UNIVERSITY OF HAWAIʻI SYSTEM
REPORT

REPORT TO THE 2024 LEGISLATURE

Report on the Potential Production and Use of
Renewable Hydrogen in Hawaiʻi

Act 140, SLH 2022

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Hawai‘i Natural Energy Institute

School of Ocean and Earth Science and Technology
University of Hawai‘i at Mānoa

POTENTIAL PRODUCTION AND USE OF RENEWABLE HYDROGEN IN HAWAI‘I

Report to the Hawai‘i State Legislature in Accordance with SB2283
Act 140, Session Laws of Hawai‘i 2022

EXECUTIVE SUMMARY

Hydrogen as a clean energy carrier has been a topic of interest since the USDOE Renewable Hydrogen Program was initiated in the 1980s. The versatility offered by the range of production methods and end-uses, and the absence of carbon emissions during use has been a draw for hydrogen for many years. Interest in hydrogen has increased, nationally and internationally, in recent years. In the US this has culminated with the recent competition to identify and fund seven hydrogen hubs across the US.

The Hawaiʻi Natural Energy Institute at the University of Hawaiʻi at Mānoa was tasked by Act 140 and SB2283, Session Laws of Hawaiʻi 2022 to "conduct a study to examine the potential for the production and use of renewable hydrogen in the State and the potential role of renewable hydrogen in achieving a local, affordable, reliable, and decarbonized energy system and economy." This report summarizes the results of this study.

Hydrogen rarely occurs freely in nature but can be produced with low life-cycle emissions from a variety of sources including waste, biomass, and renewable electricity. Once produced, hydrogen can be used in a wide range of applications cutting across the industrial, transportation and power sectors.

The production and use of renewable hydrogen for the State of Hawaiʻi is a complex undertaking requiring development of end use markets, implementation of commercial production at scale, the management of significant feedstock resources, and the development of complex and costly transport and storage infrastructure. In addition to the significant technical and financial challenges, permitting and community acceptance of projects at the required scale are a concern.

Figure 1 below shows the elements of a hydrogen energy system. Too often, organizations focus on one element of this supply chain, without consideration of all the elements or the manner in which they operate together. This report, comprised of 13 sections, addresses the many aspects needed to develop hydrogen at scale.

Potential near-term uses for hydrogen in the islands were identified in the transportation, industrial, and electric power sectors. Table 1 summarizes the proposed uses based on the assumptions used in this analysis. As shown, statewide hydrogen usages totaling approximately 102,000 MT/year were identified, with over 75% of that potential demand (76,913 MT) on Oʻahu. Of that amount, approximately 15,000 MT/year were associated with what was considered the most mature markets, industrial gas and the proposed production of sustainable aviation fuel. The largest potential uses used for this study were for electricity generation from hydrogen, targeting approximately 5% of annual electricity demand, consistent with Hawaiian Electric's (HECO) integrated grid planning (IGP) 2045 energy from firm dispatchable resources; and 20% of current fuel use for the statewide public transportation bus fleet and heavy duty trucks. These estimated for hydrogen demand should not be considered as a likely outcome. The markets for road transportation and electric power were chosen, in part, to demonstrate the required scale for hydrogen to meaningfully contribute to decarbonizing these sectors. As discussed throughout this report, these markets are not currently mature.

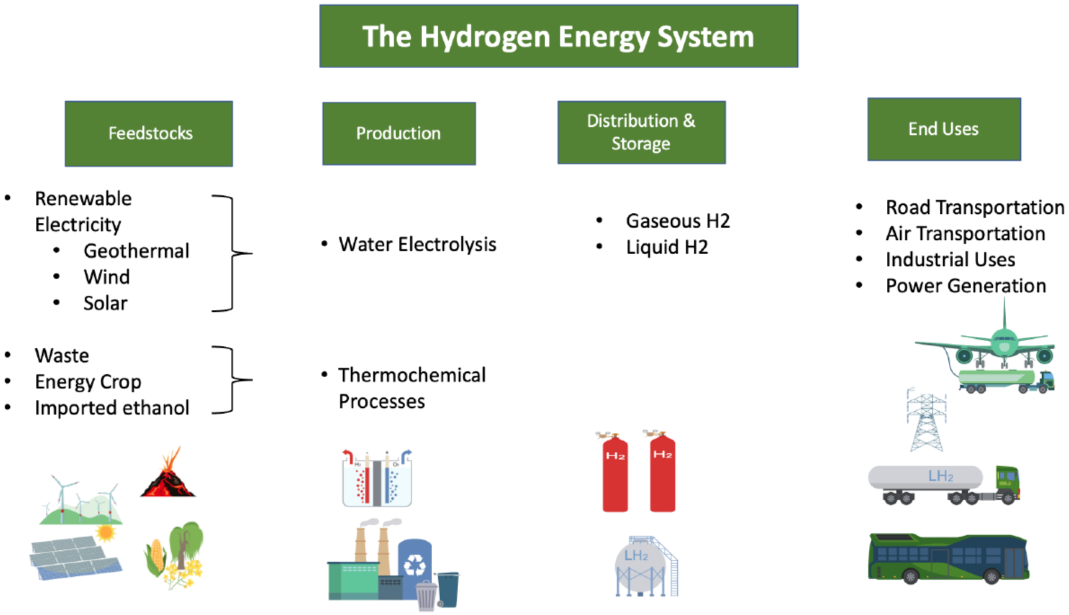

Figure 1. Diagram of a potential Hawaiʻi hydrogen energy system.

Table 1. Summary of hydrogen demand by island.

End Use	Statewide	Oʻahu	Maui	Hawaiʻi	Kauaʻi
Industrial Gas	840	840	N/A	N/A	N/A
Sustainable Aviation Fuel	15,067	15,067	N/A	N/A	N/A
Road Transportation	32,283	21,981	3,802	5,188	1,312
Electric Power Generation	54,040	39,025	6,626	5,981	2,408
Total	**102,230**	**76,913**	**10,428**	**11,169**	**3,720**

Act 140 defined renewable hydrogen as “hydrogen produced entirely from renewable sources that have lifetime emissions of no more than fifty grams of carbon dioxide per kilowatt hour,” which interpreted literally would indicate production only via electrolysis from a low emissions renewable source. A review of the literature and analysis conducted for this report showed that the thermochemical processing of waste or dedicated crops could produce hydrogen with similar or even lower life-cycle emissions than from the electrolysis of water. Section 4 provides a review of the various production technologies considered able to meet this requirement including electrolysis using renewable electricity, gasification of biomass or waste, and steam reforming (SR) of an imported biofuel such as ethanol. Material, energy, and water requirements for each are also summarized.

The feedstock availability to meet the proposed uses were evaluated and are reported in Section 5. These resources (renewable energy, waste, biomass) are not equally distributed between islands and in some instances are not available at all. Hydrogen production potential from each of these resources, by island is summarized in Table 2.

Table 2. Comparison of estimated hydrogen end-use and production potential for 2040 timeframe.

Island	**Projected H_2 Use (metric tons)**	**Production Potential by Resource/Technology**					
		Gasification of C&D	**Solar Electrolysis**	**SR of Ethanol**	**Gasification of MSW**	**Gasification of Biomass**	**Total**
	MT/yr	***MT/yr***	***MT/yr***	***MT/yr***	***MT/yr***	***MT/yr***	***MT/yr***
Oʻahu	76,913	12,224	28,218	22,542	29,720	31,283	124,007
Hawaiʻi	11,169	0	592,786	0	14,470	233,572	840,828
Maui	10,428	0	72,368	0	11,180	50,972	134,520
Kauaʻi	3,720	0	18,629	0	5,260	46,558	70,447

While all islands have the potential to meet the assumed demand, MSW and biomass are anticipated to be difficult to implement due to either complex feedstock composition or, in the case of biomass, the cost of growing a dedicated crop. Additionally, land constraints on Oʻahu or lack of acceptance to increased imports of ethanol could limit Oʻahu's potential. The feasibility of importing hydrogen to Oʻahu, from the Big Island or from outside Hawaiʻi were assessed in later parts of this report.

While resources to produce hydrogen at scale are generally available, the cost to produce hydrogen was found to be one of the key determinants on whether Hawaiʻi should pursue aggressive investment in expanding hydrogen opportunities. Existing tax credits may alleviate initial costs by a modest amount once uncertain regulations are clarified, but hydrogen production will remain capital intensive, and distribution and storage will require complex logistics for Hawaiʻi to cost effectively produce hydrogen locally. Transporting, storing, and distributing hydrogen to end users is not trivial, nor low cost. Substantial investment in equipment and infrastructure is needed to enable widespread use of hydrogen as a fuel for road transportation. Details of the cost models and the logistics for distribution and storage are presented in Sections 6 and 7. The indicative hydrogen production costs for various combinations of production and distribution/storage are presented in Table 3 below.

Table 3. Hydrogen production pathway material and energy input requirements per kg of hydrogen.

H_2 Production Technology	Feedstock	Cost of Production ($/kg)	Distribution Method	Distribution & Storage $/kg[a]	Total Cost ($/kg)
Electrolysis	Geothermal[b]	6-9	Compressed Gas	3.9-4.7	9.9-13.7
			Liquid	5.2-8.8	11.2-17.8
			Interisland	5.5	11.5-14.5
Electrolysis	Solar[c]	8-10.5	Compressed Gas	3.9-4.7	11.9-15.2
			Liquid	5.2-8.8	13.2-19.2
			Interisland	5.5	13.5-16
Gasification	Waste	2.6-4.3	Pipeline	Included in production cost	2.6-4.3
			Compressed Gas	3.9-4.7	6.5-9.0
Gasification	Biomass	2.5-6	Compressed Gas	3.9-4.7	6.4-10.7
			Liquid	5.2-8.8	7.7-14.8
			Interisland	5.5	8-11.5
Steam Reforming	Ethanol	5.2	Pipeline	Included in production cost	5.2

[a] Excluding firm power for grid applications
[b] Based on 10-15 cents, 96% load factor, $1300/kw
[c] Based on 10-15 cents, 30% load factor, $1300/kw

Less distribution and storage would be required for meeting hydrogen demand for SAF production and Hawaiʻi Gas needs on Oʻahu if nearby production of hydrogen using a waste stream can be achieved.

Shipping hydrogen between islands may be necessary to meet the estimated demand on Oʻahu if local hydrogen production capabilities fail to materialize or hydrogen demand grows substantially. Hawaiʻi Island has adequate resources and land availability to support Oʻahu's needs but interisland shipping was estimated to add an additional $5 to the cost of the delivered hydrogen, a significant barrier to cost-effective interisland transport. Based on Hawaiʻi's high cost of production and high shipping cost, competitive export of hydrogen from Hawaiʻi is unlikely.

Each portion of the hydrogen supply infrastructure is regulated by international, federal, state, and local entities. Regulations are enforced by entities which provide guidance and updates as necessary. Permitting is complex and time consuming and must be taken into account when calculating final costs including financing. Details of expected requirements are provided in Section 9.

Given the costs and complexities of producing hydrogen in Hawaiʻi, markets in the mainland are able to produce hydrogen at much lower costs due to hydropower as in the Northwest, lower cost land for PV or low cost wind power as in Texas/Gulf Coast. Some of these areas are exploring large scale hydrogen for industrial uses not present in Hawaiʻi. A summary of the winning projects is found in Section 11. Markets in Asia have similar advantages over Hawaiʻi, for example in large scale planned hydrogen production for export in Australia[1].

A number of key conclusions from this study are summarized below along with recommendations for future actions.

- Oʻahu has sufficient land and resources to meet potential near-term uses but if developed at larger scale than considered in this report, Oʻahu would be required to import hydrogen to meet its needs.
- The study concluded that all the islands other than Oʻahu have ample land to meet any reasonable on-island uses.
- Despite significant potential resources, the production of hydrogen at scale in Hawaiʻi faces significant hurdles.
- Electrolysis, a well- established, commercial production technique, is very energy intensive and, based on recent Power Purchase costs, very expensive in Hawaiʻi.
- Thermochemical processing of waste to produce hydrogen is possible but is limited by the resource and is still a developing technology with significant uncertainty regarding viability of the production processes.
- Gasification of biomass to produce hydrogen is more developed but growth of dedicated crops for energy has not, historically, been cost effective in Hawaiʻi.
- Distribution and storage of hydrogen, a necessary but often overlooked component of any hydrogen system, is logistically complex, requires substantial energy, and is expensive.

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[1] https://www.globalaustralia.gov.au/industries/net-zero/hydrogen

- While the Big Island has sufficient land to accommodate its uses and those on Oʻahu, interisland shipping was found to be complex and expensive limiting the large-scale applications of hydrogen to the neighbor islands for the foreseeable future.
- While the use of hydrogen for long-term storage (aka firm power) is an often mentioned application, the use of hydrogen to provide energy during periods of extended low solar or wind resource was found to require very large amounts of on-island storage. Although included as a potential end-use throughout the report, the amount and cost of this storage is considered prohibitive based on currently available technology.
- Interisland transport of hydrogen (Big Island to Oʻahu), for example, is logistically complex and very expensive.
- Two industrial applications, renewable hydrogen for Hawaiʻi Gas' pipeline and for Par's proposed production of Sustainable Aviation Fuel, represent near term opportunities on Oʻahu. However, use of renewable hydrogen for these applications may be limited by competition from other technologies such as RNG for Hawaiʻi Gas and on-site reforming of biofuels to provide H_2 for SAF production.
- Hydrogen-fueled road heavy duty vehicles offer a potential larger market on all islands but lack of commercially available vehicles at this time and potential completion from ever improving BEVs makes this market uncertain.
- Given the relatively high costs and logistics complexity of Hawaiʻi based hydrogen, along with more competitive hydrogen production on the mainland US and Asia, export of hydrogen from Hawaiʻi is not expected to be viable.

In summary, Hawaiʻi has the renewable resources to produce large amounts of hydrogen but high costs, lack of maturity of the end-use markets, and complex large scale logistical infrastructure are significant barriers to development at this time.

While the near-term commercialization at scale is unlikely at this time there are still things that can be done to move this technology forward and leave options open for future.

- Encourage and support the adoption of renewable hydrogen to meet the needs of the Gas Company renewable gas goals and Par's production of Sustainable Aviation Fuels.
- Encourage participation in federally funded programs to gain additional first-hand knowledge of the performance of emerging technologies.
- Address the permitting and regulatory issues now so that if/when projects materialize, they can be implemented in a timely fashion.
- Closely monitor progress on development of commercially proven MSW to hydrogen facilities worldwide. Support Kauaʻi in its 2024 RFP for MSW to fuels

conversion technologies. This effort has the added benefit of potentially providing solutions to Kauaʻi's long-standing problems with siting and maintaining landfills.

- Monitor progress of automobile companies toward commercially proven heavy duty trucks running on hydrogen. Evaluate Hawaiʻi government heavy duty vehicle fleets for potential switch to hydrogen vehicles.

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1. INTRODUCTION

The Hawaiʻi Natural Energy Institute at the University of Hawaiʻi at Mānoa has been tasked by Act 140 and SB2283, Session Laws of Hawaiʻi 2022 to "conduct a study to examine the potential for the production and use of renewable hydrogen in the State and the potential role of renewable hydrogen in achieving a local, affordable, reliable, and decarbonized energy system and economy."

The production and use of renewable hydrogen for the State of Hawaiʻi is a complex undertaking requiring development of end use markets, emerging production technologies, significant feedstock resources, and substantial transport infrastructure. It will also require considerable permitting and financial hurdles normally associated with industrial growth in Hawaiʻi. This report is comprised of 13 sections to address these issues inclusive of the 11 tasks that were specifically designated in SB2283.

Following this Introduction, Section 2, *Hydrogen Energy System*, lays the foundation for the complexity of this issue, showing the interaction of the various components needed to develop this type of energy system and economy. The *Hydrogen Uses* section then describes higher priority uses that may be realistically developed within a 2040 timeframe and which could contribute significantly to decarbonizing Hawaiʻi's energy system. These potential uses include road and air transportation, limited industrial use, and firm power production.

The next four sections on *Production Technology*, *Feedstock Availability*, *Production Costs*, and *Distribution and Storage* provide the results of analysis to quantitatively describe what is required to produce enough renewable hydrogen to meet the targeted uses. Development of renewable hydrogen economies around the world are in early stages and many of the components needed are still in pilot or demonstration stages so some uncertainty exists in these calculations.

Act 140 and SB2283 further stated that for the "purposes of this section, 'renewable hydrogen' means hydrogen produced entirely from renewable sources that have lifetime emissions of no more than fifty grams of carbon dioxide per kilowatt hour." For solar energy to support hydrogen electrolysis, HNEI reviewed over 40 references containing more than 70 life-cycle analysis (LCA) adjusting the outputs for Hawaiʻi conditions to identify production methods meeting the 50kg CO_2/kWh objective. Numerous studies show that the life-cycle greenhouse gas (GHG) emissions for appropriately chosen crops and conversion technologies can achieve similar GHG emissions. The *Production Technology* section concludes that multiple technologies still under development may ultimately prove to be commercially viable to meet these LCA GHG objectives.

These production technologies must be supported by feedstock availability, reasonable costs, and delivery logistics that make economic sense. The feedstock and cost sections quantify feedstock requirements for each production technology by island and compare these requirements to available resources. Once produced, the hydrogen must be transported to the site of intended use. The transport, storage, and distribution of this hydrogen even within each island is shown to be non-trivial, expensive to operate, and capital intensive to set up. Interisland transport is also described with its additional costs and complexities. Section 9 *Permitting and Regulatory Issues* summarizes hurdles that must be overcome to develop this type of infrastructure.

Hydrogen as an export commodity is evaluated in Section 10 and shown to be logistically and financially non-competitive with other worldwide hydrogen production under development. A section on Hydrogen Hub winners in the U.S. is also included for perspective in regard to regions with known industrial use and lower cost hydrogen production capabilities.

A *Future Uses* section is included, which describes other potential uses of hydrogen that may be viable after 2040.

The final *Conclusions and Recommendations* section summarizes costs for several scenarios which balance end uses with production, feedstock resources and transport by island. Conclusions from this work and recommendations for future efforts are included.

The Appendices contain more detailed information, discussion, and references for several of the sections.

2. HYDROGEN ENERGY SYSTEM

The use of hydrogen as a fuel for the decarbonization of Hawaiʻi's economy requires development of an integrated system. As shown schematically in Figure 2.1, the elements of this system include: 1) the cost-effective production of hydrogen; 2) efficient transport, storage, and distribution; and 3) an end-use application where the use of the hydrogen is a cost effective alternative compared to other solutions. Too often, organizations focus on one element of this supply chain, without consideration of all the elements or the manner in which they operate together.

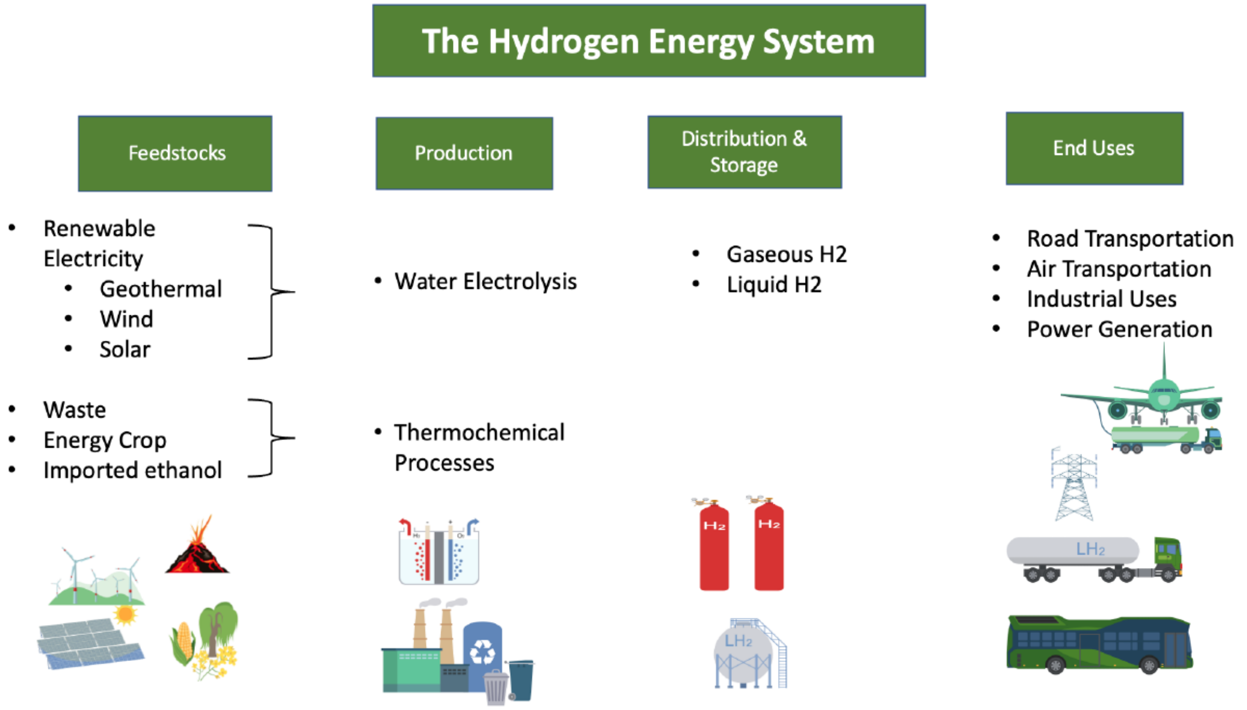

Figure 2.1. Diagram of a potential Hawaiʻi hydrogen energy system.

While end-use applications are shown at the end of the hydrogen value chain, in this study, it is addressed first. The type, scale, and location of the end-use will affect the quantity and purity required, potential feedstocks for production, and have potentially major impacts to the feasibility and cost for transport and distribution. As detailed further in the *Hydrogen Uses* section of this report, potential uses include: 1) limited industrial use to support Hawaiʻi Gas' Integrated Resource Plan; 2) renewable hydrogen for the production of sustainable aviation fuel (SAF); 3) replacement of a portion of Hawaiʻi's road transportation fuel, especially for heavy duty vehicles; and 4) for firm-power generation required for grid services in a high penetration renewable electrical system.

Hydrogen rarely occurs naturally as an isolated molecule. As shown in the left side of Figure 2.1, hydrogen (H_2) can be produced from water or from a wide range of organic materials. The energy content of hydrogen is high, with one kg of H_2 having approximately the same energy content as one gallon of petroleum fuel. The *Production Technology* section of this report summarizes the current technologies and energy needs for these two pathways.

Hydrogen is produced from water via a process called electrolysis by applying energy (electricity) to split the water into oxygen and hydrogen. When the source of electricity is renewable, hydrogen is considered renewable, or commonly referred to as "green hydrogen". One of the advantages of electrolysis is the ability to produce very pure hydrogen, offering the opportunity for use in a high efficiency fuel cell. However, electrolysis is energy intensive, requiring 55 kWh or more to produce one kg of H_2, making the cost of renewable electricity an important factor in the overall product cost, as shown in Section 6, *Production Costs*.

Hydrogen can also be produced from construction and demolition waste, municipal solid waste, and biomass using a variety of thermochemical processes using high temperatures to break down the organic materials into a mixture of gases including hydrogen. Hydrogen may be produced directly from the biomass or from an intermediate biofuel such as ethanol or pyrolysis oil. As detailed in this report, the thermochemical processes tend to be more efficient and lower cost than electrolysis, but the resulting hydrogen will require substantial additional processing if high purity is required. The availability of waste and the availability and cost of dedicated biomass (or an intermediate biofuel) are also an important consideration.

The availability of feedstock (including renewable energy and water) in Hawaiʻi for various pathways is summarized in the *Feedstock Availability* section and approximate production costs are included in the *Production Costs* section.

As shown in Figure 2.1, the transport and distribution of hydrogen from the site of production to the end-user is required. Although often overlooked, it can increase complexity and the cost of delivered hydrogen considerably. If the production and end-user are co-located and production matches the end use, the hydrogen can be transported via pipelines with minimal complexity and little need for storage. However, when the production and end-use are not co-located, or when the temporal profile of the production doesn’t match the end-use, e.g. if solar-electrolysis is used to produce a transportation fuel, significant complexity and costs may result.

While research into advanced storage technologies continues, commercial transport today is either compressed gas or low-temperature liquid hydrogen. Whether produced via electrolysis or by thermochemical conversion of organic material, transport as a gas requires additional compression. Even then, due to the low volumetric density of hydrogen, the logistics of transport may limit this to smaller applications. Transport as a liquid is more efficient volumetrically, but there is a significant capital expense and energy expense to liquefy hydrogen, which requires a temperature of -253°C (-423°F). Various scenarios for the transport and storage of hydrogen and estimated costs are evaluated for on-island transport in the *Distribution and Storage* section of the report; and estimates for interisland shipping of hydrogen is detailed in the *Interisland Shipping* section.

3. HYDROGEN USES

Hydrogen has garnered substantial broad national and international interest because of its applicability as a clean fuel for a wide variety of end uses within the industrial, transportation, and power sectors. Figure 3.1 shows Hawaiʻi's petroleum usage by sector as of 2019. The objective of this section is to identify and quantify potential uses for Hawaiʻi, in each of these sectors, with a focus on those that might be commercial in the 2040 timeframe.

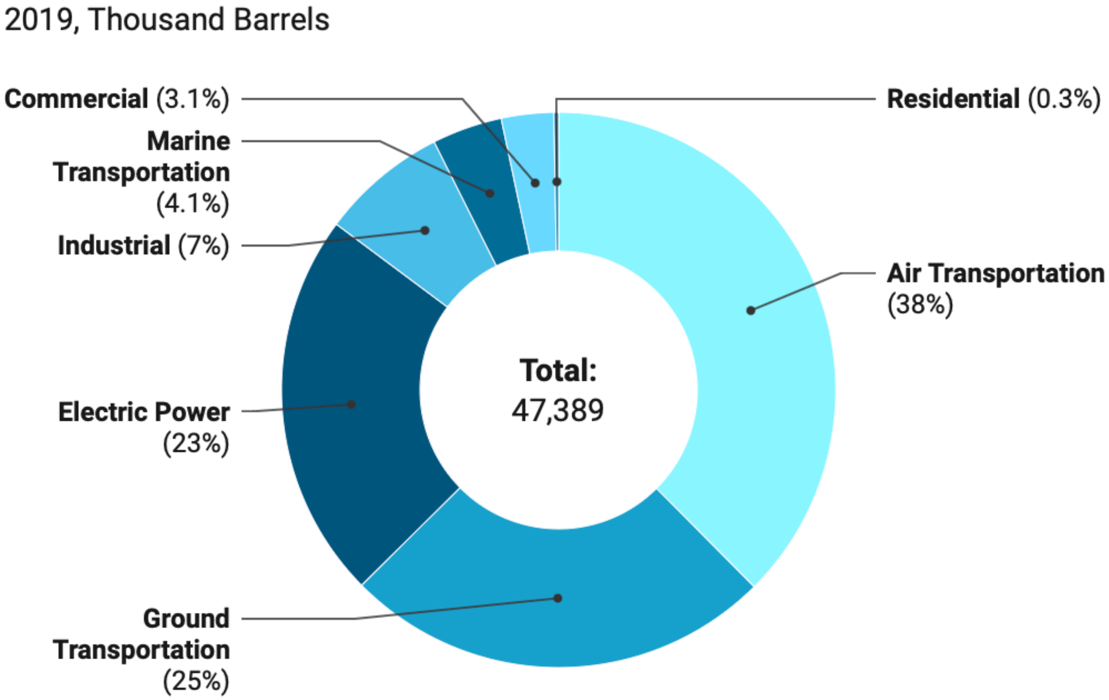

Figure 3.1. Hawaiʻi's petroleum usage by sector as of 2019[2]*.*

Selection of potential Hawaiʻi use cases are based on three criteria. Firstly, the use case must be deployable using existing or anticipated near-term technologies. This was intended to exclude large-scale hydrogen consumption for applications that are unlikely to be available in the study timeframe, such as hydrogen powered planes. Secondly, use cases where hydrogen has little likelihood of successfully competing with other technologies were excluded or minimized, such as light duty vehicles, for which the market is expected to be dominated by battery powered electric vehicles. Thirdly, the scale must be large enough to have a measurable impact on Hawaiʻi's energy mix and greenhouse gas emissions, excluding small pilot projects or niche uses.

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[2] Hawaiʻi State Energy Office with data from the U.S. Energy Information Administration, https://energy.hawaii.gov/what-we-do/clean-energy-vision/transportation

As discussed in this section and detailed further in Appendix A, statewide near-term potential for hydrogen use in Hawaiʻi is estimated to be up to approximately 102 million kg/year (102,000 metric tons (MT) per year) across the industry, transportation, and electric power sectors was identified for this analysis. This equates to approximately 5% of today's total statewide oil consumption. As shown in Table 3.1, the largest potential use identified is electric power generation based on 5% of annual electricity demand to meet firm power needs, excluding the additional electricity required to produce the hydrogen if it's generated by electrolysis. Power generation is followed by road transportation (assumed conversion of 20% of the heavy duty road vehicles fleet to hydrogen) and two industrial applications for the Island of Oʻahu; hydrogen for the local production of sustainable aviation fuel (10% of current aviation fuel) and the addition of renewable hydrogen into Hawaiʻi Gas' Oʻahu pipeline distribution system as documented in their recent RFP.

Table 3.1. Estimated hydrogen potential (MT/yr) by each end-use.

End Use	Statewide	Oʻahu	Maui	Hawaiʻi	Kauaʻi
Industrial Gas	840	840	N/A	N/A	N/A
Sustainable Aviation Fuel	15,067	15,067	N/A	N/A	N/A
Road Transportation	32,283	21,981	3,802	5,188	1,312
Electric Power Generation	54,040	39,025	6,626	5,981	2,408
Total	102,230	76,913	10,428	11,169	3,720

The results from this analysis are intended as an upper estimate for hydrogen consumption by 2040. While hydrogen for road transportation and for firm electrical power would have a large impact on GHG emission reduction in Hawaiʻi, both uses lack clear commercialization pathways. Transportation has the potential to address an otherwise difficult to clean sector of our energy economy but until hydrogen vehicles – specifically heavy-duty trucking – are commercially available, Hawaiʻi uses will likely be limited to government supported demonstrations. The use of hydrogen to provide firm power is not likely to be considered until the islands are much further along toward their 100% renewable electricity renewable portfolio standard (RPS) goals as near term additions of variable renewable resources (solar and wind) are significantly lower cost options to meeting RPS requirements.

In addition to the uncertainty of the market, other technical and economic constraints to produce, store, and transport hydrogen may impact the applicability of the end-use application and the ability to meet these potential uses on each island. Subsequent sections of this report discuss the island-specific and statewide constraints.

Transportation

Potential uses of hydrogen within the transportation sector included road, air, and marine applications. Although Hawai‘i has a significant amount of marine traffic, marine uses were excluded for the 2040 timeframe, as less than one tenth of 1% of marine vessels on order in 2021 are designated as hydrogen vessels. The opportunity for marine applications is discussed further in the *Future Uses* section. The potential uses for road and aviation applications are discussed below.

A summary discussion for each of the potential near-term transportation applications follows with additional detail in Appendix A.

Road Transportation

If Hawai‘i is to meet its greenhouse gas reduction goals, it must reduce GHG emissions from its largest source: the transportation sector. In 2019, emissions from transportation (air and ground) totaled 8.98 million metric tons CO_2 equivalent, accounting for 46% of all energy sector emissions.[3] Ground transportation alone was reported to be 4.03 million metric tons, over 20% of all energy emissions. Hydrogen, used via combustion or in fuel cells, has the potential to contribute to a reduction of emissions in this sector.

Based on recent market trends for light duty vehicles and U.S. Department of Energy (USDOE) reports, hydrogen has not been shown to have a significant advantage over batteries for light duty vehicles. With the anticipated continuing improvement of battery technology, this is not expected to change.

Recent USDOE research and industry development worldwide for hydrogen vehicles has focused on heavy duty vehicles. Heavy duty vehicles, including buses for public transportation and freight transport, are considered the most likely to benefit from the use of hydrogen due to shorter refueling times and greater range between refueling stops than possible with current BEVs. As documented in Appendix A, to estimate hydrogen usage, we have assumed that 20% of the current fuel use for the statewide public transportation bus fleet and 20% of fuel use for the heavy duty truck fleet would be replaced by hydrogen in the 2040 timeframe. For completeness, we have assumed that 1% of passenger vehicles in this timeframe will be hydrogen powered.

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[3] ICF, HNEI and UHERO, *Hawai’i Greenhouse Gas Emissions Report for 2005, 2018, and 2019*, April 2023, https://health.hawaii.gov/cab/files/2023/05/2005-2018-2019-Inventory_Final-Report_rev2.pdf

Table 3.2 shows estimated hydrogen fuel usage for each vehicle type assuming a one-to-one replacement of one gallon of fossil fuel (gasoline or diesel) with one kg of hydrogen. Commercialization of fuel cell electric vehicles (FCEV) may also offer additional efficiency savings. Appendix A includes analysis on an island by island basis.

Table 3.2. Estimated Hawaiʻi hydrogen demand for vehicle application.

Vehicle Type	% of Vehicles	Vehicle Count	Estimated Hydrogen Use per Vehicle (kg/yr)	Annual H_2 Consumption (kg/yr)
Light Duty (cars)	1	10,111	324	3,276,000
Heavy Duty	20	15,118	1,861	28,135,000
Buses	20	133	6,570	872,000
Total	N/A	N/A	N/A	32,283,000

Air Transportation

In Hawaiʻi, jet fuel accounts for approximately 38% of the petroleum products consumed. Although the Par refinery imports crude oil to produce petroleum products, jet fuel is imported. Historical consumption of jet fuel in Hawaiʻi is shown in Figure 3.2. Statewide jet fuel consumption is projected to be approximately 600 million gallons per year in 2023 based on 262 million gallons used through May of 2023.

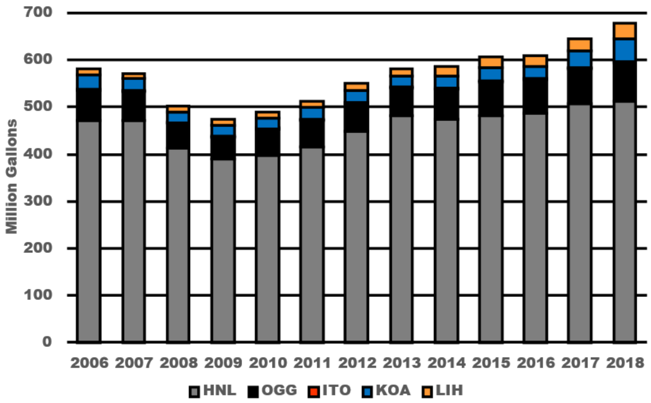

Figure 3.2. Commercial jet fuel consumption in Hawaiʻi, 2006 to 2018.

The direct use of hydrogen as fuel for aircraft is not expected to be commercial in the timeframe of interest. However, the production and use of synthetic sustainable aviation fuel (SAF) is a technically viable pathway to reduce carbon emissions while also reducing jet fuel imports to Hawaiʻi. SAF is made from renewable sources, such as plant oils and waste oils and requires additional hydrogen to meet fuel specifications. A summary of SAF production methods is included in Appendix A.

