Evaluation of Hydrogen Production and Utilization in Fuel Cell Vehicles

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Evaluation of Hydrogen Production and Utilization under Various Renewable Energy Curtailment Scenarios

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Acronyms

CO_2	Carbon Dioxide
DOE	Department of Energy
EV	Electric Vehicles
EPA	Environmental Protection Agency
FCV	Fuel Cell Vehicle
GE	General Electric
NREL	National Renewable Energy Laboratory
OEM	Original Equipment Manufacturer
KOH	Potassium Hydroxide
PPA	Power Purchase Agreement
SMR	Steam-Methane Reformation
SUV	Sports Utility Vehicle

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1.0 Executive Summary

GE performed a study that explored the theoretical operating conditions of the Oahu electricity grid assuming four theoretical Base Cases, which represent adding 600, 800, 1000 and 1000 MW of different mixes of variable renewable energy generation capacity. These large capacities of wind turbines and photovoltaic panels can create excess power that may go unused, or curtailed. A hydrogen production and storage facility can effectively utilize renewable energy that would have otherwise been curtailed. Additionally hydrogen can be used as a fuel in fuel cell vehicles (FCVs), which can replace conventionally fueled vehicles.

The ability of a hydrogen infrastructure to utilize otherwise curtailed renewable energy is evaluated in this report and considers:

- hydrogen producing electrolyzer capacities between 50 and 200 MW,
- storage vessel capacities between 65,000 and 560,000 kg, and
- hydrogen utilization for transportation.

Electrolyzer capacity ranges are determined with the goals of minimizing the amount of curtailed renewable energy and maximizing the number of FCVs supported given the magnitude and availability of curtailed renewable energy from the GE report. Both light-duty and heavy-duty FCVs are considered in this analysis. The amount of reduced petroleum and emissions that result from replacing conventionally fueled vehicles with FCV and hydrogen produced from renewable energy is derived. System costs are evaluated and presented as $/kg and $/mile driven for the various elements of a hydrogen production/storage facility and expanded over an expected plant lifetime of 40 years.

Installed electrolyzer capacity is the key driver to the amount of hydrogen that can be produced from the amount of energy available and thus the number of FCVs fueled. It was found that a 1 MW electrolyzer captures less than 1% of all curtailed energy for all Base Cases. Increasing electrolyzer capacities resulted in approximately linear hydrogen production up to 50MW where at least 25% of available curtailed energy is captured for all Base Cases. An electrolyzer capacity of 200MW would capture up to 90% of available curtailed energy, thus capacities of 50, 100, 150 and 200 MW were considered in the study. The most efficient electrolyzer capacity per percentage curtailed energy used was Base 4, 50MW. This configuration, however, only supported a minimal number (~4700) of vehicles and used only 38% of the available curtailed energy for that Base Case.

Hydrogen storage systems allow for more curtailed energy to be utilized, increased electrolyzer load factor and more vehicles supported. Storage capacities are evaluated for the maximum number of vehicles such that only curtailed energy is used to produce hydrogen. The storage requirements ranged from 65,080 kg (Base 2, 50MW) to 559,280 kg

(Base 4, 200MW). The least amount of storage required to support the maximum number of vehicles for a given electrolyzer size is consistently Base 2, with an average of ~9 kg/vehicle. The next lowest storage requirement per vehicle (Base 3) is more than two times this average at ~21 kg/vehicle. The highest case is Base 4 averaging ~33 kg/vehicle. Decreasing storage capacity lowers the capital cost, but can lead to requirements for excess (non-renewable) energy and additional electrolyzer capacity.

The presence of storage allows for vehicles to be refueled even if hydrogen is not being produced. It was found that the main driver for storage requirements is not hourly refueling schedules (which have less than a 3% influence on required storage levels for the given situation), but rather the reduction of available curtailed energy in the September to November time frame.

Hydrogen as a transportation fuel could be a useful component of the Hawaii Clean Energy Initiative because it reduces petroleum use in ground transportation and dependence on fossil fuels. When using only curtailed renewable energy, these hydrogen electrolysis will support vehicle numbers ranging from 4,025 (Base 1, 50MW) to 23,620 (Base 2, 200MW) for light-duty FCVs and 196 to 1,152 for heavy-duty FCVs. Simply replacing existing fossil-fuel powered vehicles with FCVs reduces between approximately 22.5 million and 131 million tons of CO_2 per year for the analyzed Cases. The corresponding gasoline reduction for the analyzed Cases ranges from approximately 2.5 million gallons to approximately 12.1 million gallons.

Electrolysis systems are modular for the sizes evaluated in this report and thus large differences in cost are not expected between centralized and distributed (forecourt) systems. Although large up front capital costs[1] will be incurred to purchase electrolyzers and storage capacity, the price per mile over a 40 year plant life (including electricity and estimated O & M costs[2])range from $0.15 (200 MW) to $0.23 (50 MW) per mile, slightly higher than the average conventional fossil fuel powered vehicle ($0.19/mile).

