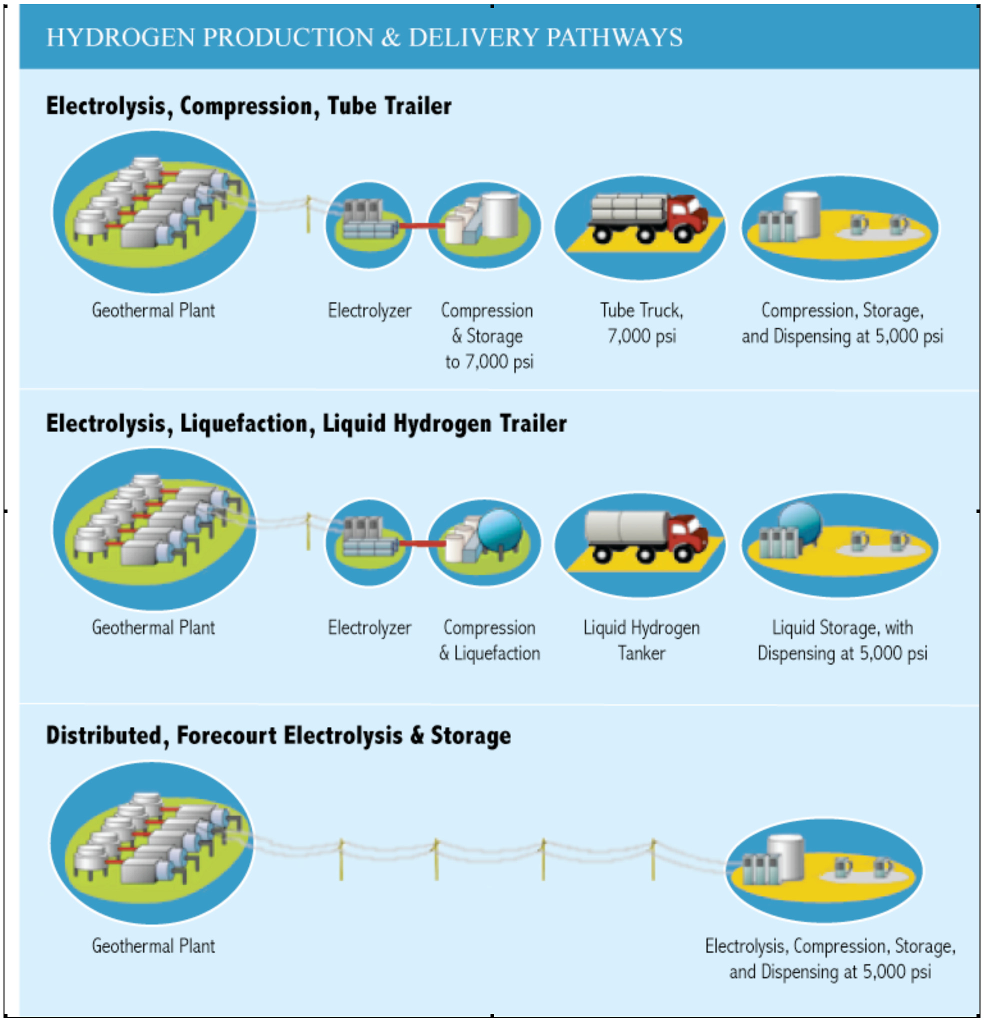

Figure F-1. Hydrogen production and delivery pathways.

The model calculates expected cost (on a per kilogram basis) to produce hydrogen using each pathway. The theoretical model component uses the compression and liquefaction component assumptions as defined by Hydrogen Analysis (H2A) analysis[90] and technology improvement multipliers based on the goals of the Hydrogen, Fuel Cells and Infrastructure Technologies (HFCIT) Program's multi-year program plan (MYPP).[91]

The model also includes parametric analyses to estimate the cost of produced hydrogen:

- Between 1 MW and 24 MW geothermal capacity in a given year
- Electricity price (varied from $0.02 per kWh to $0.50 per kWh)
- Plant construction year (varied from 2009 to 2025)

[90] H2A Analysis Website. http://www.hydrogen.energy.gov/h2a_analysis.html.
[91] DOE Hydrogen Program. Multi-Year Research and Development Demonstration Plan: Planned Program Activities for 2005 to 2015. http://www.eere.energy.gov/hydrogenandfuelcells/mypp.

Varying geothermal plant size accounts for multiple levels of available electricity due to potential geothermal energy capacity additions and increased curtailment levels. Varying the price of electricity allows for a comparison of hydrogen production costs based on different energy prices.

The GH3 model is a linear model with the specific goal of calculating the life-cycle hydrogen cost. The model is set up to investigate five constituents: electrolyzer, compressor, storage, dispenser, and other costs. Attributes of one area may be changed without inadvertently affecting another area. Each constituent includes O&M costs related to each component where appropriate, in addition to the system O&M costs.

The main inputs of the model are as follows:

- Energy Consumption (kWh/kg H_2)
  - Electrolyzer
  - Compressor
- Capital Cost ($)
  - Electrolyzer
  - Compressor
  - Storage
  - Dispenser
- Hydrogen Production (kg/hr)
- Equipment Shipping Cost ($)
- Installation Cost ($)
- Operational Hours (hrs)
- Electricity Cost ($/kWh)

The GH3 model uses quotes obtained from manufacturers, which are detailed in Table F-10. Information on existing or near-term equipment includes the following:

- Capital Cost ($)
  - Electrolyzer
  - Compressor
  - Storage Tank
  - Power Supply
  - Dispenser
- Electrolyzer Energy Consumption (kWh/kg H_2)
- Estimated O&M Cost ($)
- Equipment Shipping Cost ($)
- Installation Cost ($)
- Start-up/shut-down Stipulations for the Electrolyzer
- Electrolyzer Type and Specifications
- Equipment Footprint (ft^2)

The outputs of the model are as follows:

- Water Consumption (gal/yr) and Cost ($/gal)
- Total Hydrogen Produced (kg per year, hour and day)
- Annualized Cost ($/kg H_2 and $/yr) and Cost Contribution (%) for:

- Electricity
- Water
- Electrolyzer Capital Cost
- Compressor Capital Cost
- O&M Costs
- Storage Capital Cost
- Dispensing Capital Cost
- Other Costs

Calculations

The GH3 model uses the following equations to calculate the annual quantity of hydrogen produced and the cost of hydrogen for each pathway. For this analysis, two electrolyzers are considered: 125 kg/day and 500 kg/day. The specifications for these electrolyzers can be found in Appendix E.

Geothermal Electricity Available

To determine the amount of hydrogen that can be produced annually, the model first determines the amount of electricity available from curtailment of power from the geothermal plant, E_A:

$$E_A = E_{Curtailed} \cdot HRS \cdot CF \quad (F.1)$$

where

$E_{Curtailed}$	=	Energy available through curtailment, varied from 3 MW to 3.8 MW, based on an expected capacity addition of 8 MW and potential curtailment rates of 10% of the current geothermal capacity of 30 MW and 10% curtailment of expanded capacity of 38 MW.
HRS	=	Annual hours available for production, 3,652.5 hrs based on 365.25 days per year and 10 hours of daily curtailment during off-peak hours.
CF	=	Geothermal plant capacity factor, 0.95, as given in GeothermEx (2005).[92]

Hydrogen Production

The model uses the electrolyzer capacities and costs from manufacturer quotes to determine the maximum possible hydrogen production and the system component sizes. The electrolyzer size is determined based on adjusting the daily hydrogen production rates by first dividing the manufacturer rated daily hydrogen production by 24 hours to get the hourly production and then multiplying the hourly production by the 10 hours of available curtailed geothermal electricity. For the additional dedicated geothermal megawatts for hydrogen production (additions beginning in year 2014), a 24 hour production period has been used. The results for the two electrolyzer cases are shown in Table F-1. The full Electrolyzer Capacity shown in the first column reflects the capacity based on 24 hours of hydrogen production.

[92] "Assessment of Energy Reserves and Costs of Geothermal Resources in Hawaii." GeothermEx, Inc. for the State of Hawaii, Department of Business, Economic Development and Tourism. September 30, 2005.

Table F-1. Hydrogen Production.

Electrolyzer Capacity (kg H_2/24 hour day)	Electrolyzer Capacity (kg H_2/hr)	Electrolyzer Capacity (for 10-hour per day production; in kg H_2/day)
125	5.2	52
500	20.8	208

Electrolyzer Specifications

The electricity consumption of the electrolyzer is calculated by multiplying the manufacturer-quoted value of 52.3 kWh/kg H_2 (or 4.7 kWh/Nm^3 H_2) by the daily electrolyzer capacity to give the daily energy requirement values in Table F-2.

Table F-2. Electrolyzer Energy Requirement.

Electrolyzer (24 hour production capacity)	125 kg/day	500 kg/day
Electrolyzer Capacity (for 10-hour per day production; in kg H_2/day)	52	208
Manufacturer-quoted Energy Requirement (kWh/kg H_2)	52.3	52.3
Daily Energy Requirement For 24 Hour Production (kWh/day)	6538	26150
Daily Energy Requirement For 10 Hour Production (kWh/day)	2,720	10,878

The capital cost of the electrolyzer is determined based upon quotes from the manufacturer in the form of cost per kilowatt input power (Table F-3). These quotes are multiplied by the input power to obtain the electrolyzer capital cost. The input power is calculated as the maximum electricity necessary to operate the electrolyzer at full capacity. Since this is based on input kWs and not input kWhs, the hours of operation do not affect the capital cost of the electrolyzer.

Table F-3. Capital Cost of Electrolyzer Based on Manufacturer Quotes.

Electrolyzer Capacity (kg H_2/day)	Manufacturer-quoted Capital Cost ($/kW)	Input Power (kW)	Capital Cost ($)
125	1,200	272	$326,352
500	800	1,088	$871,200

Annualized Electrolyzer Cost

The continuous operation period of the electrolyzers was set to 10 years in the model. Year 10 of electrolyzer operation is when the manufacturer suggests major maintenance, which is estimated as 30% of the capital costs. This will be referred to as the baseline replacement cost. The baseline replacement cost impacts the annualized electrolyzer capital cost. The annualized electrolyzer capital costs (Table F-4) are determined using a 20-year payback period and 2.8% interest rate based upon The While House's Office of Management and Budget's Real Treasury Interest Rates.[93]

Table F-4. Annualized Electrolyzer Capital Costs.