Renewable hydrogen to support local production of SAF is considered one of Hawaiʻi's potential near-term opportunities. In June 2022, Par Hawaiʻi and Hawaiian Airlines announced a joint venture to produce 61 million gallons of SAF by upgrading plant-based oils and waste oils at the Par Pacific refinery on Oʻahu. As detailed in Appendix A, the hydroprocessed esters and fatty acids (HEFA) pathway, also known as hydroprocessed renewable jet (HRJ), requires about 0.25 kg hydrogen/gallon jet fuel. This project could require up to 15 million kg/year of hydrogen allowing replacement of approximately 10% of Hawaiʻi's imported jet fuel with SAF. This refinery expansion, which will also allow for production of renewable diesel, renewable naphtha, and renewable liquefied petroleum gases, is expected to be commissioned in 2025. This project fits with the International Air Transport Association's (IATA) goal of 10% SAF use by 2030.

Industrial

The primary industrial uses for hydrogen are ammonia production, the majority application; petroleum refining; methanol production; and cement, steel, and heavy machinery. With no ammonia, methanol, or steel industry currently operating in Hawaiʻi, the primary industrial uses of hydrogen in Hawaiʻi are at the Par Refinery for upgrading fuels and at Hawaiʻi Gas as an addition to their natural gas (methane) delivered via pipeline to its customers on the island of Oʻahu.

Hawaiʻi Gas recently released an RFP for green hydrogen and renewable natural gas (RNG) as part of their objective to reduce their carbon footprint. This RFP is requesting up to 2,300 kg/day (839,500 kg/yr) of renewable hydrogen. Excerpts from their RFP are quoted below showing the quantities of hydrogen requested.

> "Hawaiʻi Gas, to our knowledge, currently blends the largest proportion of hydrogen in a gas utility in North America (typically 10-12%) with the longest operating record at that composition (since 1974). The hydrogen gas blend is distributed to Oʻahu utility customers through 1,100 miles of transmission and distribution pipeline network that was constructed and maintained over the past 100+ years. Hawaiʻi Gas is seeking firm proposals for the supply of up to 65,000 therms per day of renewable natural gas, and up to 2,300 kg per day of renewable hydrogen. The upper range of 2,300 kg per day of renewable hydrogen has been scaled with the upper range of 65,000 therms per day of renewable natural gas to reach a blend of up to 15% hydrogen by volume, which is the recorded "high water" mark for the hydrogen concentration in the synthetic natural gas."[4]

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[4] https://www.hawaiigas.com/2023-rfp

Firm Power Generation for Long-Duration Energy Storage

Analysis conducted by HNEI has shown that even as the share of electricity from variable renewable generation and battery storage in Hawaiʻi approaches 100%, there will remain a need for firm, dispatchable generation resources to support the grid and provide energy during extended periods of low solar and wind resource. If used as a fuel in a combustion or chemical (fuel cell) process, renewable hydrogen can produce electricity with very low life-cycle carbon emissions. The potential to store hydrogen over long periods of time, to shift renewable energy from high production to low production periods, and the ability to access stored fuel on-demand necessitates considering its use as a future clean source of firm, dispatchable electricity generation.

For this assessment, electricity generation from hydrogen is targeting approximately 5% of annual electricity demand. The rationale for this is discussed more in Appendix A. This is consistent with Hawaiian Electric's (HECO) integrated grid planning (IGP) 2045 energy from firm dispatchable resources. In the IGP, hydrogen plays the role of a peaking plant, operating at low capacity factors most of the time when battery storage is sufficient to mitigate variability and then serving as a backup supply when variable renewable resources are limited for a sustained, multi-day period, or when demand is unexpectedly high. The estimated energy output (in GWh) for 2025 and the quantity of hydrogen to meet 5% of that demand (excluding demand for hydrogen electrolysis) via combustion or high efficiency fuel cells are summarized in Table 3.3 for each of the major islands.

Table 3.3. Annual hydrogen needed to support 5% of electricity demand in 2045.

Island	**Total Estimated Electricity Load (GWh/yr)**	**Electricity Generation (GWh/yr) from H_2**	**MT H_2/yr (assuming Combustion)**	**MT H_2/yr (assuming FCs)**
Oʻahu	10,200	510	39	27.4
Hawaiʻi	1,563	78	6	4.2
Maui	1,732	87	6.6	4.6
Kauaʻi	629	31	2.4	1.7
Statewide	14,125	706	54	37.9

Depending on conversion technology, approximately 38-54 MT/year of hydrogen is required to meet 5% of Hawaiʻi's estimated electricity demand of approximately 14,125 GWh[5]. It is important to note that the demand for firm power from hydrogen – unlike SAF,

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[5] Long-term electricity demand for HECO (Oʻahu, Hawaiʻi, and Maui) is aligned to the IGP 2045 year. KIUC load growth is extrapolated from recent load growth trends with an assumed CAGR of 1.1% from 2021-2045.

industrial, or road transportation – will be very variable over time requiring large amounts of hydrogen use over short periods of time and very little other times. This will require large amounts of additional hydrogen storage, increasing cost and complexity significantly.

Summary

Potential near-term (2040) applications for hydrogen in the islands have been identified in the transportation, industrial, and electric power sectors. However, even if these markets mature hydrogen fuels will not be a singular, or even largest, solution to the state's decarbonization goals. Based on the assumptions used in this analysis, statewide hydrogen usage in the 2040 timeframe could be as high as approximately 102,000 MT/year, with over 75% of that potential demand (76,913 MT) on Oʻahu. Of that amount, approximately 15,907 MT/year to supply hydrogen to Hawaiʻi Gas and production of SAF are considered near-term. No industrial or aviation use was identified for the neighbor islands.

Statewide potential demand, approximately 32,283 MT/year for road transportation, was estimated based on a small amount for passenger cars and 20% of the state's buses and heavy duty vehicles. This would require substantial retrofitting of the vehicle fleet for either combustion or fuel cell engines. The remaining 54,040 MT/year of the statewide demand would be to meet firm electricity generation needs. As described in Section 7, *Distribution and Storage*, the amounts of storage required for the largest identified usage, firm power, is a significant barrier.

Collectively, if these end uses are fully realized, hydrogen would reduce statewide oil consumption by approximately 5% with a similar reduction in statewide emissions.

Even if hydrogen can be produced cost-effectively, the timing for development of these market is not clear. The infrastructure required for producing, storing, moving, and distributing hydrogen for use as a transport fuel or for electricity generation, including storage tanks and refueling stations, is significant and likely to introduce other barriers to development. Distribution and storage are discussed in more detail in Section 7.

4. PRODUCTION TECHNOLOGY

In Hawaiʻi, the pathways available for renewable hydrogen production include: 1) electrolysis of water using solar, wind, or geothermal energy as the source of electricity;

2) gasification or pyrolysis of Construction and Demolition (C&D) wastes or municipal solid waste (MSW); or 3) steam reforming (SR) of imported ethanol.

Each of these production technologies carries its own set of input requirements for feedstock, land, water, and power. Each of these production technologies are described briefly below with more detailed references for each in Appendix B.

Electrolysis of Water

Electrolysis is an electrochemical process in which an electric current is applied to drive an otherwise non-spontaneous reaction. When water is used, the water is split to produce hydrogen and oxygen. This device used for this water splitting is referred to as an electrolyzer.

There are several types of electrolyzer systems at varying levels of maturity. The two most common systems for water splitting are alkaline electrolyzers and proton exchange membrane electrolyzers. Regardless of the electrolyzer technology used, all these systems require significant amounts of electricity and/or heat to enable the splitting of water into oxygen and hydrogen. If a low-emissions source of electricity is used, the hydrogen will be produced with low life-cycle emissions. The production of 1 kg of hydrogen requires a minimum of 9 liters of water and 50-60 kWh of electricity.

Gasification and Pyrolysis of Organic Matter

Gasification and pyrolysis are thermochemical processes used to break organic feedstocks (biomass or waste) into a gas (syngas) consisting of hydrogen, carbon monoxide, methane, and other hydrocarbons, and other byproducts. After removal of contaminants, the syngas can be further processed to maximize hydrogen production. For example, the theoretical yield of hydrogen from a woody biomass is approximately 165 kg H_2 per ton (6.1 kg biomass/kg H_2. Actual yields would be significantly lower due to process inefficiencies.

While there are hundreds of variations of gasification and pyrolysis technologies there are very few operating successfully on a commercial scale using wastes as feedstocks which have potential for use in Hawaiʻi.

Gasification of biomass crops can be somewhat simpler than of wastes due to less contaminants and less feedstock variation. However, the number of commercially operating biomass gasification facilities is also very limited. Additional details for a variety of gasification and pyrolysis technologies are summarized in Appendix B.

Steam Reformation of Imported Ethanol

The last method of hydrogen production considered for this study is steam reforming (SR) using imported ethanol as a feedstock. A standard modular unit for this technology, modified from common SR technology for the processing of natural gas, can produce 1,250 kg/day of hydrogen from 2,125 gallons of ethanol – equivalent to about 1 kg of hydrogen for every 5 kg of feedstock. The SR process produces substantial amounts of CO_2, which is captured within the modular system and if sequestered or used, further reduces the LCA GHG emissions for this process.

Material and Energy Needs by Production Technology

Table 4.1 summarizes the key input requirements for each production technology. Details of conversion rates shown below are included in Appendix B.

Table 4.1. Hydrogen production pathway material and energy input requirements per kg of hydrogen.

H_2 Production Technology	Material Input (kg material/kg H_2)	Water Input (kg water/kg H_2)[a]	H_2 Yield (kg H_2/acre)	Energy Input (kWh/kg H_2)
Electrolysis of Water	13.5	13.5	6,144	55-60
Gasification of Waste	13.5 - 21	2.8	N/A	1.4
Gasification of Biomass	10.5	6.9	1,728	1.2
Steam Reforming of Ethanol	5.3	1.5	N/A	0.32

[a] Water requirement for processing only.

Summary

There are a variety of feedstocks and technologies described in this section that can be used to produce hydrogen at a scale relevant to the Hawaiʻi. While only wind and possibly biomass can fully meet the requirements for renewable hydrogen production as defined in SB2283 if full life-cycle emissions are considered, all of them produce hydrogen with much lower life-cycle GHG emission than the alternatives. Although none of the technologies are deployed at large-scale currently, electrolyzers are considered commercially proven. There are limited commercial facilities or commercial demonstrations at scale in operation for gasification and SR of ethanol that can be used as references. There are also many commercial projects in the planning stages for the 2030-2040 timeframe. Each technology carries its own set of input requirements for material, land, water and power. As will be quantified in the following sections, these input requirements create limitations to production dependent upon the island location.

5. FEEDSTOCK AVAILABILITY

The objective of this section is to evaluate the ability to produce sufficient hydrogen using one or more of the local resources on each island. While the timing of the market development is a significant unknown for the uses identified in Section 2, use of renewable hydrogen in the Hawaiʻi Gas pipeline or for SAF production have the potential to be very near term. Hydrogen for road transportation would likely develop more slowly due to the need to transition the truck fleet, whether for hydrogen combustion or use in fuel cells. Finally, hydrogen for power generation is not expected until after 2040, and only if other, lower cost, renewable firm power solutions are unavailable. Resources evaluated for hydrogen production potential include electrolysis of water using renewable energy, gasification or pyrolysis of biomass or waste, and steam reforming of imported biofuel, such as ethanol.

The resources for hydrogen generation are not equally distributed between islands and in some instances are not available at all. A summary of the resource availability assessment by island is summarized below and further detail of assessment is presented in Appendix C.

Renewable Energy for Electrolysis

While a variety of renewable energy resources are available on each island, the specific renewable resources and amounts available varies significantly by island. In addition, since the utilities have already committed to additional renewable energy generation to meet RPS objectives, the potential for development of additional renewable generation to produce hydrogen is adjusted, where appropriate, to exclude land required to meet current RPS goals.

Land available for development of solar for hydrogen production is estimated based on the NREL PV-1-5 scenarios for technical potential. This scenario excludes some federal lands, urban areas, state parks, wetlands, lava flow areas, flood zones, most agricultural areas, U.S Dept. of Defense lands, and land with slopes >5%. The available potential values have been further adjusted to remove the expected land use required to meet RPS goals, as laid out in the HECO IGP portfolio for 2045. For Kauaʻi, only a limited amount of agricultural land was assumed available for additional renewables and no adjustment was made based on limited information on future resource plans for the island.

Although land-based wind development on Oʻahu is considered unlikely and, as shown in the analysis below, unnecessary for hydrogen generation on the neighbor islands, potential additional capacity for wind in the HECO territory is derived from the HECO territory utility-scale wind technical potential (NREL WIND-3-20). Kauaʻi is not expected to develop any wind resources.

Geothermal is another renewable energy resource, which could, in theory, provide 24/7 baseload firm energy and could be used to produce significant amounts of hydrogen. While geothermal has historically been limited to only Hawaiʻi Island, the Hawaiʻi Groundwater and Geothermal Resources Center (HGGRC) at the University of Hawaiʻi reports that one study estimates the geothermal capacity of Hawaiʻi Island at 1,396 MW and Maui at 139 MW. Geothermal for hydrogen production is expected to encounter significant community resistance.

Table 5.1 below summarizes the technical potential (by island) for each of these renewable resources, assuming 55kwh of electricity per kg of H_2, and after consideration of the land needs to meet RPS goals based on HECO IGP plans. Further detail, including summary tables of the total technical potential by island, can be found in Appendix C. Other land use constraints – technical, cultural, and societal – are expected to limit these resources further, but detailed consideration of these issues was beyond the scope of this report. Solar was prioritized, given more likely acceptance and the potential for modular development as the H_2 market develops.

Hydrogen production potential depends on the installed capacity and the capacity factor of the resource. Even when the higher capacity factor is considered, the wind resource is substantially smaller than solar on all islands and in some cases has faced significant community pushback. Geothermal has significant potential on Hawaiʻi Island and to a lesser extent Maui but would compete with a large solar resource for hydrogen production in terms of energy cost and also face strong community pushback based on historical sentiments towards expanding geothermal energy.

Table 5.1. Estimated available land and renewable potential (MW)[a] by Island after RPS consideration.

Island	Solar[b]		Wind[c]		Geothermal[d]	
	MW	***Acres***	***MW***	***Acres***	***MW***	***Acres***
Oʻahu	778	5,991	0	0	0	N/A
Hawaiʻi	16,344	125,846	356	122,964	1,396	N/A
Maui	1,995	15,364	75	8,969	139	N/A
Kauaʻi	514	3,995	0	NA	0	N/A
Total	19,631	151,156	431	30,368	1,535	N/A

[a] Renewable potential estimated based on available land as identified in HECO's renewable potential report.[6]

[b] Solar is considered viable on all islands.

[c] Wind shown for completeness but based on limited resource and difficulty of development, it is not included in subsequent assessments.

[d] Geothermal considered viable only beyond the 2040 timeframe.

Waste, Biomass, and Imported Ethanol

Waste and biomass are potential resources for hydrogen production on all islands and the processing of imported ethanol is a viable option for Oʻahu. Waste as a feedstock was extensively researched on an island-by-island basis in a report by HNEI in May of 2021, primarily in relation to potential production of renewable natural gas (RNG)[7]. The processing to produce hydrogen from C&D and MSW wastes is very similar to those for RNG. Production rate relationships for hydrogen vs. RNG used to estimate potential hydrogen production are described in Appendix C.

HNEI also reported that approximately 700 tons/day of convertible C&D waste are currently disposed of at the PVT landfill on Oʻahu. This waste could be converted to RNG or hydrogen. The 500 ton/day project announced by Aloha Carbon, which has the potential to produce up to 12,000 MT/yr of hydrogen, is considered the most likely potential source of hydrogen from waste in the 2040 timeframe on Oʻahu. Favoring this project are the announced closing of PVT landfill within the next 8 years and the potential for Hawaiʻi Gas and Par Petroleum to use this hydrogen. Concerns would include the

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[6] NREL, *Assessment of Wind and Photovoltaic Technical Potential for the Hawaiian Electric Company*, July 2021, https://www.hawaiianelectric.com/documents/clean_energy_hawaii/integrated_grid_planning/stakeholder_engagement/stakeholder_council/20210730_sc_heco_tech_potential_final_report.pdf

[7] HNEI, *Resources for Renewable Natural Gas Production in Hawaiʻi*, May 2021, https://www.hnei.hawaii.edu/wp-content/uploads/Resources-for-Renewable-Natural-Gas-Production-in-Hawaii.pdf.

lack of commercial gasification of C&D waste at the commercial scale and potential contaminants in the waste stream. The hydrogen from this feedstock resource would be expected to be suitable for industrial or SAF uses and for combustion engines but would require substantial upgrading to achieve the high purity required for fuel cell use. It is also possible that the Aloha Carbon facility could be more profitable producing RNG instead of hydrogen.

The HNEI study also characterized MSW availability on each island. MSW on Oʻahu is already used in the H-Power facility, which receives approximately 700,000 tons/year of waste and about 550,000 tons of which it converts to power. While this waste is already committed to producing firm electric power, it could be repurposed for hydrogen after the H-Power contract expires in 2032. Most waste on neighboring islands goes into landfills, as there is no other equivalent to H-Power on any of these islands. A detailed analysis of the composition of the waste on each island is shown in Appendix C. MSW on the neighbor islands also includes C&D waste. Recently, HDR Inc. completed a study for Kauaʻi in October 2023 on potential conversion technologies for MSW to power or fuels. An RFP soliciting proposals for MSW conversion is scheduled to be released by the County of Kauaʻi in early 2024. MSW conversion to hydrogen is included in Table 5.2 showing potential hydrogen production but is considered likely only in the “beyond 2040” timeframe due to the technology, logistics, and contractual challenges.

Dedicated crops grown on-island can also provide biomass for gasification into hydrogen. Available underutilized agricultural land in Hawaiʻi was characterized by HNEI in the same 2021 report on RNG production potential. Underutilized agricultural land suitable for non-pasture, range, or forestry uses (Land Capability Classes 1-4) are assumed to be available for growing dedicated crops to produce hydrogen. Details on additional available agricultural land including lower quality land is available in Appendix C. Hydrogen production potential is based on gasification and a biomass yields of 20 dry tons of biomass per acre/year.

Ethanol is not presently manufactured in Hawaiʻi. According to Island Energy Systems (IES), Hawaiʻi currently imports approximately 105,000 gallons per day of ethanol for blending with gasoline. Doubling ethanol imports and using the increase for hydrogen production could produce almost 62,000 kg per day of hydrogen or 22,542 MT/yr. Ethanol would only be imported to Oʻahu for hydrogen production. It should be noted that Par could also produce the hydrogen needed for its SAF or other renewable fuels by processing additional imported plant oils.

Estimates of the hydrogen production potential from C&D waste, MSW, dedicated crops, and ethanol are shown below in Table 5.2. Assumptions for the efficiency of the conversion to hydrogen are presented in Appendix C.

Table 5.2. Estimated resource and potential H_2 yield by Island.

Island	C&D[a]		MSW[b]		CROPS[c]		Imported Ethanol to H_2
	Ton/day	H_2 Yield (MT/yr)	Ton/day	H_2 Yield (MT/yr)	Acres (LCC 1-4)	H_2 Yield (MT/yr)	H_2 Yield (MT/yr)
Oʻahu	500	12,244	1506	29,720	18,104	31,283	22,542
Hawaiʻi	N/A	N/A	693	14,470	135,171	233,572	N/A
Maui	N/A	N/A	611	11,180	29,498	50,972	N/A
Kauaʻi	N/A	N/A	252	5,260	26,944	46,558	N/A
Total	500	12,244	3,062	60,630	209,717	362,385	22,542

[a] *C&D mixed with MSW of all islands except Oʻahu.*
[b] *Shown for potential but not likely in timeframe of study.*
[c] *Shown for potential but not likely in timeframe of study.*

Water Use for Hydrogen Production

Hawaiʻi has current goals to manage water consumption and hydrogen production would be another consumer of water, especially is dedicated crops or water electrolysis are used. Table 5.3 summarized the estimated water consumption directly used in the production of hydrogen for the estimated H_2 demand. While these values are not an insignificant amount of water, it compares well to historical water consumption in the state of 163,885 million gallons/yr. It should be noted that the water usage for the gasification of dedicated crops does not include water needed to grow crops.

Table 5.3. Water needed to meet the estimated hydrogen demand by production pathway.

Annual Hydrogen Water Requirements (million gallons/yr)	Oʻahu	Maui	Hawaiʻi	Kauaʻi
Estimated Hydrogen Demand (MT/yr)	76,913	10,430	11,169	3,720
Water Electrolysis	274	37	40	13
Gasification of Waste	57	8	8	3
Gasification of Crops	140	19	20	7
Steam Reformation of Ethanol	30	4	4	1

Summary

On a statewide basis, the hydrogen production potentials compare favorably to the potential uses previously shown in Section 2, in that individual island demand can be meet with on-island resources. However, Oʻahu is land constrained and has the highest potential hydrogen demand so access to the available resource may be difficult. This could require imports from neighboring islands or the mainland to meet Oʻahu's demand.

Table 5.4. Expected uses with the potential production methods on each island.

Island	**H_2 Use (metric tons)**		**Production Potential by Resource**						
			C&D	**Solar**	**Ethanol**		**MSW**	**Biomass**	**Total**
	***End-use*[a]**	***MT/yr***	***MT/yr***	***MT/yr***	***MT/yr***		***MT/yr***	***MT/yr***	***MT/yr***
Oʻahu	Industry + Transportation	37,888	12,244	28,218	22,542		N/A	N/A	63,004
	Industry + Transportation + Power	76,913	12,244	28,218	22,542		29,720	31,283	124,007
Hawaiʻi	Transportation	5,188	0	592,786	0		N/A	N/A	592,786
	Transportation + Power	11,169	0	592,786	0		14,470	233,572	840,828
Maui	Transportation	3,802	0	72,368	0		N/A	N/A	72,368
	Transportation + Power	10,428	0	72,368	0		11,180	50,972	134,520
Kauaʻi	Transportation	1,312	0	18,629	0		N/A	N/A	18,629
	Transportation + Power	3,720	0	18,629	0		5,260	46,558	70,447

As noted earlier, the most probable resources for hydrogen production are C&D wastes on Oʻahu and water electrolysis using solar energy. As evidenced in Table 5.3, these routes can meet the expected demand for the Hawaiʻi Gas pipeline, production of SAF for 10% of the state's jet fuel, and a significant amount of projected road transportation. Table 5.3 also shows hydrogen production potential from solar on Hawaiʻi, Maui, and Kauaʻi far exceed what is needed to meet the near-term demand. Given the land constraints and competing uses on Oʻahu, finding the almost 6,000 acres for hydrogen production from solar may be very difficult. Should that be the case, imported ethanol for processing in an Oʻahu refinery could make up that difference.

Longer term, there is potential for 5% of our electrical energy to be provided from hydrogen. On Hawaiʻi, Maui, and Kauaʻi, this larger demand can still be easily met using only solar. While MSW on these islands has a small potential relative to solar, by itself, it could meet the uses shown. On Oʻahu, even a doubling of current ethanol imports to produce hydrogen is insufficient to meet demand when power generation is included. The MSW for hydrogen production on Oʻahu provides ample supply, but development of MSW for hydrogen would be quite difficult and complex. Additionally, acceptance of imported ethanol for local production of hydrogen is uncertain. Should ethanol and MSW not be available, imports (from another island or external) would be needed to meet demand.

It is very important to note that this section addresses only resource availability. Other requirements, including market development, cost, distribution, and storage, and permitting must be addressed and satisfactorily addressed before any commercial development would proceed.

6. PRODUCTION COSTS

Each island has been shown to possess enough resource potential to meet the local hydrogen demand for the fraction of its industrial, aviation, and road transport needs laid out in the Hydrogen Uses section. If hydrogen for 5% of the statewide electric power is also included, Oʻahu would be required to import a renewable feedstock (ethanol for example), generate hydrogen from MSW, or receive shipments from another island. Determining if there are sufficient local resources to produce hydrogen is only one step in assessing the feasibility for local production and use of hydrogen in Hawaiʻi. Costs are also expected to play a very significant role including the costs of production, storage, and local and interisland distribution.

This section is intended to provide an estimate of the cost of producing hydrogen in Hawaiʻi for the key pathways for each island. Production costs in this section are meant to provide indicative estimates for each pathway using publicly available data and simplified project financial assumptions. These estimates should not be used as a substitute for detailed site and project-specific proposals. Site specific complexities associated with building large-scale industrial facilities could have significant impact on the final costs.

Production cost estimates for each of the key technologies are summarized below.

Water Electrolysis

Costs for the electrolytic pathway include the cost of the electrolyzer system and balance of plant, and the cost of procuring renewable energy resources. Additional “soft costs,” such as engineering, procurement, construction (EPC) costs, and permitting costs are not included in this assessment. Using utility-scale solar plants as an example, these types of costs can represent up to half of the total facility costs.

The cost of hydrogen production via electrolysis is driven primarily by the cost of electricity and less so to the cost of the electrolyzer system relative to the total amount of hydrogen produced over the project’s lifetime. Figure 6.1 shows hydrogen production costs for different electricity costs, ranging from $100-200/MWh and different electrolyzer load factors. This range is used to show the importance of electricity cost, but analysis is limited to $100-150/MWh to reflect current PPA prices. The assumed electricity price is also intended to be wholesale, or self-produced, and is lower than current retail rates in Hawaiʻi. The estimated production costs are based on an assumed 30-year amortization of capital costs and an 8% nominal weighted average cost of capital. As noted in the legend, this figure assumes a current electrolyzer capex of $1,300/kW. The cost for energy is representative of recent historical utility-scale renewable energy projects[8]. The "soft costs" for the renewable source are included in the price of electricity. Costs reported here represent the cost required for the hydrogen producer to breakeven on production costs given an assumed cost of capital only and does not include any additional profit targets beyond recouping the capital cost or additional costs for storage and transport of hydrogen to end users. Estimates for storage and transport are discussed further in the next section.

As expected, based on the estimated energy use of 55 kWh/kg of hydrogen produced, every $10/MWh increase in electricity price, the cost of hydrogen increases by $0.55/kg. For a given electrolyzer size, more efficient use of the electrolyzer (higher load factors) results in more hydrogen produced per unit per year and lower cost. However, above a 40% load factor, the impact of load factor is modest compared to the electricity cost. For reference, the lowest forecast production cost, $6/kg, equates to about $6/gallon or $252 per barrel of oil.

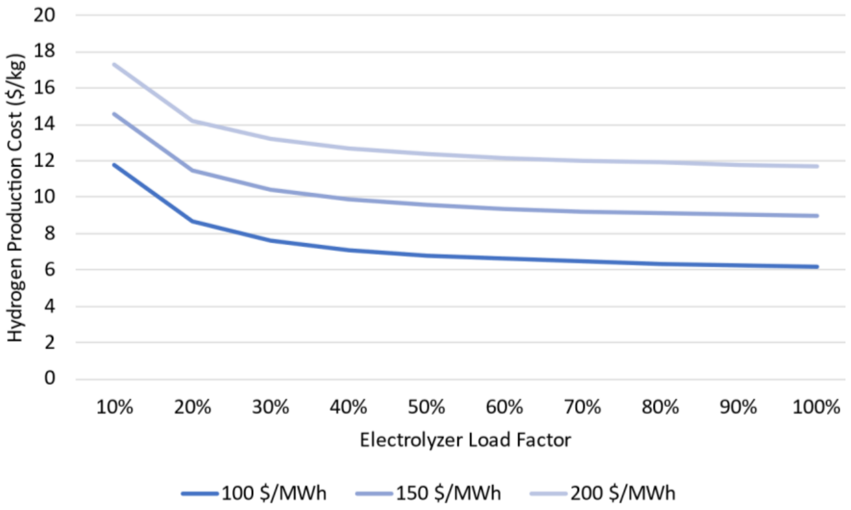

Figure 6.1. Electrolytic hydrogen load factor vs production cost at varying electricity costs (electrolyzer assumes $1,300/kW capex).[9]

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[8] Production costs shown in Figure 6.1 include electrolyzer capital cost and FO&M costs and electrolyzer replacement costs of a 30-year period. See Appendix D for more details on the financial assumptions used.

[9] Figure adapted from IEA (2019), *The Future of Hydrogen*, IEA, Paris https://www.iea.org/reports/the-future-of-hydrogen, License: CC BY 4.0

Figure 6.2 shows the relationship of production costs across a range of electrolyzer costs assuming electricity is available at $100/MWh (10 cents per kWh). In this figure, the electrolyzer costs ($/kW) represent the full cost of the electrolyzer system and the balance of plant, but not the outside battery limit costs (components of the plant not directly tied to the electrolyzer system like civil engineering work). Soft costs for the electrolyzer portion of the plant will be project specific but have been estimated and are expected to add up to $0.50 per kg, a modest increase relative to the overall production cost. More details on these assumptions are available in Appendix D. A comparison of Figures 6.1 and 6.2 show that the cost of the electrolyzer system is important but plays a modest role in reducing production costs when operating at higher load factors.

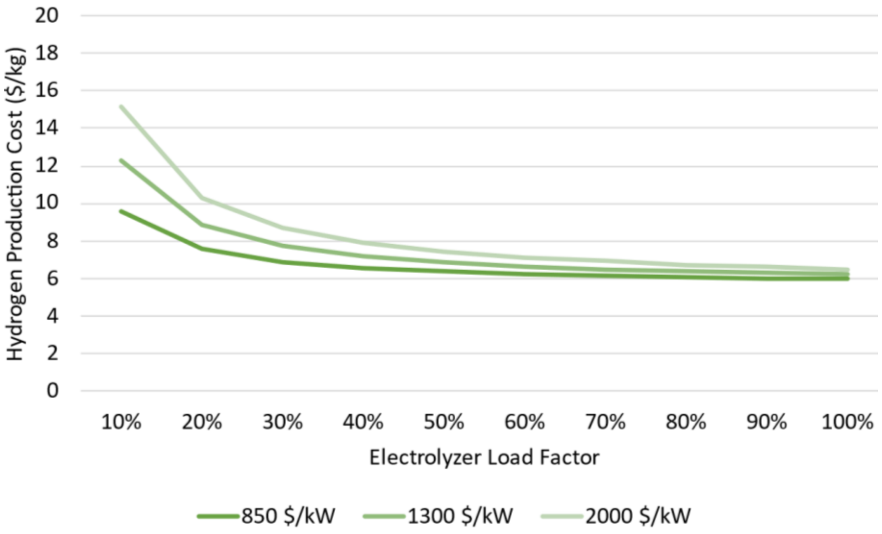

Figure 6.2. Electrolytic hydrogen load factor vs production cost at varying electrolyzer costs (electricity cost at $100/MWh).

To evaluate the tradeoffs between electricity cost, electrolyzer cost, and electrolyzer load factors, HNEI ran several cost scenarios with differing ratios of electrolyzer to PV with and without battery energy storage. Details can be found in Appendix D, but results indicate that an overbuilding of the PV system at a 1.4 MW PV to 1 MW electrolyzer ratio without energy storage resulted in the lowest cost for hydrogen produced using solar energy with electrolysis. Although including battery storage allowed for greater load factors of the electrolyzer, the additional energy cost from the battery systems negates cost savings of improving load factors.

Production costs for production hydrogen via water electrolysis powered by solar PV using solar to electrolyzer ratio described here ranges from 8 – 10.5 $/kg (unsubsidized) if prices of $100/MWh or $150/MWh are achieved. If geothermal energy is also available at these prices, the electrolyzer can operate at a higher load factor and the unsubsidized cost of production hydrogen is 6 – 9 $/kg. These values assume electrolyzer prices at $1,300/kW.

Based on these trends, the primary focus for producing hydrogen should be on acquiring low cost energy resources. Regardless of energy system used to power electrolysis, obtaining low energy costs and preferred load factors will be challenging for Hawaiʻi, as historically, renewable energy prices are much higher in the state than the mainland United States.

Thermochemical Conversion of Organic Feedstock

The total production costs for the gasification and SR pathways, include the cost of acquiring or producing the feedstock (waste, crops, or ethanol) and the gasification/SR plant costs relative to the expected total amount of hydrogen produced over a project's life. Gasification plants are typically large-scale industrial facilities to achieve economy of scale and lower cost. Based on industry experience, facilities processing less than 250 tons per day of input will be difficult to support financially. In Hawaiʻi, anything more than 1,000 tons per day is likely difficult to support due to feedstock constraints.

While capital costs for gasifying biomass are typically lower than that of MSW or C&D wastes, the feedstock costs are relatively higher due to growing, harvesting, and delivery costs. A delivered cost of $100/dry ton biomass is consistent with expected biomass costs in Hawaiʻi based on two previous assessments conducted by HNEI reviewing sugarcane, energycane, banagrass, and trees for gasification[10,11].

Many analyses have been conducted over the years to determine the production cost for producing hydrogen from biomass with widely varying outputs. Based on both historical and recent studies from several countries with biomass delivery costs similar to the Hawaiʻi estimates, the production cost of producing hydrogen via biomass gasification is expected to be in the range of $2.50-$6.0/kg. This range does not factor in complications with siting new industrial facilities in Hawaiʻi but does include a cost for delivered feedstock of approximately $100/ton. See Appendix D for a listing of references on this topic.

Although capital costs are expected to be higher for a waste to hydrogen facility, the cost of feedstock can be negative. For example, Waimānalo Gulch charges approximately $111/ton to landfill waste at the facility. Waste to hydrogen facilities would be expected to earn similar disposal fees as revenue. Since biomass from crops is estimated at a cost of approximately $100/ton, there is a net operating cost difference of $200 per ton when

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[10] HNEI, *Alternative Biofuels Development: Production, Harvesting, and Handling Assessment*, April 2014, https://www.hnei.hawaii.edu/wp-content/uploads/Biofuels-Production-Harvesting-Handling-Assessment.pdf.

[11] HNEI, *Alternative Biofuels Development: Crop Assessment*, December 2013, https://www.hnei.hawaii.edu/wp-content/uploads/Biofuels-Crop-Assessment.pdf.

comparing waste gasification to biomass gasification. With higher capital cost but lower cost of feedstock, the production costs for the gasification of waste (C&D or MSW) are expected to be modestly lower than for biomass, in the range of $2.60-4.30/kg.

OMNI has announced that their C&D waste to hydrogen project in California will produce hydrogen at less than $3/kg, which is in line with forecasted production costs[12]. Despite those projections, we don't know of any commercial scale gasification of waste to produce hydrogen.

Steam reformation is a mature and large-scale industrial process which benefits from economies of scale. However, as in waste gasification to hydrogen, there are very limited commercial scale SR facilities using ethanol to hydrogen under development. Production costs for this process would be driven by the cost of ethanol and the capital cost of the facility. As of October 2023, ethanol was at approximately $2.30/gal, making the feedstock costs for hydrogen equivalent to approximately $3.90 per kg of hydrogen with processing costs in addition to this. With interest in producing cleaner hydrogen present in the U.S., there have been some estimates developed for the ethanol to hydrogen pathway. One estimate from Golu shown in the Appendices shows the total cost of hydrogen from SR of ethanol at $5.24 per gallon. Similar to other technologies for hydrogen production, this cost would likely be lowered by tax credits.