2.0 Introduction/Background

Installing up to 1 GW of renewable energy capacity to supply Oahu with electricity raises many issues including how grid operators manage the variable nature of renewables. This problem is compounded if any large electric load such as an electric vehicle (EV) fleet is also added to the Oahu grid and not controlled. Hydrogen can be used as an effective energy storage medium that can help mitigate problems with supply variability; increase

[1] Between lowest $80.5 Million (Base 2, 50MW) and highest $461.7 Million (Base 4, 200MW)
[2] Anticipated costs not included are deprecation, equipment replacement, utilities other than electricity, engineering design, equity financing, taxes, land, permitting and fees, decommissioning and profit.

the amount of energy captured from variable renewable energy sources; and be used to power FCV's with similar or better performance characteristics than EVs.

This analysis addresses the viability and costs associated with an Oahu-based hydrogen infrastructure (i.e. electrolyzers and storage vessels) utilizing renewable energy that might otherwise be curtailed, to generate hydrogen for FCV fleets. Petroleum and CO_2 emissions that would be displaced by implementing FCV's are also quantified in this study.

2.1 Relevant Hydrogen Production Technologies

Various methods can be used to produce hydrogen gas using electrical energy and a feedstock such as water, natural gas or potassium hydroxide. This report focuses on the production of hydrogen using electrolysis. A more energy efficient method of hydrogen production using Steam-Methane Reformation (SMR) is not considered in this analysis as natural gas is not yet available on Oahu. The SMR process is not considered suitable to the given application which requires a fast ramp rate of the system due to the intermittent and quickly variable nature of renewable energy. Additionally, SMR emits the pollutant CO_2, unlike electrolysis. Further details of the respective electrolysis methods, and a comparison, are provided in Appendix A.

2.1.1 Electrolysis Parameters

Energy consumption and cost were of primary interest in the evaluation of electrolyzers for this study. The largest PEM electrolyzer commercially available produces 65 kg/day (~0.174 MW) of hydrogen but this system is to be scaled up to 736 kg/day (~ 2 MW) within two years with a target cost of approximately $1 Million/MW. The largest alkaline electrolyzer available produces 1,623 kg/day of hydrogen and is priced at about $1.3 Million/MW. These values are consistent with values presented in case studies[3] completed by the U.S. Department of Energy.

Original Equipment Manufacturer (OEM) published [4,5,6,7] energy consumption figures (kWh/kg) for both of the evaluated electrolyzer technologies are within 20% (above) of DoE's published[8] current energy consumption rate of 50 kWh/kg. This consumption rate includes the additional system equipment, or "balance of plant"[9], required for the electrolyzers to operate as designed.

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[3] http://www.hydrogen.energy.gov/h2a_prod_studies.html
[4] http://www.nel-hydrogen.com/home/?pid=160
[5] http://www.protononsite.com/pdf/HOGEN_C.pdf
[6] http://www.iht.ch/technologie/electrolysis/industry/high-pressure-electrolysers.html
[7] http://www.hydrogenics.com/products-solutions/industrial-hydrogen-generators-by-electrolysis/outdoor-installation/hystat-trade-60
[8] http://www.hydrogen.energy.gov/h2a_production.html
[9] Includes pumps, fans, computer control and safety system monitoring electronics etc.

2.2 Hydrogen Compression, Storage and Dispensing Technology

Hydrogen, in a gaseous state, is compressed and stored onboard a FCV to provide acceptable driving ranges. The onboard storage pressures are typically either 350 or 700 bar (the FCV industry is moving towards 700 bar). Fueling station storage pressures are typically either 450 or 850 bar in order to facilitate cascade filling, a procedure that involves using a pressure differential to "fast fill" the vehicle (as oppose to compressing from a lower storage pressure when the vehicle is connected).

2.3 Hydrogen Production System Energy Requirements

Throughout this report, the worst case energy consumption (80 kWh/kg) to produce and deliver hydrogen is used for analysis purposes. This is made up of ~60 kWh/kg for electrolysis (including associated plant equipment) and ~20 kWh/kg for compression, storage, and dispensing of the hydrogen (including energy conversion inefficiencies, computer control systems, instrument air compressors, lighting energy usage, etc.)

2.4 Fuel Cell Vehicle Availability

Light-duty FCVs are new to Oahu and are not yet commercially available. Current availability in the rest of the US is limited to leased commercial fleets. Large scale adoption is hindered by the small number and distribution of fueling stations (10 public stations in the US[10] as of June 2013) and the costs of the vehicles[11]. Heavy duty FCVs are currently in use in the form of municipal transit buses in places such as British Columbia and California. Published data for available FCVs is given in Table 1. Throughout this report, a fuel economy of 55 mi/kg is used for light-duty vehicles (as observed in the 2012 FCV performance testing on Oahu) and 8 mi/kg is used for buses (heavy-duty). To compare FCVs with EVs, an annual mileage of 11,000 miles was assumed for a light-duty vehicle[12] and 32,800 miles for a heavy-duty vehicle[13]. Refueling stations in Hawai`i are currently limited to US military bases and are not publically accessible.