Electrolyzer Capacity (kg H_2/day)	Annualized Electrolyzer Capital Cost ($)
125	19,033
500	50,808

Compression

The electrolyzers used for this analysis include compression up to 363 psi, so depending on the application, a compressor may not be necessary. However, for efficient hydrogen storage, it is necessary to add compressors, which increases the cost of hydrogen; this analysis includes compression unless stated otherwise. The impacts of excluding compression are illustrated in the sensitivity analysis. The quotes received from the manufacturers for compressors were for equipment at least four times larger than will be necessary for the scale of electrolyzers used. For this reason, the compressor has been estimated using the equation F.2, which is based on H2A assumptions. It should be noted that the compressor capital cost quoted from the manufacturer of $250,000 is only $10,000 (4%) higher than the calculated value for the maximum necessary compression, which could serve as validation for the calculated value.

The compressor size (in kW) is determined based on an isentropic compression equation. To compensate for the fact that this equation is based on ideal rather than actual hydrogen flow rates, all components are conservatively oversized.

$$EC_{i+1} = \frac{P_i \cdot V \cdot \frac{k}{k-1} \cdot \left[\left(\frac{P_f}{P_i} \right)^{\frac{k-1}{k}} - 1 \right]}{\eta_{isentropic}} \qquad \text{(F.2)}$$

where

[93] http://www.whitehouse.gov/omb/circulars/a094/dischist-2006.pdf.

P_i	=	Compressor input pressure, which is set equivalent to electrolyzer output pressure, 363 psia, based on manufacturer quotes.
P_f	=	Compressor output pressure, 7,000 psia, based on nominal H2A pressure for high-pressure tube-trailers. While current DOT regulations limit tube trailers to 3000 psi, the analysis allows for higher possible compression to account for technological advances and policy changes. The central gaseous production costs are based on tube-trailer delivery where the operating pressure of the tubes is 2640 psi and the maximum hydrogen capacity is 280 kg. Based on these specifications, the compressor has been conservatively oversized.
k	=	Hydrogen coefficient of specific heats, 1.4.
V	=	Hydrogen flow per second, set to $H_{2\text{-ideal}}$ (on volumetric flow basis).
$\eta_{isentropic}$	=	Isentropic compression efficiency, 0.65, typical.

Storage and Dispensing

Quotes for appropriate hydrogen storage and dispensing units were obtained from manufacturers as \$818/kg H_2 stored and \$132,000, respectively. Annualized storage and dispensing capital costs were calculated in the same manner as the annualized electrolyzer capital cost resulting in \$8,627/year and \$8,823/year, respectively.

Installation

Installation cost quotes from manufacturers include design support, the gas control panel, and pipe and fittings; these were valued at \$15,000, \$10,000, and \$10,000, respectively. These costs are included in the model as "Other Costs" and were also annualized. Electrolyzer O&M cost quotes from the manufacturers are 3% of the electrolyzer capital cost per year.

Electrolysis Raw Materials

Electrolysis requires electricity and water to produce hydrogen. The baseline analysis case uses an electricity cost of \$0.10/kWh, which is the assumed minimum possible cost for electricity on Hawaii. The sensitivity analysis shows how the cost of hydrogen is affected by varying the electricity rates.

The costs of the other electrolysis input, "Water," are based on rates from the Hawaii Department of Water Supply for a 5/8"meter size. Based on this meter size, there is a \$12/month charge and a rate of \$0.00075/gallon. Annual water cost has little effect on the final cost of hydrogen where the annual costs for the 500 kg/day electrolyzer operated for 10 hours/day are only \$227.

Yearly Electrolyzer Additions

To calculate the values for the two proposed scenarios of deployment, the model was configured to allow the addition of new equipment in any given year. For our analysis equipment was added in years 2012, 2014, 2017, and 2023.[94] The costs were calculated using the results from each electrolyzer size (based on hours of production) multiplied by

[94] Details of the deployment scenarios assumed are given in the Roadmap section, delineating when, where, how many and what capacity dispensing is implemented.

the number of individual electrolyzers added. The sum of all costs was then divided by the amount of hydrogen produced by the entire system to reach the cost of hydrogen per kilogram in a given year.

Central Gaseous Hydrogen Production

Central gaseous production was analyzed for the deployment strategy and was found to be a good method of large scale hydrogen production. Central gaseous production benefits from being located at or near the electricity generation site. This allows lower electricity rates because transmission and distribution (T&D) costs do not apply, which significantly lowers the rate in Hawaii. The limitation on central gaseous production is that the produced hydrogen must be delivered. Delivery is accomplished using high pressure tube tractor trailers. The additional costs of delivery add, on average, $1.89 to the final delivered cost of hydrogen; however, since electricity price is the major price driver, these additional costs are acceptable. The detailed assumptions for the additional delivery costs are equal to those given in Table F-5 for liquid hydrogen delivery with the only exceptions being the specifications for the trailer, which has a capital cost of $350,000 and a capacity of 280 kg.

Central Liquid Hydrogen Production

For the central liquid hydrogen production case, the costs, like the compressor, were modeled based on H2A assumptions. The hydrogen production portion of the model is not dependent on distributed generation or central production, so the additional costs of liquefying hydrogen were annualized and added to the final cost of hydrogen. These extra costs make the central liquid hydrogen production case feasible only if the electricity cost per kilowatt-hour is approximately $0.20/kWh less than that obtainable for the distributed production case. Further explanation for these conclusions is located in the results section below (Comparison of Distributed Production, Central Gaseous Production, and Central Liquefied Production). The details of assumptions for liquefying hydrogen and for liquid delivery are given in Table F-5.

Table F-5. Liquefaction Specifications.

LIQUEFACTION	
Liquefier(s) Size	548 kW
Liquefier Energy Demand	9.8 kWh/kg
Annual Liquefier Energy Consumption	1,902,983 kWh
Lifetime	20 years
O&M as Percentage of Capital	57%
Capital Cost of Liquefier	$8,561,800
Annual O&M Cost	$128,427
TRUCK DELIVERY	
Round-trip Distance	290 miles
Tractor Cost	$100,000
Tank Trailer Cost	$625,000 for liquid; $300,000 for gaseous
Tractor Trailer O&M Costs (includes driver, labor, repair, maintenance, and operating)	$300,000
Technology Cost Improvement Multiplier	66%
Cost Contingency	57%
Tank Capacity	3,653 kg
Max Trips per Day	2
Tractor/Trailer Units Required	1
Diesel Cost	$5.30
Truck Gas Mileage	6 mpg
Single Trip Fuel Cost	$256
Daily Diesel Cost	$512
Annual Diesel Cost	$187,130
Total Capital Investment	$520,536
Total Fixed O&M Costs	$300,000

The number of tractor-trailer units, N_{trucks}, required is calculated as follows and rounded up to the next whole number, as seen in equation F.3:

$$N_{trucks} = \frac{H_{2-ideal}}{Cap_{trailer} \cdot T_{max}} \quad (F.3)$$

where

$Cap_{trailer}$ = Liquid storage trailer capacity, 3,653 kg, based on H2A.
T_{max} = Maximum trips per day for single truck, 1.5 for liquid transport, estimated based on anticipated loading and unloading times.

Hydrogen Cost

The total hydrogen cost, C_{H2}, consists of capital, O&M, electricity, water, and fuel charges, as seen in equation F.4.

$$C_{H_2} = C_{Capital} + C_{O\&M} + C_{Electricity} + C_{Water} + C_{Fuel} \quad (F.4)$$

The value of each cost component is then calculated based on equation F.5:

$$\left[C_{Capital} = \sum_{Components} \left(C_{Component} \cdot M_C \cdot M_{TI} \cdot P_{Elec}\right)\right] \quad (F.5)$$

where

$C_{Component}$ = Individual capital component costs.
M_C = Cost contingency multiplier, 13% for compressors and 57%, for liquefiers and storage based on project and engineering contingencies listed in H2A. Contingency also conservatively set to 57% for electrolyzers.
M_{TI} = Technology cost improvement multiplier, which is a function of the projected year in which the component will be built and is based on projected cost improvements from HFCIT Multi-Year Program Plan.
P_{Elec} = Price paid for electricity, varied from \$0.00/kWh to \$0.50/kWh in parametric runs.

Results

Comparison of Distributed Production, Central Gaseous Production, and Central Liquefied Production

To determine whether distributed hydrogen production, central gaseous hydrogen production, or central hydrogen production with liquefaction is more feasible, the cost per kilogram of hydrogen produced was calculated for each case using electricity prices ranging from $0.02 to $0.50. Distributed production requires grid electricity, which includes transmission and distribution (T&D) costs. The HELCO Schedule P Rate for Large Power Use Businesses (Demand 200 kW or greater; 100,000 kWh/month or greater energy use) is $0.26/kWh.[95] For the centralized liquid case, there are no T&D costs, but the high capital cost of the liquefier, the additional electricity consumed by the liquefier, and the truck delivery costs of the liquid hydrogen all result in a higher hydrogen cost. Central gaseous production requires truck delivery, but does not require special equipment or additional electricity. Figure F-2 shows the cost for each case. From the graph it is seen that the additional costs associated with the central liquid production case does not allow it to be economically competitive with the distributed production at $0.26/kWh unless the electricity rates for central liquid production are below $0.10, which is not feasible. Central gaseous production will be subject to the same electricity rates as the central liquid case and will always be more economical. For these reasons, the central liquid production case was not considered as a feasible component for the roadmap.

[95] Average Electric Rates for Hawaiian Electric Co., Maui Electric Co. and Hawaii Electric Light Co. http://www.heco.com.