Effects of Federal Tax Credits on Production Costs

There are over a dozen direct and indirect tax incentives related to the production of hydrogen that have been passed into law. However, although legislation has passed, regulations are not yet set for many of these credits. Uncertainty remains regarding eligibility in some cases[13]. There are also significant disagreements between proponents of different hydrogen production technologies (SR of fossil fuels with carbon capture vs. water electrolysis) regarding how these tax credits should apply[14].

This section describes some of the production tax credits (PTC), investment tax credits (ITC), and renewable fuel standard credits (RINs) that may apply to hydrogen produced for the different end users described in this report. Estimates on what value these credits may have in reducing costs of hydrogen assume any project is eligible for the stated tax

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[12] Lane, *Low Cost Green Hydrogen: The Digest's 2022 Multi-Slide Guide to Omni Conversion Technologies*, March 16, 2022, https://www.biofuelsdigest.com/bdigest/2022/03/16/low-cost-green-hydrogen-the-digests-2022-multi-slide-guide-to-omni-conversion-technologies/8/.

[13] Jeffrey Karp, *Treasury Department/Internal Revenue Service Delay in Issuing Guidance Means Hydrogen Producers Remain Uncertain About Tax Credit Eligibility Under the Inflation Reduction Act*, Sept 2023, https://www.jdsupra.com/legalnews/treasury-department-internal-revenue-2429098/

[14] N. Kaufman & A. Corbeau, *The Battle for the US Hydrogen Production Tax Credits*, April 2023, https://www.energypolicy.columbia.edu/the-battle-for-the-us-hydrogen-production-tax-credits/

credits at their full rate. However, it is recommended that caution is taken with these assumptions prior to final regulations or incentives being set due to the ongoing development of regulations.

For renewable energy in Hawaiʻi, the investment tax credit (30% of the project energy system capex) may be more beneficial than the production tax credit ($26/MWh of electricity produced) for cost reductions since it provides a percentage reduction in a qualifying facilities capital cost. Since Hawaiʻi typically sees higher capital costs than the mainland, it translates to higher savings for renewable energy to power water electrolysis in the range of $1-2/kg over the life of the project.

For hydrogen production, if the full hydrogen production tax credit of $3/kg is achievable by projects in Hawaiʻi, it translates to a $0.76/kg reduction in the production cost of hydrogen over a 30-year project life. Together, these major federal tax credits could reduce the hydrogen production costs by approximately $1-3/kg. See Appendix D for more details on the financial assumptions used to levelized the tax credit value.

Additional cost reductions may be available for the SR of ethanol pathway if the existing renewable fuel standard credit worth $1.50/gal is available for road transportation uses[15]. This credit, typically for ethanol blending in gasoline, may translate to a $2.5/kg hydrogen value if extendable to hydrogen as an alternative fuel; however, it is not clear at this time what final regulations would apply to hydrogen made from ethanol.

Additional tax credits are available for hydrogen production, storage, and use, which may further decrease the cost of scaling hydrogen as a decarbonization tool. For simplicity, these were not assessed in detail. It is also important for Hawaiʻi to consider the stability of future investments after tax credits expire. Projects should not be solely viable due to subsidies if cost reductions do not materialize, particularly on the storage and distribution side of the hydrogen system as will be explored in the following section. Table 6.1 below lists the titles of additional tax credits that may be applicable to hydrogen depending on its production pathway and end use.

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[15] https://www.biofuelsdigest.com/

Table 6.1. List of IRA sections that are relevant, both directly and indirectly, to either the supply or demand of hydrogen.

Title	Section	Supply	Demand
Alternative Fuel Vehicle Refueling Property Credit	30C		X
Tax Credit for Biodiesel, Renewable Diesel, and Alternative Fuels	40A		X
Sustainable Aviation Fuel Credit	40B		X
Carbon Oxide Sequestration Credit	45Q	X	
Zero-Emission Nuclear Power Production Credit	45U	X	
Credit for Production of Clean Hydrogen	45V	X	
Qualified Commercial Clean Vehicles	45W		X
Advanced Manufacturing Production Credit	45X	X	
Clean Energy Production Credit	45Y		X
Clean Fuel Production Credit	45Z	X	
Advanced Energy Project Credit	48C	X	
Clean Electricity Investment Credit	48E	X	
Depreciation for Qualified Facilities, Qualified Property, and Energy Storage Technology; Code §168(e)(3)(B)	168B	X	

Summary

Each of the production pathways explored in this report presents different challenges when considering land and resource availability. This section added an additional layer focused on the cost to produce a kilogram of hydrogen using gasification, SR, or water electrolysis technologies. The cost to produce hydrogen is one of the key determinants on whether Hawaiʻi should pursue aggressive investment in expanding hydrogen opportunities. Existing tax credits may alleviate initial costs by a modest amount, but hydrogen production will remain capital intensive and require complex logistics for Hawaiʻi to cost effectively produce hydrogen locally. The indicative hydrogen production costs for each technology are summarized in Table 6.2 below.

Table 6.2. Summary table of unsubsidized hydrogen production costs.

Production Technology	Hydrogen Production Cost ($/kg)	Source
Water Electrolysis	6-10.5	HNEI Calculations
Gasification of Waste	2.5 - 4.5	Literature Review
SR of Ethanol	5 - 6.5	Literature Review
Gasification of Biomass (crops)	2.5 - 6	Literature Review

7. DISTRIBUTION AND STORAGE

Transporting, storing, and distributing hydrogen to end users is one of the most complex, costly, and overlooked elements of the system required to enable hydrogen use. The challenge is twofold in that hydrogen is inherently difficult and inefficient to store and, in the case of Hawaiʻi, will require entirely new delivery and storage infrastructure.

Today, hydrogen production is done most often via steam reforming (SR) of natural gas for petroleum refining and is co-located with the end use. When production matches the end-use, storage is minimized allowing cost-effective transport through pipelines. When pipelines are not feasible and when production and end-use are not well matched, transport and storage become significantly more complex. Such will be the case when hydrogen production comes from the use of a variable renewable energy source, such as solar, to electrolyze water. In such a case, hourly, daily, and even seasonal variability will impact the design of the transport and storage system.

In this work, several end-uses with very different temporal requirements and several potential production methodologies with very different production profiles have been proposed. Analysis of all options for transport and storage is beyond the scope of this report. However, key aspects for likely mixes of production and end use, and the estimated costs for these systems are summarized below with more detail provided in Appendix E.

In the sections below, the core requirements for transport and storage as both a gas and a liquid are described. For comparison, core capital and operations expense items are evaluated and presented on a cost/kg basis. These costs are then applied to different possible combinations of production and end-use to estimate the additional cost imposed by transport and storage. Transport via pipeline is possible for some scenarios involving Hawaiʻi Gas and the PAR SAF operations and is discussed separately. However, should current plans for gasification of C&D waste not materialize, these end-uses would require the same distribution and storage infrastructure as the road transportation applications. Power generation is not expected to be an end use until much later, and the consumption profile varies drastically compared to the other end uses. Therefore, the focus of discussion and costs are based on providing hydrogen for road transportation which requires a distributed network of refueling stations, necessitating delivery and storage.

Gaseous Distribution and Storage

Figure 7.1 below shows a representative distribution system based on transport and storage from a distributed production facility to either a central or distributed end-use using gaseous hydrogen. As shown in the figure, potential elements of a gaseous distribution system include compressors, gaseous hydrogen tanks and trailers, and trucks for transport to the site(s) of use. Each major component is described in detail below.

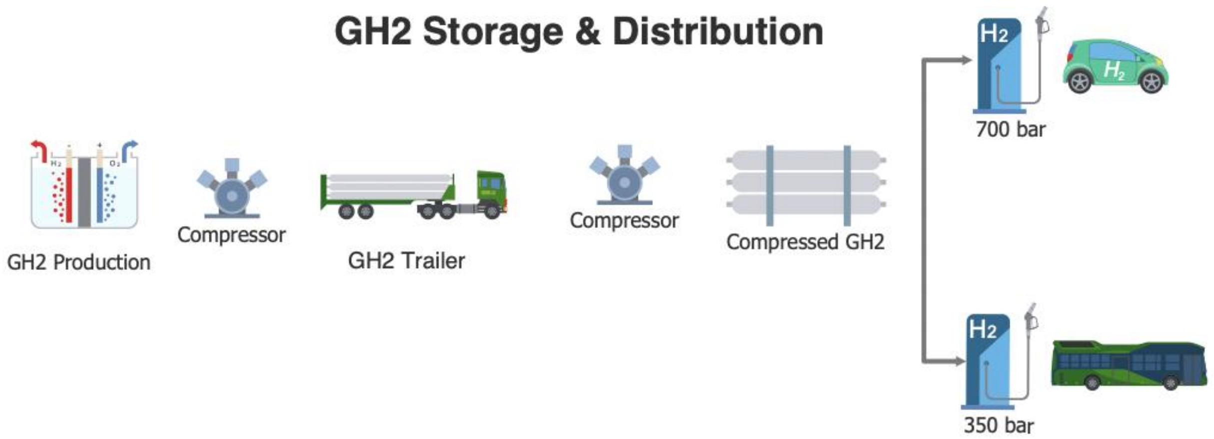

Figure 7.1. Storage and distribution for a gaseous hydrogen system.

a) Compression at the production site is required for efficient truck transport and delivery to the site(s) of use. Typical truck transport occurs at 250 bar. Compressors able to achieve the required pressures are available at capacities between 25 kg and 100 kg per hour. This report assumes the compressor is rated at 90 kg per hour. Multiple compressors will be used in parallel to compress hydrogen at production sites for distribution based on the required kg/day of delivery. Energy consumption for compression is assumed to be 9 kWh/kg of hydrogen to bring it to the desired pressure.
b) Gaseous hydrogen trailers are typically composed of many cylinders and vary in pressure and total hydrogen capacity expressed in kilograms. It is assumed that one gaseous hydrogen trailer can hold 873 kg (0.873 MT) of hydrogen at 250 bar.
c) It is assumed that the delivery method for gaseous hydrogen is a “drag-and-drop” approach where an empty trailer is swapped with a full one for each delivery.
d) On-island transport between production sites and end use sites requires trucks to haul gaseous trailers. It is assumed that one truck can haul one trailer per day for delivery of a full trailer and return of an empty trailer. The total number of trucks and drivers required to deliver hydrogen is based on the number of delivery trailers required to deliver a daily hydrogen target. It is assumed that hydrogen fueled tractor trucks will be used to haul trailers.
e) Dispensing at hydrogen refueling stations would be expected to drawdown the delivered gaseous storage tanks for refueling into hydrogen powered vehicles. However, this study did not include an assessment of the number or cost for dispensing stations.

Liquid Distribution and Storage

Figure 7.2 below shows a representative distribution system based on transport and storage from a distributed production facility to either a central or distributed end-use using liquid hydrogen. As shown in the figure, some of the key components for liquid hydrogen distribution include the liquefaction plant, liquid hydrogen transport trailers, and trucks to deliver the hydrogen to end users. Each major component is described in detail below.

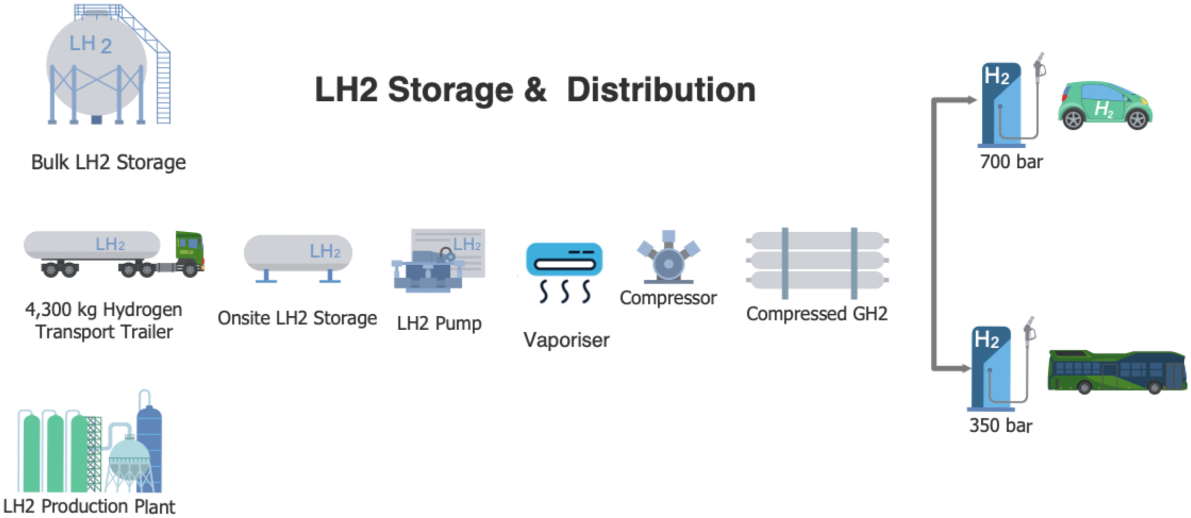

Figure 7.2. Storage and distribution for a liquid hydrogen system.

a) Each production site requires a liquefaction plant to cool hydrogen down to -253°C and produce liquid hydrogen and it is stored in Zero Boil Off (ZBO) bulk storage tanks. Both the capital cost and energy requirements per kilogram of hydrogen for liquefaction decrease as the scale of the plant increases. This analysis assumes liquefaction plants ranging from 2,000 kg/day to 15,000 kg/day and assumes 13-20 kWh/kg to liquefy hydrogen. The choice for the size of the liquefaction plant depends on the scale of the daily hydrogen demand and the size of the production facility.

b) Liquid hydrogen trailers are composed of a single tank kept at cryogenic temperatures to keep hydrogen at -253°C. The capacity for liquid hydrogen trailers can vary depending on the end use requirement, however in this analysis, it is assumed that one liquid hydrogen trailer can carry 4,300 kg.

c) The delivery method for liquid hydrogen is assumed to be done using a “refill” approach where a liquid hydrogen tank at a dispensing station is refilled by the trailer for each delivery.

d) On-island transport between production site(s) to end users requires trucks to haul the liquid hydrogen trailers. It is assumed that one truck can deliver one liquid hydrogen trailer per day per delivery. The total number of trucks and drivers required to deliver hydrogen is based on the number of delivery trailers required to deliver a daily hydrogen target. It is assumed that hydrogen fueled tractor trucks will be used to haul trailers.

e) Dispensing stations are needed at the delivery site for refueling hydrogen powered vehicles. This study did not include an assessment of the number or cost for dispensing stations. In general, the dispensing sites may vaporize liquid hydrogen into a gaseous state and then compress it into high pressure gaseous storage tanks for dispensing to vehicles. If liquid storage is available for vehicles in the future, then liquid hydrogen can be directly transferred into them without need for vaporization and recompression.

Buffer Storage for Distribution

Both gaseous and liquid delivery options may require a buffer tank before distribution to accommodate the difference between hydrogen production and consumption needs. This is especially true if hydrogen is produced using renewable energy since production profiles will not match consumption profiles. Depending on the storage system, the buffer would require either compressors or a liquefaction plant and gaseous or liquid hydrogen storage tanks. Offtake from the buffer storage would be available through the same delivery trucks used in the distribution system. The key components for the buffer storage assumed in this analysis are detailed below:

a) Several 6,700 kg zero boil off Liquid hydrogen or 873 kg gaseous hydrogen storage tanks will be required to meet a 3-day buffer storage assumption for each island.
b) Either a series of compressors or liquefaction plants are required to fill the buffer storage system. It is assumed that the 3-day buffer storage should be capable of refilling completely over 7-days.

Buffer Storage for Power Generation

As discussed in Section 3, *Hydrogen Uses*, some level of dispatchable firm power generation will be required even when the penetration of variable renewables and storage approaches 100% to cover persistent, multi-day droughts in wind and solar production that cannot be met with battery energy storage. One potential way to meet this grid need is to produce and store hydrogen during periods of high renewable energy for use when renewable resources are limited.

The daily and seasonal variability of renewable energy production creates a mismatch between when hydrogen is produced and when it would be consumed for power generation. Figure 7.3 below is an example for Maui, that shows daily hydrogen production (blue) and the use of hydrogen for power generation to meet capacity shortfalls (red). As shown, the summer months tend to have excess hydrogen production on any given day. During winter months there are days or series of days where large quantities of hydrogen are needed to generate electricity to meet load.

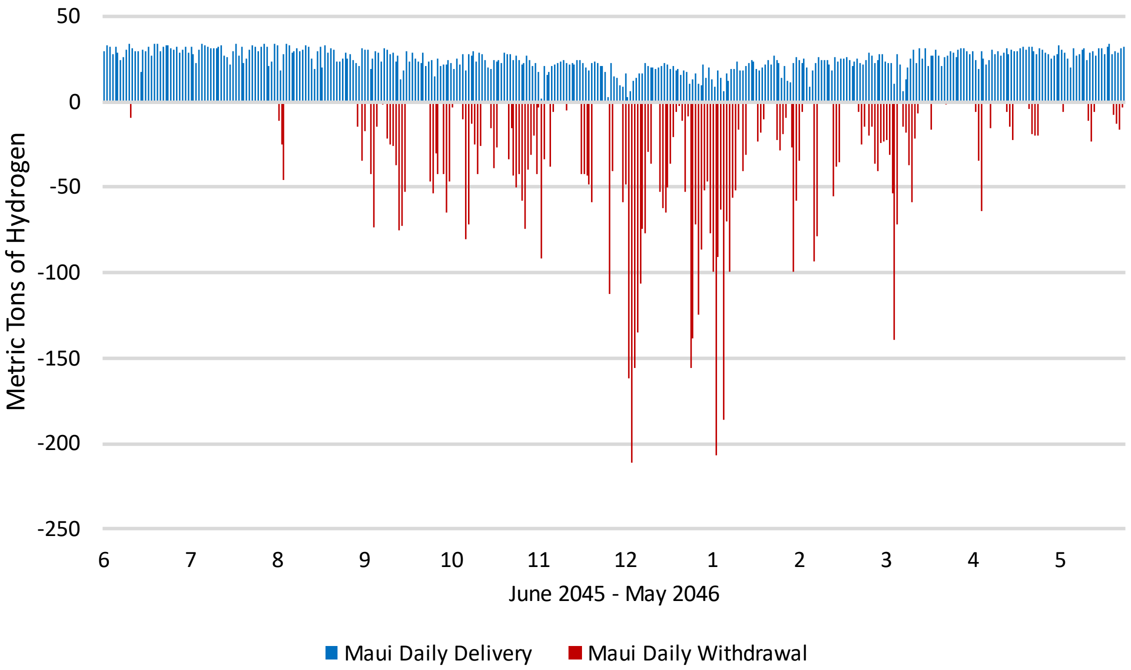

Figure 7.3. Maui Daily Hydrogen Delivery vs. Withdrawal for June 2045 - May 2046.

For context, in this case hydrogen delivery averages around 24 MT per day, but daily offtake can be up to 200 MT per day, over 10 times the daily production. The periods where high use is needed are often for several days at a time. This means a very large amount of hydrogen needs to be available in storage to serve demand. Again, referring to this Maui example it was found that storage, equivalent to approximately 200 days of average hydrogen production would be needed. For reference, a 3 to 5-day buffer was assumed for the transportation uses.

Unfortunately, Hawaiʻi does not possess the geologic formations (i.e. salt domes) to enable low-cost storage of large quantities of hydrogen that may be possible on the mainland. Instead, this use case would require construction of massive hydrogen storage, likely in the form of large liquid hydrogen tanks like the one recently built by NASA which holds 330 metric tons of hydrogen.

Figure 7.4. NASA 330 metric ton large-scale liquid hydrogen storage tank[16].

In the Maui example, several of these large-scale storage tanks would be required. The scale of hydrogen storage for an island like Oʻahu, with approximately 6 times the annual electricity demand would be proportionally larger. The scale of this storage requirement is one part of why firm power generation from hydrogen was not considered as an end use in the near-term. Given the uncertainty of the cost and infrastructure required to deploy these storage solutions at scale in Hawai'i this end use was not further assessed, and costs were not estimated.

Summary

Based on the delivery and buffer storage systems described above, Table 7.1 details the daily hydrogen delivery target, number of trucks required, the estimated capital and operating costs, and the total $/kg cost of delivering hydrogen for the road transportation end use. Costs include the assumption that 3-days of buffer storage matches the delivery type (gaseous or liquid). Details on each island's delivery and buffer storage system using gaseous or liquid hydrogen are in Appendix E.

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[16] Photo Credit: https://www.mcdermott.com/getmedia/19c65361-b828-4fee-ae5c-99ca8e25cc89/Cape-Canaveral-NASA-Hydrogen-Storage-digital.pdf.aspx

Table 7.1. Daily hydrogen delivery targets, transport needs, and associated costs.

Island	Daily Delivery	Delivery Type	Trucks Required	Buffer Tanks Needed	Capital Cost ($/kg)	Operating Cost ($/kg)	Total Cost ($/kg)
Oʻahu	60,000 kg/day	Gaseous	69	357	1.8	2.1	3.9
		Liquid	15	46	2.3	2.9	5.2
Maui	10,000 kg/day	Gaseous	12	36	1.9	2.3	4.2
		Liquid	3	5	2.8	4.6	7.4
Hawaiʻi	14,000 kg/day	Gaseous	17	49	1.9	2.2	4.1
		Liquid	4	6	2.7	4.5	7.2
Kauaʻi	4,000 kg/day	Gaseous	5	12	2.0	2.7	4.7
		Liquid	1	2	3.8	5.0	8.8

The above table addresses the cost per kilogram for delivering hydrogen for road transportation on each island.

Transporting, storing, and distributing hydrogen to end users is not trivial, nor low cost. Substantial investment in equipment and infrastructure is needed to enable widespread use of hydrogen as a fuel for road transportation. Although this analysis reviewed several factors important to the cost of delivered hydrogen, there are additional cost and logistics factors to consider. While gaseous hydrogen distribution may seem feasible from a cost perspective, it requires a very large fleet of delivery vehicles, which may be impractical to operate making the higher density liquid hydrogen more practical.

Liquid hydrogen is more competitive in cost terms for Oʻahu relative to the other islands because of its scale. But for small markets gaseous hydrogen may make more sense in cost terms. For Oʻahu, it is assumed that if hydrogen can be produced from C&D waste or SR of imported ethanol that transportation and storage costs will be minimal for the SAF and Hawaiʻi Gas uses which are located close by and can be connected by pipeline. However, if centralized hydrogen production from C&D wastes does not materialize, these end uses would require similar infrastructure and additional cost adders to have hydrogen delivered.

Prioritization of future investments should consider the minimization of additional infrastructure to store and transport hydrogen to end users. Existing industrial end uses on Oʻahu may require less infrastructure for meeting hydrogen demand for SAF production and Hawaiʻi Gas needs if centralized production of hydrogen can be achieved at low cost and with low greenhouse gas emissions. These uses may be the most promising hydrogen market in Hawai'i given these factors.

8. INTERISLAND SHIPPING

Shipping hydrogen between islands, or from the mainland, may be necessary to meet the estimated demand on Oʻahu if local hydrogen production capabilities fail to materialize or hydrogen demand grows substantially (see Section 5, Table 5.4). Due to the resource and land availability on Hawaiʻi Island, it is possible that hydrogen could be shipped to Oʻahu to serve hydrogen demand. This section explores the core components required for shipping a targeted amount of hydrogen and provides an estimate in $/kg for how much shipping hydrogen to O'ahu from Hawai'i Island and distributing it via liquid hydrogen trucks costs for end users.

Inter-island shipping of hydrogen is expected to require liquid hydrogen to maximize the amount of hydrogen sent per shipment. The core components for enabling hydrogen shipping are like the liquid hydrogen distribution system and require liquefaction plants, liquid hydrogen iso-containers for delivery and shipping, trucks to bring hydrogen to the port, shipping barges and tugboats. A description of each of the components required in this system is provided below and figures 8.1 and 8.2 illustrate the 3,000 kg hydrogen ISO containers and the barge delivery system.

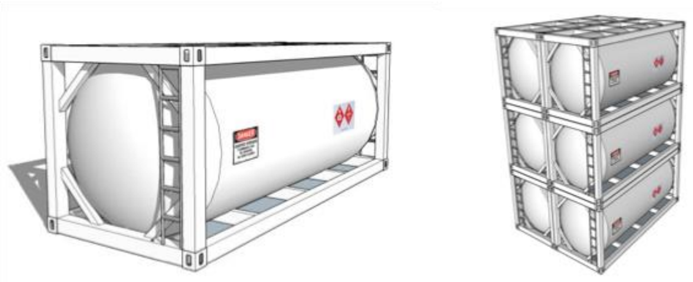

Figure 8.1. 3,000 kg LH_2 ISO-containers.

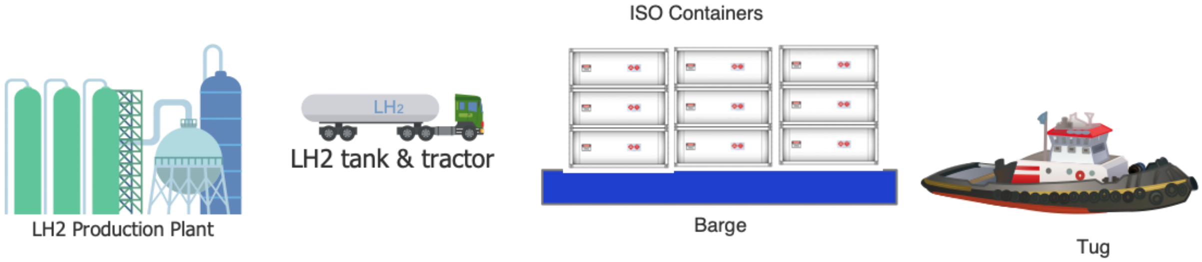

Figure 8.2. Transport of LH_2 from Hawaiʻi Island to Oʻahu.

a) Liquefaction plants are required at distributed hydrogen production sites to enable transport of liquid hydrogen to a port for loading into shipments. It is assumed that larger-scale 15,000 kg/day liquefaction plants are used due to the scale of shipping amounts. This liquefaction plant assumes 13 kWh/kg to liquefy hydrogen.

b) Liquid hydrogen 3,000 kg ISO containers mounted on flatbed trailers are used to transport hydrogen from production sites to the port to load onto barges.
c) Transporting the storage trailers is done by trucks running on hydrogen. One truck is assumed to deliver two trailers per day to the port.
d) At the port, the ISO containers are transferred from the flatbed to a barge for shipping. It is assumed that multiple sets of ISO-containers are required. One set at the destination port, one set in transit, and one set being filled at the production port.
e) A barge and tugboat are used to transport hydrogen to the destination port.
f) Filling, transporting, and offloading the liquid hydrogen requires time for safe handling and travel. Therefore, there must be enough equipment to enable several days' worth of hydrogen demand to buffer travel time between islands.
g) A zero boil off liquid hydrogen buffer storage is assumed to be present on Oʻahu to accommodate the delay in deliveries and ensure steady supply to match demand.

The example used for shipping liquid hydrogen from Hawaiʻi Island to Oʻahu is based on a target delivery of 60,000 kg/day. The assumptions on how this system is expected to operate are based on consultation with Island Energy Services (IES) estimations on equipment and operations to deliver 20,000 kg/day of liquid hydrogen from Hawaiʻi Island to Oʻahu. The steps to deliver liquid hydrogen are detailed below and costs are presented on a $/kg basis in Table 8.1. More details on estimated equipment quantities and costs are provided in Appendix F.

a) Production and liquefaction of liquid hydrogen occurs on Hawaiʻi Island at four sites sized to produce 15,000 kg/day of liquid hydrogen and delivered via trucks.
b) The roundtrip shipping delivery time is assumed to be four days with the shipment size meeting four days of demand, or 240,000 kg (four days of 60,000 kg/day requirement).
c) It is assumed that a diesel powered tugboat brings a leased barge loaded with eighty (80) 3,000 kg liquid hydrogen ISO-containers.
d) On Oʻahu, a bulk storage tank is available and sized to provide a five-day buffer based on IES assumptions. It is expected that the tank would be similar to the 330,000 kg liquid hydrogen tank recently built by NASA.

Table 8.1. Delivery and associated costs for shipping LH_2 from Hawaiʻi Island to Oʻahu.

Shipping Route	**Daily Delivery**	**Shipping Round Trip**	**Shipment Size**	**Capital Cost ($/kg)**	**Operating Cost ($/kg)**	**Total Cost ($/kg)**
Hawaiʻi Island to Oʻahu	60,000 kg	4 days	240,000 kg	2.7	2.8	5.5

It is assumed that once it arrives on O'ahu, the liquid hydrogen would be distributed using a similar network of liquid hydrogen trailers to make deliveries to end users. This allows for a direct comparison of the costs for liquefaction and shipping liquid hydrogen relative to liquefaction and distribution on-island alone. Based on an assumed delivery of 60,000 kg/day of liquid hydrogen to Oʻahu, the additional cost for to supply liquid hydrogen to Oʻahu from Hawaiʻi Island is relatively modest at $0.30/kg higher than if liquid hydrogen were only stored and distributed on-island. This relatively close cost between the two options is due to the relatively low cost of leasing a barge and tugboat for deliveries of ISO-containers loaded with hydrogen. The added cost of delivering liquid hydrogen to the port on Hawaiʻi Island is also relatively minimal. This analysis did not assume any additional costs attributed to new port infrastructure on either island to accommodate these deliveries. If the available land and scale provided by Hawaiʻi Island could reduce the cost of energy and liquefaction, then it may provide a more cost competitive hydrogen solution than local production on O'ahu.

9. PERMITTING AND REGULATORY ISSUES

The application of hydrogen as an energy carrier has been expanding into industrial and transportation sectors enabling sustainable energy resources and providing a zero-emission energy infrastructure. The hydrogen supply infrastructure includes processes from production and storage to transportation and distribution, to end use. Each portion of the hydrogen supply infrastructure is regulated by international, federal, state, and local entities. Regulations are enforced by entities which provide guidance and updates as necessary. While energy sources such as natural gas are currently regulated via the Code of Federal Regulations (CFR) and United States Code (USC), there might be some ambiguity as to which regulations are applicable to hydrogen and where regulatory gaps may exist. A Sandia National Laboratory 2021 report entitled "Federal Oversight of Hydrogen Systems" contains an excellent overview of the regulations that apply to hydrogen, and those that may indirectly cover hydrogen as an energy carrier participating in a sustainable zero emission global energy system[17]. As part of this effort, the infrastructure of hydrogen systems and regulation enforcement entities are defined, and a visual map and reference table were developed. This regulatory map and table can be used to identify the boundaries of federal oversight for each component of the hydrogen supply value chain which includes production, storage, distribution, and use.

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[17] Baird, Austin Ronald, Ehrhart, Brian David, Glover, Austin Michael, and LaFleur, Chris Bensdotter. *Federal Oversight of Hydrogen Systems*. United States: N. p., 2021. Web. doi:10.2172/1773235.

Installers of hydrogen systems are also required to use local building codes, National Fire Protection Association (NFPA) codes, and the International Code Council (ICC) International Fire Code (IFC) for code requirements and engage with the authority having jurisdiction (AHJ) for safety and permitting approvals. Local jurisdictions can and have adopted many different requirements that must be followed for installations under their purview.

Permitting any large infrastructure project in Hawaiʻi is challenging due to Hawaiʻi's many protected species and environments, active cultural and historic archaeological sites, and complex land use laws exacerbated by limited developable land area. In addition, public opposition to large infrastructure projects, including renewable energy development, is a concern. Most clean hydrogen projects have the potential to cause environmental impacts, especially if not implemented properly.

However, many of the potential impacts can be alleviated or mitigated through careful adherence to federal, state, and county laws, regulations, and permitting requirements; implementation of well-planned best management practices and mitigation measures; and early consideration of local community concerns.

Because hydrogen is not widely deployed in Hawaiʻi at present, educating AHJs and the public on hydrogen risks and proven mitigation strategies will be a necessary early step in the permitting process. Efficiently acquiring the permits and approvals required for a hydrogen project will require upfront transparency and ongoing communication with regulators and the public.

Permitting risks will likely come from new production facilities to be built on undisturbed 'green fields' that may not have existing studies or permits. Permitting risks for these new 'green field' projects can be mitigated through appropriate site selection, pre-assessment, and early outreach and engagement including the AHJs and nearby communities. Projects sited on poorly rated agricultural land can greatly reduce the land use regulatory oversight.

Permitting risks for new microgrid, distribution, and storage infrastructure can be mitigated by co-locating them at existing already permitted facility sites. New community microgrid projects may also require minimal permitting if sited appropriately. For example, while new permits are needed for hydrogen facilities, NELHA operates within the framework of prior environmental reviews and is pre-permitted for many kinds of activities including production of renewable energy.

The Hawaiʻi State Energy Office (HSEO) is a valuable resource that can assist hydrogen project developers under its statutory authority to facilitate the efficient, expedited permitting of energy efficiency, renewable energy, clean transportation, and energy resiliency projects. HSEO has established positive and productive relationships with the Hawaiʻi-based federal, state, and county authorities having jurisdiction (AHJs) over a diversity of energy projects in Hawaiʻi.

Details of permitting regulations and resources are provided in Appendix G

10. EXPORT/IMPORT POTENTIAL

As can be seen from previous sections, while meeting only 20% of transportation uses is very challenging, there are sufficient resources that may still be potential for additional hydrogen production for export from Hawaiʻi Island. However, as noted, costs for electrolysis based on unsubsidized hydrogen production are estimated to be $6/kg to $10.5/kg. Local distribution and storage is in addition to this cost and ranges from $4/kg - $9/kg depending on scale and method of distribution (gaseous versus liquid). Additional costs are expected for importing hydrogen to O’ahu from Hawai’i Island and estimated at about $5.5/kg ($0.3/kg higher than on-island storage alone). Exports to Asia or mainland U.S would be expected to be higher, over $5/kg without local distribution and storage considered. Markets in the mainland are able to produce hydrogen at much lower costs due to hydropower as in the Northwest, lower cost land for PV or low cost wind power as in Texas/Gulf Coast. These projects are described in the following section on US DOE Hydrogen Hub. Markets in Asia have similar advantages over Hawaiʻi, for example in large scale planned hydrogen production for export in Australia[18] or the Middle East. There is not expected to be credible potential for competitive export of hydrogen from Hawaiʻi.

Import of large quantities of hydrogen from Asia, or the West or Gulf coasts of US would be similar in complexity to LNG due to pressure and temperature requirements. Hawaiʻi Gas imports limited quantities of LNG in packaging uniquely specific to Hawaiʻi. Expansion of LNG imports was looked at extensively in 2014-2016 before being rejected in favor of renewable power objectives[19]. Although production costs are expected to be lower in Asia and U.S. Mainland, shipping costs, including liquefaction, could still be over $5/kg depending on electricity prices for liquefaction and operational shipping costs. Given the potential uses described in Hawaiʻi and the local production potential, it would only make sense to import to Oʻahu. Importation of hydrogen may be less expensive than importation of ethanol to produce hydrogen locally. However, at the present time

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[18] https://www.globalaustralia.gov.au/industries/net-zero/hydrogen

[19] https://www.utilitydive.com/news/hawaiian-electric-hawaii-gas-cancel-lng-import-terminal-agreement/417539/#

transport of hydrogen other than in gas cylinders is very limited. Under the estimated uses it does not seem reasonable to import hydrogen to Hawai'i.