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[10] http://www.afdc.energy.gov/fuels/hydrogen_locations.html

[11] FCV vehicle price to consumers cannot accurately be predicted at this time. Toyota has repeatedly publically estimated that its small SUV will be priced "somewhere between $50K and $100K".

[12] "2011 HNEI Oahu Electric Vehicle Survey Technical and Descriptive Report," Market Trends Pacific; January 2012.

[13] Typical Honolulu Public Transit Bus travel http://www1.honolulu.gov/dts/about.htm

Table 1. Performance Characteristics for Available FCVs

Make	Model	Year	Fuel Economy	Range	Fuel Capacity	Tank Pressure	Vehicle Class	Type of Fuel Cell
			mi/kg	mi	kg	Psi		
Honda[14]	FCX Clarity	2012	60	240	3.92	5000	Midsized Car	PEM
Mercedes-Benz[15]	F-Cell	2012	52	190	3.7	10000	Midsized Car	PEM
General Motors	Fuel Cell EV	2010	55	200	4.2	10000	SUV	PEM
New Flyer[16]	Fuel Cell Bus FC3	2012	8	300-350	50	5000	Heavy Duty	PEM
New Flyer[7]	Fuel Cell bus FC2	2010	7	250-300	43	50000	Heavy Duty	PEM

3.0 Analysis

The feasibility of utilizing curtailed renewable energy from the four Base Cases to generate hydrogen for FCV use is assessed. Various configurations of electrolyzer and storage capacities for each Base Case are evaluated to determine the number of FCVs that could be supported by the generated hydrogen, as well as the resultant costs per kilogram of hydrogen. Fueling times and rates for FCVs are varied in the analysis, but had little effect (less than 3%) on system requirements such as electrolyzer size and storage capacity. For simplicity, a constant hourly refueling rate was calculated by evenly dividing the annual aggregate fuel requirement for all FCVs by the number of hours in the year.

Using only as-available curtailed renewable energy to produce hydrogen, the effects of varying levels of storage are then evaluated. The variable measured in this analysis include:

i. the capacity of hydrogen production equipment necessary to utilize portions of the curtailed energy for four different curtailed energy cases,
ii. the amount of FCVs that such systems could support,
iii. the amount of displaced petroleum,
iv. the amount of emissions from hydrogen production and from use in FCVs, and
v. the costs of the hydrogen production, storage and fueling systems.

Four curtailed energy Base Cases, provided from the GE study on the integration of renewables on Oahu, were evaluated for hydrogen production. These Cases, shown in

14 http://automobiles.honda.com/fcx-clarity/specifications.aspx
15 http://www.mbusa.com/mercedes/benz/green/electric_car
16 http://www.sunline.org/clean-fuels-fleet

Table 2 as Base 1 through Base 4, represent the addition of various combinations of wind and solar renewable energy capacities onto the Oahu electricity grid.

Table 2. Curtailed Energy Cases

Cases	System Capacity (MW)			Total Curtailed Energy (GWh)
	Total	Wind	Solar PV	
Base 1	600	500	100	209.791
Base 2	1000	700	300	735.662
Base 3	1000	500	500	400.653
Base 4	800	500	300	261.525

GE generated hourly average curtailed power values for a year for each Base Case. Due to the hourly resolution of the data, the power was assumed to be constant for each hour for the purpose of energy calculations (i.e. each day has 24 different power values and curtailed power within each hour is assumed to be constant for each hour's duration). This data is used to evaluate the hourly supply, demand and storage of hydrogen over a year according to the following three constraints, each with its own set of underlying assumptions.

1. The **capacity of electrolyzers** operating on the Oahu grid, assuming:
    a. electrolyzers, which typically can ramp to full capacity in a matter of seconds, exactly follow the hourly curtailed power profiles,
    b. a control network exists that matches distributed or centralized electrolyzer load to hourly curtailed power,
    c. an electrical network exists that is able to deliver curtailed renewable energy to the hydrogen infrastructure, and
    d. the amount of electric energy required to produce dispensed hydrogen (by weight) is 80 kWh/kg[17].
2. The **capacity of hydrogen storage** available, assuming:
    a. hydrogen is compressed and stored as it is produced, and
    b. if the storage is full, no additional hydrogen is produced.
3. **Vehicle performance** limitations, assuming:
    a. fuel cell vehicle efficiency is 55 mi/kg for light-duty and 8 mi/kg for buses[18], and

[17] See Section 2
[18] See Table 1

b. the aggregate FCV fuel requirement is distributed evenly throughout the year such that hourly refueling rates are constant (due to the previously mentioned negligible effects that varying fueling frequency has on hydrogen storage requirements).

3.1 Curtailed Energy Captured and Hydrogen Produced

The amount of curtailed energy that could be captured by a hydrogen production facility and the subsequent amount of hydrogen that could be produced from this energy was calculated. The size of aggregate electrolyzer and storage capacity were two factors that limited the amount of curtailed energy that could be captured.