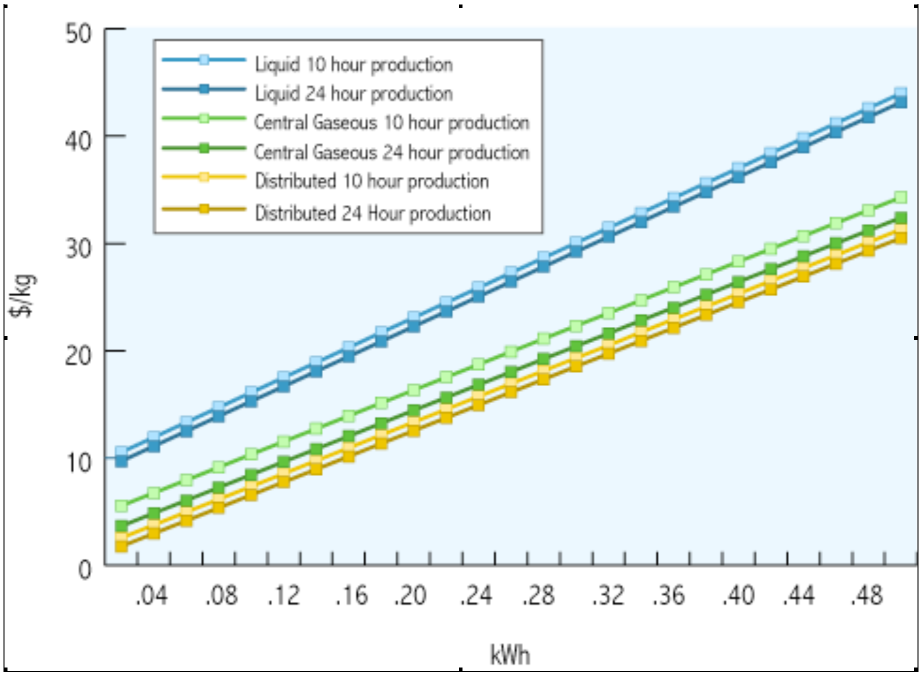

Figure F-2. Cost per kilogram of hydrogen per kWh.

Total Hydrogen Produced

Based on the roadmap, Figure F-3 shows the total hydrogen produced per year and the amount of diesel fuel that this hydrogen would displace based on the efficiency difference between a diesel vehicle and a fuel cell vehicle. By year 2025, the 3,788,828 kilograms of hydrogen produced could displace 5,737,368 gallons of diesel fuel.

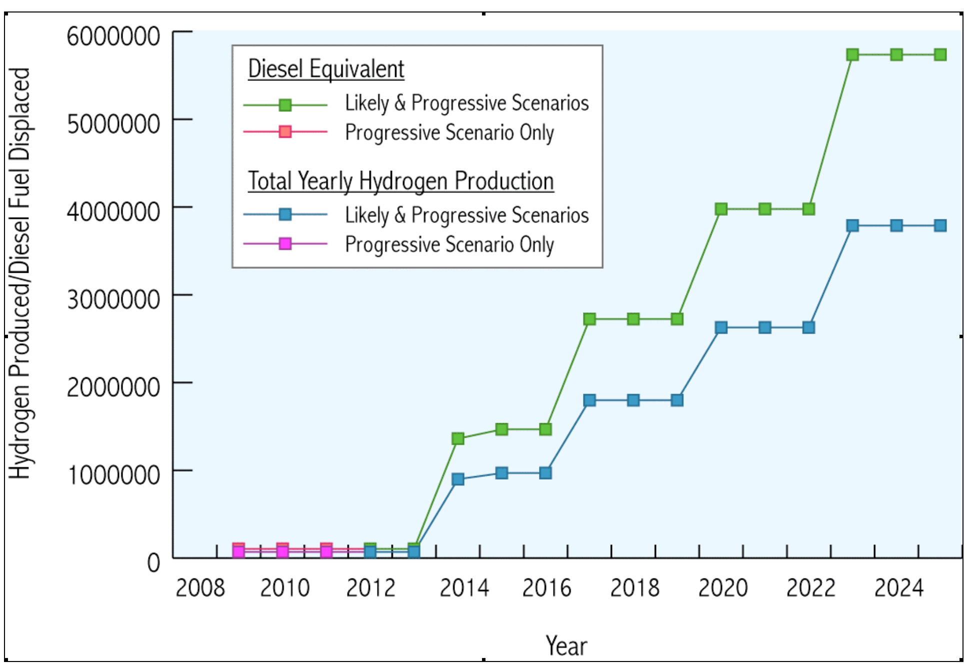

Figure F-3. Total hydrogen produced and the amount of diesel fuel displaced per year.

Fuel Usage Projection

To calculate the amount of hydrogen necessary to replace certain percentages of the Hawaii County transportation fleet, it was necessary to have a fuel usage projection for the year 2025. Figure F-4 shows the fuel usage for the State of Hawaii from the years 1990-2006.[96] A trend line was calculated, and the results showed that an additional 7,274,900 gallons of fuel were used per year. Hawaii County accounts for approximately 17.9% of the total State of Hawaii fuel usage, so this percentage was applied to the total additional fuel per year for the State, which resulted in 1,302,000 additional gallons of fuel used in Hawaii County per year. Hawaii County's fuel use in 2006 was 95,723,000 gallons, so based on the calculations, the projected fuel use for Hawaii County in year 2025 was found to be 120,465,000 gallons.

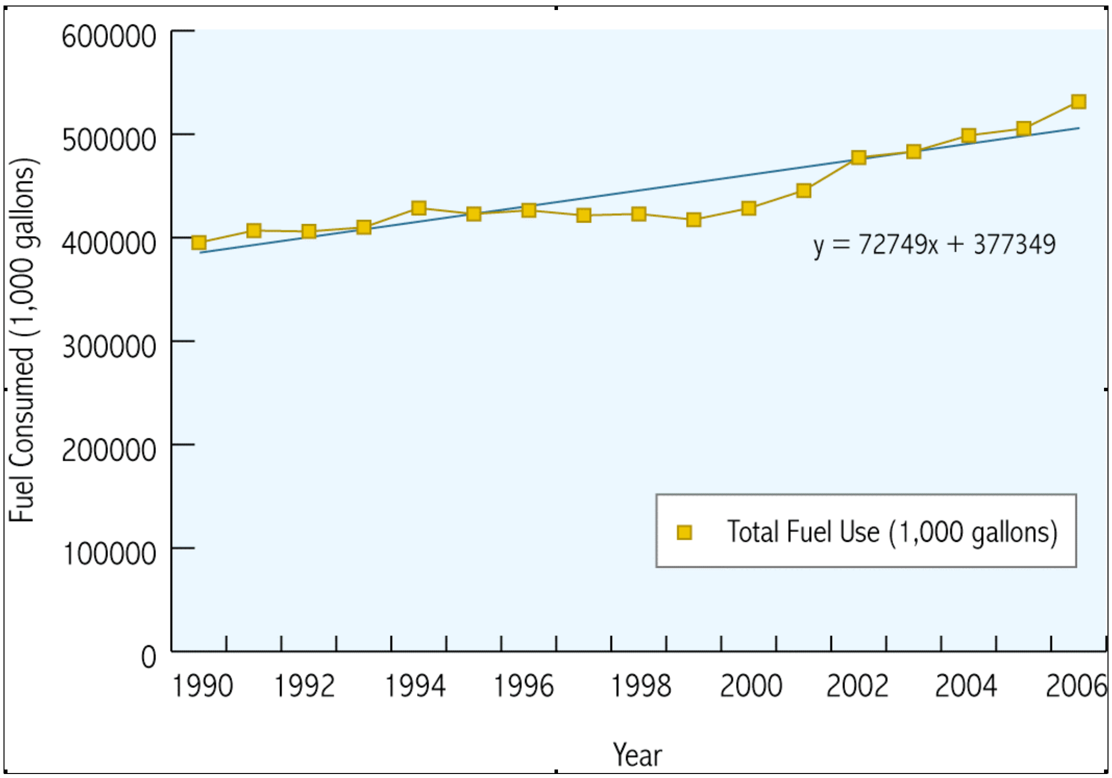

Figure F-4. Hawaii fuel usage 16-year trend.

Cost Components of Electrolyzers

Figure F-5 shows the cost components for a 125 kg/day electrolyzer and a 500 kg/day electrolyzer. The cost of electricity ($0.10/kWh for these results) is the primary factor, but it is a larger percentage for the 500 kg/day electrolyzer. For this reason our scenarios put precedence on adding the larger electrolyzers to minimize the percentages contributed by capital cost.

[96] Hawaii DBEDT 2007 Databook Section 18.17.

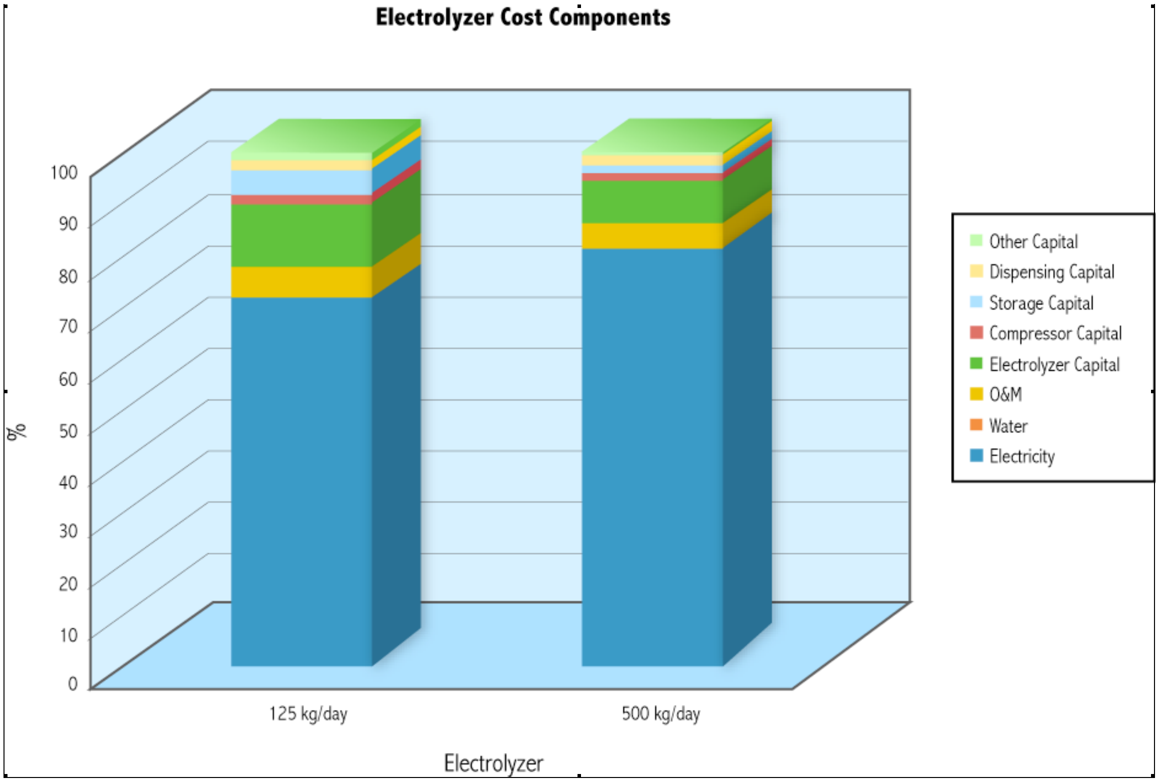

Figure F-5. Cost components for each electrolyzer.