11. U.S. H_2 HUB ACTIVITIES

One of the latest drivers pushing the United States towards deploying clean hydrogen across the economy comes from the Bipartisan Infrastructure Law H2Hub program, which recently selected winners for $7 billion in potential funding to support large-scale hydrogen hubs across the country[20]. While these projects are not yet guaranteed to receive funding or be built, they represent a substantial investment in clean hydrogen production in the U.S. towards a variety of end uses and approximately 3 million metric tons of hydrogen production per year.

A summary of the hubs selected by USDOE is provided in Table 11.1 to give additional context for the scale and cost that these types of projects entail since these two factors were considered limiting when assessing Hawaiʻi's potential for deploying hydrogen to decarbonize its economy. All the selected projects include some form of thermal conversion (e.g., natural gas to hydrogen or waste to hydrogen) and/or electrolysis (e.g., from wind/solar or nuclear energy). The prevalence of lower cost fossil based hydrogen (with carbon capture and storage), as well as industrial end uses not relevant to Hawaiʻi stands in contrast to the estimated demand and production technologies assessed in this report. Based on development on the mainland, it is clear that there is continued difficulty for renewable hydrogen to compete with fossil based on hydrogen in both cost and scale terms. In addition, wind and solar projects in the mainland are often 50-75% less than similar projects in Hawaiʻi. These regions also have lower costs for large infrastructure projects in general.

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[20] https://www.whitecase.com/insight-alert/hydrogen-hub-projects-awarded-7-billion-us-department-energy

Table 11.1. USDOE regional clean H2Hub projects[21].

Selected H2Hub Project	Location	Federal Cost Share	Projected Production	Targeted End Use
Appalachian Regional Clean Hydrogen Hub (ARCH2)	WV, OH, PA	Up to $925 million	N/A	HDV & Industry
Alliance for Renewable Clean Hydrogen Energy (ARCHES)	CA	Up to $1.2 billion	500 MTD by 2030; 45,000 MTD by 2045	Backup power, public transit, ports, HDV
HyVelocity H2Hub	TX	Up to $1.2 billion	9,000 MTD	HDV, power generation, ammonia, marine fuel, refineries
Heartland Hub (HH2H)	MN, ND, SD	Up to $925 million	N/A	Fertilizer & power generation
Mid-Atlantic Clean Hydrogen Hub (MACH2)	DE, NJ, PA	Up to $750 million	85 MTD to 600 MTD	HDV, sanitation vehicles, power generation, combined heat and power
Midwest Alliance for Clean Hydrogen (MachH2)	IL, IN, MI	Up to $1 billion	N/A	Steel & glass, power generation, refining, HDV, SAF
Pacific Northwest Hydrogen Hub (PNWH2)	MT, OR, WA	Up to $1 billion	50 MTD to 100 MTD	HDV, ports, power generation/peaking, refining, data centers

Hawaiʻi Hydrogen Hub

The state of Hawaiʻi, along with other Pacific Island partners, participated in the USDOE hydrogen hub competition as well. Although the Hawaiian hub was not selected for funding, the efforts of the public and private partnerships to garner federal funding provided a strong basis for future hydrogen projects to target high-value applications for decarbonization.

The proposed Hawaiʻi Hub's mission statement was to "eliminate price volatility and reduce energy costs and greenhouse gas emissions in high-value transportation, energy storage and electric power applications." It also sought to do the following:

- Serve as a linchpin in accelerating Hawai'i's renewable energy and decarbonization strategy, thus contributing to energy security and national security;
- Provide significant net benefits to Hawai'i's diverse communities through green jobs, higher wages, and delivery of reliable, secure, clean, and affordable energy;

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[21] https://www.energy.gov/sites/default/files/2023-10/H2Hubs_National_Briefing_0.pdf

- Match and phase in appropriate end users from ground-transportation, maritime, and aviation sectors operating locally, to ensure supply and demand balance; and
- Focus on hard-to-electrify or hard-to-abase sectors first, including heavy-duty ground and marine transportation and aviation.

The Hawaiian hub mission statement connects well with the results of this study. Producing large volumes of hydrogen for use across many sectors of Hawai’i’s economy will be challenging given the scale of production and storage challenges. However, focusing on high-value applications where few alternatives exist is the first step towards developing a greater understanding of how hydrogen can benefit Hawaiians and aid reaching decarbonization goals. To reiterate, Hawaiʻi’s highest value sectors for hydrogen use are likely some form of hydrogen use in aviation fuels (SAF) and existing industrial demand (Hawaiʻi Gas), firm power generation/long duration storage for renewable energy and decarbonizing heavy duty vehicles where battery electric vehicles can’t compete.

12. FUTURE USES

In addition to the hydrogen uses considered for analysis in this report, there are other developing technologies that were not considered as near-term, due to either technological or market readiness. The intent of this section is to identify these future potential markets and provide an initial assessment of the potential demand. Two opportunities for future expansion of Hawaiʻi’s use of hydrogen are for the production of electrofuels for marine or aviation application, for future hydrogen powered aircrafts, and cold ironing (shore power) for ships.

Electrofuels

Electrofuels are a class of synthetic fuels produced electrochemically, in a reactor similar to an electrolyzer operating in reverse, that utilize carbon dioxide and hydrogen to produce new or drop in replacement fuels. Methanol, diesel, and aviation fuel represent some of the potential areas for fuel replacement. When the hydrogen is produced from electrolysis using renewable energy or by other processes with low LCA GHG emissions, the LCA emission from use of the fuel are greatly reduced.

Marine

As the world looks towards decarbonization goals, the International Maritime Organization (IMO) has established its own goals to reduce the carbon intensity of maritime shipping.

Today, the goals are to reduce emissions from shipping by 40% by 2030 and 70% by 2050, relative to 2008 levels[22]. There are several pathways for hydrogen to contribute to a zero or low emissions alternative to the intermediate and heavy fuel oil (IFO/HFO) used today for large-scale shipping. These pathways include gaseous hydrogen, liquid hydrogen, ammonia, and methanol.

As an example of the potential hydrogen use of marine fuels, an assessment of the use of hydrogen to produce e-methanol was conducted. In Hawaiʻi, maritime fuel consumption historically represents approximately 4% of total statewide petroleum consumption[23], approximately 82 million gallons of gasoline, equivalent on an energy basis to approximately 152 million gallons of methanol. Replacement of 50% of Hawaiʻi's marine fuels with methanol, assuming equivalent engine efficiency, would require approximately 72 million metric tons of hydrogen – a large increase in demand relative to the assumptions in this report. While hydrogen is one of the major components required for e-methanol production, the other is carbon dioxide. Acquiring enough CO_2 may prove challenging and costly for producing methanol in-state.

Aviation

National Renewable Energy Laboratory (NREL) has reported that the electrofuels process could produce jet fuel with an energy efficiency of 43%, using renewable electricity with 2.3 kilograms of hydrogen used to produce one gallon of jet fuel.[24] Production of 61 million gallons of e-jet fuel by this process (same quantity as proposed by PAR for the production of SAF) would require approximately 140 million kg of hydrogen per year. While this is an order of magnitude larger than the hydrogen requirement for SAF, the other reactant is CO_2, not pyrolysis or other bio-oil feedstock. Similar to the situation for methanol, acquiring enough CO_2 is a likely barrier to the commercialization of this process.

Hydrogen Fueled Aircrafts

Hydrogen has been considered as a potential zero-emissions fuel source for aviation for many years. It can be used in a fuel cell to convert hydrogen to electric power or with developing technologies to be combusted directly. There are multiple companies exploring the development of hydrogen powered aircraft including Airbus who have

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[22] IMO, *Initial IMO GHG Strategy*, 2023, https://www.imo.org/en/MediaCentre/HotTopics/Pages/Reducing-greenhouse-gas-emissions-from-ships.aspx

[23] Hawaiʻi State Energy Office, Hawaiʻi's Energy Facts and Figures, November 2020, https://energy.hawaii.gov/wp-content/uploads/2020/11/HSEO_FactsAndFigures-2020.pdf

[24] E. Ringle, *What if Biorefineries Could Produce 45% More Fuel With Fewer Emissions – All With the Same Amount of Land and Corn?*, March 2023, https://www.nrel.gov/news/program/2023/new-consortium-advances-technologies-that-use-renewable-energy-to-turn-carbon-dioxide-into-fuel.html

announced intentions to have a commercial hydrogen-powered aircraft in service by 2035[25].

Another company that is developing hydrogen-powered aircraft is ZeroAvia. ZeroAvia is developing a hydrogen-powered aircraft that can carry up to 19 passengers. The company has already completed a number of test flights with its hydrogen-powered aircraft, and it is aiming to have a commercial aircraft in service by 2024[26].

It is difficult to estimate hydrogen fuel usage per aircraft mile traveled at this time due to many uncertainties in final aircraft design and supporting infrastructure, but if commercialized this would represent a very large market opportunity for renewable hydrogen.

Cold Ironing (Shore Power)

Cold ironing is a process of providing shoreside electrical power to a ship at berth while its main and auxiliary engines are turned off. This can help to reduce air pollution and noise emissions from ships. Once the ship if docked, it can be connected to shore via cable and the ship's engines can be turned off. Cold ironing can be used for a variety of ships, including container ships, cruise ships, and tankers, but is most effective for ships that spend a long time in port, such as container ships. The benefits of cold ironing include reduced air pollution, reduced noise pollution, and improved energy efficiency.

The main challenges of cold ironing include cost, availability or port infrastructure, and compatibility of the ship. To alleviate these issues, Hawaiʻi's proposal to the USDOE Hydrogen Hub solicitation assumed there would be two cruise ships per day powered by hydrogen and fuel cells with an annual consumption of just under 10,000 MT H_2 per year. While not large relative to some of the other potential future uses, it is one that warrants continued monitoring.

13 CONCLUSION AND RECOMMENDATIONS

Hydrogen as a clean energy carrier has been a topic of interest since the USDOE Renewable Hydrogen Program was initiated in the 1980s, but interest, nationally and internationally, has increased substantially in recent years. US interest has grown to new levels with the competition to identify and fund seven hydrogen hubs across the US.

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[25] https://www.airbus.com/en/innovation/low-carbon-aviation/hydrogen/zeroe

[26] https://zeroavia.com/ecojet/

Hydrogen's appeal results largely from the absence of emissions during use. Hydrogen rarely occurs freely in nature but can be produced from a variety of sources including waste, biomass, and renewable electricity. Once formed, hydrogen can potentially be used in a wide range of applications within the industrial, transportation and power sectors. The versatility offered by the range of production and end-uses has been a draw for hydrogen for many years. At the same time, hydrogen has faced a number of hurdles impacting commercialization including the high cost and/or energy intensive production, complex and costly infrastructure for distribution and storage, and competition from more cost-effective technologies for various end-use applications.

In this study, in response to Act 140 and SB2283, Session Laws of Hawaiʻi 2022, HNEI conducted a study "to examine the potential for the production and use of renewable hydrogen in the State and the potential role of renewable hydrogen in achieving a local, affordable, reliable, and decarbonized energy system and economy."

Act 140 defined renewable hydrogen as "hydrogen produced entirely from renewable sources that have lifetime emissions of no more than fifty grams of carbon dioxide per kilowatt hour", which interpreted literally would indicate production only via electrolysis from a low emissions renewable source. A review of the literature and analysis, however, showed that the thermochemical processing of waste or dedicated crops could produce hydrogen with similar or even lower life-cycle emissions than from the electrolysis of water using renewable energy sources. In response, all potential hydrogen production technologies able to meet the desired lifetime emissions were considered.

The production and use of renewable hydrogen for the State of Hawaiʻi was found to be a complex and costly undertaking. The study found that the development of costly and complex infrastructure required for the distribution and storage of hydrogen and the lack of mature end use markets were significant barriers. Table 13.1 below summarizes the estimated range of costs for different low emissions production methods and distribution and storage methods.

Table 13.1. Hydrogen production pathway material and energy input requirements per kg of hydrogen.

H_2 Production Technology	Feedstock	Cost of Production ($/kg)	Distribution Method	Distribution & Storage $/kg[a]	Total Cost ($/kg)
Electrolysis	Geothermal[b]	6-9	Compressed Gas	3.9-4.7	9.9-13.7
			Liquid	5.2-8.8	11.2-17.8
			Interisland	5.5	11.5-14.5
Electrolysis	Solar[c]	8-10.5	Compressed Gas	3.9-4.7	11.9-15.2
			Liquid	5.2-8.8	13.2-19.3
			Interisland	5.5	13.5-16
Gasification	Waste	2.6-4.3	Pipeline	Included in production cost	2.6-4.3
			Compressed Gas	3.9-4.7	6.5-9.0
Gasification	Biomass	2.5-6	Compressed Gas	3.9-4.7	6.4-10.7
			Liquid	5.2-8.8	7.7-14.8
			Interisland	5.5	8-11.5
Steam Reforming	Ethanol	5.2	Pipeline	Included in production cost	5.2

[a] Excluding firm power for grid applications
[b] Based on 10-15 cents, 96% load factor, $1300/kw
[c] Based on 10-15 cents, 30% load factor, $1300/kw

A number of key conclusions from this study are summarized below along with recommendations for future actions.

- Oʻahu has sufficient land and resources to meet potential near-term uses but if developed at larger scale than considered in this report, Oʻahu would be required to import hydrogen to meet its needs.
- The study concluded that all the islands other than Oʻahu have ample land to meet any reasonable on-island uses.
- In spite of significant potential resources, the production of hydrogen at scale in Hawaiʻi faces significant hurdles.
- Electrolysis, a well- established, commercial production technique, is very energy intensive and, based on recent Power Purchase costs, very expensive in Hawaiʻi.

- Thermochemical processing of waste to produce hydrogen is possible but is limited by the resource and is still a developing technology with significant uncertainty regarding viability of the production processes.
- Gasification of biomass to produce hydrogen is more developed but growth of dedicated crops for energy has not, historically, been cost effective in Hawaiʻi.
- Distribution and storage of hydrogen, a necessary but often overlooked component of any hydrogen system, is logistically complex, requires substantial energy, and is expensive.
- While the Big Island has sufficient land to accommodate its uses and those on Oʻahu, interisland shipping was found to be complex and expensive limiting the large scale applications of hydrogen to the neighbor islands for the foreseeable future.
- While the use of hydrogen for long-term storage (aka firm power) is an often mentioned application, the use of hydrogen to provide energy during periods of extended low solar or wind resource was found to require very large amounts of on-island storage. Although included as a potential end-use throughout the report, the amount and cost of this storage is considered prohibitive based on currently available technology.
- Interisland transport of hydrogen (Big Island to Oʻahu), for example, is logistically complex and very expensive.
- Two industrial applications, renewable hydrogen for Hawaiʻi Gas' pipeline and for Par's proposed production of Sustainable Aviation Fuel, represent near term opportunities on Oʻahu. However, use of renewable hydrogen for these applications may be limited by competition from other technologies; such as RNG for Hawaiʻi Gas and on-site reforming of biofuels to provide H_2 for SAF production.
- Hydrogen-fueled road heavy duty vehicles offer a potential larger market on all island but lack of commercially available vehicles at this time and potential completion from ever improving BEV makes this market uncertain.
- Given the relatively high costs and logistics complexity of e based hydrogen, along with more competitive hydrogen production on the mainland US and Asia, export of hydrogen from Hawaiʻi is not expected to be viable.

In summary, Hawaiʻi has the renewable resources to produce large amounts of hydrogen but costs, lack of maturity of the end-use markets, and complex large scale logistical infrastructure are significant barriers to development at this time.

While near-term commercialization at scale is unlikely at this time there are still things that can be done to move this technology forward and leave options open for the future.

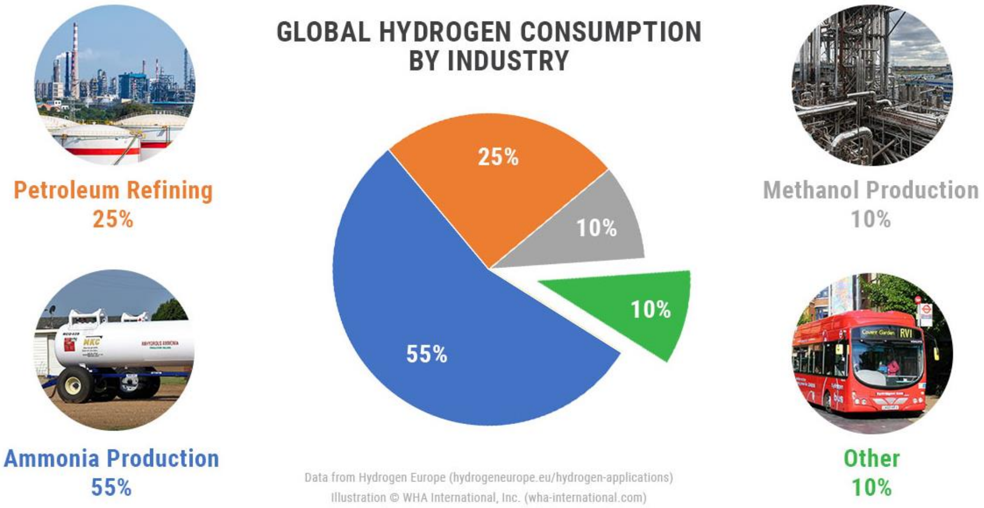
- Encourage and support the adoption of renewable hydrogen to meet the needs of the Gas Company renewable gas goals and Par's production of Sustainable Aviation Fuels.
- Encourage participation in federally funded programs to gain additional first-hand knowledge of the performance of emerging technologies.
- Address the permitting and regulatory issues now so that if/when projects materialize, they can be implemented in a timely fashion.
- Closely monitor progress on development of commercially proven MSW to hydrogen facilities worldwide. Support Kauaʻi in its 2024 RFP for MSW to fuels conversion technologies. This effort has the added benefit of potentially providing solutions to Kauaʻi's long standing problems with siting and maintaining landfills.
- Monitor progress of automobile companies toward commercially proven heavy trucks running on hydrogen. Evaluate Hawaiʻi government heavy duty vehicle fleets for potential switch to hydrogen vehicles.

APPENDIX A: POTENTIAL HYDROGEN USES IN HAWAIʻI

This first appendix provides references noted in the *Hydrogen Uses* section of the report, along with additional detailed information on potential uses of hydrogen in Hawaiʻi in the 2040 timeframe. The uses are categorized under: 1) industrial, including hydrogen blending by Hawaiʻi Gas, 2) transportation, including road and air, and 3) power generation.

Industrial

The primary industrial uses for hydrogen are ammonia production, petroleum refining, methanol production, cement, steel and heavy machinery. As shown in Figure A.1, ammonia production, petroleum refining, and methanol production account for 90% of hydrogen use, globally.



Data from Hydrogen Europe (hydrogeneurope.eu/hydrogen-applications)
Illustration © WHA International, Inc. (wha-international.com)

Figure A.1. Consumption of hydrogen globally by industry[27]*.*

There is no ammonia, methanol, or steel industry currently operating in Hawaiʻi. The primary industrial uses of hydrogen in Hawaiʻi are at the Par Refinery for upgrading fuels and at Hawaiʻi Gas as an addition to their natural gas (methane) delivered via pipeline to customers on the island of Oʻahu.

Hawaiʻi Gas, the only regulated gas utility in Hawaiʻi, recently released an RFP for green hydrogen and RNG.

> “Hawaiʻi Gas, to our knowledge, currently blends the largest proportion of hydrogen in a gas utility in North America (typically 10-12%) with the longest

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[27] Adapted from WHA International, Inc. Top industrial uses of hydrogen: Industrial Hydrogen Safety. https://wha-international.com/hydrogen-in-industry/.

> operating record at that composition (since 1974). The hydrogen gas blend is distributed to Oʻahu utility customers through 1,100 miles of transmission and distribution pipeline network that was constructed and maintained over the past 100+ years."[28]

This RFP is requesting up to 2,300 kg/day (839,500 kg/yr) of renewable hydrogen to increase the concentration of hydrogen in their gas to 15%. Based on current sales of 383 million therms/yr, if Hawaiʻi Gas replaced all the hydrogen produced in their SNG plant from petroleum-based naphtha with renewable hydrogen, total demand for renewable hydrogen could reach 13,561,210 kg/yr. An alternative is to replace the fossil based natural gas with RNG without the need for hydrogen. Hawaiʻi Gas' RFP is also requesting supply of RNG.

Transportation

Hydrogen can potentially be used as a replacement for fossil fuels in ground and aviation applications. Replacement of a portion of the transportation fuels could have a significant impact on Hawaiʻi's GHG emissions. In this section we estimate the amount of hydrogen required to displace the fuel in 1% of the light duty vehicles, 20% of the buses and heavy duty vehicles, and as an input for Par's proposed production of sustainable aviation fuel.

Hydrogen can potentially be used as a replacement for fossil fuels in ground and aviation applications. With transportation responsible for over 40% of Hawaiʻi's emission, replacement of a portion of the transportation fuels could have a significant impact on Hawaiʻi's GHG emissions. In this section we estimate the amount of hydrogen required to displace the fuel in 1% of the light duty vehicles, 20% of the buses and heavy duty vehicles, and to provide hydrogen for Par's proposed production of sustainable aviation fuel.

Road Transportation

Based on 2023 tax reports, Hawaiʻi uses approximately 48.5 million gallons of diesel and 426 million gallons of gasoline statewide per year. On-highway diesel use is primary for freight trucks and buses while gasoline is used in both light duty vehicles (LDVs) and freight trucks.

This study developed an estimate of the amount of hydrogen required to displace 20% of the freight truck and bus sectors and 1% of LDVs assuming a simple 1 kg H_2 for 1 gallon of fuel replacement. Twenty percent was selected, in part to be large enough to have an impact on the state's emissions, but it should not be assumed that this will be achieved.

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[28] https://www.hawaiigas.com/2023-rfp

In addition to producing hydrogen cost-effectively, replacement of fuel for transportation will require availability of vehicles. Currently there are no hydrogen trucks in Hawaiʻi. While several companies are working to develop hydrogen trucks, none are currently available commercially. Replacement of fuel for 1% of LDVs was assumed but with advances in battery technology, this is a low probability market.

The amount of hydrogen required to meet the proposed targets was estimated based on numbers of registered vehicles and liquid fuel from the Department of Taxation Tax Base and Tax Collections for FY 2023[29]. Table A.1 summarizes the DBEDT vehicle registration data, the highway diesel use, and gasoline use by island.

Table A.1. Fossil fuel usage data by vehicle types for the state and its counties.

VEHICLE TYPE & FUEL USAGE	**Statewide**	**Oʻahu**	**Hawaiʻi**	**Kauaʻi**	**Maui**
VEHICLE REGISTRATIONS, 2023					
Diesel Vehicles					
Light duty vehicles, diesel (LDV)	7,328	2,295	2,798	891	1,344
Public buses, diesel	654	540	60	22	32
Freight trucks, diesel	23,995	10,628	7,254	2,298	3,815
Gasoline Vehicles					
Freight trucks, gasoline	51,655	34,714	7,433	2,115	7,393
Light duty vehicle, gasoline	1,015,827	593,765	186,142	77,659	158,261
FUEL USE - (HI Liquid Fuel Tax Base)					
Diesel, Highway	48,533,876	27,197,237	12,143,674	3,061,571	6,131,394
Gasoline	426,416,206	249,953,170	82,677,241	29,677,583	64,108,212

Diesel use for buses was estimated based on an assumption of 40,000 miles per year and consumption of 6 MPG. Light duty diesel vehicles were assumed to have an annual mileage of 8,000 miles and consumption of 25 MPG. Remaining diesel was assumed to be used by the freight trucks, yielding an average usage of 1861 gallons per year. Gasoline freight trucks were then assumed to have the same usage. Assuming 20% of all freight trucks and 1% of LDV are converted to hydrogen, and assuming comparable

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[29] https://www.dbedt.hawaii.gov/economic/files/2023/09/Monthly_Energy_Data.xlsx

mileage with hydrogen, the annual usage was calculated. The results are shown in Table A2.

Table A.2. Estimated hydrogen usage by vehicle type for the state and its counties (rounded to nearest thousand).

VEHICLE HYDROGEN USAGE	**Statewide**	**Oʻahu**	**Hawaiʻi**	**Kauaʻi**	**Maui**
Buses (20%)	872,000	720,000	80,000	29,000	43,000
Freight trucks (20%)	28,135,000	19,508,000	4,393,000	1,010,000	3,225,000
Light duty vehicle (1%)	3,276,000	1,753,000	716,000	273,000	535,000
Total Vehicle Hydrogen Usage	32,283,000	21,981,000	5,188,000	1,312,000	3,802,000

As expected, Oʻahu is the biggest consumer with approximately 22,000 MT per year, followed by Hawaiʻi Island with just over 5,000 MT per year. On all islands, based on the assumptions of this analysis, freight trucks are the major user. While LDVs are only at 1%, they command 3,275 MT of hydrogen consumption but represent a low probability market. Finally, buses represent the smallest segment using only have 872 MT across the state, but could be the earliest adopter.

Sustainable Aviation Fuel

In Hawaiʻi, jet fuel accounts for nearly two-fifths of the petroleum products consumed. Because of significant demand from military installations and commercial airlines, jet fuel makes up a larger share of total petroleum consumption in Hawaiʻi than in any other state, except for Alaska.

There are a variety of ways to reduce these imports by using hydrogen. Three possibilities are: 1) production of SAF via electrofuels process or upgrading of fats or oils, 2) direct use for combustion in hydrogen aircraft under development, and 3) use in FCEV aircrafts under development. According to a Rhodium Group report[30], other options include battery operated aircraft and efficiency gains on decarbonizing the air transport sector (Figure A.2).

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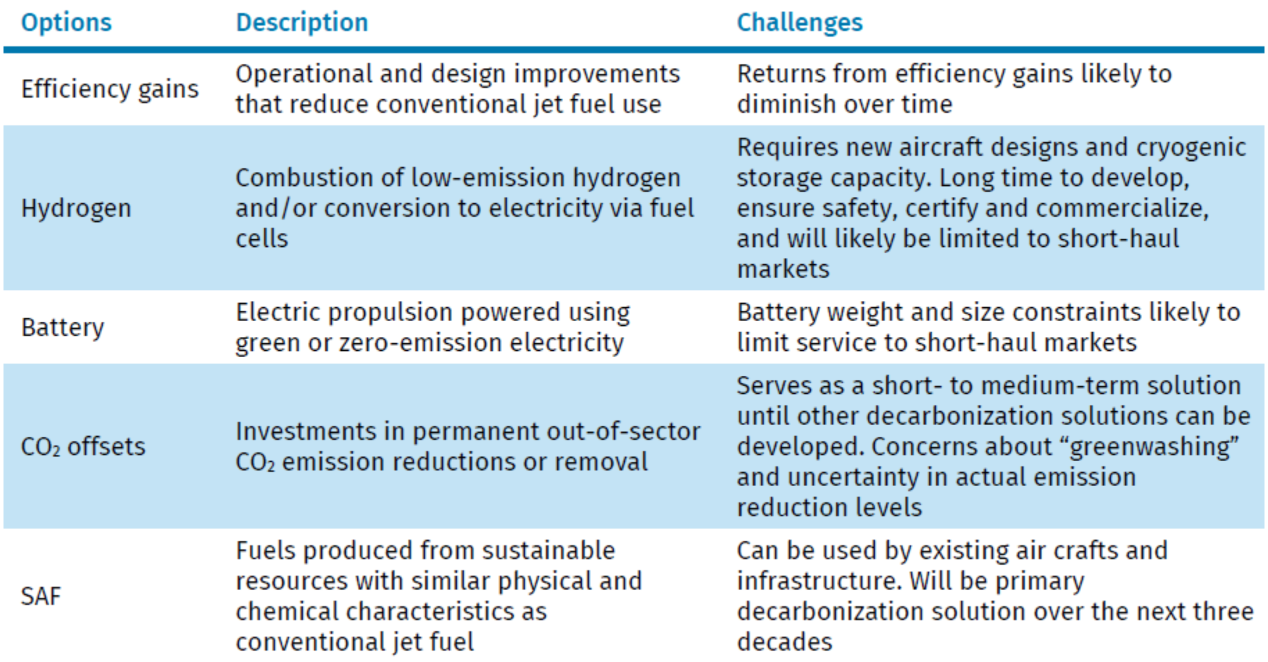
[30] Rhodium Group, https://rhg.com/research/sustainable-aviation-fuels/



Options	Description	Challenges
Efficiency gains	Operational and design improvements that reduce conventional jet fuel use	Returns from efficiency gains likely to diminish over time
Hydrogen	Combustion of low-emission hydrogen and/or conversion to electricity via fuel cells	Requires new aircraft designs and cryogenic storage capacity. Long time to develop, ensure safety, certify and commercialize, and will likely be limited to short-haul markets
Battery	Electric propulsion powered using green or zero-emission electricity	Battery weight and size constraints likely to limit service to short-haul markets
CO_2 offsets	Investments in permanent out-of-sector CO_2 emission reductions or removal	Serves as a short- to medium-term solution until other decarbonization solutions can be developed. Concerns about “greenwashing” and uncertainty in actual emission reduction levels
SAF	Fuels produced from sustainable resources with similar physical and chemical characteristics as conventional jet fuel	Can be used by existing air crafts and infrastructure. Will be primary decarbonization solution over the next three decades

Source: Shell (2021), Rhodium Group

Figure A.2. Primary options for decarbonizing the aviation sector, per the Rhodium Group.

According to the International Air Transport Association (IATA), SAF production worldwide reached at least 79 million gallons in 2022, a 200% increase from 2021[31]. In the United States, SAF production reached 15.8 million gallons in 2022, which accounts for less than 0.1% of the total jet fuel used by major U.S. airlines. The IATA has set a goal of using 10% SAF by 2030 and the U.S. government has set a goal of using 3 billion gallons of SAF by 2030. 43 airlines have also committed to different SAF uptake levels going from 5-30% by 2030, with most committing to 10% SAF use.

The use of SAF is currently limited to 50% of the jet fuel mix for all airlines. However, the typical percentage of SAF blending is currently less than 1% of jet fuel consumed due to lack of supply and costs. There are a number of initiatives underway to increase the production and use of SAF.

In Hawaiʻi, Par Pacific announced a $90 million investment to develop the state’s largest liquid renewable fuels manufacturing facility. The targeted 2025 project “will produce approximately 61 million gallons per year of sustainable aviation fuel, renewable diesel, renewable naphtha, and renewable liquefied petroleum gases. Renewable fuels provide a low-carbon alternative to fossil fuels and are considered a “drop-in” replacement for conventional diesel, jet fuel, and other fuels used to generate electricity.”[32] Par will have

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[31] https://www.iata.org/en/pressroom/2022-releases/2022-12-07-01/

[32] https://www.parpacific.com/press-releases/par-pacific-announces-hawaii-renewable-cogeneration-facility-development-plans

the flexibility to produce a variety of renewable fuels for itself and its customers. It will also have the flexibility to produce hydrogen from imported or locally source plant oils, as well as purchase renewable hydrogen from others to further decarbonize its fuels products. Additionally, Hawaiian Airlines, the state's largest and longest-serving carrier, and Par Pacific announced plans to study the commercial viability of locally produced SAF[33].

SAF production can be accomplished by: 1) upgrading waxes from gasification of various renewable materials, such as woodwaste, other biomass or wastes; 2) hydroprocessing of plant based oils, such as announced by Par; 3) or direct production through electrofuels processes combining CO_2 with hydrogen via reverse water gas shift reactors and Fischer-Trophs (FT) conversion processes. Each of these production pathways require hydrogen.

An example of upgrading of FT waxes starting with gasification of biomass is shown in Figure A.3. The hydrocracking step, including some additional hydroprocessing requires ~0.39kg H_2/gal of jet fuel based on process flow diagrams from JBP LLC. In this case, 23,790,000 kg of hydrogen per year could be used to produce 61 million gallons of SAF.

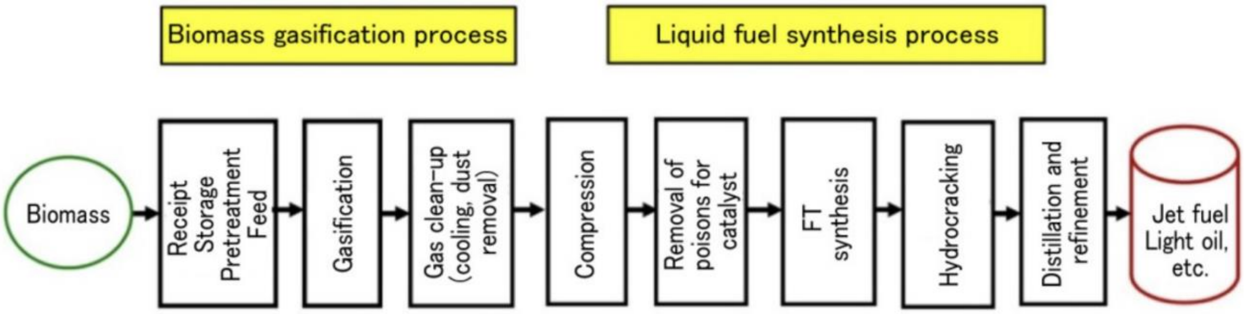

Figure A.3. Example process for upgrading FT waxes to synthetic fuels[34].

In the UK, British Airways and Velocys is developing its Altato facility in Immingham, North East Lincolnshire that could convert up to 500,000 tons of municipal solid waste into SAF[35].

Upgrading of plant oils using the Hydroprocessed Esters and Fatty Acids (HEFA) pathway, also known as Hydroprocessed Renewable Jet HRJ requires less hydrogen at

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[33] https://www.parpacific.com/press-releases/hawaiian-airlines-and-par-pacific-announce-plan-jointly-explore-sustainable-aviation
[34] https://www.mhi.co.jp/technology/review/pdf/e583/e583090.pdf
[35] https://www.reenergize.community/velocys-welcomes-uk-government-plan-for-saf-revenue-mechanism/

about 0.247 kg/gallon[36]. For the 61 million gallons a year as planned by Par Refinery, this would require 15,067,000 kg of hydrogen per year.

Power Generation

Power generation was determined to be a potential long-term use for hydrogen in Hawai'i. The need for firm dispatchable power generation is detailed in this section and the calculations to determine how much hydrogen would be required to provide firm power generation on an annual basis are provided in detail here. While assessment of the storage requirements for firm power generation in the main body of the report determined that it was infeasible and cost prohibitive for current technology to accomplish the topic of sourcing firm dispatchable power for Hawai'i's long-term needs continues. If hydrogen storage technology matures and decreases in cost alongside production costs it may become more competitive with alternative renewable firm power options.

The Need for Firm Dispatchable Power

The long-term need for firm dispatchable power was assessed by both HNEI and HECO. Analysis indicated that substantial amounts of solar PV and battery storage can be integrated into the grid if resource siting challenges and community concerns are addressed. This approach is seen as the most promising and lowest cost pathway for achieving the state's RPS goals in coming years.

While variable renewable energy sources like wind and solar, along with battery storage, can cost-effectively meet renewable targets and enable the retirement of some oil capacity, there will still be a need for dispatchable firm capacity. Dispatchable firm capacity refers to power generation that is available for a sustained period, irrespective of weather conditions or the availability of wind and solar resources.