The hourly curtailed power values generated by GE were evaluated to determine the upper and lower limits for electrolyzer capacities to be analyzed. It was found that hourly curtailed power magnitudes of less than 1 MW occurred 50 - 75% of the time in the four Base Cases (Figure 1 and Appendix B), although this range of power resulted in less than one percent of total available energy over a whole year for all Base Cases. A 1 MW electrolyzer for example, running at full capacity when the curtailed energy is larger than 1 MW, captures less than 1% of the available curtailed energy in all Base Cases. A minimum 25% utilization of yearly curtailed energy was chosen as a lower limit for the study. To capture this amount 25% of nameplate capacity necessitates an aggregate electrolyzer capacity of at least 50 MW (hydrogen output for electrolyzer capacities below this level scale linearly with captured curtailed energy).

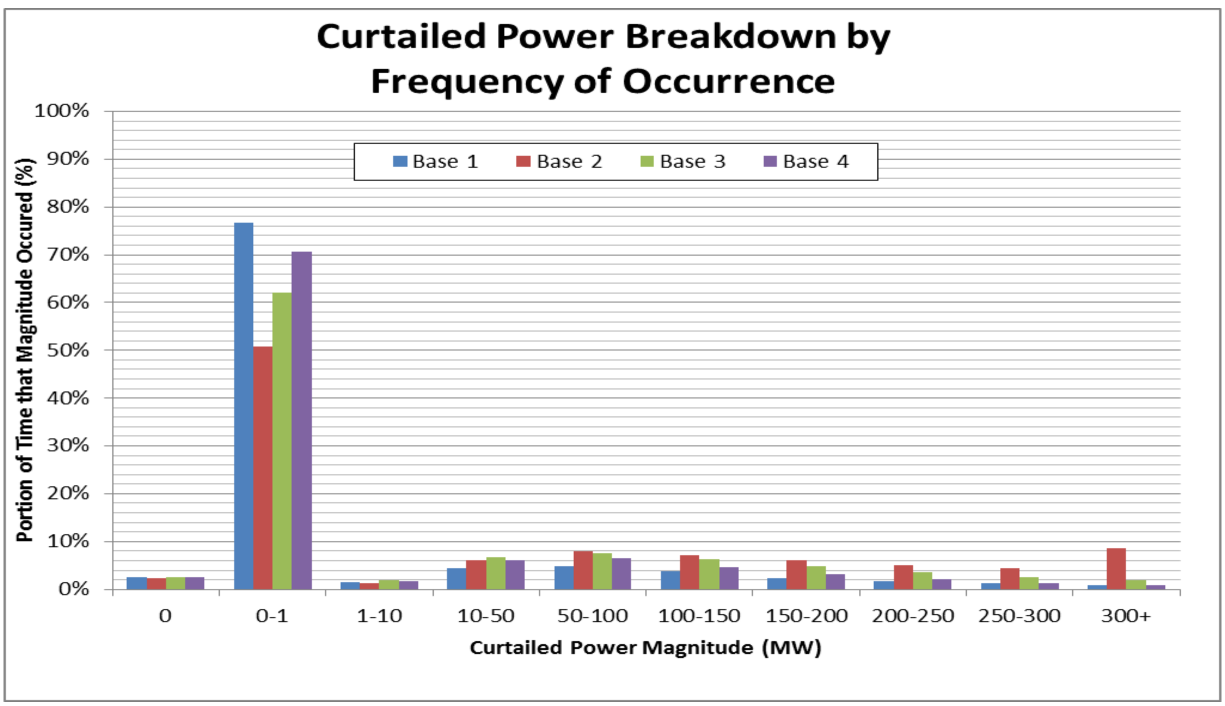


Figure 1: Frequency Distribution of Hourly Curtailed Energy (8,760 hours per year)

The upper limit for aggregate electrolyzer capacity was chosen to be 200 MW. This electrolyzer capacity was found to capture upwards of 75% of curtailed energy in all Base Cases and greater than 90% in Base 4. Beyond this size, increased electrolyzer capacity results in diminishing returns of captured curtailed energy (except in Base 2) due to a majority of the hourly power values being less than 200 MW. The effects of varying electrolyzer capacities were determined by evaluating capacities in steps of 50 MW between 50 and 200 MW. Smaller electrolyzer capacities resulted in less energy captured, while larger capacities resulted in reduced electrolyzer usage[20].

The maximum amount of curtailed energy that could be captured by these various electrolyzer strategies, given in Table 3, was calculated under the assumption that storage capacities were not a limiting factor and system efficiency was 80 kWh/kgH_2.