Figure F-6 illustrates the individual cost components for each electrolyzer.

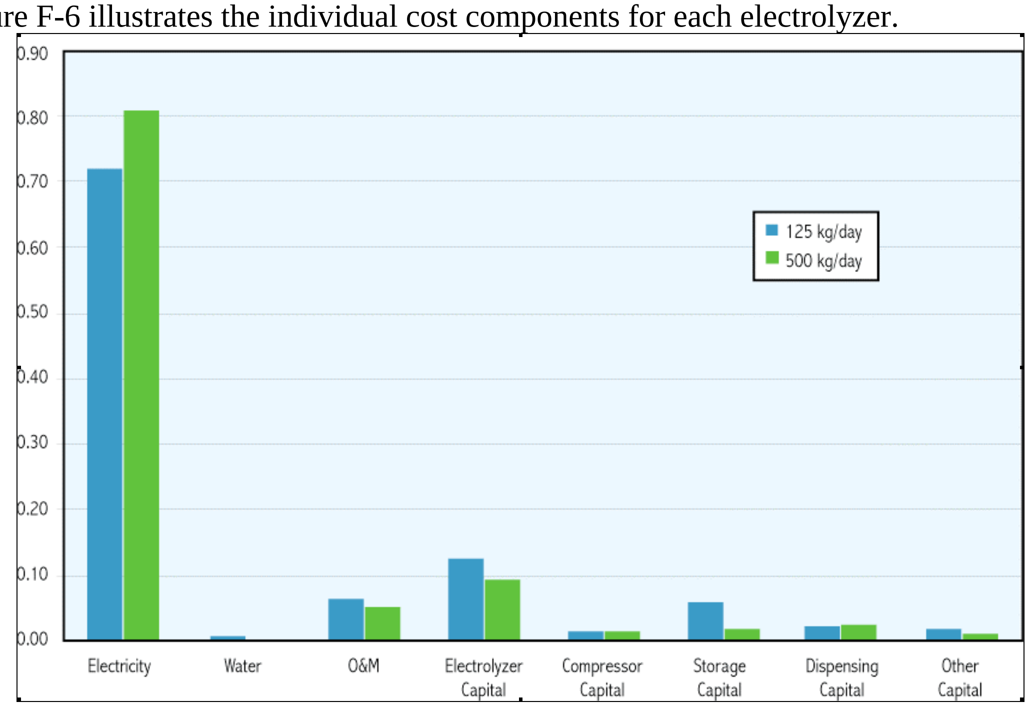

Figure F-6. Individual cost components of hydrogen production.

The electrolyzer capital cost plays a more significant role in the smaller-size electrolyzer, while electricity cost is a more dominant contributor in the larger-size electrolyzer.

Comparison of DOE Goals and GH3 Results

Table F-6 shows how the results of the GH3 model compare to the 2012 goals as set in the DOE Hydrogen, Fuel Cell and Infrastructure Technologies (HFCIT) Program's MYPP.

Table F-6. Comparison of DOE Goals and GH3 Results.

Category	GH3 Results (500 kg/day Electrolyzer Used)	2007 DOE Goals for Year 2012
$/kg or $/GGE	$6.57	$3.70
Electricity Cost	$0.10/kWh	$0.039/kWh
Electrolyzer Capital Cost	$0.68/kg	$0.70/kg
Electrolyzer Energy Efficiency	63%	69%
O&M	$0.37	$0.60

The 500 kg/day electrolyzer used by the GH3 model compares favorably with the HFCIT MYPP 2012 goals. Using the MYPP's electricity price goal of $0.039/kWh, the 500 kg/day electrolyzer would produce hydrogen at $3.35. As discussed, the capital cost of the electrolyzer for the base case GH3 results is the most optimistic value, which is shown through the results being $0.02 lower than the MYPP 2012 goals. Additionally, because the case considered in this comparison does not use a compressor or truck delivery, the O&M costs are significantly lower. These issues will be addressed in the sensitivity analysis.

Comparison of Hydrogen Costs per Mile

Figure F-7 displays the costs per mile for fuel cell buses, as compared to diesel cost projections. It is projected that diesel fuel prices will continue to go up. The diesel fuel costs start at the 2008 average of $5.30/gallon[97] and are projected to rise 4% per year based on the past 10-year CPI averages from the Bureau of Labor Statistics. The hydrogen case presented uses $0.26/kWh for the curtailed geothermal electricity (distributed hydrogen production) and $0.15/kWh for the dedicated geothermal electricity (central gaseous hydrogen production). The cost per mile values for the hydrogen fuel cell bus decreases annually, while the diesel prices continue to increase. In the year 2020, the fuel cell bus becomes more economical than a diesel bus. The diesel fuel price in 2020 is $7.85/gallon and the hydrogen price is $11.73, but due to the increased efficiency of the fuel cell bus, hydrogen is economically competitive.

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[97] American Automobile Association. Fuel Gauge Report. Hawaii Metro Averages: Hilo, HI. http://www.fuelgaugereport.com/HImetro.asp.

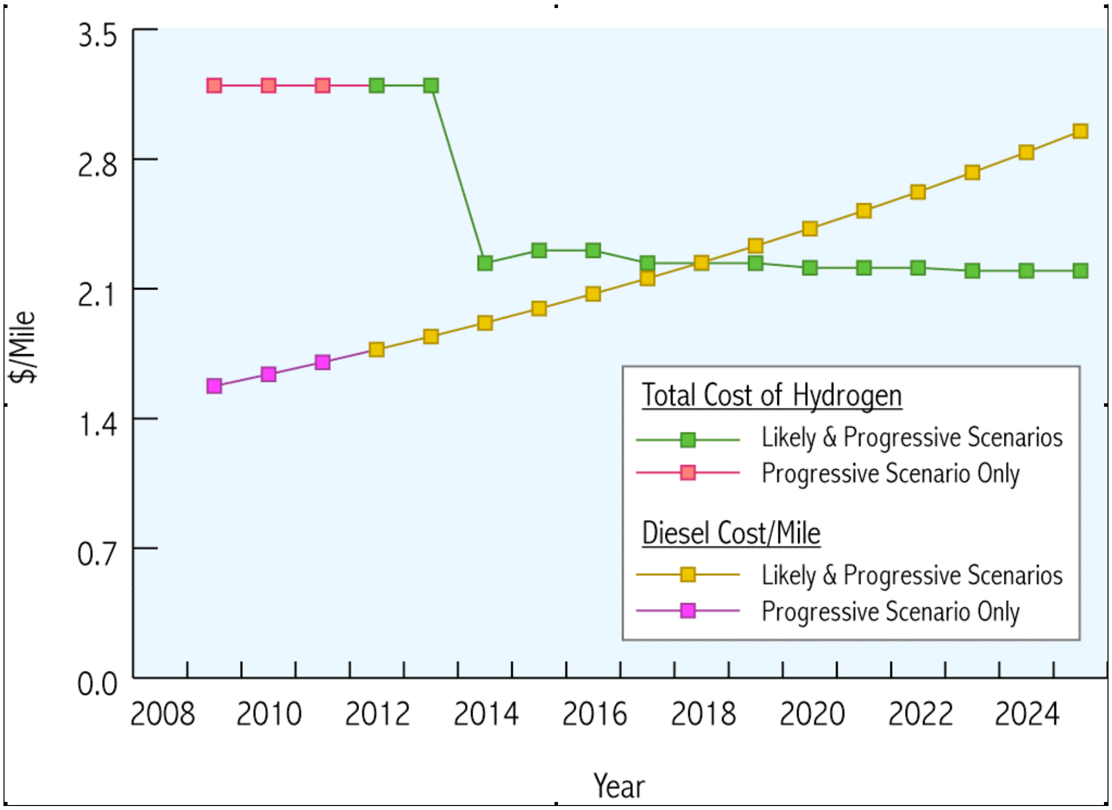

Figure F-7. Cost per mile of fuel cell bus compared to diesel bus.

Sensitivity Analyses

Electricity Rate

As seen in Figures F-5 and F-6, the electricity rate is by far the most important cost component for hydrogen. Figure F-8 shows the primarily linear relationship between electricity cost per kilowatt-hour and the cost per kilogram of hydrogen produced.

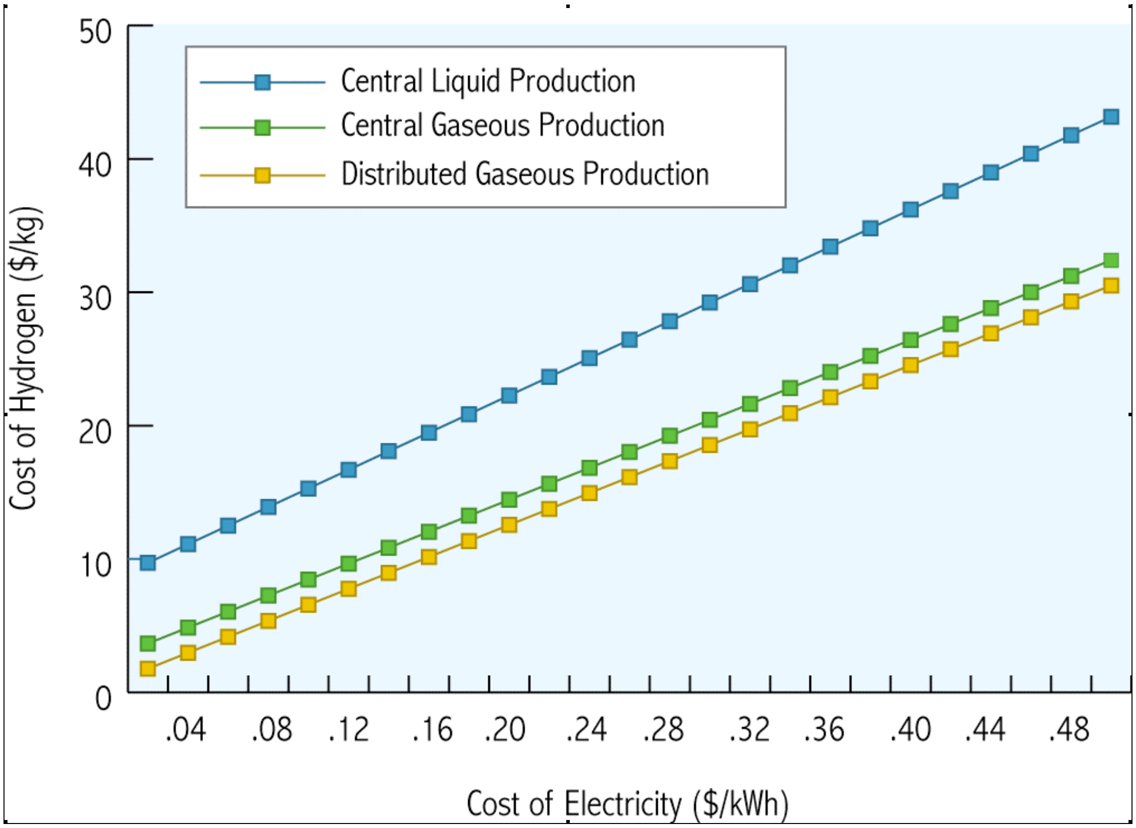

Figure F-8. Electricity rate sensitivity.