Given the recent legislative actions and proposed firm renewable procurements by the utility, HNEI conducted a series of analyses to identify the minimum amount of firm renewable capacity that may be required at increasing levels of increasing solar, wind, and battery storage. The actual firm renewable capacity needed may be higher due to planning for plant outages and other contingencies. The findings indicate that on Oʻahu, even in a very high variable renewable energy and storage grid, there is a need for firm capacity of 650-900 MW (Figure A.4). At very high penetration of variable renewable

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[36] G. Pipitone, et al., 2023, *Sustainable aviation fuel production using in-situ hydrogen supply via aqueous phase reforming: A techno-economic and life-cycle greenhouse gas emissions assessment*, Journal of Cleaner Production, 418, 138141.

generation, these resources would run sparingly, but even at 95% penetration based on energy, significant firm capacity would still be required for reliability.

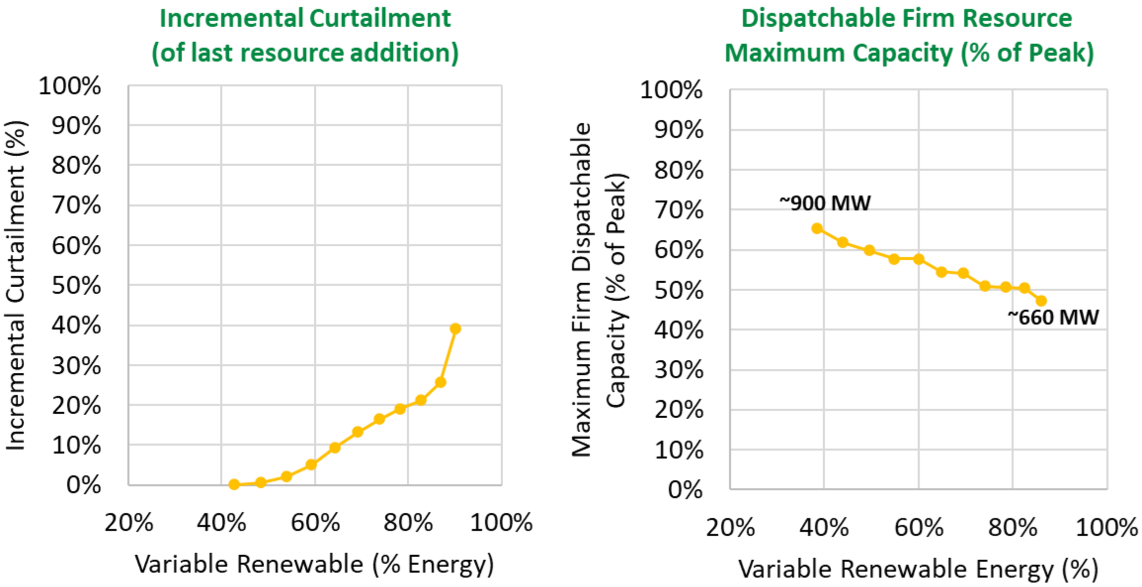

Figure A.4. Curtailment of the next MW of renewable energy grows exponentially as variable renewable energy as penetration increases reaches very high levels (left). Maximum firm dispatchable capacity required as variable renewable energy penetration grows (right).

Specifically, these resources are needed to cover for multi-day periods of low wind and solar after battery storage resource have been depleted.

There are limited zero emission resources available to provide firm capacity, and each has limitations that must be considered. Biomass and biodiesel, even if run sparingly, would require feedstocks exceeding what can be grown locally, requiring imported fuels. Substantial geothermal is available on Hawaiʻi Island, but would likely require subsea, interisland cables for Oʻahu and Maui. Hydrogen and other forms of multi-day storage have also been identified as a means to provide firm capacity. For this evaluation, it's been assumed that approximately 5% of each island's annual electricity demand would be met by a dispatchable firm power resource. This is consistent with the recently released preferred resource portfolios from HECO[37].

Power Generation Technology Assumptions

The GE LM6000 (aeroderivative combustion turbine) is used as the proxy resource of a future 100% hydrogen combustion turbine plant. Today, it is capable of approximately 40-80% hydrogen blending, and it is assumed here that no change in heat rate or efficiency

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[37] HECO, *Integrated Grid Plan Preferred Plans and Next Steps*, November 2023, https://hawaiipowered.com/igpreport/IGP_SupplementalResponse_Nov-14-2023.pdf

occurs when burning 100% hydrogen[38]. While both the fuel cell and gas turbine generator properties are shown in Table A.3 below, given the high costs associated with fuel cell technology, the mature state of combustion turbine technology, and the likelihood of new investment in combustion turbines, it was assumed that an aeroderivative combustion turbine would be used for firm power generation to estimate hydrogen demand.

Typically, Lower Heating Value (LHV) is not used to assess actual power plant performance because fuels energy contents are reported and priced using Higher Heating Values (HHV). However, because hydrogen production from water electrolysis is typically expressed using LHV the LHV heat rate for power generation was used for consumption and prices for consistency.

Table A.3. Hydrogen power generation plant characteristics.

Turbine Property	Aeroderivative Combustion Turbine[39]	Stationary PEM Fuel Cell
Net Output (MW)	50	50
Lower Heating Value Heat Rate (Btu/kWh)	8,702	6,120
Lower Heating Value Efficiency (%)	41.4%	55.8%

Annual Hydrogen Demand

The long-term electric power demand for Hawaiʻi uses HECO's IGP plan for 2045 for Oʻahu, Hawaiʻi, and Maui. Kauaʻi (KIUC) future load growth was extrapolated based on recent growth trends and assuming a 1.1% compound annual growth rate from 2021-2045. These were the total annual energy values used to calculate the amount of energy the hydrogen fueled power plants must provide.

Based on the efficiency of an aeroderivative combustion turbine powered using hydrogen (Table A.3) and the LHV of hydrogen of 33.33 kWh/kg, the net production from the system would be approximately 0.076 metric tons of hydrogen per MWh of electricity production (76 kg H_2/MWh). Table A.4 below summarizes the projected annual energy demand, total energy from hydrogen generation, and the required amount of hydrogen to generate the annual energy target of 5%.

Table A.4. 2045 electric power demand and hydrogen need for 5% of annual energy.

Island	2045 Annual Energy (GWh)	5% of Energy met by Hydrogen (GWh)	Annual Hydrogen for Electricity Generation (kg)
Oʻahu	10,200	510	39,025,301

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[38] GE, *Hydrogen Overview*, 2022, https://www.ge.com/content/dam/gepower-new/global/en_US/downloads/gas-new-site/future-of-energy/hydrogen-overview.pdf

[39] GE, *LM6000 Turbine Specifications*, https://www.ge.com/gas-power/products/gas-turbines/lm6000

Maui	1,732	87	6,626,204
Hawaiʻi	1,563	78	5,980,593
Kauaʻi	629	31	2,408,290
Total	14,125	706	54,040,388

Challenges for Hydrogen as Firm Dispatchable Power

As discussed throughout the report, enabling hydrogen use in any sector may require significant amounts of storage. Using hydrogen as a source of firm dispatchable power in a high renewable energy grid and produced via water electrolysis and renewable energy will require very large-scale hydrogen storage. This is due to the magnitude of the daily hydrogen offtake when firm power generation is needed relative to the daily supply of hydrogen from renewables and electrolysis. Figure A.5 below illustrates this challenge for the Maui grid in the 2045 case.

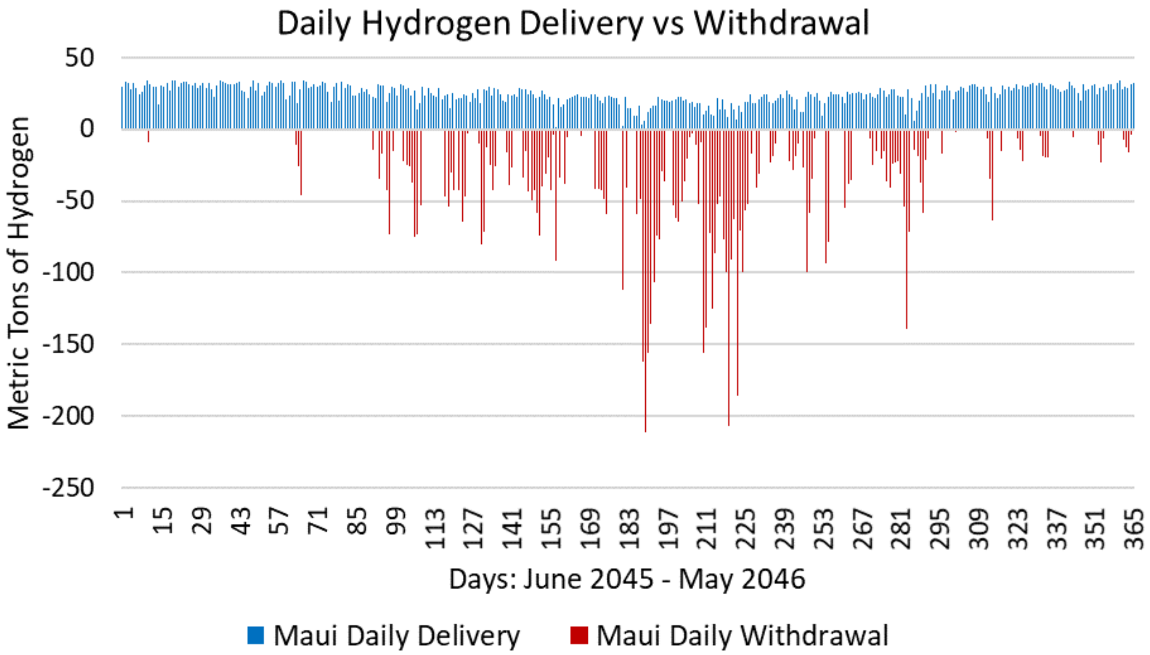

Figure A.5. Maui 2045 grid daily hydrogen production from solar and water electrolysis and daily consumption for power generation using aeroderivative combustion turbines.

In this case, hydrogen production is relatively steady every day of the year, but the withdrawal can be more than 10 times the daily production. This is due to the coincidence of both diminished hydrogen production due to low solar output and the need for large amounts of power generation from hydrogen to meet electricity demand. More discussion on the challenges, both technical and economic, of providing enough storage for hydrogen to effectively be a source of firm dispatchable power generation is discussed in *Appendix E: Distribution and Storage*.

APPENDIX B: PRODUCTION TECHNOLOGY

The production of hydrogen can be accomplished using several different processes with different types of feedstocks. This report assessed two production methods, electrolysis and thermochemical processing of organic (biologic) materials. This appendix section provides additional detail on each of these broad categories to supplement the brief overview provided in the main body of the report.

Water Electrolysis

In general, water electrolysis is the process by which electricity is used to split water into hydrogen and oxygen. There are several types of electrolyzers in use today with additional types under development. All electrolyzers have an anode, cathode, and an electrolyte to enable splitting water as shown in the simple diagram.

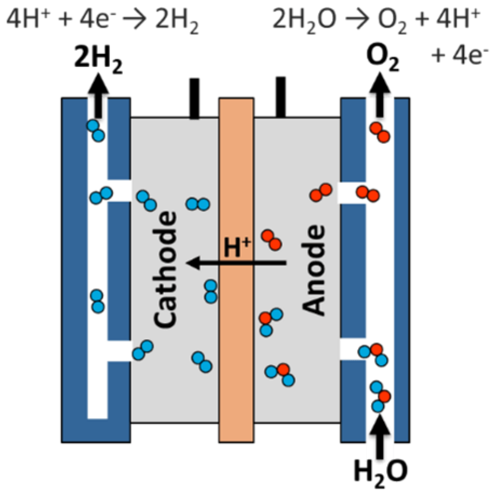

Figure B.1. Illustration of water electrolysis for production hydrogen gas[40]*.*

A brief overview of the types of electrolyzers available today is provided below.

- Alkaline Electrolyzers (AE): These electrolyzers have been commercially available for years and are the cheapest electrolyzers today. In general, they function by hydroxide ions being transported through the electrolyte typically using liquid alkaline solutions of sodium or potassium hydroxide.
- Polymer Electrolyte Membrane (PEM): These electrolyzers are commercially available today and seeing growing interest because of the potential to integrate them into variable renewable energy resources. The electrolyte for PEMs is a thin,

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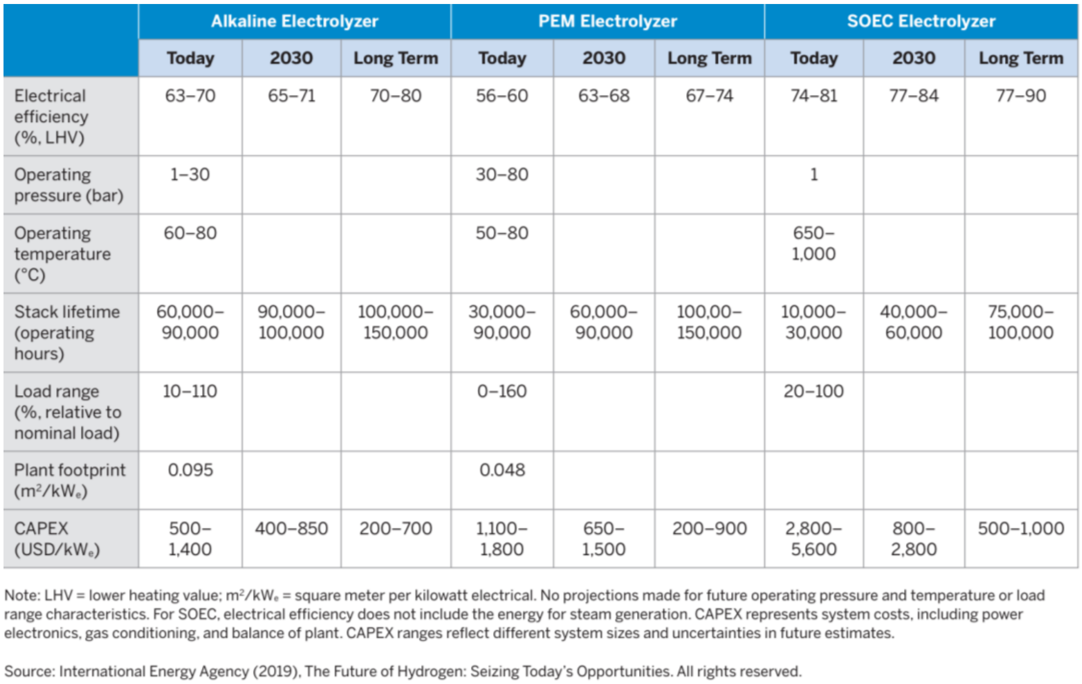
[40] Diagram from U.S. Dept. of Energy, https://www.energy.gov/eere/fuelcells/hydrogen-production-electrolysis

solid plastic material. Water is split at the anode and positively charged hydrogen ions flow to the cathode to form hydrogen gas.

- Solid Oxide Electrolyzers (SOEC): These electrolyzers are currently available, but expensive and see short operational lifetimes. They function by using a solid ceramic material for the electrolyte which conducts oxygen at high temperatures. Hydrogen gas is formed at the cathode by reacting steam with electricity while the oxygen ions flow to the anode.

A 2022 ESIG study[41] focused only on the PEM electrolyzer for cost considerations because it is generally considered as more capable for integrating variable power sources, thus being suitable for integration with renewable energy. Table B.1 from the study provides more detailed information on the technical and economic aspects of each electrolyzer type including forecasts for future costs.

Table B.1. Technical and economic parameters for different types of electrolyzers under development.



	Alkaline Electrolyzer			PEM Electrolyzer			SOEC Electrolyzer		
	Today	**2030**	**Long Term**	**Today**	**2030**	**Long Term**	**Today**	**2030**	**Long Term**
Electrical efficiency (%, LHV)	63–70	65–71	70–80	56–60	63–68	67–74	74–81	77–84	77–90
Operating pressure (bar)	1–30			30–80			1		
Operating temperature (°C)	60–80			50–80			650–1,000		
Stack lifetime (operating hours)	60,000–90,000	90,000–100,000	100,000–150,000	30,000–90,000	60,000–90,000	100,00–150,000	10,000–30,000	40,000–60,000	75,000–100,000
Load range (%, relative to nominal load)	10–110			0–160			20–100		
Plant footprint (m^2/kW_e)	0.095			0.048					
CAPEX (USD/kW_e)	500–1,400	400–850	200–700	1,100–1,800	650–1,500	200–900	2,800–5,600	800–2,800	500–1,000

Note: LHV = lower heating value; m^2/kW_e = square meter per kilowatt electrical. No projections made for future operating pressure and temperature or load range characteristics. For SOEC, electrical efficiency does not include the energy for steam generation. CAPEX represents system costs, including power electronics, gas conditioning, and balance of plant. CAPEX ranges reflect different system sizes and uncertainties in future estimates.

Source: International Energy Agency (2019), The Future of Hydrogen: Seizing Today's Opportunities. All rights reserved.

Water Electrolysis System

As discussed in the report, a water electrolysis system involves more than just the electrolyzer and balance of plant typically included in the capital cost estimates shown in literature. Often capital costs reflect uninstalled costs for plant components "inside battery

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[41] ESIG, *Increasing Electric Power System Flexibility: The Role of Industrial Electrification and Green Hydrogen Production*, January 2022, https://www.esig.energy/wp-content/uploads/2022/01/ESIG-Industrial-Elec-Hydrogen-report-2022.pdf

limit" which reflects the area where the electrolytic process and equipment is located. Additional costs and development requirements for the facility "outside battery limit" include the additional civil infrastructure required to develop the site, such as providing water onsite, roads, electrical grid connections, and other site requirements. In addition to this, uninstalled capital costs typically do not include project financing, siting, permitting, site development, and additional engineering and labor costs associated with building the facility.

As discussed in the report, additional costs beyond strictly the capital cost for a plant can be 1:1 the cost of the electrolyzer stack. Another hurdle likely to be encountered is that costs for BOP and outside battery limit costs are unlikely to benefit from cost curve reductions that could be achieved via mass manufacturing of electrolyzer stacks since most of these components are already mature technologies and produced at scale. Increasing vertical scale (electrolyzer and plant hydrogen output) will help reduce costs, but only if a market is available to offtake larger production otherwise the plant will suffer from higher capital costs with low offtake.

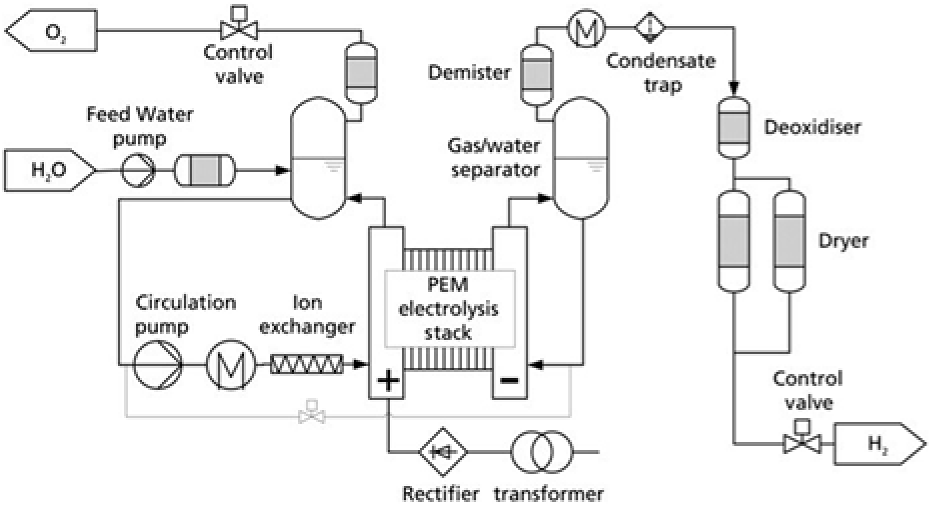

Figure B.2. Example PEM electrolysis stack and balance of plant diagram[42].

Thermochemical Processing

Production of hydrogen using thermochemical processing can encompass gasification, pyrolysis and steam reforming. Details using each of these conversion processes are discussed below for MSW, C&D wastes, biomass, and ethanol.

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[42] Diagram from SynerHy, https://synerhy.com/en/2022/02/balance-of-plant-bop-of-an-electrolyser/

Gasification and Pyrolysis

There are hundreds of variations of gasification and pyrolysis technologies for the conversion of biomass or waste to gas or liquid products. To be successful, especially for hydrogen production, these gasification technologies must be integrated with appropriate feedstock preparation and gas cleanup technologies. While there are numerous references available based on complex models, lab scale equipment and pilot plant facilities, very few of these technologies have operated successfully on a commercial scale using biomass, MSW, or C&D wastes as feedstocks.

A previous HNEI study[43] identified the theoretical maximum conversion rate to hydrogen from biomass, given specific biomass and specific gasification process. These theoretical conversion rates will vary with type of biomass. This paper noted "this is 78% of the theoretical maximum yield of 165 g H_2 kg^{-1} of dry, ash-free biomass for this feedstock." 165 g H_2/kg biomass is equivalent to 6.06 kg biomass/kg hydrogen.

Numerous other studies assessed various biomass gasification processes[44,45,46,47,48,49]. All demonstration and commercial scale facilities will be well below the theoretical maximums noted in the previous reference.

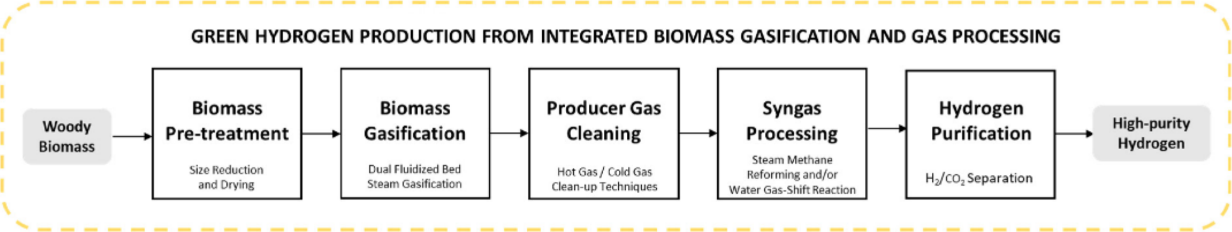

Figure B.3. Gasification of Biomass for hydrogen production.

Waste gasification is more complex due to its heterogeneous composition, its inclusion of components that could result in heavy metal or other forms of contamination and its

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[43] S. Turn, et al., 1998, *An experimental investigation of hydrogen production from biomass gasification*, Inter. Journal of Hydrogen Energy, 23(8), 641-648.

[44] J. Castro, et. al, 2022, *Simulation and Techno-Economic Assessment of Hydrogen Production from Biomass Gasification-Based Processes: A Review*, Energies, 15(22), 8455.

[45] NREL, *Biomass to Hydrogen Production Detailed Design and Economics Utilizing the Battelle Columbus Laboratory Indirectly Heated Gasifier*, May 2005, https://www.nrel.gov/docs/fy05osti/37408.pdf

[46] J.P Ciferno, et al., *Benchmarking Biomass Gasification Technologies for Fuels, Chemicals and Hydrogen Production*, for USDOE and NETL, June 2002, https://netl.doe.gov/sites/default/files/netl-file/BMassGasFinal_0.pdf

[47] Y. Kalinci, et al., 2012, *Life cycle assessment of hydrogen production from biomass gasification systems*, Inter. Journal of Hydrogen Energy, 37(10), 14026-14039.

[48] IEA Bioenergy, *Hydrogen from biomass gasification*, December 2018, https://www.ieabioenergy.com/wp-content/uploads/2019/01/Wasserstoffstudie_IEA-final.pdf

[49] S. Mishra, et al., 2021, *Review on biomass gasification: Gasifiers, gasifying mediums, and operational parameters*, Materials Science for Energy Technologies, 4, 329-340.

variation in quality of mix or these components[50,51]. There is one commercially operating facility in Canada operated by Enerkem converting MSW to methanol, but no commercially operating facilities converting MSW to hydrogen[52,53].

Kauaʻi County has been evaluating the potential for the production of fuels from their landfill. Eleven pyrolysis and gasification technologies were recently reviewed by HDR Engineering in their study for the County of Kauaʻi[54]. While showing potential, all of these technologies are deemed pre-commercial.

OMNI has made the most progress in developing projects converting C&D waste to hydrogen, but none are commercially operating to date. It is worth noting that their announced project in California[55] is converting C&D waste to hydrogen at a modular scale is appropriate for Hawaiʻi. This project is worth monitoring closely to determine actual commercial success or not. Aloha Carbon has announced their plans for converting C&D waste to fuels on Oʻahu using OMNI or GTI technology[56]. This facility could have the flexibility to produce hydrogen, RNG or SAF.

Although these gasification technologies are not yet commercially proven, it is worth noting in a DOE NETL report[57] that R&D development efforts continue. The report found that "based on screening-level analyses, hydrogen costs could be reduced through technology advancement to between $1.30 and $1.40 per kilogram depending on pathway. Therefore, beyond RD&D improvements, the report also explored the following factors for cost reduction: plant scale, market scenarios, plant site location, optimization of carbon dioxide (CO_2) transport and storage, byproduct sales, CO_2 valuation, and integration with other energy systems."

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[50] S. Margarida Santos, et al., 2023, *Waste Gasification Technologies: A Brief Overview*, Waste, 1(1), 140-165.

[51] H. Shafiq, et al., 2021, *Steam gasification of municipal solid waste for hydrogen production using Aspen Plus® simulation*, Discover Chemical Engineering, 1, 4.

[52] https://enerkem.com/solution/technology

[53] https://www.energy.gov/articles/doe-releases-first-series-reports-highlighting-pathways-toward-clean-hydrogen-earthshot

[54] HDR Engineering, Inc., *Study of Feasible Technologies for Long-Term Management of Municipal Solid Waste on the Island of Kauaʻi*, April 2023, https://www.kauai.gov/files/assets/public/v/1/public-works/images/solid-waste/documents/study-of-feasible-technologies-for-long-term-management-of-municipal-solid-waste-on-the-island-of-kauai-20230428r2.pdf

[55] https://www.businesswire.com/news/home/20210421006131/en/OMNI-CT-Brings-First-of-Its-Kind-Waste-to-Hydrogen-Product-to-Market-in-the-Fight-Against-Climate-Change

[56] https://alohacarbon.com/wp-content/uploads/2022/01/Aloha-Carbon-HI-for-website-2022-01.pdf

[57] NETL, *Hydrogen Shot Technology Assessment: Thermal Conversion Approaches*, December 2023, https://www.netl.doe.gov/projects/files/HydrogenShotTechnologyAssessmentThermalConversionApproaches_120523.pdf

It is worthwhile for Hawaiʻi to continue to monitor commercial progress of these production technologies as a potential path toward reducing landfill requirement while simultaneously replacing imported petroleum.

Steam Reforming (SMR) of Ethanol

According to IES, Hawaiʻi currently imports approximately 105,000 gallons per day of ethanol for blending with gasoline. Doubling ethanol imports and using the increase for hydrogen instead of gasoline blending could theoretically produce 61,760 kg per day of hydrogen or 151,515,280 kg/yr.

Golu has developed an SMR technology to convert ethanol to hydrogen with CO2 as a usable byproduct[58,59]. This technology is proven at a commercial modular scale, but is not in commercial operation yet. Commercial facilities are under development for potential operation by 2025. These modules could be co-located at Par or Hawaiʻi Gas coincident to where renewable hydrogen would be required, therefore eliminating or vastly reducing any transport issues.

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[58] https://www.sbibioenergy.com/golu-h2

[59] https://www.biofuelsdigest.com/bdigest/2021/02/23/renewable-ethanol-to-green-hydrogen-the-digests-2020-multi-slide-guide-to-sbi-bioenergys-golu-h2/

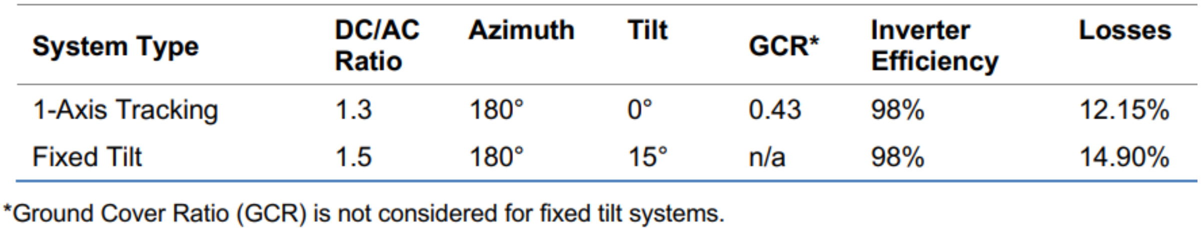
APPENDIX C: FEEDSTOCK AVAILABILITY

An in-depth study[60] was conducted in 2020 and 2021 by NREL in collaboration with HECO to develop estimates on the technical potential for utility-scale and rooftop solar deployment in HECO's territory. This study served as the basis for determining the technical potential of high capacity factor resources to produce hydrogen using water electrolysis by island. For this study, high capacity factor resources were assumed to have capacity factors greater than or equal 20% for solar PV and experience greater than 8.5 m/s average wind speeds for wind resources.

Solar Potential

The assumptions on solar system configurations used by NREL in their assessment are shown in Table C.1 below. This study assumed only 1-Axis tracking would be used because it has greater output at approximately the same cost as fixed tilt solar and maximizing energy production is crucial for making low cost hydrogen from electrolysis.

Table C.1. NREL study utility-scale solar system configurations.



System Type	DC/AC Ratio	Azimuth	Tilt	GCR*	Inverter Efficiency	Losses
1-Axis Tracking	1.3	180°	0°	0.43	98%	12.15%
Fixed Tilt	1.5	180°	15°	n/a	98%	14.90%

*Ground Cover Ratio (GCR) is not considered for fixed tilt systems.

The full technical potential for 1-Axis tracking solar systems in Hawaiʻi under the NREL PV-1-5 scenario are shown in Table C.2 below for each island. This scenario excludes some federal lands, urbane areas, state parks, wetlands, lava flow areas, flood zones, most agricultural areas, Dept. of Defense lands, and land with slopes >5%. The number of acres required to develop this solar was based on NRELs assumption of 7.7 acres/MW.

Table C.2. Utility-scale solar technical potential by island for NREL PV-1-5.

Island	High CF 1-Axis Tracking Solar Potential (MW)	Technical Potential Land Use (acres)
Oʻahu	1,862	14,337
Maui	2,496	19,219
Hawaiʻi	16,603	127,843

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[60] Grue et. al, Assessment of Wind and Photovoltaic Technical Potential for the Hawaiian Electric Company, July 2021, https://www.hawaiianelectric.com/a/9390

Since the NREL study was only done for HECO islands, the technical potential for Kauaʻi uses a simpler approach. The HNEI 2021 study[61] on RNG potential by island provides a breakdown of underutilized agricultural land based on its capability class. To limit reliance on prime agricultural land for renewable development, land capability classes only suitable for pasture, range, or forestry were assumed to also be available for renewable energy for electricity or hydrogen production. Solar potential was calculated based on the assumption of 7.7 acres/MW.

Table C.3. Estimated utility-scale solar technical potential for Kauaʻi.

Island	High CF 1-Axis Tracking Solar Potential (MW)	Underutilized Land LCC 5-6 (acres)
Kauaʻi	514	3,955

To estimate the technical potential of solar available for hydrogen production, each island's future total solar capacity from HECO's 2045 IGP were subtracted from the technical potential number. Kauaʻi expects to reach approximately 80% renewable energy if the West Kauaʻi Energy Project (WKEP) is completed. No additional renewable energy expansion was assumed for Kauaʻi due to lack of long-term plans, but the estimated hydrogen demand on Kauaʻi is small and the technical potential value used is conservative for a small subset of underutilized land so it is unlikely that solar for hydrogen at this scale would conflict with RPS goals.

Table C.4. Utility-scale solar technical potential and remaining potential for hydrogen by island.

Island	High CF Technical Potential (MW)	Assumed Solar by 2045 (MW)	Solar for Hydrogen Potential (MW)	Solar for Hydrogen Potential (kg)
Oʻahu	1,862	1,084	778	28,218,000
Maui	2,496	501	1,995	72,368,000
Hawaiʻi	16,603	259	16,344	592,786,000
Kauaʻi	514	NA	514	18,630,000

The production potential for hydrogen from solar and water electrolysis was calculated using the remaining solar technical potential by island. The conversion assumed 55 kWh/kg of hydrogen and solar with a capacity factor of 23%. Based on these assumptions and the 7.7 acre/MW land use intensity for solar, water electrolysis powered by solar can produce 4,710 kg/acre/yr.

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[61] HNEI, *Resource for renewable natural gas production in Hawaii*, May 2021, https://www.hnei.hawaii.edu/wp-content/uploads/Resources-for-Renewable-Natural-Gas-Production-in-Hawaii.pdf

Wind Potential

Ultimately, the technical potential for solar PV was the focus for hydrogen production due to several factors, such as greater community pushback to wind developments, modularity of solar farms, and lower cost/ease of development for solar relative to wind. For completeness, the potential for hydrogen from land-based wind resource is provided in this section. The assumptions used by NREL for assessing wind turbine potential is shown below.

Table C.5. NREL study utility-scale wind system configuration.

System Type	Capacity	Hub Height	Rotor Diameter	Turbulence Coefficient	Wind Shear Coefficient	Losses
Wind	3,450kW	105m	136m	0.132	0.31	16.70%

It was assumed that the 8.5 m/s wind speed threshold resulted in an average capacity factor of 40%. The NREL study assumption for land use was 82 acres/MW for wind. The technical potential by island is shown in Table C.6 below.

Table C.6. Utility-scale wind technical potential by island for NREL Wind-3-20 speeds >8.5 m/s.

Island	High CF Wind Potential (MW)	Technical Potential Land Use (acres)
Oʻahu	89	7,298
Maui	200	16,400
Hawaiʻi	415	34,030

The same assumption on land use available for solar development on Kauaʻi was used for wind, resulting in the technical potential shown in Table C.7 below.

Table C.7. Estimated utility-scale wind technical potential for Kauaʻi.

Island	High CF Wind Potential (MW)	Underutilized Land LCC 5-6 (acres)
Kauaʻi	48	3,955

The production potential for hydrogen from wind and water electrolysis was calculated using the remaining high capacity factor wind technical potential by island. The conversion assumed 55 kWh/kg of hydrogen and wind with a capacity factor of 40%. Based on these assumptions and the 82 acre/MW land use intensity for wind, water electrolysis powered by wind can produce 769 kg/acre/yr. While wind produces less hydrogen per acre, the 82 acre/MW assumption is based on the plant boundary for the wind farm which overstates the direct land use from the turbine footprints. For this report though, plant boundary assumes no other land use available under the turbines.

Table C.8. Utility-scale wind technical potential and remaining potential for hydrogen by island.

Island	High CF Wind Technical Potential (MW)	Assumed Total Wind by 2045 (MW)	Wind for Hydrogen Potential (MW)	Wind for Hydrogen Potential (kg)
Oʻahu	89	123	0	0
Maui	200	125	75	22,424,000
Hawaiʻi	415	60	355	4,731,000
Kauaʻi	48	0	48	3,042,000

Dedicated Energy Crops

Determining the amount of land available in Hawaiʻi to produce crops for biomass gasification started by reviewing current agricultural land use in Hawaiʻi. The 2021 HNEI study[62] on RNG potential breaks down current land use into crops, commercial forestry, and pastures for each island, which is shown in Table C.9 below.