Table 3. Maximum Curtailed Energy Captured as a Percentage of Total Possible for Each Base Case with Various Electrolyzer Capacities

Case	Maximum Curtailed Energy Captured as % of Available by Electrolyzer Capacity				
	50MW	100MW	150MW	200MW	Total Available Energy (MWh)
Base 1	36.5%	62.0%	78.6%	89.2%	209,790.71
Base 2	25.8%	47.0%	63.6%	76.3%	735,661.64
Base 3	33.9%	59.1%	76.5%	87.9%	400,653.33
Base 4	38.0%	64.0%	80.5%	90.7%	261,524.98

It is clear that larger electrolyzers utilize more of the curtailed renewable energy. Doubling electrolyzer capacity doesn't necessarily double the amount of energy captured though. The most effective utilizzation of electrolyzer capacity can be determined by dividing energy captured by electrolyzer capacity and then normalizing across each Base Case. Table 4 provides the results of this anlysis.

Table 4. Effectiveness of Electrolyzer Utilization in Each Scenario

Case	Effectiveness of Electrolyzer Use				
	50MW	100MW	150MW	200MW	Total Available Energy (MWh)
Base 1	0.73	0.62	0.52	0.45	209,790.71
Base 2	0.52	0.47	0.42	0.38	735,661.64
Base 3	0.68	0.59	0.51	0.44	400,653.33
Base 4	0.76	0.64	0.54	0.45	261,524.98

[20] See Section 3.4

While the Base 2 - 200 MW strategy captured the most available energy (MWh) and Base 4 - 200 MW strategy captured the highest percentage of energy (see Table 3), they do not utilize the electrolyzer capacity the most effectively. The highest ratio of percentage of energy captured to electrolyzer capacity is consistently Base 4, (see Table 4). When comparing the electrolyzer capacities, a 50 MW electrolyzer system yields the highest ratios, with Base 4 yielding the highest ratio of all (0.76%/MW - energy captured to electrolyzer capacity). This configuration, however, yields the most efficient utilization of available energy, it does not yield the quantities of fuel necessary for a wide adoption of FCVs because the Total Available Energy is relatively low. From Figure 6 found later in this analysis, this configuration will only support 4,700 light duty, or 229 heavy duty vehicles, leaving 62% of curtailed energy uncaptured (Table 3: 100% - 38% = 62%)

The maximum amount of hydrogen that could be generated from the curtailed energy captured by the various electrolyzer of varying capacities (listed in Table 3 - Graphed in Appendix C) is shown in Table 5. Again, storage capacities were assumed to be infinite and system efficiency was assumed to be 80 kWh/kgH_2.

Table 5. Maximum Amount of Hydrogen Production for Each Base Case Using Various Electrolyzer Capacities

Case (Available Energy)	Maximum H2 Produced (kg) by Electrolyzer Capacity				
	50MW	100MW	150MW	200MW	Infinite
Base 1 (210 GWh)	957,048	1,625,607	2,060,133	2,338,269	2,625,000
Base 2 (736 GWh)	2,370,643	4,319,686	5,844,894	7,013,680	9,200,000
Base 3 (401 GWh)	1,699,282	2,958,541	3,832,798	4,404,116	5,012,500
Base 4 (262 GWh)	1,242,309	2,091,670	2,630,087	2,963,435	3,275,000

When storage components (cylinders, compressors, etc.) are incorporated with the electrolysis system, a hydrogen system acts as an energy storage medium capable of capturing a large portion of the curtailed renewable energy for each Base Case that may have otherwise been wasted. Once stored, this hydrogen can then be used for on-demand vehicle refueling. Limiting storage capacities were found to have significant effects on FCVs supported and excess thermal energy required, as discussed in the next section.

3.2 Fuel Cell Vehicles Supported

The amount of both light-duty and heavy-duty (bus) FCVs that could be supported using hydrogen produced from curtailed renewable energy was calculated. Assumptions and boundary conditions were made to narrow the scope of the analysis. It was assumed that light-duty vehicles have a fuel economy of 55 miles/kgH_2 (Table 1) and travel 11,000 miles per year. Fuel cell buses were assumed to have a fuel economy of 8 miles/kgH_2 and travel 32,800 miles per year.

An hourly analysis was performed to determine the effects of various vehicle refueling schedules. Hydrogen production was limited to utilizing only curtailed energy from renewables without supplemental thermal energy production. Hydrogen storage levels were added as a constraint such that if the storage was full and more curtailed renewable energy was available, no hydrogen would be produced. No significant change in vehicles supported (maximum <1%) or storage requirements (maximum 3%) occurred when the vehicles fueled evenly throughout the day or evenly within a four hour window between 5:00 pm and 9:00 pm. Due to the large amounts of storage involved, refueling schedules had a negligible effect and thus, for the purposes of this analysis, it was assumed that hydrogen consumption was distributed evenly throughout the year.

An example of hourly storage levels with a generation configuration of Base 1 - 100 MW electrolyzer capacity and 200,000 kg of storage (equating to ~6500 light-duty vehicles, see Table 8) fueling evenly throughout the year is provided in Figure 2. This example shows the large reduction in stored hydrogen over the September to November time present in each Base Case. The long duration of reduced availability of the curtailed energy, combined with another "low point" in the mid February timeframe, were the determining factors for the quantity of hydrogen storage required to support a given number of vehicles using only curtailed renewable energy. Evaluating only a single year, results in full storage tanks at the end of the year. A multi-year analysis could help determine if more vehicles could be incrementally supported over time with the given infrastructure, but if the curtailed energy quantities were identical, no more vehicles could be supported without increasing storage capacity.