Electrolyzer Capital Cost

As previously discussed, the base line case for this analysis used the optimistic cost per kilowatt to price the electrolyzer. Table F-7 shows how the cost per kilogram of hydrogen is affected by varying the electrolyzer capital cost.

Table F-7. Electrolyzer Capital Cost Sensitivity.

Electrolyzer Capacity (kg/day)	Input Power (kW)	Optimistic $/kW	Pessimistic $/kW	Optimistic Capital Cost ($)	Pessimistic Capital Cost ($)
125	272	1,200	1,500	326,352	407,940
500	1,088	800	900	871,200	979,056

Compressor

The base line case for this analysis utilizes a compressor able to augment the electrolyzer's inherent compression of 363 psi to 7000 psi. Table G8 illustrates how the utilization of a compressor affects the cost per kilogram of hydrogen.

Table F-8. Compressor Sensitivity.

Electrolyzer Capacity (kg/day)	Capital Cost of Compressor ($)	Energy Requirement of Compressor (kWh/kg H_2)	Additional Cost of Hydrogen with Compression (Cost in $/kg H_2)
125	23,471	6.95	0.84
500	92,437	6.99	0.78

By-product Oxygen

The 125 kg/day and 500 kg/day electrolyzers have the same gaseous flow rates of 5.2 kg/hr hydrogen and 48 kg/hr oxygen. As shown in Table F9, if 100% of the oxygen produced is captured and sold, it would offset approximately $0.17/kg of the cost of hydrogen.

Table F-9. Oxygen By-product Sensitivity.

Electrolyzer Capacity (kg/day)	Hydrogen per 10-Hour Production Day (in kg)	Oxygen per 10-hour Production Day (in kg)	Value of Oxygen Based on $0.02/kg	Hydrogen Cost Offset Due to Sale of Oxygen
125	52	428	$8.56	$0.17
500	208	1,712	$34.24	$0.17

Project Lifetime

The project lifetime was varied for 7, 10, 15, and 20 years to examine how the payback period affected the cost of hydrogen. As expected, the cost per kilogram hydrogen decreases as the number of years for payback increases (Figure F-9).

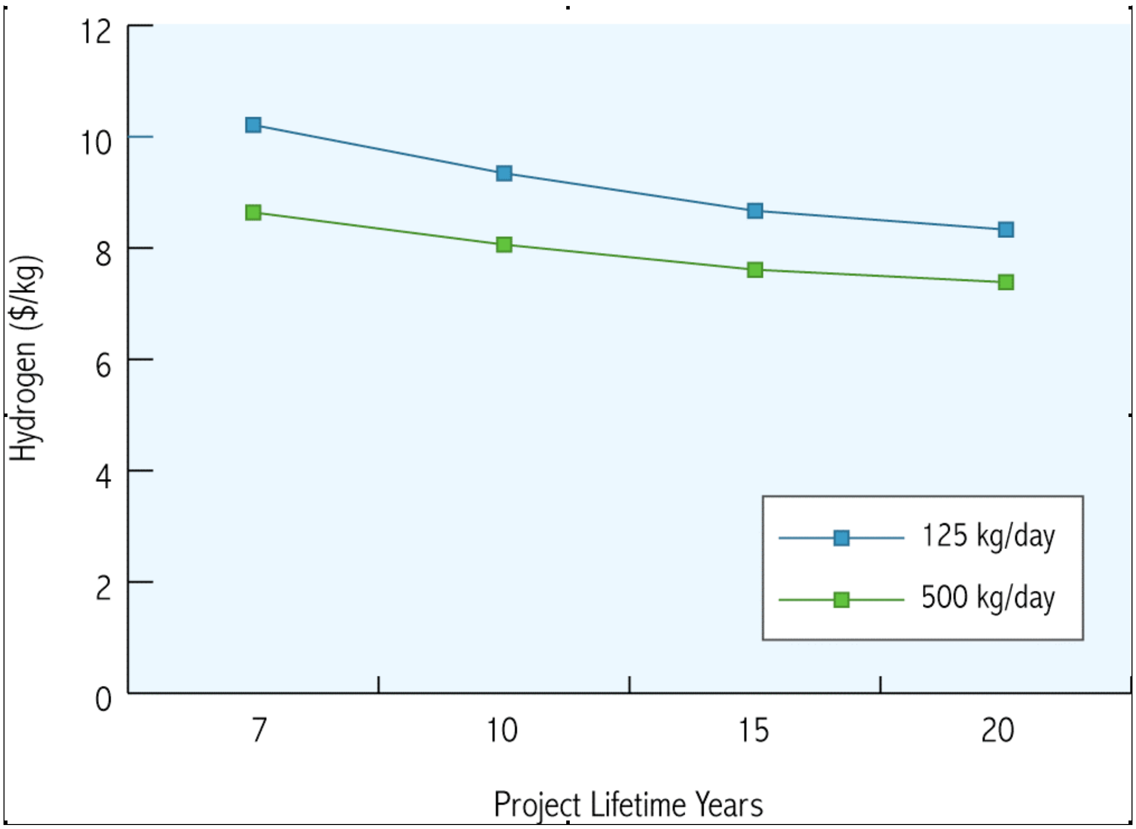

Figure F-9. Cost of hydrogen variations by project lifetime.

Financial Incentives

If financial incentives are available to offset some of the initial capital costs, the cost per kilogram of hydrogen will decrease. Figure F-10 illustrates the cost per kilogram of hydrogen based on financial incentives covering 0-100% of the capital costs for the electrolyzer, storage, dispenser, and installation costs.

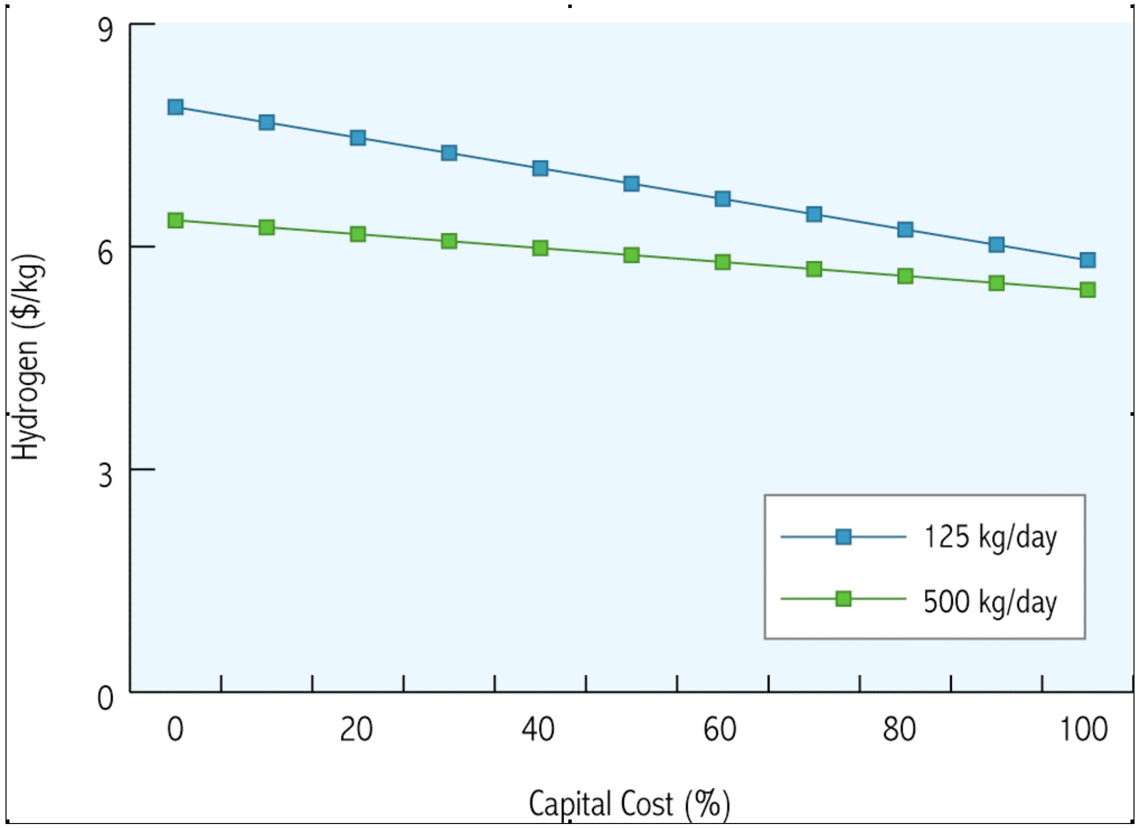

Figure F-10. Hydrogen cost variations by percentage of capital cost covered by financial incentives.

Total Funding

For hydrogen to be immediately competitive with diesel fuel at $5.30/gallon, it must reach $8.02/kg. As seen in the top graph of Figure F-11, electricity rates of $0.26/kWh for distributed production and $0.15/kWh for central gaseous production will not produce hydrogen at this cost. Figure F-11 also shows the amount of funding that will be required for hydrogen to be produced at $8.02/kg. This is calculated by first obtaining the difference between the actual hydrogen costs and $8.02 in a given year and multiplying this difference by the total hydrogen produced.