Table C.9. Potential RNG land use by land use for each island.

City & County	Crops (acres)	Commercial Forestry (acres)	Pasture (acres)	Total (acres)
Kauaʻi	19,567	1,743	41,934	63,244
Oʻahu	22,328	26	18,464	40,818
Maui	43,327	33	108,447	151,807
Hawaiʻi	40,088	21,061	554,324	615,473
Total	128,968	22,863	761,430	913,261

While each island has existing agricultural industries, it is assumed that these existing uses are not able to support additional crops dedicated to hydrogen production. To quantify the available land for dedicated hydrogen crops we use Table C.10 below, taken from the HNEI report, which characterizes two broad categories of underutilized land for each island. Underutilized land is described using the land capability class (LCC) metric.

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[62] HNEI, *Resource for renewable natural gas production in Hawaii*, May 2021, https://www.hnei.hawaii.edu/wp-content/uploads/Resources-for-Renewable-Natural-Gas-Production-in-Hawaii.pdf

LCC 1-4 land is generally suitable for agriculture and LCC 5-6 land is more suitable for pasture, range, or forestry uses.

Table C.10. Underutilized land by LCC for each island.

City & County	LCC 1-4 (acres)	LCC 5-6 (acres)	Total (acres)
Kauaʻi	26,944	3,955	30,899
Oʻahu	18,104	1,629	19,733
Maui	29,498	7,115	36,613
Hawaiʻi	135,171	57,089	192,260
Total	251,782	76,888	328,760

It is assumed that only land capability classes 1-4 are productive enough to grow the necessary energy crops for hydrogen production. Another assumption made is that each acre of crops yields 18.1 dry metric tons/year of biomass. The conversion of biomass to hydrogen, in mass terms, is 10.5 dry kg biomass per kg of hydrogen. This is a better efficiency relative to the waste pathway because of less contamination assumed for dedicated crops. Based on this assumption, the total hydrogen production potential from dedicated crops for each island is summarized in Table C.11 below.

Table C.11. Potential hydrogen production from dedicated crops for each island.

City & County	LCC 1-4 (acres)	Crops Hydrogen Potential (kg)	% of Island Demand
Kauaʻi	26,944	46,558,000	1,251%
Oʻahu	18,104	31,283,000	41%
Maui	29,498	50,972,000	489%
Hawaiʻi	135,171	233,572,000	2,091%

Substantial amounts of hydrogen can be developed from dedicated crops and biomass gasification if the crop yields and conversion rates assumed are achieved. However, real constraints are more likely to be realized due to competing land uses or community acceptance. The future demand for hydrogen and the total cost of producing hydrogen from crops will also dictate the feasibility of crop gasification.

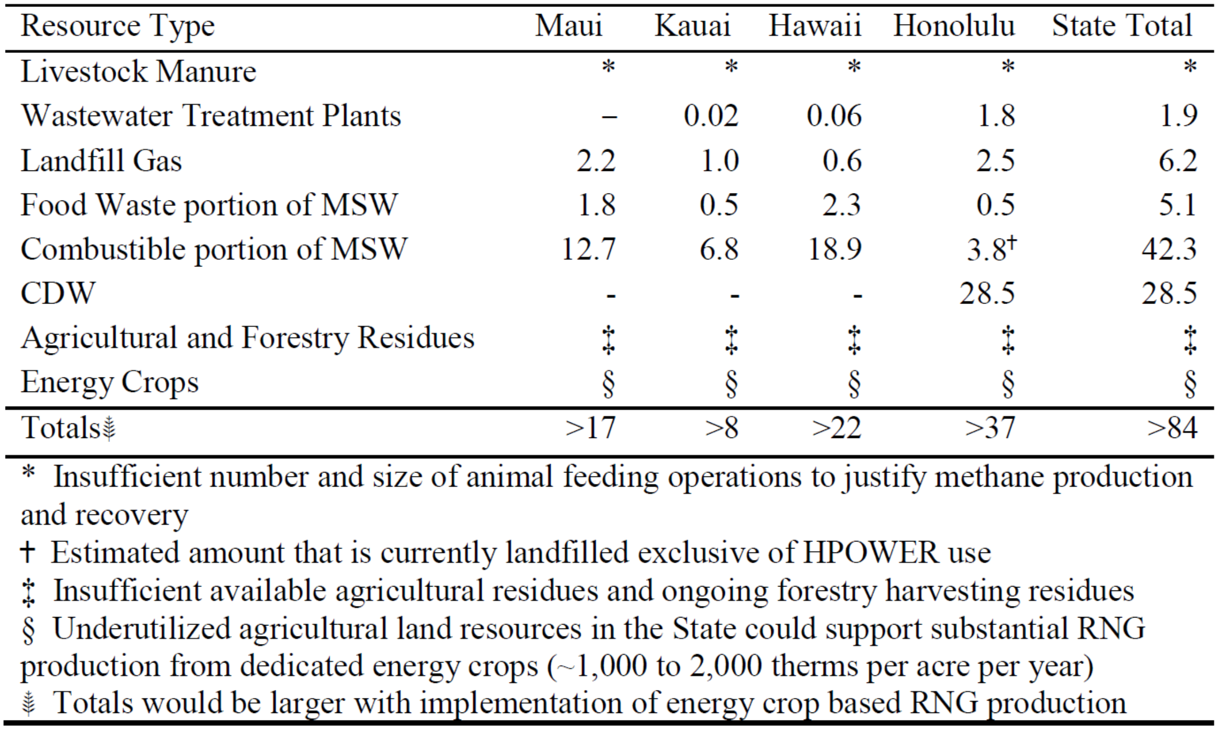
Wastes

Wastes in Hawaiʻi have been studied extensively. Wastes are of concern due to limited acceptable sites for landfills, limited on-island recycling and concern for ocean pollution and contamination of aquifers. Conversion technologies to fuels have always been of interest, but other than combustion for power generation, very few of these technologies have been proved on a commercial scale. In Hawaiʻi, the majority of convertible wastes including greenwaste, C&D wastes and MSW are combined and landfilled except on Oʻahu.

Construction and Demolition (C&D)

C&D waste on Oʻahu is currently landfilled at PVT. The 2021 HNEI study found that “CDW is disposed separately in the City & County of Honolulu. Approximately 260,000 tons per year (~700 tons per day) (~236,000 Mg y-1 or 635 Mg d-1) of CDW is disposed at the PVT CDW landfill in Nanakuli. Roughly 20% of the material is inert with the remainder combustible with an energy content of 7,740 Btu/lb (18 MJ kg-1) (Bach et al., 2019). Assuming 90% material recovery and preparation yield and 60% conversion efficiency (Alamia et al., 2017; GTI, 2019), the CDW material landfilled on Oʻahu could potentially produce up to 28.5 million therms (3,000 TJ) per year of RNG.” Table C.12 shown below and taken from the HNEI report summarizes total waste per island in terms of its potential to produce RNG.

Table C.12. Summary of RNG potential (million therms RNG/year) for resources in Hawaiʻi.



Resource Type	Maui	Kauai	Hawaii	Honolulu	State Total
Livestock Manure	*	*	*	*	*
Wastewater Treatment Plants	–	0.02	0.06	1.8	1.9
Landfill Gas	2.2	1.0	0.6	2.5	6.2
Food Waste portion of MSW	1.8	0.5	2.3	0.5	5.1
Combustible portion of MSW	12.7	6.8	18.9	3.8†	42.3
CDW	-	-	-	28.5	28.5
Agricultural and Forestry Residues	‡	‡	‡	‡	‡
Energy Crops	§	§	§	§	§
Totals⸙	>17	>8	>22	>37	>84

* Insufficient number and size of animal feeding operations to justify methane production and recovery
† Estimated amount that is currently landfilled exclusive of HPOWER use
‡ Insufficient available agricultural residues and ongoing forestry harvesting residues
§ Underutilized agricultural land resources in the State could support substantial RNG production from dedicated energy crops (~1,000 to 2,000 therms per acre per year)
⸙ Totals would be larger with implementation of energy crop based RNG production

This waste could be converted to RNG or hydrogen. Aloha Carbon and OMNI have announced C&D waste conversion projects for hydrogen production. Based on conversion rates shown in the table below from HNEI, OMNI, and Aloha Carbon described in the *Production Technologies* section, these 700 tons of C&D wastes could produce up to 17.3 thousand MT/yr of hydrogen.

Table C.13. Conversion rates for potential hydrogen production from C&D wastes.

Process Example	**Input (ton/ day)**	**H_2 Production (kg/day)**	**RNG Production (therm/day)**	**Waste Conversion (kg waste/therm)**	**Waste Conversion (kg waste/kg H_2)**	**Hydrogen production (MT/yr)**
GTI	700	N/A	78,000	8.15	N/A	17,330
OMNI Aloha Carbon	500	33,546	55,000	8.26	13.5	12,244
OMNI CA	200	13,700	N/A	N/A	14.6	5,000

Since the 2021 HNEI report was written, PVT has been denied its expansion request and is in the process of shutting down within the next 5 years or filling up within 8 years[63,64].

Aloha Carbon is planning a new conversion facility, as described in the State of Hawaiʻi Hydrogen Hub proposal, to convert 500 tpd of this waste into hydrogen and RNG. According to their FELS 1 engineering study, their facility will be able to convert 500 tpd of C&D waste to either 12,200, MT/yr of hydrogen or 19,800,000 therms of RNG/yr.

The conversion rates referenced in the HNEI study are based on GTI gasification technology. The conversion rates referenced in the Aloha Carbon study are based on OMNI technology. Another reference is from OMNI's announced project in California to convert C&D wastes to hydrogen.

Municipal Solid Waste (MSW)

The HNEI RNG study also characterized MSW available on each island and Table C.14 excerpted from the report summarized primarily for food wastes also lists total MSW amounts.

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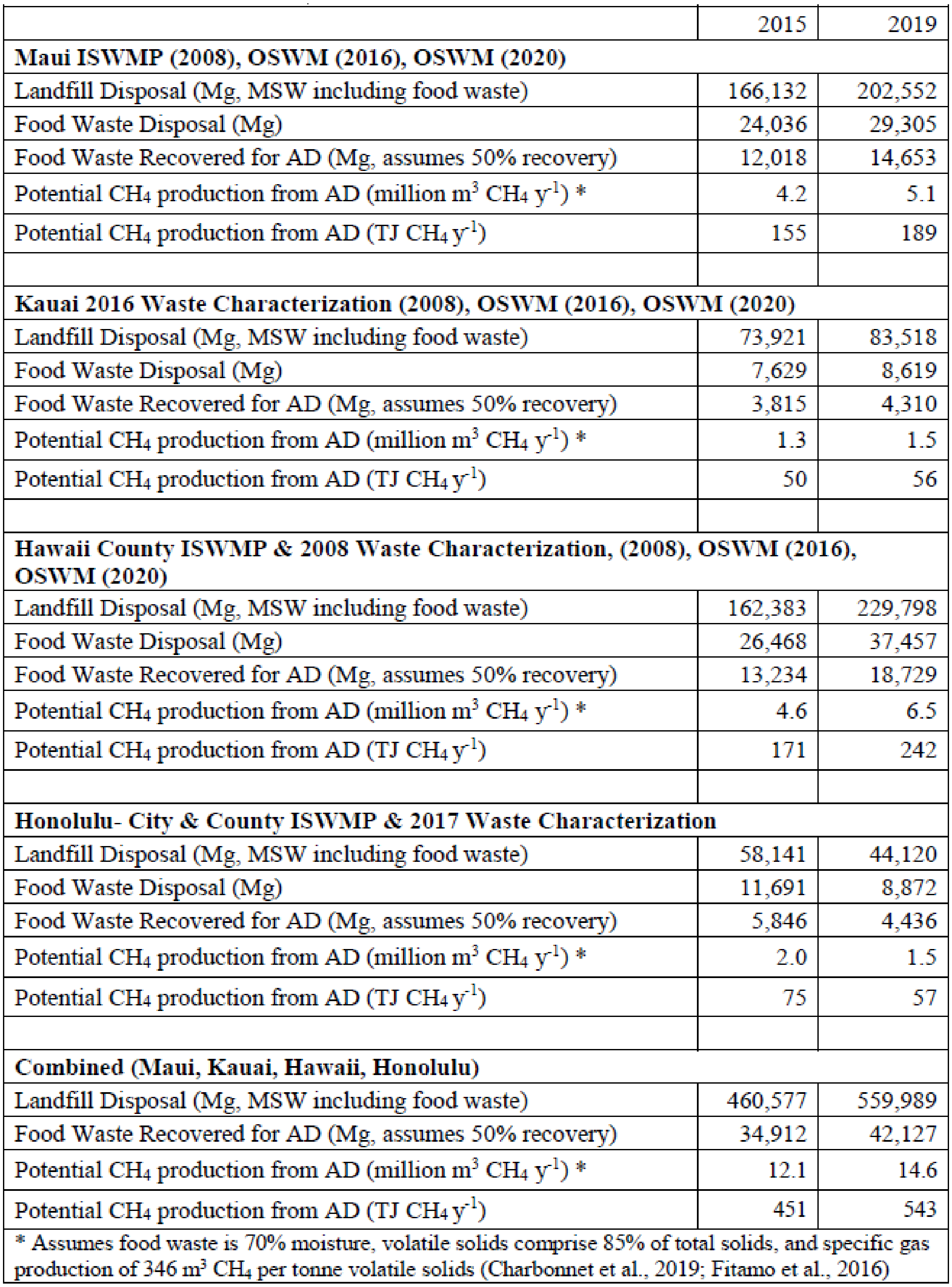
[63] https://spectrumlocalnews.com/hi/hawaii/news/2022/10/20/what-happens-to-oahu-s-trash-and-recyclables

[64] https://www.wastetodaymagazine.com/news/hawaii-lawmakers-pass-bill-blocking-oahu-landfill-expansion/

Table C.14. County food waste disposal and associated methane potential via anaerobic digester (AD) by county.



	2015	2019
Maui ISWMP (2008), OSWM (2016), OSWM (2020)		
Landfill Disposal (Mg, MSW including food waste)	166,132	202,552
Food Waste Disposal (Mg)	24,036	29,305
Food Waste Recovered for AD (Mg, assumes 50% recovery)	12,018	14,653
Potential CH_4 production from AD (million m^3 CH_4 y^{-1}) *	4.2	5.1
Potential CH_4 production from AD (TJ CH_4 y^{-1})	155	189
Kauai 2016 Waste Characterization (2008), OSWM (2016), OSWM (2020)		
Landfill Disposal (Mg, MSW including food waste)	73,921	83,518
Food Waste Disposal (Mg)	7,629	8,619
Food Waste Recovered for AD (Mg, assumes 50% recovery)	3,815	4,310
Potential CH_4 production from AD (million m^3 CH_4 y^{-1}) *	1.3	1.5
Potential CH_4 production from AD (TJ CH_4 y^{-1})	50	56
Hawaii County ISWMP & 2008 Waste Characterization, (2008), OSWM (2016), OSWM (2020)		
Landfill Disposal (Mg, MSW including food waste)	162,383	229,798
Food Waste Disposal (Mg)	26,468	37,457
Food Waste Recovered for AD (Mg, assumes 50% recovery)	13,234	18,729
Potential CH_4 production from AD (million m^3 CH_4 y^{-1}) *	4.6	6.5
Potential CH_4 production from AD (TJ CH_4 y^{-1})	171	242
Honolulu- City & County ISWMP & 2017 Waste Characterization		
Landfill Disposal (Mg, MSW including food waste)	58,141	44,120
Food Waste Disposal (Mg)	11,691	8,872
Food Waste Recovered for AD (Mg, assumes 50% recovery)	5,846	4,436
Potential CH_4 production from AD (million m^3 CH_4 y^{-1}) *	2.0	1.5
Potential CH_4 production from AD (TJ CH_4 y^{-1})	75	57
Combined (Maui, Kauai, Hawaii, Honolulu)		
Landfill Disposal (Mg, MSW including food waste)	460,577	559,989
Food Waste Recovered for AD (Mg, assumes 50% recovery)	34,912	42,127
Potential CH_4 production from AD (million m^3 CH_4 y^{-1}) *	12.1	14.6
Potential CH_4 production from AD (TJ CH_4 y^{-1})	451	543

* Assumes food waste is 70% moisture, volatile solids comprise 85% of total solids, and specific gas production of 346 m^3 CH_4 per tonne volatile solids (Charbonnet et al., 2019; Fitamo et al., 2016)

This does not include the MSW delivered to the H-POWER facility on Oʻahu. The H-POWER facility receives approximately 700,000 tpy of waste. It's been reported that

"Covanta's contract with the City and County of Honolulu requires that H-POWER receive 800,000 tons of trash every year, which it has never done, so the city must pay a fee."[65] Not all of this waste is convertible. H-POWER removes up to 25,000 tons per year of metals for recycling. Glass and other inerts are also removed prior to processing. Approximately 90% of the MSW could be convertible to hydrogen instead of power. MSW has a lower rate of conversion than C&D wastes due to increased moisture content and variations in BTU content vs C&D waste which is primarily woodwaste. Based on these assumptions, the MSW delivered to H-POWER on Oʻahu could potentially be converted into 27.26 thousand MT of hydrogen per year.

The H-POWER contract expires in 2032 unless extended. This MSW could be diverted to an alternative facility to produce more hydrogen on Oʻahu. However, the power produced from the H-POWER plant is considered renewable and therefore this would require a replacement of ~60 MW of firm renewable power to maintain progress toward RFP objectives.

MSW is comprised of a myriad of wastes. An example of this breakdown can be seen in the Table C.15 below from a study completed by HDR Engineering, Inc. for the County of Kauaʻi[66]. This study projected forward the composition of this waste projected forward through 2045. This includes C&D wastes as there is no equivalent to PVT on neighbor islands. Approximately 90% of these wastes could be converted to hydrogen. Using 2030 projections of 101,000 tons and the conversion rate of 20.8 kg waste/kg of hydrogen, 3.97 thousand MT/yr of hydrogen could be produced on Kauaʻi. Greenwastes for neighbor islands are also included in the MSW wastes as can be seen in the example of the breakdown for Kauaʻi wastes under "other organics" showing "leaves and grasses, prunings and trimmings, and branches and stumps." Greenwastes can be converted to hydrogen (13.6 kg waste/kg hydrogen) in a more efficient manner than MSW (20.8 kg waste/kg hydrogen) and within the range of C&D wastes (12.6-14.6 kg waste/kg hydrogen).

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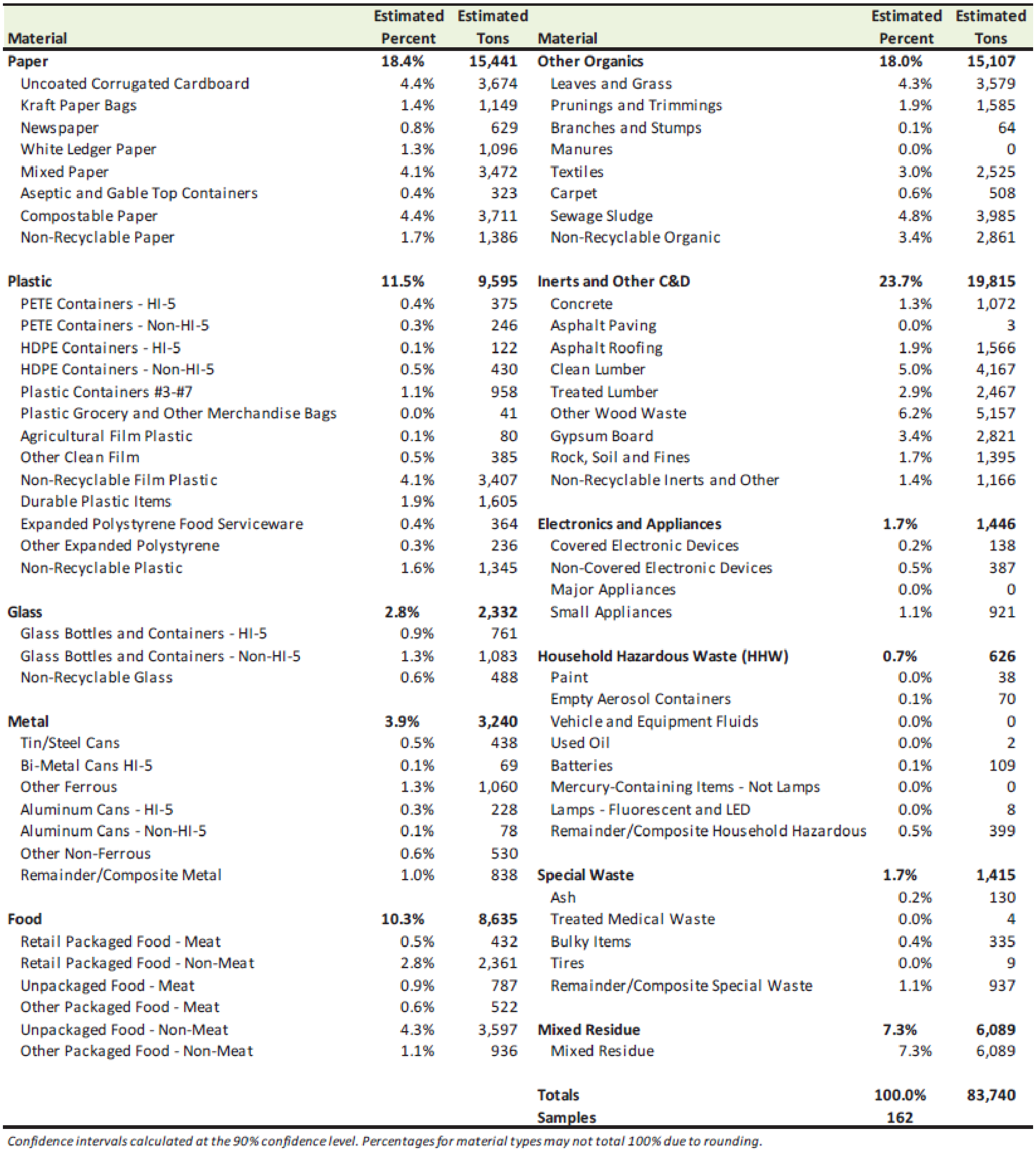
[65] https://spectrumlocalnews.com/hi/hawaii/news/2022/10/20/what-happens-to-oahu-s-trash-and-recyclables

[66] HDR Engineering, Inc., *Study of Feasible Technologies of Municipal Solid Waste on the Island of Kauai*, for the County of Kauai, April 2023, https://www.kauai.gov/files/assets/public/v/1/public-works/images/solid-waste/documents/study-of-feasible-technologies-for-long-term-management-of-municipal-solid-waste-on-the-island-of-kauai-20230428r2.pdf

Table C.15. Detailed composition of Kauaʻi's overall countywide composition, 2016.



Material	Estimated Percent	Estimated Tons	Material	Estimated Percent	Estimated Tons
Paper	**18.4%**	**15,441**	**Other Organics**	**18.0%**	**15,107**
Uncoated Corrugated Cardboard	4.4%	3,674	Leaves and Grass	4.3%	3,579
Kraft Paper Bags	1.4%	1,149	Prunings and Trimmings	1.9%	1,585
Newspaper	0.8%	629	Branches and Stumps	0.1%	64
White Ledger Paper	1.3%	1,096	Manures	0.0%	0
Mixed Paper	4.1%	3,472	Textiles	3.0%	2,525
Aseptic and Gable Top Containers	0.4%	323	Carpet	0.6%	508
Compostable Paper	4.4%	3,711	Sewage Sludge	4.8%	3,985
Non-Recyclable Paper	1.7%	1,386	Non-Recyclable Organic	3.4%	2,861
Plastic	**11.5%**	**9,595**	**Inerts and Other C&D**	**23.7%**	**19,815**
PETE Containers - HI-5	0.4%	375	Concrete	1.3%	1,072
PETE Containers - Non-HI-5	0.3%	246	Asphalt Paving	0.0%	3
HDPE Containers - HI-5	0.1%	122	Asphalt Roofing	1.9%	1,566
HDPE Containers - Non-HI-5	0.5%	430	Clean Lumber	5.0%	4,167
Plastic Containers #3-#7	1.1%	958	Treated Lumber	2.9%	2,467
Plastic Grocery and Other Merchandise Bags	0.0%	41	Other Wood Waste	6.2%	5,157
Agricultural Film Plastic	0.1%	80	Gypsum Board	3.4%	2,821
Other Clean Film	0.5%	385	Rock, Soil and Fines	1.7%	1,395
Non-Recyclable Film Plastic	4.1%	3,407	Non-Recyclable Inerts and Other	1.4%	1,166
Durable Plastic Items	1.9%	1,605			
Expanded Polystyrene Food Serviceware	0.4%	364	**Electronics and Appliances**	**1.7%**	**1,446**
Other Expanded Polystyrene	0.3%	236	Covered Electronic Devices	0.2%	138
Non-Recyclable Plastic	1.6%	1,345	Non-Covered Electronic Devices	0.5%	387
			Major Appliances	0.0%	0
Glass	**2.8%**	**2,332**	Small Appliances	1.1%	921
Glass Bottles and Containers - HI-5	0.9%	761			
Glass Bottles and Containers - Non-HI-5	1.3%	1,083	**Household Hazardous Waste (HHW)**	**0.7%**	**626**
Non-Recyclable Glass	0.6%	488	Paint	0.0%	38
			Empty Aerosol Containers	0.1%	70
Metal	**3.9%**	**3,240**	Vehicle and Equipment Fluids	0.0%	0
Tin/Steel Cans	0.5%	438	Used Oil	0.0%	2
Bi-Metal Cans HI-5	0.1%	69	Batteries	0.1%	109
Other Ferrous	1.3%	1,060	Mercury-Containing Items - Not Lamps	0.0%	0
Aluminum Cans - HI-5	0.3%	228	Lamps - Fluorescent and LED	0.0%	8
Aluminum Cans - Non-HI-5	0.1%	78	Remainder/Composite Household Hazardous	0.5%	399
Other Non-Ferrous	0.6%	530			
Remainder/Composite Metal	1.0%	838	**Special Waste**	**1.7%**	**1,415**
			Ash	0.2%	130
Food	**10.3%**	**8,635**	Treated Medical Waste	0.0%	4
Retail Packaged Food - Meat	0.5%	432	Bulky Items	0.4%	335
Retail Packaged Food - Non-Meat	2.8%	2,361	Tires	0.0%	9
Unpackaged Food - Meat	0.9%	787	Remainder/Composite Special Waste	1.1%	937
Other Packaged Food - Meat	0.6%	522			
Unpackaged Food - Non-Meat	4.3%	3,597	**Mixed Residue**	**7.3%**	**6,089**
Other Packaged Food - Non-Meat	1.1%	936	Mixed Residue	7.3%	6,089
			Totals	**100.0%**	**83,740**
			Samples	**162**	

Confidence intervals calculated at the 90% confidence level. Percentages for material types may not total 100% due to rounding.

Imported Ethanol

Rough estimate of total ethanol imported estimate is around ~2,500 barrels per day which is ~38,000,000 gallons per year. Most of this ethanol is blended into gasoline at 10% by volume. The ethanol meets ASTM D-4806 and is denatured with hydrocarbon[67]. The shipping infrastructure is already set up to receive and blend ethanol in Hawaiʻi and could be expanded with minimal change.

Ethanol is no longer required to be blended into gasoline, however, its lower price currently provides incentives to continue to do so[68]. Golu SMR technology referenced in the *Production Technologies* section shows a conversion rate of 1.7 gallons of ethanol for each kg of hydrogen[69].

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[67] Per correspondence with IES
[68] https://www.sema.org/news-media/enews/2015/28/hawaii-bill-eliminate-ethanol-gasoline-signed-law
[69] https://www.sbibioenergy.com/golu-h2-articlev1#

APPENDIX D: PRODUCTION COSTS

Understanding the production costs of the different hydrogen production technologies assessed in this report is a key step to determining the feasibility of hydrogen as a decarbonization tool in Hawai’i. While it was determined that ample feedstocks are available in Hawai’i, the actual cost of using those resources to produce hydrogen needed to be assessed to inform recommendations on hydrogen’s potential in the state. To accomplish this, two approaches were used. The first approach used estimated capital costs for major equipment components (like solar PV and electrolyzers) and calculated a levelized cost of hydrogen over a 30-year project life for comparison between technology types. The other method involved a literature review based on studies where costs for materials and capital are likely like costs in Hawai’i. The biomass, waste, and ethanol production technologies used a literature review to determine production costs and sources are included in the appendix.

An example of the levelized cost analysis is provided in this appendix section for water electrolysis using solar PV. This method was also used to calculate the $/kg cost for the distribution and storage system estimates.

Cost Methodology: Example

To develop a $/kg estimate of hydrogen for each component of the hydrogen system modeled (production, storage, and distribution) a capital recovery factor calculation was used to annualize capital expenditures. It was assumed that the hydrogen project life would be 30-years to match the assumed asset life of the energy system (solar PV). This assumption is consistent with NREL assumptions in their annual technology baseline report[70]. The electrolyzer assumptions were based on a review of current PEM electrolyzer parameters and assumed to be replaced every 10 years, see water electrolysis appendix section.

The capital recovery factor, shown below, was calculated for two asset lives (30-year and 10-year) based on a real weighted average cost of capital (Real WACC). The choice to use a Real WACC instead of a nominal one was due to the capital cost values for renewable energy being reported in real dollars.

$$Capital\ Recovery\ Factor\ (CRF)_{Asset\ Life} = \frac{WACC * (1 + WACC)^{Asset\ Life}}{(1 + WACC)^{Asset\ Life} - 1}$$

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[70] NREL, Simple LCOE and CRF Calculation, https://www.nrel.gov/analysis/tech-lcoe-documentation.html

Using the capital recovery factor allows for capital costs to be converted from a present value expenditure in real dollars to an annualized present value based on the life of the asset and the cost of capital required to recover the initial expense. Annualized capital costs are calculated using the following formula:

$$Annual\ Capital\ Cost = Capital\ Cost * \ CRF_{Asset\ Life}$$

After annualizing the capital costs, the fixed operations and maintenance cost (FO&M Cost) and any potential tax credit values for renewable energy and hydrogen production also need to be properly accounted for to develop a $/kg estimate for hydrogen system component.

Typically, FO&M costs are reported as annual values based on the system size ($/kW-yr), but these values occur over the life of the project and need to be translated into present values based on the WACC rate used. A similar process was done for determining the value of the clean energy production tax credit and the hydrogen production tax credit. Although the tax credits only last for 10 years after production begins, the effect of reducing production costs is levelized over the 30-year project life.

$$Present\ Value\ Annual\ FO\&M\ Cost = \frac{\left[\sum_{Year=1}^{Asset\ Life} (Annual\ FO\&M\ Cost) * \frac{1}{(1+WACC)^{Year}}\right]}{Asset\ Life}$$

Using annual capital cost and present value annual FO&M cost calculations reviewed above the following section details the calculations and annual cash flows for a 1 MW (1.4 MW DC) solar plant used to power a 1 MW PEM electrolyzer. Tables D.1 through D.4 detail the system and financial assumptions for this case. Capital and FO&M costs for the solar system use the $100/MWh values.

Table D.1. Example production cost calculation system assumptions for hydrogen production using 1 MWac PV (1.4 MWdc) to power a 1 MW PEM Electrolyzer.

Energy System Properties	Assumption	Unit
Renewable Type	Solar	-
Capacity	1	MWac (1.4 MWdc)
Capital Cost	3,159	$/kW
FO&M Cost	49.6	MW
Asset Life	30	years

Table D.2. Example production cost calculation system assumptions for hydrogen production using 1 MWac PV (1.4 MWdc) to power a 1 MW PEM Electrolyzer.

Electrolyzer System Properties	Assumption	Unit
Electrolyzer Type	PEM	-
Capacity	1	MW
Capital Cost	1,300	$/kW
FO&M Cost	39	$/kW-yr
Replacement Cost	520	$/kW
Asset Life	10	Years

Table D.3. Example production cost calculation system assumptions for hydrogen production using 1 MWac PV (1.4 MWdc) to power a 1 MW PEM Electrolyzer.

Financial Assumptions	Assumption
Total Project Life	30
Nominal WACC	8.0%
Real WACC	5.4%
Inflation Rate	2.5%
CRF (30-yr)	6.8%
CRF (10-yr)	13.2%

Table D.4. Example production cost calculation system assumptions for hydrogen production using 1 MWac PV (1.4 MWdc) to power a 1 MW PEM Electrolyzer.

Tax Credit Assumptions	Assumption	Unit
Energy Production Tax Credit	26	$/MWh
Energy Investment Tax Credit	30%	of Capex
Hydrogen Production Tax Credit	3	$/kg
Production Tax Credit Life	10	years

Table D.5. Example calculations for developing $/kg estimates for hydrogen system components using a capital recovery factor approach for a 30-year project.