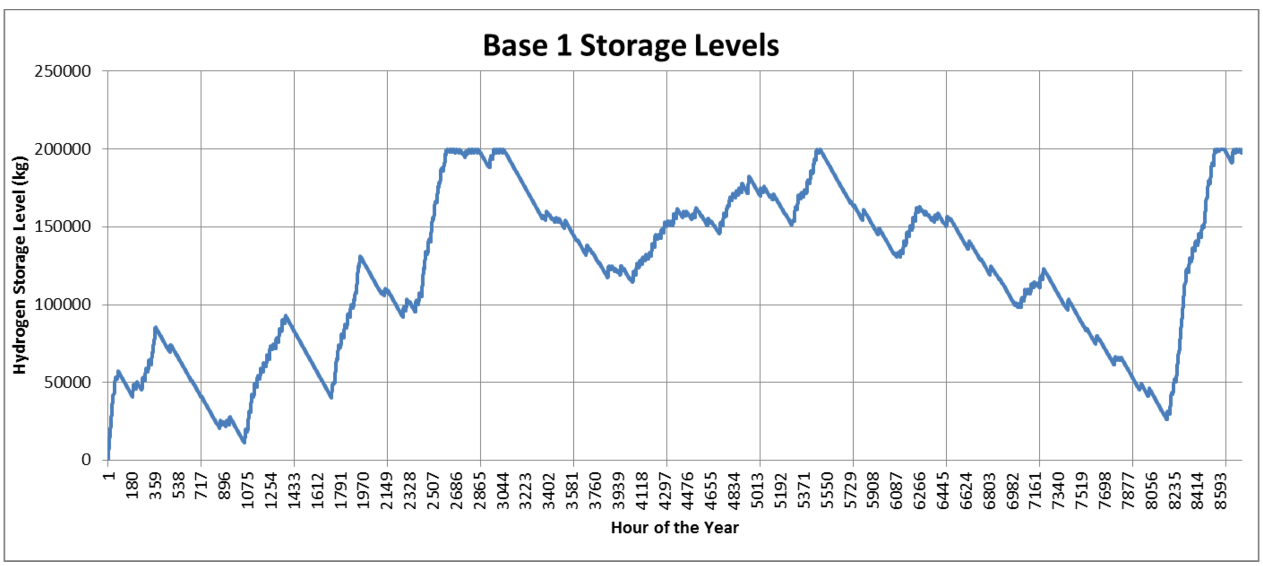


Figure 2. Hourly Hydrogen Storage Levels for Base 1 with 100 MW Electrolyzer and 200,000 Kg Storage Capacity Assuming Evenly Distributed Hourly Consumption

The maximum number of FCVs' that could be supported using the hydrogen produced by a given electrolyzer capacity, using only curtailed renewable energy, was calculated by assuming that storage levels were infinite. The results are directly related to the amount of curtailed renewable energy available in each Base Case and the aggregate electrolyzer capacity. It was found that vehicle numbers ranged from 4,025 to 23,620 for light-duty FCVs and 196 to 1,152 for heavy-duty FCVs, as shown in Table 7. Please see Appendix D for graphs of total number of light-duty and heavy-duty miles and storage capacities for each Base Case and electrolyzer capacity.

Table 6. Total Number of Light Duty FCV's Supported with Infinite Storage

Case	Light Duty Vehicles Supported			
	50MW	100MW	150MW	200MW
Base 1	4,025	6,960	8,740	9,775
Base 2	7,705	14,095	19,395	23,620
Base 3	6,000	10,625	14,200	16,795
Base 4	4,700	8,100	10,710	12,545

Table 7. Total Number of Heavy Duty FCV's Supported with Infinite Storage

Case	Heavy Duty Vehicles Supported			
	50MW	100MW	150MW	200MW
Base 1	196	339	426	476
Base 2	376	687	946	1152
Base 3	292	518	693	819
Base 4	229	395	520	612

The number of vehicles possible for heavy-duty FCVs is significantly less than what is possible for light-duty vehicles because heavy-duty vehicles have nearly $1/7^{th}$ of the fuel economy and travel 3 times as far in a year. The largest number of vehicles supported occurred in Base 2 with a 200 MW electrolyzer capacity, while the smallest amount of vehicles occurred in Base 1 with a 50 MW electrolyzer capacity, as is shown in Table 7. This result is due to the largest amount of energy available in Base 2 and the largest amount of that energy captured by a 200 MW electrolyzer system.

Minimum levels of storage capacity were calculated for the above number of vehicles assuming only curtailed renewable energy was used. Storage levels were similar for both light-duty and heavy-duty FCVs and ranged from 65,000 to 559,000 kg as is shown below in Table 8.