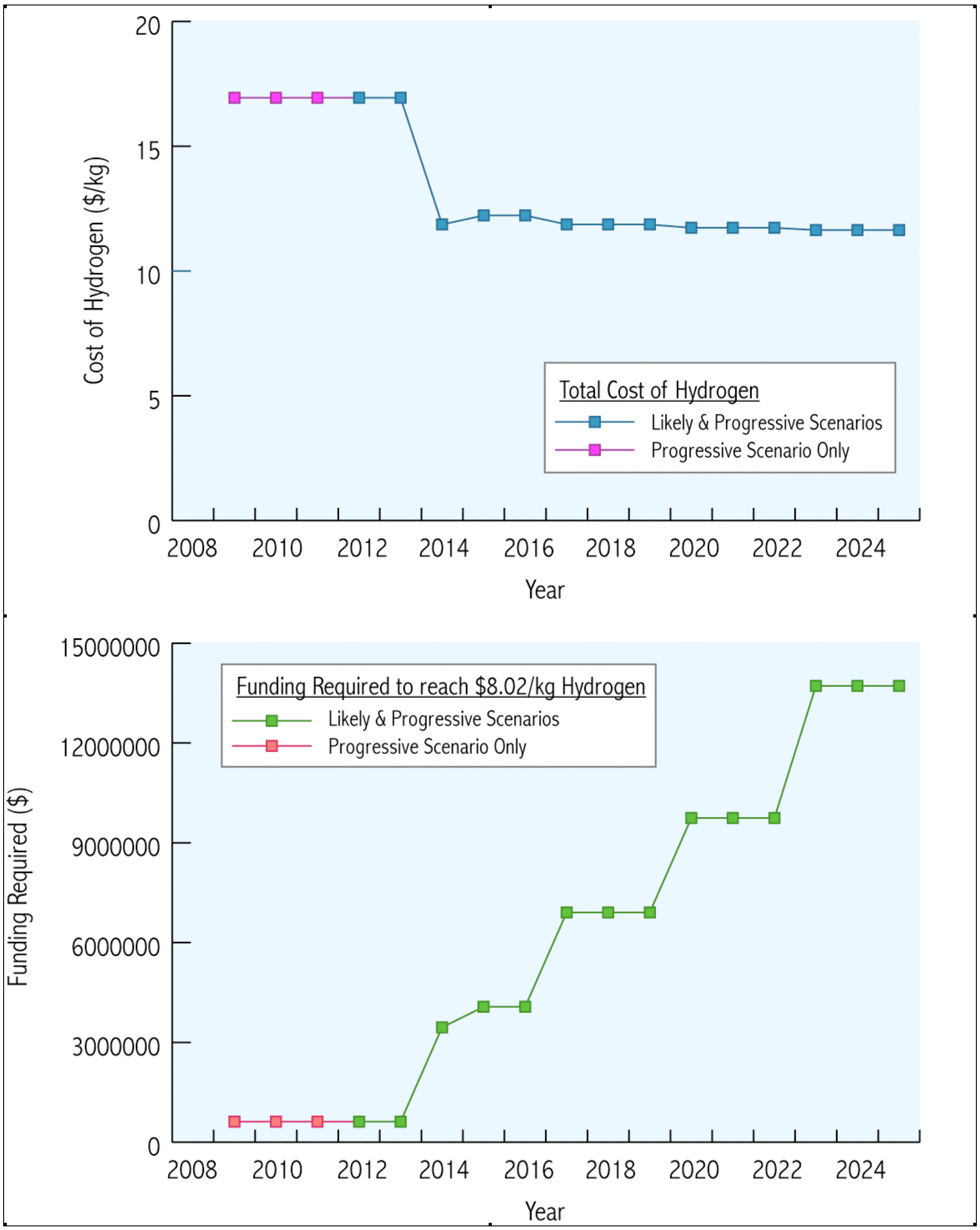

Figure F-11. Total funding necessary to reach $8.02/kg hydrogen

Tornado Chart Summary

As seen in Figure F-12, electricity cost has the greatest effect and is the only variable capable of enabling hydrogen costs to be reduced to a point close to DOE targets. The base line case in this example does not utilize compression and assumes a $0.10/kWh cost of electricity. The addition of compression, which is likely for most applications, will increase the cost per kilogram of hydrogen, as will using the pessimistic values for the capital cost of the electrolyzer. Financial incentives have the second largest effect in reducing hydrogen cost. Sale of by-product oxygen reduces the cost of hydrogen by $0.17/kg. Using the low, or optimistic, values from the tornado chart (Figure F-12) for all the factors except electricity ($0.10/kWh), the cost per kilogram of hydrogen for the large electrolyzer is $5.03.

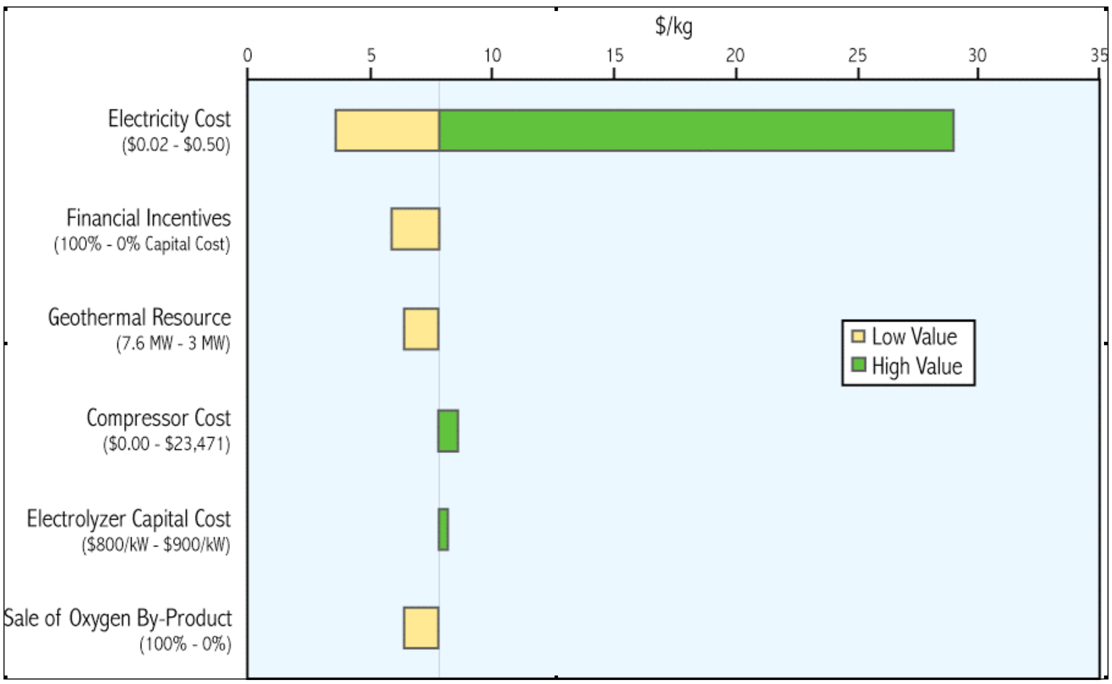

Figure F-12. Sensitivity analysis for 500 kg/day electrolyzer.

Table F-10. Modeling Assumptions

MODELING ASSUMPTIONS	
Hours of Operation	10 hours Curtailed; 24 hours Dedicated
Hawaii Cost of Labor Multiplier	0.94
Water Meter Size	5/8”
Monthly Water Meter Charge	$12.00
Cost of Water Usage	$0.00075
Dispenser Capital Cost	$132,000
Dispenser Lifetime	20 years
Storage Capital Cost	$818/kg; $102,250 for 125 kg/day; $409,900 for 500 kg/day
Storage Lifetime	20 years
Installation Design Support	$15,000
Mechanical Equipment: Gas Control Panel	$10,000
Mechanical Equipment: Pipe and Fittings	$10,000
Maintenance and Spares per Annum	$10,000
Yearly Electrolyzer O&M	3% of capital cost; $26,136 for 500kg/day
Electrolyzer 10-year maintenance	30% of capital cost; $261,360
Assumed Production Loss	1% hydrogen produced
LIQUEFACTION	
Liquefier(s) Size	548 kW
Liquefier Energy Demand	9.8 kWh/kg
Annual Liquefier Energy Consumption	1,902,983 kWh
Lifetime	20 years
O&M as Percentage of Capital	57%
Capital Cost of Liquefier	$8,561,800
Annual O&M Cost	$128,427
TRUCK DELIVERY	
Round-trip Distance	290 miles
Tractor Cost	$100,000
Tank Trailer Cost	$625,000 for liquid; $300,000 for gaseous
Tractor Trailer O&M Costs (includes driver, labor, repair, maintenance, and operating)	$300,000
Technology Cost Improvement Multiplier	66%
Cost Contingency	57%
Tank Capacity	3,653 kg for liquid; 280 kg for gaseous
Max Trips per Day	2
Tractor/Trailer Units Required	1
Diesel Cost	$5.30
Truck Gas Mileage	6 mpg
Single Trip Fuel Cost	$256
Daily Diesel Cost	$512
Annual Diesel Cost	$187,130
Total Capital Investment	$520,536
Total Fixed O&M Costs	$300,000

COMPRESSION		
Compressor(s) Size	$EC_{i+1} = \frac{P_i \cdot V \cdot \frac{k}{k-1} \cdot \left[\left(\frac{P_f}{P_i}\right)^{\frac{k-1}{k}} - 1\right]}{\eta_{isentropic}}$	
Compressor Outlet Pressure (up to)	7,000 psi	
Compressor Outlet Pressure (up to)	476 atm	
Annual Energy Consumption	(Operation hours/year)*(Compressor Size)	
Cp/Cv	1.40	
Compressor Isentropic Efficiency	65%	
Lifetime	20	
O&M as Percentage of Capital	1.5%	
Compressor Cost	$6,300 / kg / hour flow	
Technology Cost Improvement Multiplier	92%	
Technology Cost Improvement Multiplier (in 5 yr)	92%	
Technology Cost Improvement Multiplier (in 10 yr)	80%	
Technology Cost Improvement Multiplier (in 15 yr)	80%	
Cost Contingency	25.0%	
Capital Cost of Compressor	$221,848 for 500 kg/day	
Annual O&M Cost	3327.72	
ELECTROLYZER SPECIFICATIONS		
Category	125 kg/day	500 kg/day
Cost	$1,200 - $1,500 / kW input power	$800 - $900 / kW input power
Electricity Consumption	52.3 kWh/kg	52.3 kWh/kg
Hourly Production	5.2 kg	20.8 kg
Outlet Pressure	363 psi	363 psi
Lifetime	20 years	20 years
O&M Costs	30% of capital cost after 10 years	30% of capital cost after 10 years
Standard Hydrogen Purity	99.9%	99.9%
Power Supply	380 – 600 VAC / 50 – 60 Hz, 3 phase	380 – 600 VAC / 50 – 60 Hz, 3 phase
Packaging	Indoor or outdoor operation. Optional steel containers or ISO container (10', 20', 40')	Indoor or outdoor operation. Optional steel containers or ISO container (10', 20', 40') Estimated.
Oxygen Production	42.8 kg/hour	171.2 kg/hour

Appendix G: Possible Future Integration of Other Renewables

To fuel a significant portion of the Big Island's passenger vehicles, it is likely that other renewable energy resources besides geothermal will be needed to meet hydrogen production demands. Many other renewable resources on the Big Island are currently underutilized and could be harnessed as complementary sources of hydrogen production to augment renewable hydrogen efforts. The two energy sources with the most potential to supply the excess electricity are wind and biomass.