Energy Case: $100/MWh solar PV	**Annual Energy Production (MWh/yr)**	**Annual Hydrogen Production (kg/yr)**	**Annual Energy Capex**	**Annual Energy FO&M**	**Electrolyzer Capex**	**Electrolyzer Replacement 1**	**Electrolyzer Replacement 2**	**Electrolyzer FO&M**	**Energy Investment Tax Credit**	**Energy Production Tax Credit**	**Hydrogen Production Tax Credit**	**Total Cost - Unsubsidized**	**Total Cost - ITC + H2 PTC**	**Total Cost - PTC + H2 PTC**
30-yr Total	71,400	1,285,367	$6,425,445	$731,679	$1,713,601	$406,416	$240,975	$575,312	-$1,927,633	-$469,444	-$975,207	$10,093,429	$7,190,588	$8,648,778
Total Per Year	2,380	42,846	$214,181	$24,389	$57,120	$13,547	$8,032	$19,177	-$64,254	-$15,648	-$32,507	$336,448	$239,686	$288,293
$/kg	NA	NA	$4.99	$0.57	$1.33	$0.32	$0.19	$0.45	-$1.50	-$0.36	-$0.76	$7.85	$5.59	$6.72
Project Year	**Present Value Annualized Cash Flows**													
1	2,380	42,883	$214,181	$47,074	$171,360			$37,014	-$64,254	-$58,729	-$122,097	$469,630	$283,278	$288,804
2	2,380	42,844	$214,181	$44,677	$171,360			$35,129	-$64,254	-$55,738	-$115,775	$465,347	$285,318	$293,835
3	2,380	42,844	$214,181	$42,402	$171,360			$33,340	-$64,254	-$52,899	-$109,879	$461,283	$287,150	$298,505
4	2,380	42,844	$214,181	$40,242	$171,360			$31,642	-$64,254	-$50,205	-$104,283	$457,426	$288,888	$302,937
5	2,380	42,844	$214,181	$38,193	$171,360			$30,031	-$64,254	-$47,649	-$98,973	$453,765	$290,538	$307,144
6	2,380	42,844	$214,181	$36,248	$171,360			$28,501	-$64,254	-$45,222	-$93,932	$450,291	$292,104	$311,136
7	2,380	42,844	$214,181	$34,402	$171,360			$27,050	-$64,254	-$42,919	-$89,149	$446,993	$293,590	$314,926
8	2,380	42,844	$214,181	$32,650	$171,360			$25,672	-$64,254	-$40,733	-$84,609	$443,864	$295,001	$318,522
9	2,380	42,844	$214,181	$30,987	$171,360			$24,365	-$64,254	-$38,659	-$80,300	$440,894	$296,339	$321,935
10	2,380	42,844	$214,181	$29,409	$171,360			$23,124	-$64,254	-$36,690	-$76,211	$438,075	$297,610	$325,174
11	2,380	42,844	$214,181	$27,911		$40,642		$21,947	-$64,254			$304,681	$240,427	$304,681
12	2,380	42,844	$214,181	$26,490		$40,642		$20,829	-$64,254			$302,142	$237,888	$302,142
13	2,380	42,844	$214,181	$25,141		$40,642		$19,768	-$64,254			$299,732	$235,478	$299,732
14	2,380	42,844	$214,181	$23,861		$40,642		$18,761	-$64,254			$297,445	$233,191	$297,445
15	2,380	42,844	$214,181	$22,646		$40,642		$17,806	-$64,254			$295,275	$231,020	$295,275
16	2,380	42,844	$214,181	$21,492		$40,642		$16,899	-$64,254			$293,215	$228,960	$293,215
17	2,380	42,844	$214,181	$20,398		$40,642		$16,039	-$64,254			$291,260	$227,005	$291,260
18	2,380	42,844	$214,181	$19,359		$40,642		$15,222	-$64,254			$289,404	$225,149	$289,404
19	2,380	42,844	$214,181	$18,373		$40,642		$14,447	-$64,254			$287,643	$223,388	$287,643
20	2,380	42,844	$214,181	$17,437		$40,642		$13,711	-$64,254			$285,972	$221,717	$285,972
21	2,380	42,844	$214,181	$16,549			$24,097	$13,013	-$64,254			$267,841	$203,587	$267,841
22	2,380	42,844	$214,181	$15,707			$24,097	$12,350	-$64,254			$266,336	$202,081	$266,336
23	2,380	42,844	$214,181	$14,907			$24,097	$11,721	-$64,254			$264,907	$200,652	$264,907
24	2,380	42,844	$214,181	$14,148			$24,097	$11,124	-$64,254			$263,551	$199,296	$263,551
25	2,380	42,844	$214,181	$13,427			$24,097	$10,558	-$64,254			$262,264	$198,009	$262,264
26	2,380	42,844	$214,181	$12,743			$24,097	$10,020	-$64,254			$261,042	$196,788	$261,042
27	2,380	42,844	$214,181	$12,094			$24,097	$9,510	-$64,254			$259,883	$195,629	$259,883
28	2,380	42,844	$214,181	$11,478			$24,097	$9,025	-$64,254			$258,783	$194,528	$258,783
29	2,380	42,844	$214,181	$10,894			$24,097	$8,566	-$64,254			$257,739	$193,484	$257,739
30	2,380	42,844	$214,181	$10,339			$24,097	$8,130	-$64,254			$256,748	$192,493	$256,748

Water Electrolysis System

To supplement the main report discussion of production costs for water electrolysis, HNEI conducted more detailed cost calculations for a few select renewable energy and water electrolysis systems described in the table below. The intent of this section is to show the high-level quantitative assessment done to calculate cost for hydrogen production on a $/kg basis assuming a 30-year project life. Furthermore, this analysis serves as the basis for assuming the 1.4 MW solar PV system provides lower cost hydrogen via water electrolysis. Calculations used to develop costs for the energy system and electrolyzer are in the cost calculations appendix.

Each system was modeled to power a 1 MW electrolyzer based on PEM electrolysis technical parameters (55.55 kWh/kg and flexible loading). The costs for the higher PV build and battery storage cases are above the $100 or $150/MWh energy price because oversizing the systems relative to the base case introduces increased costs due to wasted energy and higher capital and fixed costs.

Table D.6. Renewable energy systems and $/MWh cost modeled to power a 1 MW electrolyzer.

Water Electrolysis Energy Systems	Electrolyzer Load Factor (%)	Hydrogen Production (kg/yr)	$100/MWh Energy Case	$150/MWh Energy Case
1.4 MW PV	27%	42,822	100	150
2.8 MW PV	39%	62,342	138	206
2.8 MW PV + 1 MW 4hr BESS	51%	80,895	148	221
1 MW Geothermal	96%	151,388	100	150

The solar model assumed 1-Axis tracking with a 1.4 MW DC/MW AC overbuild. This assumption for overbuilding the DC side of a solar plant is consistent with recent trends and provides a higher AC capacity factor for solar plants. This benefits the project by increasing energy production in the shoulder hours of the day due to the overbuilding of the DC side of the plant which allows for greater loading of the electrolyzer.

A production cost model was used to assess solar generation, battery storage charging/discharging, and electrolysis load to produce hydrogen across 8,760 hours of operation. This approach allowed for optimizing battery charging and discharging to serve the electrolyzer load for systems that had batteries included and account for the clipping of solar due to the overbuild of DC solar capacity assumed relative to the electrolyzer size (1.4 MW solar compared to 1 MW electrolyzer).

Each system can produce different amounts of hydrogen, but at different costs. Resource cost assumptions are provided in Table D.7 below. Adding battery storage is a cost adder, raising the $/MWh cost of the system. Battery costs are presented in Table D.8 to show the effect of adding storage to increase hydrogen production. Costs shown are before tax credits.

Table D.7. Renewable energy system capital and fixed operations costs for each energy price case.

Energy System Costs	**$100/MWh Energy Case**	**$150/MWh Energy Case**
Solar Capital Cost ($/kW)	3,160	4,726
Solar Capital FO&M ($/kW-yr)	50	74
Geothermal Capital Cost ($/kW)	9,879	14,792
Geothermal FO&M ($/kW-yr)	351	526

Table D.8. 4-hr battery system capital and fixed operations costs for each energy price case.

4-hr Battery System Costs	**$100/MWh Energy Case**	**$150/MWh Energy Case**
Capital Cost	2,640	3,947
FO&M Cost	60	89
$/MWh Adder	10	15

Costs on a $/kW basis presented here are significantly higher than stated in literature, but this is partially due to capital cost numbers representing only portions of total system costs or differences in financing assumptions, such as requiring a higher rate of return on projects than are assumed here. The starting point for capital and operating costs was the 2026 projection for renewable energy costs from HECO's IGP. However, the energy costs were scaled so that the base energy source (solar or geothermal) would be $100/MWh or $150/MWh to better reflect the cost of energy relative to recently completed/bid projects in Hawaiʻi. Even if solar reached $60/MWh in Hawaiʻi, the cost of hydrogen production alone would still be significant at approximately 4.5 $/kg (inclusive of tax credits) due to the intermittent operation of the electrolyzer (~30% load factor) as shown in the main body of the report.

Electrolyzer costs were also assessed using a range of costs. In contrast to solar PV and geothermal, there is no existing information on large-scale electrolyzer costs for producing green hydrogen in Hawaiʻi to provide information on costs beyond those provided in literature. Typically, literature includes some consideration of electrolyzer balance of plant, but as discussed in the main section of the report on production costs, the additional soft costs or costs related to site development and actual project deployment can be 40-50% of the total system cost. This was the rationale for using a range of costs due to the uncertainty in today's market and limited data points.

Table D.9. Electrolyzer system capital, fixed operations, and replacement costs.

Electrolyzer Capital and Operating Costs	$850/kW Capital Cost	$1,300/kW Capital Cost	$2,000/kW Capital Cost
Fixed Operations and Maintenance ($/kW-yr)	25.5	39	60
Replacement Cost ($/kW)	340	520	800

The results of applying the cost calculation method for each system at the different electricity cost assumptions are shown below for the electrolyzer price of 1,300 $/kW.

Table D.10. Water electrolysis production costs for various configurations $100/MWh energy and electrolyzers at 1,300 $/kW.

Water Electrolysis Energy Systems	Energy Cost ($/MWh)	Energy Cost ($/kg)	Electrolyzer Cost ($/kg)	Total Cost ($/kg)	Subsidized Cost – ITC + H_2 PTC ($/kg)
1.4 MW PV	100	5.6	2.3	7.9	5.6
2.8 MW PV	138	7.7	1.6	9.2	6.4
2.8 MW PV + 1 MW 4hr BESS	148	8.5	1.2	9.7	7.0
1 MW Geothermal	100	5.6	0.6	6.2	4.1

Table D.11. Water electrolysis production costs for various configurations $150/MWh energy and electrolyzers at 1,300 $/kW.

Water Electrolysis Energy Systems	Energy Cost ($/MWh)	Energy Cost ($/kg)	Electrolyzer Cost ($/kg)	Total Cost ($/kg)	Subsidized Cost – ITC + H_2 PTC ($/kg)
1.4 MW PV	150	8.3	2.3	10.6	7.6
2.8 MW PV	206	11.4	1.6	13	9.2
2.8 MW PV + 1 MW 4hr BESS	221	12.7	1.2	13.9	10.3
1 MW Geothermal	150	8.3	0.6	9.0	6.2

The same costs are presented here for the 2,000 $/kW electrolyzer case.

Table D.12. Water electrolysis production costs for various configurations $100/MWh energy and electrolyzers at 2,000 $/kW.

Water Electrolysis Energy Systems	Energy Cost ($/MWh)	Energy Cost ($/kg)	Electrolyzer Cost ($/kg)	Total Cost ($/kg)	Subsidized Cost – ITC + H_2 PTC ($/kg)
1.4 MW PV	100	5.6	3.5	9.1	6.8
2.8 MW PV	138	7.7	2.4	10.1	7.2
2.8 MW PV + 1 MW 4hr BESS	148	8.5	1.9	10.3	7.7
1 MW Geothermal	100	5.6	1.0	6.6	4.5

Table D.13. Water electrolysis production costs for various configurations $150/MWh energy and electrolyzers at 2,000 $/kW.

Water Electrolysis Energy Systems	Energy Cost ($/MWh)	Energy Cost ($/kg)	Electrolyzer Cost ($/kg)	Total Cost ($/kg)	Subsidized Cost – ITC + H_2 PTC ($/kg)
1.4 MW PV	150	8.3	3.5	11.9	8.8
2.8 MW PV	206	11.4	2.4	13.9	10
2.8 MW PV + 1 MW 4hr BESS	221	12.7	1.9	14.5	10.9
1 MW Geothermal	150	8.3	1.0	9.3	6.6

The results of this analysis indicate that if achievable, geothermal energy could produce the lowest cost hydrogen based on the $100 and $150/MWh energy cases. However, given the limited availability of geothermal potential today (only Maui and Hawaiʻi Island), the priority uses for direct electrification using geothermal energy, and the potential for community pushback on accessing more geothermal energy only solar PV was assessed for determining production costs using water electrolysis. If advancements in geothermal technology increase its accessibility across the Hawaiian Islands and communities accept its development, then it may be the most favorable route for producing hydrogen using water electrolysis.

Waste, Biomass, and Ethanol to Hydrogen Production Cost Details

The costs of growing dedicated energy crops for gasification is well documented based on experience. Tipping fees shown as negative costs to MSW operating facilities are also well documented. However, there are very few commercially operating gasification facilities for biomass, C&D wastes or MSW wastes to fuels that can be used for valid cost references. There are myriad studies and simulations for these type facilities, as well as announcements of expectations from developers of planned waste to hydrogen plants.

All cost data for gasification should be viewed as estimates to be confirmed once the first commercial plants have been in operation for at least the first year. This appendix includes examples of various studies as well as developer announcements.

Dedicated Crops Cost

There are many reliable studies on the costs of growing dedicated energy crops that could be used in biomass gasification facilities. Costs shown in Table D.14 below from an HNEI study are $61-67/dry ton for energy crops or trees in 2013. Using the US Bureau of Statistics inflation calculator, $67 would be equivalent to $89.55 in September 2023.[71] These numbers do not include land costs. Land costs vary significantly from island to island, but for plots over 500 acres needed to support energy crops, a range of $3000 to $10,000 per acre is reasonable to use. As an example, a recent contract on Hawaiʻi Island for 2127 acres of agricultural land was $10.900,000.[72] This is equivalent to $5124/acre and $11.14/dry ton at 23 dry tons per acre year over 20 years or $256 per acre per year. For another reference point, this compares to long term lease costs of an average of $200 per acre for farmland in Hawaiʻi[73]. Adding this $11.14 per dry ton of existing land costs to inflation adjusted costs of planting and harvesting of $89.55 per dry ton equals $100.69 per dry ton as shown in the table below. Costs of land and crops will vary from island to island in Hawaiʻi, however $100 per ton is considered a reliable rough estimate for costs of energy crops. The table below is an excerpt from the HNEI report of the cost per ton of dry matter for different energy crops in 2023 dollars and including land costs. See the appendix for a more detailed table from the report.

Table D.14. Summary of cost per dry ton of matter for energy crops in Hawaiʻi – 2013 dollars.

	Sugarcane	**Energycane**	**Banagrass**	**Trees**
Cost per ton of dry matter ($/ton)	$66-105	$67	$66	$61
Cost Adjusted for Inflation & Land ($/ton)	$100-151	$101	$99	$93

The full table from the HNEI report on dedicated biomass crops is shown in Table D.15 below for additional detail.

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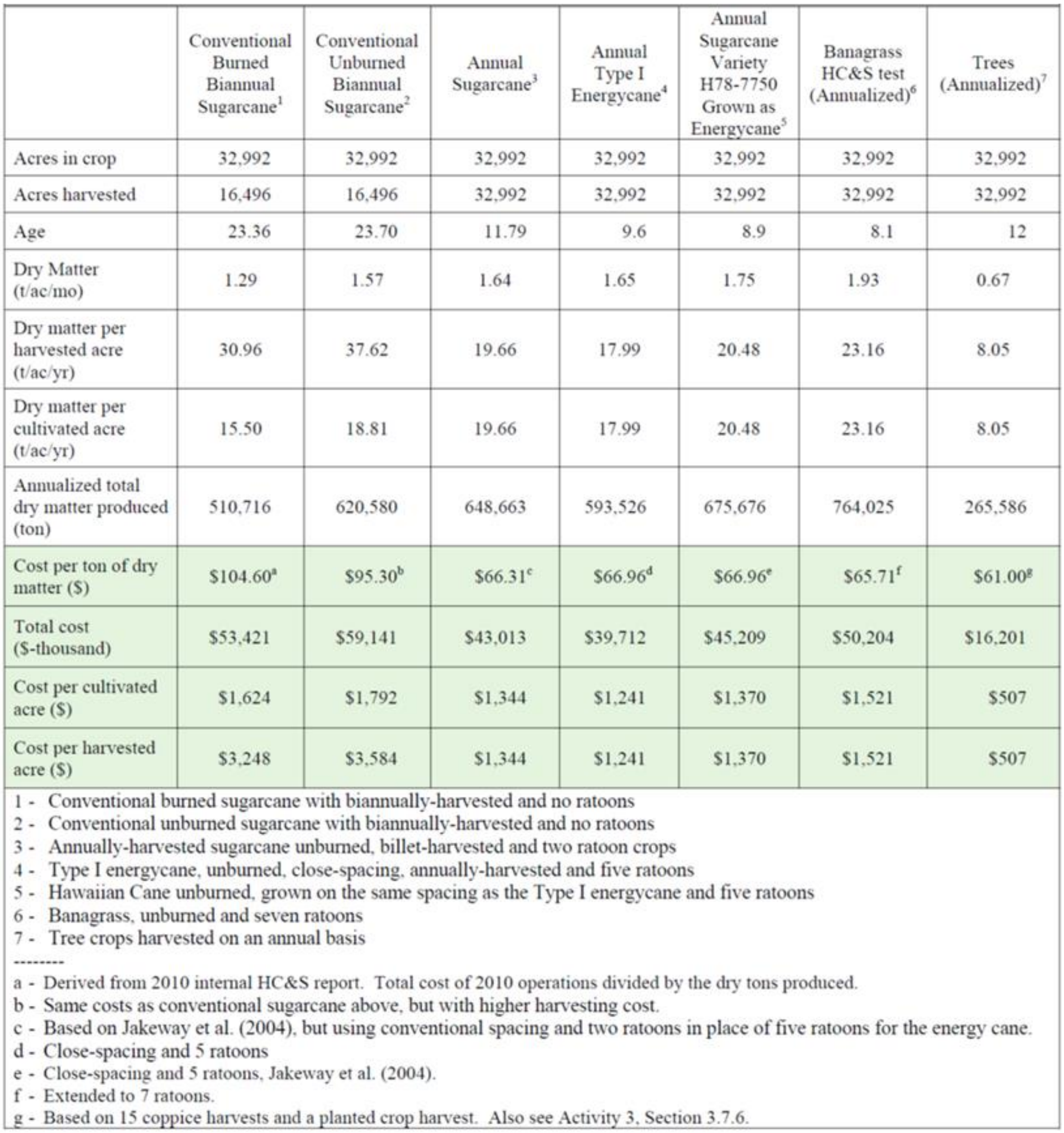
[71] U.S. Bureau of Statistics Inflation Calculator, https://www.bls.gov/data/inflation_calculator.htm

[72] Example of land cost for 2,127 acres of agricultural land on Hawaiʻi Island

[73] Examples of long term lease costs for farmland in Hawaiʻi, https://hellohomestead.com/how-to-start-homesteading-in-hawaii/; https://www.landwatch.com/hawaii-county-hawaii-farms-and-ranches-for-sale/pid/414352528.

Table D.15. Cost of production for conventional sugarcane and estimated costs of production for the Short List crops[74].



	Conventional Burned Biannual Sugarcane[1]	Conventional Unburned Biannual Sugarcane[2]	Annual Sugarcane[3]	Annual Type I Energycane[4]	Annual Sugarcane Variety H78-7750 Grown as Energycane[5]	Banagrass HC&S test (Annualized)[6]	Trees (Annualized)[7]
Acres in crop	32,992	32,992	32,992	32,992	32,992	32,992	32,992
Acres harvested	16,496	16,496	32,992	32,992	32,992	32,992	32,992
Age	23.36	23.70	11.79	9.6	8.9	8.1	12
Dry Matter (t/ac/mo)	1.29	1.57	1.64	1.65	1.75	1.93	0.67
Dry matter per harvested acre (t/ac/yr)	30.96	37.62	19.66	17.99	20.48	23.16	8.05
Dry matter per cultivated acre (t/ac/yr)	15.50	18.81	19.66	17.99	20.48	23.16	8.05
Annualized total dry matter produced (ton)	510,716	620,580	648,663	593,526	675,676	764,025	265,586
Cost per ton of dry matter ($)	$104.60[a]	$95.30[b]	$66.31[c]	$66.96[d]	$66.96[e]	$65.71[f]	$61.00[g]
Total cost ($-thousand)	$53,421	$59,141	$43,013	$39,712	$45,209	$50,204	$16,201
Cost per cultivated acre ($)	$1,624	$1,792	$1,344	$1,241	$1,370	$1,521	$507
Cost per harvested acre ($)	$3,248	$3,584	$1,344	$1,241	$1,370	$1,521	$507

1 - Conventional burned sugarcane with biannually-harvested and no ratoons
2 - Conventional unburned sugarcane with biannually-harvested and no ratoons
3 - Annually-harvested sugarcane unburned, billet-harvested and two ratoon crops
4 - Type I energycane, unburned, close-spacing, annually-harvested and five ratoons
5 - Hawaiian Cane unburned, grown on the same spacing as the Type I energycane and five ratoons
6 - Banagrass, unburned and seven ratoons
7 - Tree crops harvested on an annual basis
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a - Derived from 2010 internal HC&S report. Total cost of 2010 operations divided by the dry tons produced.
b - Same costs as conventional sugarcane above, but with higher harvesting cost.
c - Based on Jakeway et al. (2004), but using conventional spacing and two ratoons in place of five ratoons for the energy cane.
d - Close-spacing and 5 ratoons
e - Close-spacing and 5 ratoons, Jakeway et al. (2004).
f - Extended to 7 ratoons.
g - Based on 15 coppice harvests and a planted crop harvest. Also see Activity 3, Section 3.7.6.

Recent studies for hydrogen from biomass gasification show costs between $2.50-$6/kg for forecasts as compared to other hydrogen production methods. As noted below,

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[74] GreenEra LLC (prepared for Hawai'I Natural Energy Institute), *Task 4 Alternative Energy Systems: Alternative Biofuels Development: Crops Assessment*, December 2013, https://www.hnei.hawaii.edu/wp-content/uploads/Biofuels-Crop-Assessment.pdf

ultimate costs for gasification are very dependent on the previously discussed costs of feedstock, whether it be positive for biomass or negative for wastes[75].

For example, Salkuyeh et al. found “the minimum selling price for a kilogram of hydrogen to be $3.10 [18] at a feedstock cost of $100/dry ton of biomass. evaluated the cost and… found that, with a feedstock cost of $100/dry ton of biomass, the minimum selling price for a kilogram of hydrogen to be $3.10 [18]. Another group of researchers reviewed…hydrogen production from residual waste [19]. This study focused on the interesting premise of accepting a fee for biomass… making the cost of biomass negative… if a gate fee is charged for feedstock waste, hydrogen prices could be as low as $1.40 per kilogram… which underscores the sensitivity of production costs to feedstock prices.”

As of 2023, additional techno-economic analysis of biomass gasification for hydrogen production concluded “Ultimately, the cost of transported hydrogen in a 40 metric ton/day facility was calculated to be $3.47/kg H_2 in Klamath County, Oregon (which serves both the Oregon and California markets), $4.11/kg H_2 in Park County, Colorado, and $3.63/kg H_2 in Middlesex County, Massachusetts. “A sensitivity analysis found transportation distance and biomass availability to be major factors in these costs.”

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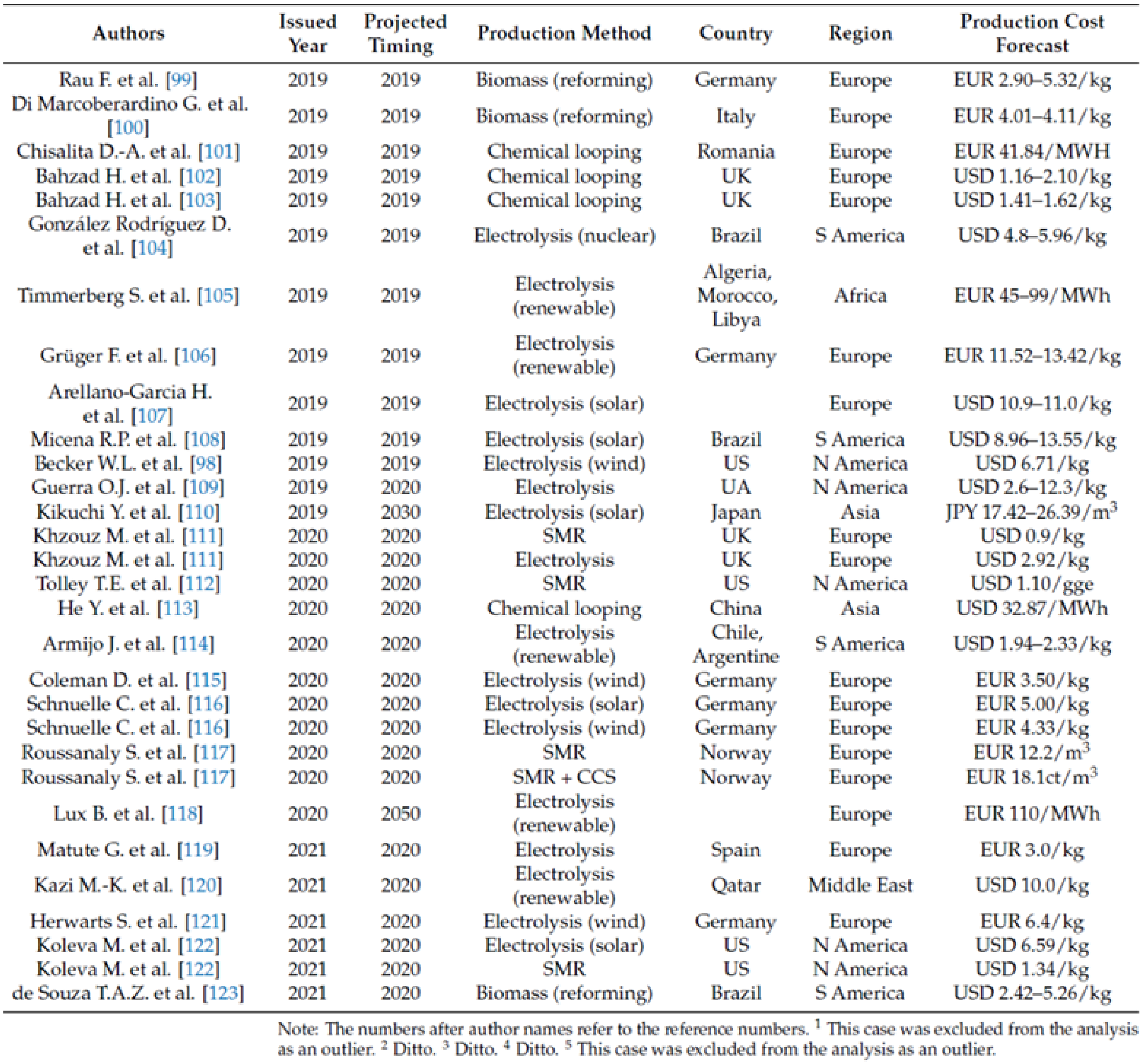
[75] B. Cook et al., 2024, *Techno-economic analysis of biomass gasification for hydrogen production in three US-based case studies*, Inter. Journal of Hydrogen Energy, 49D, 202-218.

Table D.16. Excerpt of table production cost for hydrogen production technologies[76].



Authors	Issued Year	Projected Timing	Production Method	Country	Region	Production Cost Forecast
Rau F. et al. [99]	2019	2019	Biomass (reforming)	Germany	Europe	EUR 2.90–5.32/kg
Di Marcoberardino G. et al. [100]	2019	2019	Biomass (reforming)	Italy	Europe	EUR 4.01–4.11/kg
Chisalita D.-A. et al. [101]	2019	2019	Chemical looping	Romania	Europe	EUR 41.84/MWH
Bahzad H. et al. [102]	2019	2019	Chemical looping	UK	Europe	USD 1.16–2.10/kg
Bahzad H. et al. [103]	2019	2019	Chemical looping	UK	Europe	USD 1.41–1.62/kg
González Rodríguez D. et al. [104]	2019	2019	Electrolysis (nuclear)	Brazil	S America	USD 4.8–5.96/kg
Timmerberg S. et al. [105]	2019	2019	Electrolysis (renewable)	Algeria, Morocco, Libya	Africa	EUR 45–99/MWh
Grüger F. et al. [106]	2019	2019	Electrolysis (renewable)	Germany	Europe	EUR 11.52–13.42/kg
Arellano-Garcia H. et al. [107]	2019	2019	Electrolysis (solar)		Europe	USD 10.9–11.0/kg
Micena R.P. et al. [108]	2019	2019	Electrolysis (solar)	Brazil	S America	USD 8.96–13.55/kg
Becker W.L. et al. [98]	2019	2019	Electrolysis (wind)	US	N America	USD 6.71/kg
Guerra O.J. et al. [109]	2019	2020	Electrolysis	UA	N America	USD 2.6–12.3/kg
Kikuchi Y. et al. [110]	2019	2030	Electrolysis (solar)	Japan	Asia	JPY 17.42–26.39/m^3
Khzouz M. et al. [111]	2020	2020	SMR	UK	Europe	USD 0.9/kg
Khzouz M. et al. [111]	2020	2020	Electrolysis	UK	Europe	USD 2.92/kg
Tolley T.E. et al. [112]	2020	2020	SMR	US	N America	USD 1.10/gge
He Y. et al. [113]	2020	2020	Chemical looping	China	Asia	USD 32.87/MWh
Armijo J. et al. [114]	2020	2020	Electrolysis (renewable)	Chile, Argentine	S America	USD 1.94–2.33/kg
Coleman D. et al. [115]	2020	2020	Electrolysis (wind)	Germany	Europe	EUR 3.50/kg
Schnuelle C. et al. [116]	2020	2020	Electrolysis (solar)	Germany	Europe	EUR 5.00/kg
Schnuelle C. et al. [116]	2020	2020	Electrolysis (wind)	Germany	Europe	EUR 4.33/kg
Roussanaly S. et al. [117]	2020	2020	SMR	Norway	Europe	EUR 12.2/m^3
Roussanaly S. et al. [117]	2020	2020	SMR + CCS	Norway	Europe	EUR 18.1ct/m^3
Lux B. et al. [118]	2020	2050	Electrolysis (renewable)		Europe	EUR 110/MWh
Matute G. et al. [119]	2021	2020	Electrolysis	Spain	Europe	EUR 3.0/kg
Kazi M.-K. et al. [120]	2021	2020	Electrolysis (renewable)	Qatar	Middle East	USD 10.0/kg
Herwarts S. et al. [121]	2021	2020	Electrolysis (wind)	Germany	Europe	EUR 6.4/kg
Koleva M. et al. [122]	2021	2020	Electrolysis (solar)	US	N America	USD 6.59/kg
Koleva M. et al. [122]	2021	2020	SMR	US	N America	USD 1.34/kg
de Souza T.A.Z. et al. [123]	2021	2020	Biomass (reforming)	Brazil	S America	USD 2.42–5.26/kg

Note: The numbers after author names refer to the reference numbers. [1] This case was excluded from the analysis as an outlier. [2] Ditto. [3] Ditto. [4] Ditto. [5] This case was excluded from the analysis as an outlier.

Waste Costs

Relative to gasification of dedicated energy crops, there are fewer data points available for determining the cost of converting construction and demolition (C&D) and municipal solid wastes (MSW) to hydrogen. After consultation and review of a few developers' forecasts, a range of potential production costs was developed. Aloha Carbon (planning for production of hydrogen from C&D waste on Oʻahu) agreed that an expected range of costs between $2.60-4.30/kg is reasonable. Another announcement, from OMNI, included an expectation of production costs under $3/kg from their planned California

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[76] T. Miyagawa, et al., 2022, *Hydrogen Production Cost Forecasts since the 1970s and Implications for Technological Development*, Energies, 15(12), 4375.

project[77]. Lastly, Ways2H2 has plans for a waste to hydrogen facility and have expressed that $3-5/kg of hydrogen is expected. They state: "[The cost] is very much dependent on what kind of feedstock we have, but typically we are now comfortable at $5 per kilogram," chief executive Jean-Louis Kindler tells *Recharge*. "And we can go down to about half that, let's say $3 a kilogram… [within] five years."[78]

However, these costs do not reflect the financing costs or profits required by the developer and as discussed above, they are very sensitive to actual waste disposal fees the gasification facility receives to offset costs. While these announcements and discussions with industry confirm projected production cost values, all of these costs should be regarded as targets until operational data is available and project financing and developer profits are taken into account.

Ethanol Costs

Hydrogen from ethanol using Golu SR technology is very dependent upon the cost of ethanol, which can vary substantially depending on related commodities such as corn and RIN credits. Rough estimates for total costs of hydrogen based on an example ethanol cost of $2.75/gal and a modular facility for 1.25 MT/day are shown below at $4,769/ton = $5.24/kg of hydrogen.

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[77] FuelCellWorks, *OMNI CT Brings First-of-Its-Kind Waste to Hydrogen Product to California*, April 2021, https://fuelcellsworks.com/news/omni-ct-brings-first-of-its-kind-waste-to-hydrogen-product-to-california/

[78] L. Collins, *It's much cheaper to produce green hydrogen from waste than renewables*, April 2020, https://www.rechargenews.com/transition/its-much-cheaper-to-produce-green-hydrogen-from-waste-than-renewables/2-1-801160

APPENDIX E: DISTRIBUTION AND STORAGE

As discussed in the main body of the report, the transport, storage, and distribution of hydrogen in Hawaiʻi was assessed primarily for the road transportation end use. Outside of road transportation, only Oʻahu has other estimated hydrogen uses beyond power generation. Since power generation was determined to have a very different hydrogen offtake profile compared to the other end-uses, (which assumed flat daily profiles for offtake) it was not assessed in the same framework.

This section provides additional detail on the assumed quantities of equipment, energy consumption, and labor to operate the hydrogen distribution system on each island using the gaseous or liquid hydrogen routes for road transportation. The buffer storage costs are also only for road transportation except in the case for Oʻahu which includes buffer storage for the SAF and Hawaiʻi Gas needs. Many of the assumptions on equipment sizing, operational needs, and travel distance come from consultation with IES on potential plans to deliver hydrogen via interisland shipping.

The calculations to turn capital costs and annual operating costs shown here into the $/kg estimates shown in the report use the method outlined in the *Production Costs Appendix*.

Equipment needs for distributing hydrogen were all based on currently available technology and generic cost estimates. These costs do not reflect project specific economics. All projects considered for actual investment in Hawaiʻi should require a request for proposal process detailing a specific cost component breakdown.

Each distribution system also assumes that some amount of buffer storage is required to allow for a steady supply of hydrogen for end users. No optimization on the required size of buffer storage was done, but an assumption of three days of storage was used. The storage medium (gaseous or liquid) was assumed to match the delivery system. The buffer storage system also had a refill requirement which assumed that storage must be able to refill within seven days of depletion and it was assumed that storage would be drawn down approximately one time a month or 12 times a year.

A simple assessment of the labor required to operate each distribution system was also done, although this is far from an exhaustive list and additional quantities of labor can only be assessed via actual detailed plans.

Table E.1. Labor requirement assumptions.

Labor Type	Salary Assumption	Number per Island
Operators – Storage & Distribution	$120,000/yr	2
Lab Technicians	$120,000/yr	2
Mechanics – Truck	$120,000/yr	4
Mechanics – Trailers	$120,000/yr	4
Accountants	$120,000/yr	1
Schedulers	$120,000/yr	1

The total number of truck drivers required varies by island due to the number of storage tanks needed to be delivered each day.

Soft costs were also assumed to take the form of insurance, maintenance, spare parts, contingency, and GET. These costs were calculated as a % of capital cost for the equipment.

Table E.2. Soft cost assumption for major equipment.

Soft Cost Category	% of Capex
Insurance	2.5
Maintenance	2.5
Spare Parts	2.5
Contingency	20
GET	4.71

Gaseous Distribution and Storage Details

This section details the quantities and cost of the major components for delivering and storing hydrogen using the gaseous hydrogen route for each island. Each island uses the same equipment estimates but at different scales depending on the daily metric tons of hydrogen for delivery. Assumptions on equipment sizing and cost per unit are provided in the table below.

Table E.3. Gaseous hydrogen distribution and storage capital equipment summary.

System Component	$ per Unit
873 kg Gaseous Tube Trailer	680,000
Hydrogen Tractor Truck	700,000
90 kg/hr Compressor	1,400,000

The assumptions used to determine the operating costs are presented for the gaseous system below. Major operating costs include the energy to compress hydrogen, the cost of hydrogen to fuel the tractor trucks, and the labor to facilitate delivery.