Table 8. Hydrogen Storage Level Requirements for to Support Maximum Number of Vehicles

Case	Light Duty Vehicle H_2 Storage Requirements (Kg)			
	50MW	100MW	150MW	200MW
Base 1	100,240	223,160	329,830	411,710
Base 2	65,080	125,410	182,100	244,670
Base 3	83,770	200,980	333,800	454,700
Base 4	106,500	221,420	390,840	559,280

As previously mentioned, the large capacity of storage required is primarily driven by a the lowest levels of availability of curtailed renewable energy in the GE model in the September to November time frame, and the assumption that vehicle fueling and hydrogen production begin simultaneously at the start of the year. Base 1 requires the largest storage to vehicle ratio (an average of 34 kg/vehicle) of all the Base Cases (Appendix E).

Storage levels in a plant are dependent on fleet sizes, available curtailed renewable energy and electrolyzer capacity. A larger vehicle fleet, which corresponds with larger electrolyzer capacities, requires more fuel and depletes storage levels faster. Changes in available curtailed renewable energy are more critical with larger vehicle fleets due to this high level of demand. The September to November time frame in the GE study, in which a lull in available curtailed renewable energy occurs, has storage levels drastically depleted in scenarios with larger vehicle fleets and is the main constraint when sizing storage. Smaller vehicle fleets correspond with smaller electrolyzer and thus require more storage. Initial hydrogen production and demand also influence storage size. As a consequence of the model, began at the same time, but in reality production and storage would likely occur before demand started.

An absolute maximum number of FCVs that can be supported was calculated by assuming a "Perfect Tracking" scenario for Base 2 (largest amount of available curtailed energy) in which all energy available is converted to hydrogen and consumed in vehicles. The maximum number of light-duty FCVs possible is 45,975 vehicles and the maximum number of heavy-duty FCVs is 2,240 vehicles. A vehicle fleet of this size would require a 553 MW electrolyzer capacity and storage capacity of 766,560 kg. The "Perfect Tracking" scenario results in more vehicles than the electrolyzer limited strategy described above, because all available curtailed renewable energy is converted to hydrogen and consumed in FCVs. It is not limited by electrolyzer or storage capacity. Also, all hydrogen produced is consumed by the end of the year. It is noted that the evaluation techniques used in this section of the report could be applied to derive storage requirements for other mixes of fleet vehicles, such as those used by the U.S. Department of Defense.

In an effort to determine which Base Case and electrolyzer capacity yields the most efficient configuration, a comparison was made between the maximum vehicles possible, the total curtailed energy of each Base Case, and the various electrolyzer capacities. The metric was calculated as

A summary of the values of these metrics is provided in Table 9.

Table 9. Performance Metric Summary for the Various Base Cases and Electrolyzer Strategies

FCV Type	Minimum Metric Scenarios			Maximum Metric Scenarios			Average
	Metric Value	Base Case	Electrolyzer Capacity	Metric Value	Base Case	Electrolyzer Capacity	Metric Value
Buses	0.008	2	200MW	0.019	1	50MW	0.013
Light Duty Vehicles	0.161	2	200MW	0.384	1	50MW	0.259

For both light-duty and heavy-duty FCVs, the metric decreased as electrolyzer size increased. This means that if the electrolyzer capacity is doubled, the vehicles supported may only be increased by a factor of 1.7. This is due to reduced electrolyzer utilization with larger electrolyzer capacities, as discussed in Section 3.4. Base 1 (500MW of wind and 100MW of solar) consistently yields the highest metric of all the Cases except for a 200 MW capacity electrolyzer, in which Base 4 is higher. An electrolyzer capacity of 50 MW in Base 1 yields the highest metric of all strategies. Though this strategy requires a larger amount of storage relative to other Base Cases (13% above average), it provides the most vehicle miles per unit of electrolyzer capacity and available energy.

The previous analysis considered storage levels large enough to prevent the need for any additional electricity beyond curtailed renewables. A study was performed on light-duty vehicle strategies to determine the effects of reducing storage levels and allowing for electricity to be sourced from places other than curtailed renewables (it should be noted that energy purchased from the grid may not experience the same reduced costs that renewables do). Storage levels were reduced by 25% and 50% from the minimum levels required to produce hydrogen from only curtailed renewables, while the number of vehicles expected to be supported was kept constant. The results, shown in Table 10, gives the amount of energy required from additional sources (typically thermal generation) to satisfy the same number of supported vehicles.

Table 10 (Graphed in Appendix F) also shows the percentage of total energy to produce hydrogen that comes from non-renewable sources for each strategy.