Wind

Intermittent generation and off-peak curtailment often results in a surplus of electricity from wind. Thus, wind is one possible source of renewable energy for hydrogen production. The island currently has three primary wind energy projects in operations totaling over 30 MW of capacity. On the Big Island's South Point, the Pakini Nui Wind Farm's fourteen 1.5-MW wind turbines began operation in April 2007, accounting for 20.5 MW of capacity – enough to power over 10,000 homes. In 2006, Hawi Renewable Development built a 10.5-MW wind farm on the northernmost point of the island, called Upolu Point (Figure G-1). The third, and oldest, wind farm on the Big Island is the Lalamilo Wind Farm in Waikoloa, which is now owned by HELCO. The farm's output has gradually declined over the past few years as the turbines have worn out. In 2006, Lalamilo's capacity was estimated at only 1.2 MW, but HECO has announced plans of adding up to 10 MW of wind energy at this site. [98]

Figure G-1. Wind farm at Upolu Point. (Source: HECO)

With more than 40 MW of wind capacity expected in the near future, the surplus wind energy on the Big Island has the potential to produce approximately 260,000 kg of hydrogen (at a 10% curtailment rate) annually.

[98] Department of Business, Economic Development & Tourism, State of Hawaii. Wind: Use of Wind Energy in Hawaii. Last modified 5/16/08. http://hawaii.gov/dbedt/info/energy/renewable/wind.

Biomass

A variety of biomass resources exist on the Big Island, but only a small amount of biomass is actually utilized for energy production purposes. In Sentech's December 2006 study, *A Rational Deployment Scenario for Renewable Hydrogen on the Island of Hawaii*,[99] a Hawaii Natural Energy Institute (HNEI) report[100] was referenced to catalogue the available biomass resources for each county in Hawaii. For the Big Island, annual production of potential resources included 410 tons of swine manure, 1,520 tons of poultry waste, 19,000 tons of macadamia nut shells, 110,000 tons of municipal solid waste, 24,000 tons of food wastes, 183 tons of sewage sludge, and 1,850 tons of fat, oil and grease wastes.

Interest in biomass resource development on the Big Island appears to be growing. For example, a 30 MW biomass combustion plant has been proposed by Hamakua Biomass Energy (HBE) and is planned for Hamukua. In addition, a biomass-powered generation facility to be built in O'okala plans to produce renewable energy from scrap wood. Under a power purchase agreement (PPA) between Hawaii Electric Light Company (HELCO) and Tradewinds Forest Products, LLC, the 2-3.6 MW of electricity developed at the generation facility will be purchased by HELCO on a scheduled basis. Subject to an amended PPA, Tradewinds has displayed interest in starting sales to HELCO in fall of 2010.[101]

Specific to biomass conversion technologies, a consortium of groups[102] has recently formed to explore the potential of using biomass gasifiers for hydrogen production. Led by the Gas Technology Institute, the consortium also includes HNEI, the Electric Power Research Institute, Calla Energy Partners and HECO. The consortium could potentially become a valuable partner in biomass to hydrogen production if research appears promising.

Advanced Geothermal Technologies

The lower KERZ region (where PGV is located) is especially appealing due to its high reservoir temperatures of 580-650 ^{o}F, resulting in greater recovery efficiencies. Lower-temperature resources on the Big Island, such as Hualalai (northeast of Kailua-Kona) and the Mauna Loa Southwest Rift Zone (near South Point), with potential for geothermal development have therefore been viewed as less economically feasible locations for electricity generation. Expansion beyond the KERZ region, however, may be beneficial to a growing hydrogen infrastructure since it would minimize ground transportation of hydrogen as well as decrease the need for cross-island electricity transmission to hydrogen generation sites.

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[99] Liu, et al. 2006. *A Rational Deployment Scenario for Renewable Hydrogen on the Island of Hawaii*. Sentech, Inc., for the U.S. Department of Energy. December 1.

[100] Hawaii Natural Energy Institute. 2002. Biomass and Bioenergy Resource Assessment: State of Hawaii. December.

[101] Hawaiian Electric Company, Inc. 2007 Renewable Portfolio Standard Status Report. For the Year Ended December 31, 2007.

[102] Hawaii Natural Energy Institute, University of Hawaii at Manoa. Biomass Resource Assessments: Biomass Resources for Hydrogen Production via Gasification. http://www.hnei.hawaii.edu/bio.assess.asp.

Recently, companies like United Technologies have introduced a system capable of utilizing low-temperature geothermal resources for electricity generation from waste hot water. United Technologies has developed a modular, 200 kW power plant that can convert temperatures down to 165 ^{o}F into electricity through a reverse cooling system that vaporizes a hydrofluorocarbon refrigerant to drive a turbine.[103] This technology makes sites like Hualalai and Mauna Loa Southwest more appealing for providing more efficient power and geographically expanding the potential generation sites of hydrogen throughout the Big Island.

[103] Patel-Predd, Prachi. 2006. *Power from Not-So-Hot Geothermal*. Technology Review. Published by MIT. September 21.

Appendix H: Other Potential Partners, Cooperating Groups and Supporters

The following selected entities have the potential to add value to the implementation and deployment of this Roadmap, subject to the conditions at implementation:

- **Regulatory Agencies:** The Hawaii Public Utilities Commission (PUC) "regulates all franchised or certificated public service companies operating in the state; prescribes rates, tariffs, charges and fees; determines the allowable rate of earnings in establishing rates; issues guidelines concerning the general management of franchised or certificated utility businesses; and acts on requests for the acquisition, sale, disposition or other exchange of utility properties, including mergers and consolidations."[104] The PUC may set electricity rates that will aid in bringing overall implementation costs down.

  Communication with two primary Hawaii County departments would be required to design and build hydrogen generation and dispensing stations: the Department of Planning and the Department of Public Works. Both agencies are involved in permitting. The Department of Planning provides technical advice to the Mayor and the Planning Commission and County Council on all planning and land use matters. The Department of Public Works is responsible for all matters relating to engineering, public and private building construction and inspection, acquisition of public and private properties for pubic purposes, and building permits.

- **National Laboratories:** National laboratories conducting research and development of hydrogen, fuel cells, and/or renewable energy applications may wish to participate in demonstrations or projects on the Big Island to collect data on new technologies. Three labs that are currently highly involved in this type of research are the National Renewable Energy Laboratory (NREL), Argonne National Laboratory (ANL), and Sandia National Laboratory (SNL).

- **Trade Associations / Other Organizations:** Many supporters of the introduction of hydrogen and other renewables on the Big Island may be interested in assuming an active role in its implementation. They can play an important role in assisting with the education and outreach efforts tied to the deployment of this Roadmap. Several organizations and associations are envisioned to play an active role:

  - **National Hydrogen Association (NHA):** The NHA brings together representatives from the automobile industry; the fuel cell industry; aerospace; federal, state, and local government; energy providers; and many other industry stakeholders, having reached a membership of 100 organizations. It allows stakeholders to exchange important information and engage in cooperative projects, while promoting the role of hydrogen throughout the energy community. Large national conferences, as well as focused specific forums organized by the association, can enable hydrogen efforts (such as those on the

[104] Public Utilities Commission. http://www.hawaii.gov/budget/puc/.

Big Island and in the State of Hawaii) to come to the forefront and allow for valuable partnerships to develop for the deployment of infrastructure for hydrogen produced from renewable resources.

- **U.S. Fuel Cell Council (USFCC):** The USFCC, another large nationwide association, is an industry association that promotes the commercialization of fuel cells in the U.S. Members include representatives from fuel cell companies, automakers and their suppliers. The USFCC provides a forum for members to play a role in shaping programs, policies, and practices needed to successfully commercialize fuel cells. As these technologies are tested on the Big Island, interactions with this association will be key for both information exchange and potential partnerships.
- **Geothermal Energy Association (GEA):** The GEA is a trade association consisting of companies that support the expanded use of geothermal energy and the development of geothermal resources worldwide for electrical power generation and direct-heat uses. With geothermal resources being considered for the production of hydrogen, interactions with this association will allow for information exchange on advanced technologies, as well as the attraction of developers of these technologies to the island.
- **Hydrogen Utility Group (HUG):** This group grew out of the relationships that the U.S. Department of Energy's (DOE) Office of Energy Efficiency & Renewable Energy (EERE) built with the utility industry. HUG has now become a working group consisting of utilities from the U.S. and Canada, DOE, NREL, Electric Power Research Institute (EPRI), and NHA. The group aims to accelerate utility integration of promising hydrogen energy-related technologies. It offers a forum for utilities to share experiences, build business cases, identify challenges (regulatory, technical, and strategic), identify opportunities, and provide input on various existing and future roadmaps and R&D programs. It is anticipated that HUG will be able to assist in the implementation of this Roadmap (and other efforts) in ways that will benefit the hydrogen and utility communities.
- **National Energy Laboratory of Hawaii Authority (NELHA):** NELHA is a state agency that provides information resources and facilities for energy-related research, education, and commercial activities. It operates a technology park in Kailua-Kona and is strategically located close to the Kona International Airport. The NELHA site includes office and laboratory facilities, demonstrations of renewable technologies, and leasable open land for research, education, and commercial project use. It may serve as a setting for the deployment envisioned on the Kona side.
- **Office of Hawaiian Affairs (OHA):** OHA functions as both a government agency and as a trust to provide the opportunity for a better life and future for Hawaiians. The organization has shown interest in energy projects and also receives royalties from the geothermal resource located on the island.
- **Council for Native Hawaiian Advancement (CNHA):** CNHA is a national, member-based, non-profit organization engaged in community development programming in Native communities in Hawaii and the Pacific. It is one of the largest national organizations serving Native Hawaiians, with membership of

over 150 organizations and agencies that work with and serve Native populations, providing expertise in community development technical assistance and training, communications and consulting, public policy initiatives and the coordination of events and conferences.
  - **Kona-Kohala Chamber of Commerce (KKCC):** The KKCC is a major business advocacy organization located on the west side of the Big Island. The KKCC membership represents all geographic areas of West Hawaii, reaching over 700 members. Its mission is to advocate a successful business environment in West Hawaii.