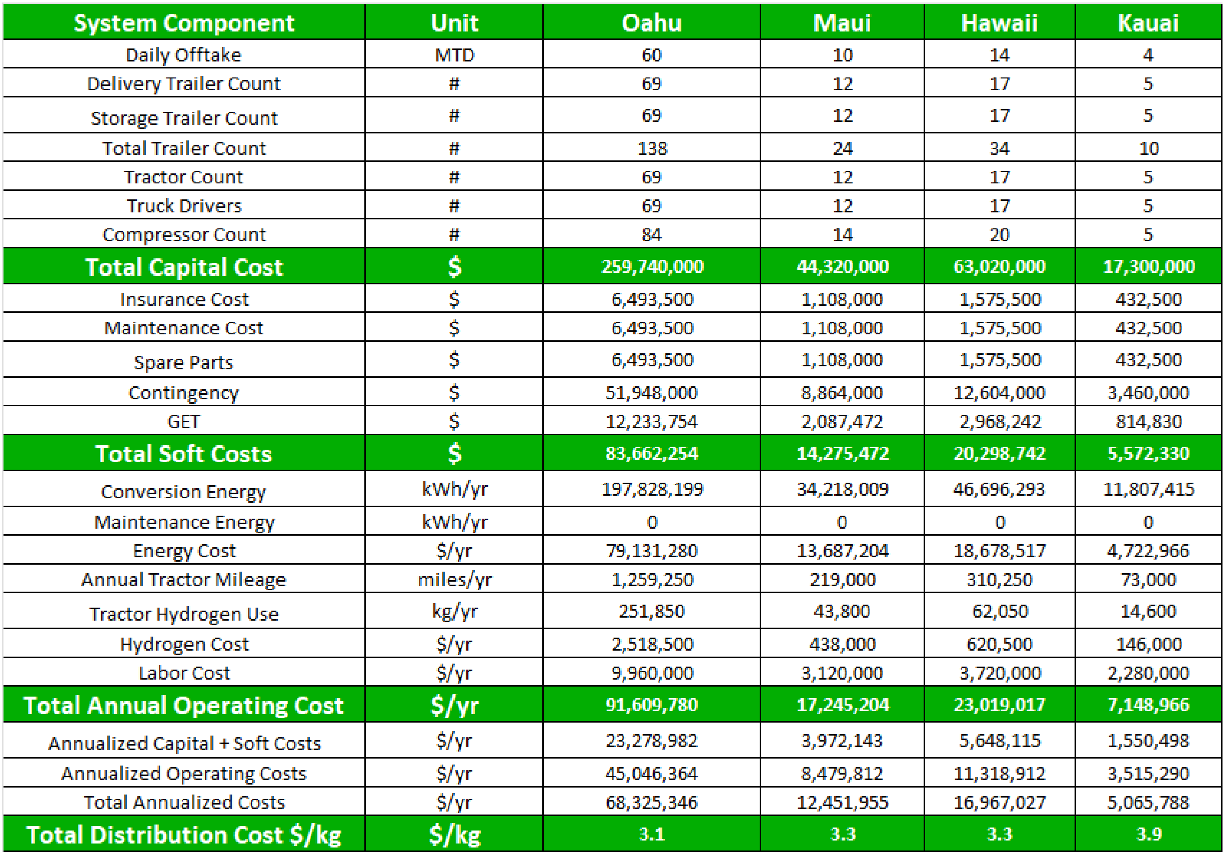
Table E.4. Gaseous hydrogen distribution and storage operating cost summary.

System Component	Value	Unit	Assumption
Compression Energy	9	kWh/kg	Assumption of energy to compress and cooling needs for compressor
Compression Energy Cost	0.40	$/kWh	Approximate grid electricity rate
Hydrogen Cost (Tractor Truck)	10	$/kg	Cost assumed for hydrogen fueled tractor trucks to distribute hydrogen to end users
Daily Deliveries per Tractor Truck	1	Delivery/day	One truck delivers one trailer per day
Roundtrip Delivery Mileage	50	Miles/day	50 miles assumed per delivery
Tractor Truck Fuel Use	0.2	kg/mile	

Gaseous Distribution and Storage Details by Island

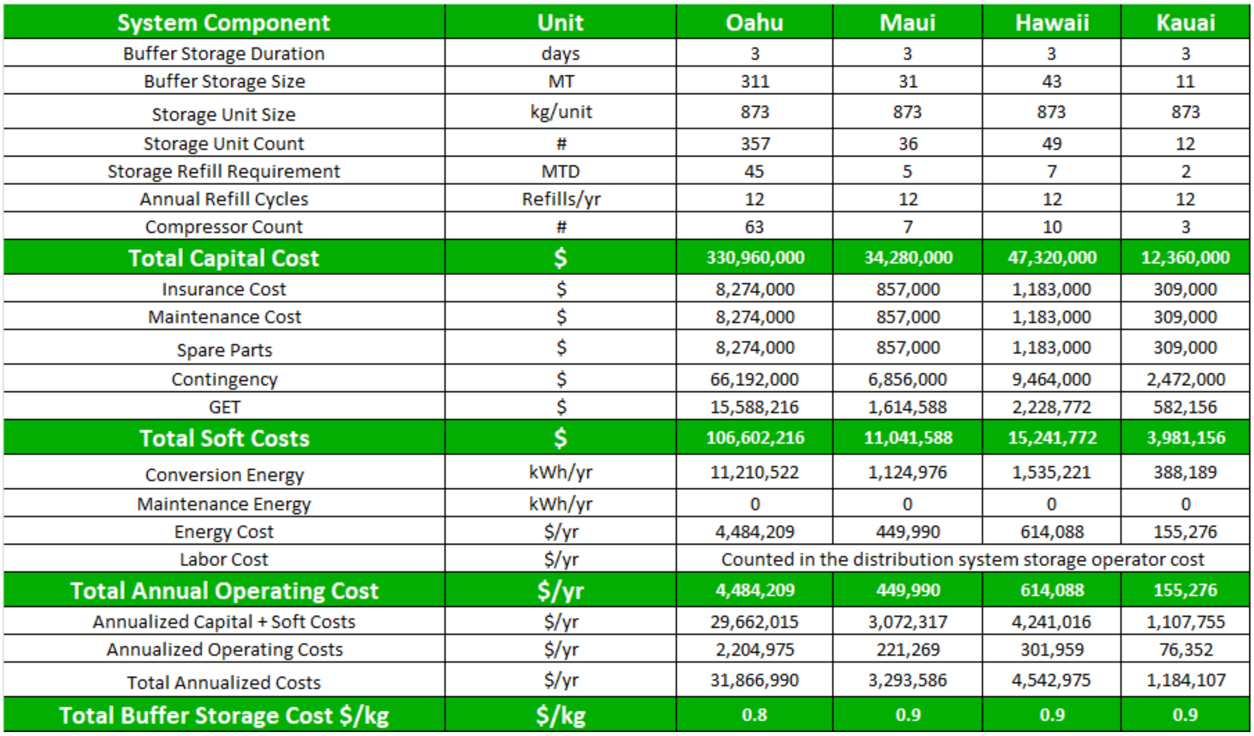
The tables below detail the capital and operating costs by island to provide the stated target metric tons per day of gaseous hydrogen for road transportation and the cost breakdown for the buffer storage system.

Table E.5. Gaseous hydrogen distribution system component and cost breakdown by island.



System Component	Unit	Oahu	Maui	Hawaii	Kauai
Daily Offtake	MTD	60	10	14	4
Delivery Trailer Count	#	69	12	17	5
Storage Trailer Count	#	69	12	17	5
Total Trailer Count	#	138	24	34	10
Tractor Count	#	69	12	17	5
Truck Drivers	#	69	12	17	5
Compressor Count	#	84	14	20	5
Total Capital Cost	**$**	**259,740,000**	**44,320,000**	**63,020,000**	**17,300,000**
Insurance Cost	$	6,493,500	1,108,000	1,575,500	432,500
Maintenance Cost	$	6,493,500	1,108,000	1,575,500	432,500
Spare Parts	$	6,493,500	1,108,000	1,575,500	432,500
Contingency	$	51,948,000	8,864,000	12,604,000	3,460,000
GET	$	12,233,754	2,087,472	2,968,242	814,830
Total Soft Costs	**$**	**83,662,254**	**14,275,472**	**20,298,742**	**5,572,330**
Conversion Energy	kWh/yr	197,828,199	34,218,009	46,696,293	11,807,415
Maintenance Energy	kWh/yr	0	0	0	0
Energy Cost	$/yr	79,131,280	13,687,204	18,678,517	4,722,966
Annual Tractor Mileage	miles/yr	1,259,250	219,000	310,250	73,000
Tractor Hydrogen Use	kg/yr	251,850	43,800	62,050	14,600
Hydrogen Cost	$/yr	2,518,500	438,000	620,500	146,000
Labor Cost	$/yr	9,960,000	3,120,000	3,720,000	2,280,000
Total Annual Operating Cost	**$/yr**	**91,609,780**	**17,245,204**	**23,019,017**	**7,148,966**
Annualized Capital + Soft Costs	$/yr	23,278,982	3,972,143	5,648,115	1,550,498
Annualized Operating Costs	$/yr	45,046,364	8,479,812	11,318,912	3,515,290
Total Annualized Costs	$/yr	68,325,346	12,451,955	16,967,027	5,065,788
Total Distribution Cost $/kg	**$/kg**	**3.1**	**3.3**	**3.3**	**3.9**

Table E.6. Gaseous hydrogen distribution system buffer storage component and cost breakdown by island.



System Component	Unit	Oahu	Maui	Hawaii	Kauai
Buffer Storage Duration	days	3	3	3	3
Buffer Storage Size	MT	311	31	43	11
Storage Unit Size	kg/unit	873	873	873	873
Storage Unit Count	#	357	36	49	12
Storage Refill Requirement	MTD	45	5	7	2
Annual Refill Cycles	Refills/yr	12	12	12	12
Compressor Count	#	63	7	10	3
Total Capital Cost	**$**	**330,960,000**	**34,280,000**	**47,320,000**	**12,360,000**
Insurance Cost	$	8,274,000	857,000	1,183,000	309,000
Maintenance Cost	$	8,274,000	857,000	1,183,000	309,000
Spare Parts	$	8,274,000	857,000	1,183,000	309,000
Contingency	$	66,192,000	6,856,000	9,464,000	2,472,000
GET	$	15,588,216	1,614,588	2,228,772	582,156
Total Soft Costs	**$**	**106,602,216**	**11,041,588**	**15,241,772**	**3,981,156**
Conversion Energy	kWh/yr	11,210,522	1,124,976	1,535,221	388,189
Maintenance Energy	kWh/yr	0	0	0	0
Energy Cost	$/yr	4,484,209	449,990	614,088	155,276
Labor Cost	$/yr	Counted in the distribution system storage operator cost			
Total Annual Operating Cost	**$/yr**	**4,484,209**	**449,990**	**614,088**	**155,276**
Annualized Capital + Soft Costs	$/yr	29,662,015	3,072,317	4,241,016	1,107,755
Annualized Operating Costs	$/yr	2,204,975	221,269	301,959	76,352
Total Annualized Costs	$/yr	31,866,990	3,293,586	4,542,975	1,184,107
Total Buffer Storage Cost $/kg	**$/kg**	**0.8**	**0.9**	**0.9**	**0.9**

Total costs for the gaseous distribution and buffer storage system range from 3.9-4.8 $/kg to distribute and storage gaseous hydrogen to meet the estimated annual road transportation demand and provide buffer storage for all end uses except hydrogen for power generation.

Liquid Distribution and Storage Details

This section details the quantities and cost of the major components for delivering and storing hydrogen using the liquid hydrogen route for each island. Each island uses the same equipment estimates but at different scales depending on the daily metric tons of hydrogen for delivery. Assumptions on equipment sizing and cost per unit are provided in the table below.

Table E.7. Liquid hydrogen distribution and storage capital equipment summary.

System Component	$ per Unit
4,300 kg Liquid Hydrogen Trailer	1,400,000
Hydrogen Tractor Truck	700,000
Liquefaction Plant (2,000-15,000 kg/day)	14-73 million

The assumptions used to determine the operating costs are presented for the gaseous system below. Major operating costs include the energy to liquefy hydrogen, the cost of hydrogen to fuel the tractor trucks, and the labor to facilitate delivery.

Table E.8. Liquid hydrogen distribution and storage operating cost summary.

System Component	Value	Unit	Assumption
Liquefaction Energy	13 or 20	kWh/kg	Plants <15,000 kg/day used 20 kWh/kg.
Liquefaction Energy Cost	0.40	$/kWh	Approximate grid electricity rate
Hydrogen Cost (Tractor Truck)	10	$/kg	Cost assumed for hydrogen fueled tractor trucks to distribute hydrogen to end users
Daily Deliveries per Tractor Truck	1	Delivery/day	One truck delivers one trailer per day
Roundtrip Delivery Mileage	50	Miles/day	50 miles assumed per delivery
Tractor Truck Fuel Use	0.2	kg/mile	

Liquid Distribution and Storage Details by Island

Tables E.9 and E.10 below detail the capital and operating costs by island to provide the stated target metric tons per day of liquid hydrogen for road transportation and the cost breakdown for the buffer storage system.

Total costs for the liquid distribution and buffer storage system range from 5.2-8.8 $/kg to distribute and store liquid hydrogen to meet the estimated annual road transportation demand and provide buffer storage for all end uses except hydrogen for power generation.

Table E.9. Liquid hydrogen distribution system component and cost breakdown by island.

System Component	Unit	Oahu	Maui	Hawaii	Kauai
Daily Offtake	MTD	60	10	14	4
Delivery Trailer Count	#	15	3	4	1
Storage Trailer Count	#	15	4	4	2
Total Trailer Count	#	30	7	8	3
Tractor Count	#	15	3	4	1
Truck Drivers	#	15	3	4	1
Liquefaction Plants	#	4	2	3	2
Total Capital Cost	**$**	**342,761,199**	**72,164,559**	**104,396,839**	**33,854,094**
Insurance Cost	$	8,569,030	1,804,114	2,609,921	846,352
Maintenance Cost	$	8,569,030	1,804,114	2,609,921	846,352
Spare Parts	$	8,569,030	1,804,114	2,609,921	846,352
Contingency	$	68,552,240	14,432,912	20,879,368	6,770,819
GET	$	16,144,052	3,398,951	4,917,091	1,594,528
Total Soft Costs	**$**	**110,403,382**	**23,244,205**	**33,626,222**	**10,904,404**
Conversion Energy	kWh/yr	285,751,843	76,040,020	103,769,540	26,238,700
Maintenance Energy	kWh/yr	0	0	0	0
Energy Cost	$/yr	114,300,737	30,416,008	41,507,816	10,495,480
Annual Tractor Mileage	miles/yr	273,750	54,750	73,000	14,600
Tractor Hydrogen Use	kg/yr	54,750	10,950	14,600	2,920
Hydrogen Cost	$/yr	547,500	109,500	146,000	29,200
Labor Cost	$/yr	3,480,000	2,040,000	2,160,000	1,800,000
Total Annual Operating Cost	**$/yr**	**118,328,237**	**32,565,508**	**43,813,816**	**12,324,680**
Annualized Capital + Soft Costs	$/yr	30,719,688	6,467,689	9,356,480	3,034,145
Annualized Operating Costs	$/yr	58,184,365	16,013,113	21,544,131	6,060,292
Total Annualized Costs	$/yr	88,904,053	22,480,802	30,900,611	9,094,437
Total Distribution Cost $/kg	**$/kg**	**4.0**	**5.9**	**6.0**	**6.9**

Table E.10. Liquid hydrogen distribution system buffer storage component and cost breakdown by island.

System Component	Unit	Oahu	Maui	Hawaii	Kauai
Buffer Storage Duration	days	3	3	3	3
Buffer Storage Size	MT	311	31	43	11
Storage Unit Size	kg/unit	6,700	6,700	6,700	6,700
Storage Unit Count	#	46	5	6	2
Storage Refill Requirement	MTD	45	5	7	2
Annual Refill Cycles	Refills/yr	12	12	12	12
Liquefaction Plants	#	3	1	1	1
Total Capital Cost	**$**	**378,695,899**	**47,632,280**	**51,132,280**	**21,477,047**
Insurance Cost	$	9,467,397	1,190,807	1,278,307	536,926
Maintenance Cost	$	9,467,397	1,190,807	1,278,307	536,926
Spare Parts	$	9,467,397	1,190,807	1,278,307	536,926
Contingency	$	75,739,180	9,526,456	10,226,456	4,295,409
GET	$	17,836,577	2,243,480	2,408,330	1,011,569
Total Soft Costs	**$**	**121,977,949**	**15,342,357**	**16,469,707**	**6,917,757**
Conversion Energy	kWh/yr	48,578,927	7,499,838	10,234,804	2,587,927
Maintenance Energy	kWh/yr	647,875	65,014	88,723	22,434
Energy Cost	$/yr	19,690,721	3,025,941	4,129,411	1,044,144
Labor Cost	$/yr	Counted in the distribution system storage operator cost			
Total Annual Operating Cost	**$/yr**	**19,690,721**	**3,025,941**	**4,129,411**	**1,044,144**
Annualized Capital + Soft Costs	$/yr	33,940,305	4,269,004	4,582,688	1,924,862
Annualized Operating Costs	$/yr	9,682,322	1,487,916	2,030,514	513,427
Total Annualized Costs	$/yr	43,622,627	5,756,919	6,613,202	2,438,289
Total Buffer Storage Cost $/kg	**$/kg**	**1.2**	**1.5**	**1.3**	**1.9**

APPENDIX F: INTERISLAND SHIPPING

Based on the results presented in the main body of the report, interisland shipping can potentially be a cost effective solution to providing large quantities of hydrogen to O’ahu from neighboring islands. If the cost of producing hydrogen can be $0.5 – 1/kg lower on a neighboring island, then there is potential for interisland shipping of liquid hydrogen to be cost competitive relative to strictly local production and distribution of hydrogen on O’ahu. However, as noted in the report, interisland shipping remains costly, essentially doubling the cost of producing hydrogen. This section provides additional detail on the types and quantities of equipment used to develop a cost estimate for interisland shipping of liquid hydrogen.

Interisland Shipping: System Components

This section details the quantities and cost of the major components for delivering and storing liquid hydrogen from Hawaiʻi Island to Oʻahu. This case was investigated to determine the total cost adder in $/kg that shipping liquid hydrogen interisland would add to the cost of delivered hydrogen on Oʻahu.

In a future where on-island supplies of hydrogen fall short, or demand for hydrogen grows beyond the estimates in the main report, Oʻahu will require some amount of interisland shipping to meet demand. Many of these assumptions come from consultation with IES on shipping 20,000 kg/day of liquid hydrogen to Oʻahu from Hawaiʻi Island.

Table F.1. Liquid hydrogen shipping and storage capital equipment summary.

System Component	$ per Unit
3,000 kg Liquid Hydrogen ISO-containers	1,100,000
330,000 kg Liquid Hydrogen Storage (90% fill rate)	60,200,000
Hydrogen Tractor Truck	700,000
Liquefaction Plant (15,000 kg/day)	73,000,000

The assumptions used to determine the operating costs are presented for the interisland liquid system below. Major operating costs include the energy to liquefy hydrogen, the cost of hydrogen to fuel the tractor trucks, and the labor to facilitate delivery. The only difference assumed for labor is an increase in the number of truck drivers to facilitate bringing hydrogen from production sites on Hawaiʻi Island to ports for delivery.

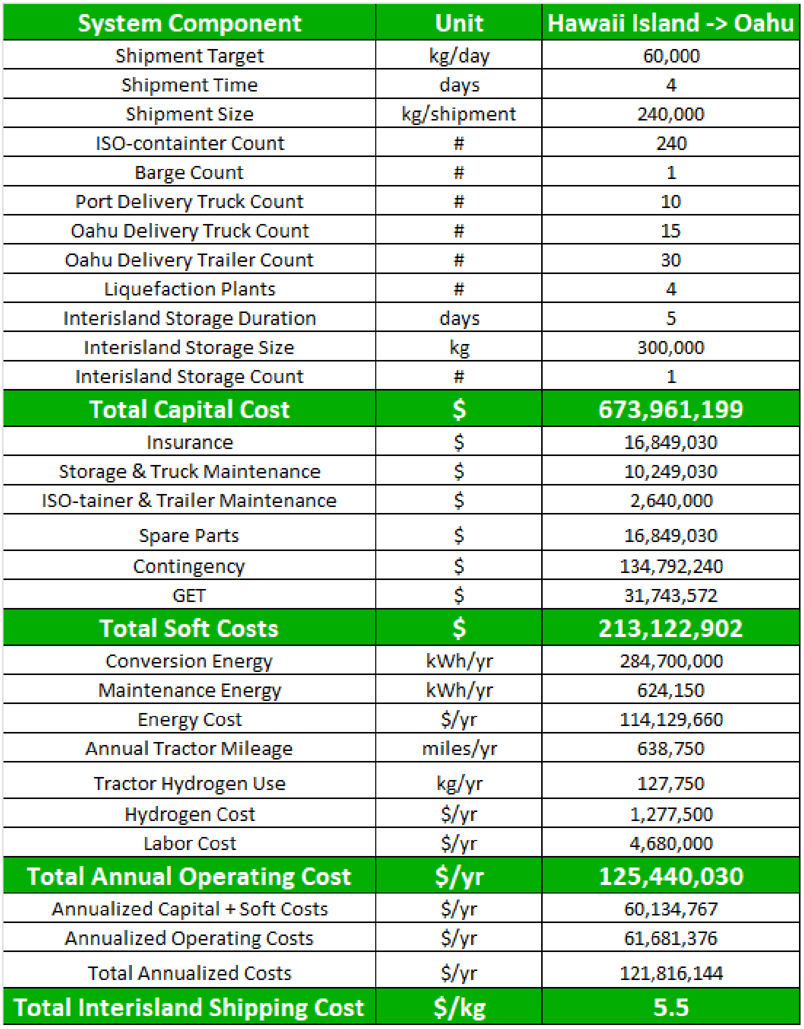
Table F.2. Liquid hydrogen distribution and storage operating cost summary.

System Component	Value	Unit	Assumption
Liquefaction Energy	13	kWh/kg	For the 15,000 kg/day plant
Liquefaction Energy Cost	0.40	$/kWh	Approximate grid electricity rate
Hydrogen Cost (Tractor Truck)	10	$/kg	Cost assumed for hydrogen fueled tractor trucks to distribute hydrogen to end users
Daily Deliveries per Tractor Truck to Port	2	Delivery/day	One truck delivers 2 trailers per day
Daily Deliveries per Tractor Truck to Oʻahu Users	1	Delivery/day	One truck delivers one trailer per day
Roundtrip Delivery Mileage	50	Miles/day	50 miles assumed per delivery
Tractor Truck Fuel Use	0.2	kg/mile	Tractor truck hydrogen consumption

Interisland Shipping: Cost Details

Table F.3 below detail the capital and operating costs to liquefy hydrogen on Hawaiʻi Island, ship it to Oʻahu, and distribute it via liquid hydrogen trucks assuming a 60,000 kg/day (60 MTD) delivery target.

Table F.3. Interisland shipping of liquid hydrogen from Hawaiʻi Island to Oʻahu.



System Component	Unit	Hawaii Island -> Oahu
Shipment Target	kg/day	60,000
Shipment Time	days	4
Shipment Size	kg/shipment	240,000
ISO-containter Count	#	240
Barge Count	#	1
Port Delivery Truck Count	#	10
Oahu Delivery Truck Count	#	15
Oahu Delivery Trailer Count	#	30
Liquefaction Plants	#	4
Interisland Storage Duration	days	5
Interisland Storage Size	kg	300,000
Interisland Storage Count	#	1
Total Capital Cost	**$**	**673,961,199**
Insurance	$	16,849,030
Storage & Truck Maintenance	$	10,249,030
ISO-tainer & Trailer Maintenance	$	2,640,000
Spare Parts	$	16,849,030
Contingency	$	134,792,240
GET	$	31,743,572
Total Soft Costs	**$**	**213,122,902**
Conversion Energy	kWh/yr	284,700,000
Maintenance Energy	kWh/yr	624,150
Energy Cost	$/yr	114,129,660
Annual Tractor Mileage	miles/yr	638,750
Tractor Hydrogen Use	kg/yr	127,750
Hydrogen Cost	$/yr	1,277,500
Labor Cost	$/yr	4,680,000
Total Annual Operating Cost	**$/yr**	**125,440,030**
Annualized Capital + Soft Costs	$/yr	60,134,767
Annualized Operating Costs	$/yr	61,681,376
Total Annualized Costs	$/yr	121,816,144
Total Interisland Shipping Cost	**$/kg**	**5.5**

The total cost to liquefy, ship, and distribute hydrogen produced on Hawaiʻi Island to Oʻahu is 5.5 $/kg. While more expensive than liquefaction and distribution on-island, there is the potential for hydrogen production costs to be lower on Hawaiʻi Island than on Oʻahu which could result in a cost effective route being shipping liquid hydrogen to Oʻahu from neighboring islands.

APPENDIX G: PERMITTING

Appendix G is a compendium of many of the permitting and regulatory resources that can be used to delve deeper into the requirements for deploying hydrogen systems in Hawaiʻi. A good starting point is the Hawaiʻi State Energy Office (HSEO) which has many programs to assist project developers.

Hawaiʻi State Energy Office Resources

The HSEO can provide assistance in identifying the federal, state, and county permits required for a project's individual facilities and infrastructure. The HSEO offers several online resources to facilitate the siting and permitting of individual projects including:

- **HSEO Project Development Center Tools**[79]: The resources in this section are intended to identify all potential permits, approvals, and issues early in the project development stage to inform decision-making by all parties before significant project investments are made. Links to online permitting tools used by other agencies are also included. These resources can also help identify opportunities for public input or involvement in required regulatory proceedings.

  Federal, State, and County permits potentially required in Hawaiʻi[80]: The attached list includes Federal, State, and County permits that could be required for a large renewable energy project in Hawaiʻi. The list is advisory only and may not contain all required permits and approvals.

  Renewable EnerGIS Siting Tool[81]: Renewable EnerGIS supports the siting of renewable energy projects by providing information on specific Hawaiʻi parcels to help inform the site assessment process, including renewable energy resource indicators, climate, topography, zoning, and other relevant site characteristics. This tool also empowers users to query sites in Hawaiʻi with certain attributes that may or may not be desired for development such as island, acreage, solar radiation, land use district, soil type(s), potential warm groundwater, and/or the presence of critical habitat(s), special management area(s), and reserve(s). Renewable EnerGIS benefits a broad audience by providing information that can be used by landowners, developers, communities, individuals, regulatory entities, policymakers, non-government organizations, and other stakeholders. No special skills, software, or experience with geographic information systems (GIS) are needed.

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[79] https://energy.hawaii.gov/information-center/project-development-center-tools/project-permitting-assistance-and-resources/#

[80] https://energy.hawaii.gov/wp-content/uploads/2022/07/HSEO-Permit-List_2022-07-12.xlsx

[81] https://energy.hawaii.gov/information-center/project-development-center-tools/renewable-energis-mapping-tool/

- **Renewable Energy Permitting Wizard**[82]: The Renewable Energy Permitting Wizard helps to identify the county, state, and federal permits and approvals that may be required for large development projects in Hawaiʻi and the sequence in which the approvals may be obtained. The Wizard facilitates the appropriate siting of large projects and serves to reduce soft costs associated with project siting and permitting due diligence.
- **Permit Guide (2015)**[83]: This Guide provides information on siting and permitting renewable energy facilities in Hawaiʻi, including lessons learned from actual Hawaiʻi renewable energy projects.
- **Department of Health e-Permitting Portal**[84]: The e-Permitting Portal is provided as a service for the public by the DOH EHA. The EHA oversees the overall administration of the Environmental Management Division (EMD), Environmental Health Services Division (EHSD), and State Laboratories Division (SLD); including branches within each of these divisions. The EHA also provides overall administration of the Offices of Compliance Assistance, Environmental Planning, Environmental Resources, and Hazard Evaluation and Emergency Response.

Authorities Having Jurisdiction (AHJs)

AHJs involved in the oversight of projects include but are not limited to:

- **Federal:**
  - U.S. Environmental Protection Agency,
  - U.S. Army Corps of Engineers,
  - U.S. Occupational Safety and Health Administration,
  - U.S. Pipeline and Hazardous Materials Safety Administration,
  - U.S. Department of Transportation (DOT),
  - U.S. Coast Guard,
  - U.S. National Oceanic and Atmospheric Administration,
  - U.S. Fish and Wildlife Service, and
  - U.S. DOD.
    - Hydrogen projects on DOD land, namely Indo-Pacific Command (INDOPACOM), will be primarily regulated by federal laws and processes.
- **State:**
  - Department of Land and Natural Resources,
  - Department of Health.

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[82] https://energy.hawaii.gov/information-center/project-development-center-tools/renewable-energy-permitting-wizard/

[83] https://energy.hawaii.gov/wp-content/uploads/2022/05/DBEDT-Permit-Guide_V3_04-30-15R.pdf

[84] https://eha-cloud.doh.hawaii.gov/epermit/

  - Office of Hawaiian Affairs.
  - Native Hawaiian Historic Preservation Council.
  - Hawaiʻi Coastal Zone Management Program.
  - Land Use Commission.
  - Office of Conservation and Coastal Lands.
  - Department of Transportation.
  - Department of Agriculture.
  - Public Utilities Commission, and
  - Department of Labor and Industrial Relations.
- **County:**
  - Various departments within the City and County of Honolulu, County of Maui, County of Kauaʻi, and County of Hawaiʻi. Hawaiʻi's four main counties oversee most construction and zoning permits.

Laws

Laws relevant to hydrogen project permitting include but are not limited to:

- **National Environmental Policy Act (NEPA) (42 USC 4321, et seq.)**[85]
- **Endangered Species Act**[86]: The Endangered Species Act of 1973 provides a framework to conserve and protect endangered and threatened species and their habitats both domestically and abroad.
- **Marine Mammal Protection Act of 1972**[87]: The Marine Mammal Protection Act was enacted on October 21, 1972. The MMPA established a national policy to prevent marine mammal species and population stocks from declining beyond the point where they ceased to be significant functioning elements of the ecosystems of which they are a part.
- **Migratory Bird Treaty Act**[88]: The statute makes it unlawful without a waiver to pursue, hunt, take, capture, kill, or sell nearly 1,100 species of birds listed therein as migratory birds. A March 2020 update of the list increased the number of species to 1,093.
- **Magnuson-Stevens Fishery Conservation and Management Act**[89]: The Magnuson–Stevens Fishery Conservation and Management Act (2007) is the primary law that governs marine fisheries management in U.S. federal waters

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[85] https://www.epa.gov/nepa
[86] https://www.fws.gov/law/endangered-species-act
[87] https://www.fisheries.noaa.gov/topic/marine-mammal-protection
[88] https://www.fws.gov/law/migratory-bird-treaty-act-1918
[89] https://www.fisheries.noaa.gov/resource/document/magnuson-stevens-fishery-conservation-and-management-act

- **Clean Water Act ([CWA] 33 USC 1251-1387)**[90]: The Clean Water Act (CWA) establishes the basic structure for regulating discharges of pollutants into the waters of the United States and regulating quality standards for surface waters.
- **Rivers and Harbors Act of 1899 ([RHA] 33 USC 403)**[91]: The Rivers and Harbors Act of 1899 (RHA) (33 U.S.C. Sec. 401 et seq.) is the initial authority for the U.S. Army Corps of Engineers (ACOE) regulatory permit program to protect navigable waters in the development of harbors and other construction and excavation.
- **Comprehensive Environmental Response, Compensation, and Liability Act**[92]: Comprehensive Environmental Response, Compensation, and Liability Act. Congress passed the Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA or commonly known as Superfund) in response to a growing national concern about the release of hazardous substances from abandoned waste sites.
- **National Historic Preservation Act**[93]: The National Historic Preservation Act of 1966 requires federal agencies to consider the impact their actions have on our historic resources.
- **Coastal Zone Management Act**[94]: This *act*, administered by *NOAA*, provides for the management of the nation's *coastal* resources, including the Great Lakes.
- **United States Coast Guard Vessel and Waterways Regulation**[95]
- **Federal Energy Regulatory Commission**[96]
- **Hawaiʻi Revised Statutes**[97]
- **Hawaiʻi Endangered Species Law**[98]
- **Hawaiʻi Environmental Response Law**[99]

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[90] https://www.epa.gov/laws-regulations/summary-clean-water-act
[91] https://www.fisheries.noaa.gov/inport/item/59646
[92] https://www.epa.gov/laws-regulations/summary-comprehensive-environmental-response-compensation-and-liability-act
[93] https://www.nps.gov/subjects/historicpreservation/national-historic-preservation-act.htm
[94] https://coast.noaa.gov/czm/act/
[95] https://www.ecfr.gov/current/title-33/chapter-I/subchapter-P/part-160
[96] https://www.ferc.gov
[97] https://portal.ehawaii.gov/government/hawaii-legislature/
[98] https://www.capitol.hawaii.gov/hrscurrent/vol03_ch0121-0200d/HRS0195D/HRS_0195D-0004.htm
[99] https://www.capitol.hawaii.gov/hrscurrent/vol03_ch0121-0200d/hrs0128d/hrs_0128d-.htm

Hydrogen Safety Codes and Standards

Codes and standards are needed to enable the safety of hydrogen and fuel cell systems and to facilitate the use of hydrogen as a fuel. Building codes and equipment standards provide a systematic and accurate means of measuring and communicating product risk and insurability to the customer, general public, and fire-safety certification officials.

"Codes" are established by jurisdictions—for example, building codes, fire codes, building ordinances, etc. Today, there are over 44,000 jurisdictions in the United States, and some of these existing jurisdictional codes could affect hydrogen use. "Standards" are agreed upon to enable consistency, compatibility, and safety. Many organizations are cooperating in the development of codes and standards to enable safety and encourage the safe commercialization of hydrogen uses. A key leadership role is provided by the Hydrogen and Fuel Cell Technologies Office.

Additional Resources

H2Tools is a best practices resource and free, online national hydrogen safety training resource for emergency responders.

The Hydrogen Safety Bibliographic Database provides references to reports, articles, books, and other resources for information on hydrogen safety as it relates to production, storage, distribution, and use.

The H2Tools Lessons Learned Database provides lessons learned and other relevant information gained from actual experiences working with hydrogen. The database contains records of events involving hydrogen or hydrogen-related technologies.

The Codes and Standards - Permitting Tools website identifies model codes and standards to help local permitting officials deal with proposals for hydrogen fueling stations, fuel cell use for telecommunications facilities, and other hydrogen projects. Links to web-based training resources are also identified on this site.

The Hydrogen and Fuel Cell Codes and Standards Database serves as a searchable home for relevant codes and standards and is regularly updated to reflect changes in the codes and standards.

The Introduction to Hydrogen Safety for First Responders web-based course, administered by the Center for Hydrogen Safety, provides an "awareness level" hydrogen overview for fire, law enforcement, and emergency medical personnel.

The Hydrogen Safety Panel provides several resources for download, including guidance for safety planning for projects and an example safety plan to encourage a safety mindset for all aspects of project planning.

The Hydrogen Safety Best Practices Manual is an online manual that captures the wealth of knowledge and experience related to the safe handling and use of hydrogen that exists as a result of its extensive history in a wide variety of applications. The purpose of the manual is to share this knowledge gathered from numerous experts, public domain documents, and references in an online, easy-to-use manner.