- **Non-profit Organizations.**
  - **Hawaii Energy Policy Forum (HEPF)**: The University of Hawaii at Manoa HEPF was initiated to facilitate collaborative energy planning and policy making among a wide range of business, government, and community representatives.[105]
  - **Hawaii Renewable Energy Alliance (HREA):** HREA, established in 1995, is a non-profit corporation started by a group of representatives from the renewable energy industry, public interest groups, and state and local government agencies that were concerned with the energy future of Hawaii.
  - **Kohala Center**: The Kohala Center is an independent, not-for-profit academic institute located on the Big Island that acts as a living laboratory and classroom for research and education in the environmental sciences.[106]
  - **Hawaii Island Economic Development Board (HIEDB), Inc**: Registered in Hawaii since 1984, HIEDB is a private non-profit corporation. The Board specializes in the facilitation of federal resource programs and the implementation of economic development projects.[107]

- **Venture Capital:** Hawaii's progressive atmosphere and support for sustainable initiatives includes businesses with interest and activity in financing renewable energy projects and supporting the reduction of Hawaii's dependence on imported oil. These venture capital and business incubation companies can act as valuable resources in providing seed funding for technology development and aiding in the firm establishment of hydrogen in the energy portfolio.

  According to the Hawaii Institute for Public Affairs[108], venture capital fund managers with a history of investing in the State of Hawaii are expected to raise a combined $128 million over the next two years. These investments will help meet the anticipated venture capital demand of $147 million by Hawaiian companies during the next three years ($49 million annually). Primary factors contributing to this growth of venture capital investments include strong companies in the renewable energy and life sciences fields; favorable state research and development and

[105] Hawaii Energy Policy Forum. www.hawaiienergypolicy.hawaii.edu.
[106] Kohala Center, www.kohalacenter.org.
[107] Hawaii Island Economic Development Board. www.hiedb,org.
[108] "Venture Capital: An assessment of Market Opportunities." Prepared by Hawaii Institute for Public Affairs. January 2008. Source: PWC/NVCA data, press clippings, company annual reports, interviews.

technology tax credits; key infrastructure; and rising visibility and credibility of local entrepreneurs and companies. Venture capital funds active in Hawaii are listed in Table H-1.

Table H-1: Venture Capital Funds Active in Hawaii since 2002.[109]

Hawaii Focused	Hawaii Presence	Occasional Investment
Hawaii Venture Group	Advantage Capital Partners	American Pacific Ventures
HEAVEN Fund*	Finistere Partners	Arcadia Holdings
HMS Capital Management	Garage Ventures	Avalon Ventures
Kolohala Ventures	Global Venture Capital	Cornerstone Holdings
Lava Ventures	Integra Ventures	M/C Venture Partners
PacifiCap Group	Invencor	Menlo Ventures
Palm Cove Capital	Startup Capital Ventures	Palo Alto Partners
Tradewind Capital	Technology Partners	Stockton Ventures
UPSIDE Fund*		Sulfur Creek Ventures

*Managed by other firms already on the list, but with a separate/distinct investment focus.

- **Private Industry.** According to the National Research Council, nearly 75% of hydrogen investment over the next 15 years ($200 billion total) will need to be made by private industry in order to successfully introduce hydrogen as a viable transportation fuel.[110] Required investments include research and development, vehicle deployment, and needed infrastructure. Potential private industry players responsible for contributing to this investment include auto OEMs, electrolyzer manufacturers, and fuel cell developers.

  Many private industry players have a hydrogen presence in the State of Hawaii. Fuel cell manufacturers that have participated in hydrogen-related projects in Hawaii include UTC Fuel Cells, Hydrogenics Corporation, Ballard Power Systems, Plug Power Inc., and IdaTech, LLC. Hydrogen storage and delivery companies that have participated in hydrogen-related projects in Hawaii include The Gas Company of Hawaii and AirGas GasPro, Inc. Electrolyzer suppliers with past experience in Hawaii include Teledyne Energy Systems and Hydrogenics Corporation.

[109] *Ibid.*
[110] Committee on Assessment of Resource Needs for Fuel Cell and Hydrogen Technologies, National Research Council. 2008. Transitions to Alternative Transportation Technologies: A Focus on Hydrogen.

Appendix I: Economic Impacts

This analysis indicates that hydrogen use for transportation will result in significantly higher fuel prices when compared to traditional fuels. Nevertheless, the use of hydrogen provides other benefits that are described below.

Reduced Demand for Imported Oil

As previously mentioned, the State of Hawaii relies on imported petroleum for about 90% of its energy. By continuing to harness geothermal energy attainable on the Big Island, the demand for imported oil can be reduced, which also helps stabilize electricity costs in the long term. PGV has provided enough energy to replace 6 million barrels of imported oil since 1993.

The use of hydrogen derived from geothermal energy will also contribute to the reduced demand for imported oil. The deployment strategy laid out by this Roadmap will produce 3,788,828 kg H_2 annually in the final deployment stage. Fuel cell buses will be able to travel 20,080,788 miles/yr at this time (based on 5.28 miles/kg), which would displace 5,737,368 gallons of diesel fuel annually (based on 3.5 miles/gallon for a diesel bus).

Revenue to Remain within State[111]

PGV contributes to Hawaii's economy through local, state, and federal taxes, as well as royalties. As a reference point, annual taxes and royalties amount to over $2.5 million a year for the PGV plant – including nearly $1 million in royalties during 2005 alone. Of the PGV plant's royalties, 50% goes to the state, 30% goes to the county, and 20% goes to the Office of Hawaiian Affairs.

Byproduct Oxygen Demand

Oxygen, a by-product of electrolysis, can be collected at hydrogen generation stations for use in the island's aquaculture industry, which was valued at $17.5 million in 2006.[112] Fish farmers benefit from increased production, lower feed costs, and higher profitability.

While the Hawaii Agriculture Statistics Service no longer discloses exact production amounts of finfish by county (to avoid disclosure of individual operations), the Big Island produced over 1.5 million pounds of finfish (e.g., tilapia) in 1999.[113] Assuming the same amount today, the demand for dissolved oxygen would amount to 67.5 kg/hr, or 1,620 kg/day.[114] At the end of the roadmap timeline, in year 2025, the oxygen generated through all the operational electrolyzers reaches 3,595 kg/day. This would exceed the demand from the aquaculture industry on the Big Island.

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[111] Liz Battocletti, Bob Lawrence & Associates, Inc. 2006. *The Economic, Environmental, and Social Benefits of Geothermal Use in Hawaii.* June. http://www.geothermal-biz.com/Docs/HI.pdf.

[112] National Agricultural Statistics Service, USDA, Hawaii Field Office. 2007. *Hawaii Aquaculture.* September 4.

[113] Hawaii County Data Book 2007. Table 15.23 – Aquaculture Acreage, Population, and Value, Hawaii County: 1985 to 2005.

[114] Assuming 4.5 g oxygen / 100 lbs fish / hour outlined in "Tank Culture of Tilapia." The Fish Site. http://www.thefishsite.com/articles/136/tank-culture-of-tilapia.

Of course, oxygen can also be sold as a raw product. A large market currently exists for oxygen with an estimated latent demand (or potential industry earnings) reaching $5 billion in 2006 (Table I-1).[115] Oxygen generated as a byproduct of electrolysis has commonly been estimated to sell for $0.02-0.025 / kg.[116,117,118]

Table I-1. Market for Oxygen (U.S. $ mil): 2001-2011.[119]

YEAR	U.S. MARKET	WORLD MARKET
2001	956.42	4,666.76
2002	993.82	4,686.46
2003	1,032.49	4,707.75
2004	1,072.66	4,731.21
2005	1,114.39	4,778.20
2006	1,157.75	4,956.19
2007	1,202.80	5,163.59
2008	1,249.60	5,380.29
2009	1,298.22	5,606.73
2010	1,348.73	5,843.37
2011	1,401.20	6,090.70

Eco-Tourism

Hawaii's economic vitality greatly depends on its tourism industry, with millions of tourists visiting the islands each year. Visitor numbers are approximately seven times that of the resident population of the islands, and these tourists expend over $10 billion during their stays (for example, tourist expenditures in 2007 were $12.8 billion).[120] The tourists visiting the Big Island may be interested in visiting the hydrogen dispensing sites to learn first-hand about the hydrogen demonstrations on the island. Visitors may also enjoy shuttle rides on hydrogen-powered buses to and from resorts, shopping areas, and other tourist sites. In the future, hydrogen vehicles may also be made available to rent, targeting interested tourists.

Enhanced Educational Curricula

Local colleges and secondary schools on the Big Island could leverage local research, development, and deployment activities related to hydrogen and fuel cells in order to enhance their areas of specialization. This would provide students with opportunities to

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[115] Philip M. Parker. 2005. INSEAD. www.icongrouponline.com.
[116] Stuart Energy. 2003. *Production of Hydrogen from Renewable Electricity: The Electrolysis Component.* Workshop on Electrolysis Production of Hydrogen from Wind and Hydropower. NREL DC Office. September 8.
[117] Levene, J.I. "Economic Analysis of Hydrogen Production from Wind." National Renewable Energy Laboratory. NREL/CP-560-38210. May 2005.
[118] D. Gray et al. "Hydrogen from Coal." Mitretek Technical Paper – MTR 2002-31. Delivered to U.S. DOE NETL. July 2002.
[119] Philip M. Parker. 2005. INSEAD. www.icongrouponline.com.
[120] DBEDT. Outlook for the Economy.

experience the technologies they are being taught about first-hand via site visits to learning centers as well as interactions with manufacturers. This interaction would help educate students about the technology, infrastructure, and environmental benefits of a hydrogen economy. Furthermore, private industry may choose to partner with schools and faculty members to help design and develop appropriate technical curriculum and possibly initiate future internship and job opportunities. All these opportunities can be leveraged to emphasize energy issues related to the Big Island and create awareness of the possibilities afforded by new technologies,

Social Responsibility
By promoting the use of renewably produced hydrogen, in conjunction with advanced vehicle technologies, Hawaii will foster a cleaner, healthier and more stable energy and economic future for its residents.