Table 10. Additional Annual Thermal Energy Required for a 25% and 50% Reduction in Storage Capacity

Amount of Additional Energy Required to Support LDV Fleet with 25% Storage Reduction (Non-Renewable GWh)				
Case	**50MW**	**100MW**	**150MW**	**200MW**
Base 1	4.168	8.034	11.111	13.069
Base 2	5.953	11.379	17.677	19.241
Base 3	3.397	7.510	13.046	18.007
Base 4	4.927	9.912	14.710	18.835
	Percent from Non-Renewable Sources			
Base 1	5.4%	6.2%	6.7%	7.0%
Base 2	3.1%	3.3%	3.8%	3.4%
Base 3	2.5%	3.2%	4.3%	5.1%
Base 4	4.9%	5.9%	7.0%	7.9%
Amount of Additional Energy Required to Support LDV Fleet with 50% Storage Reduction (Non-Renewable Energy GWh)				
Case	**50MW**	**100MW**	**150MW**	**200MW**
Base 1	9.226	20.530	27.409	31.976
Base 2	21.278	47.859	80.697	94.998
Base 3	12.230	18.320	29.826	39.694
Base 4	10.765	21.526	33.881	43.673
	Percent from Non-Renewable Sources			
Base 1	12.0%	15.8%	16.6%	17.1%
Base 2	11.2%	13.8%	17.3%	16.9%
Base 3	9.0%	7.7%	9.7%	11.3%
Base 4	10.8%	12.8%	16.1%	18.4%

The above analysis shows the sensitivity of various electrolyzer and storage configurations to varying levels of storage capacity.   The largest amount of additional energy is required for cases where more vehicles are supported.. These configurations have a high sensitivity to varying storage levels because storage levels are more optimized to the vehicle fleets and available curtailed energy. Anomalies (25% reduction: Base 2 – 200MW and 50% reduction: Base 3 – 50MW) occur in typical patterns for increasing electrolyzer sizes. More research is needed to determine the exact cause, but curtailed energy profiles are believed to result in these outliers.

The highest additional energy requirement per Base Case for a 25% reduction in storage capacity occurred for Base 4 at 6.4% on average and 7.9% maximum, with a 200 MW electrolyzer capacity. Base 1 had the highest additional energy requirement, on average, for the 50% storage reduction scenario, while Base 4 had the highest single value with a 200 MW electrolyzer capacity at 18.4% of total energy used to produce hydrogen. Bases 1 and 4 each have much less installed renewable power capacity and thus more hydrogen must be produced from thermal generation sources than in Bases 2 and 3 when storage is constrained. The costs associated with installing additional thermal generation capacity to cover a reduction in hydrogen storage was not analyzed as part of this study. It is noted that it would be required for only 3-4 months of the year, thus if installed for this purpose only, would sit idle 2/3 - 3/4's of the year.

3.3 Emissions from Hydrogen Production and Use in Fuel Cell Vehicles

Since FCVs emit only water, no harmful emissions would be released in the production of hydrogen or driving of FCVs. In fact, harmful emissions would be reduced to the extent that FCV miles displace miles from conventionally fueled vehicles. Calculations were performed using data published by the Environmental Protection Agency (EPA) and DOE to determine the amount of petroleum and CO_2 emissions that would be displaced by various light-duty FCV configurations only from vehicle consumption of fuel. Emissions generated and energy used during production of petroleum based fuels was not included. Table 11 and Table 12 show the amount of CO_2 and petroleum reduced in a year, respectively, calculated by replacing light-duty gasoline vehicles with FCVs for the amount of vehicles supported by each Base Case and electrolyzer capacity.

Table 11. CO_2 Emissions Reduction from Hydrogen Production from Curtailed Renewables in the Above Scenarios

	Emissions Reduction (kilograms)[21]			
	50MW	100MW	150MW	200MW
Base 1	22,484,110	38,879,355	48,822,639	54,604,267
Base 2	43,041,011	78,736,281	108,342,687	131,944,019
Base 3	33,516,686	59,352,464	79,322,823	93,818,789
Base 4	26,254,737	45,247,526	59,827,284	70,077,804

Table 12. Displaced Petroleum by Light-Duty FCVs Using Hydrogen Produced from Curtailed Renewables in the Above Scenarios

	Petroleum Reduction (gallons)[22]			
	50MW	100MW	150MW	200MW
Base 1	2,068,781	3,577,321	4,492,210	5,024,182
Base 2	3,960,238	7,244,588	9,968,698	12,140,275
Base 3	3,083,897	5,461,068	7,298,557	8,632,342
Base 4	2,415,719	4,163,261	5,504,756	6,447,915

Vast amounts of petroleum and airborne pollution would be displaced by any of the hydrogen system scenarios. This is largely due to using renewable energy to produce the hydrogen and the nearly zero emissions (*except water*) of a FCV.

As shown in Section 3.2, if storage levels were reduced, then excess non-renewable energy would be needed to support the same amount of vehicles over the year. The amount of energy needed in the Base Cases ranges analyzed here resulted in up to nearly 100 GWh per year and typically occurring over a span of 3-4 months. Therefore, to maintain steady hydrogen supply, energy would likely need to be sourced from large fossil fuel thermal generators resulting in increased harmful emissions and increased imported oil. It is also possible, depending on the number of vehicles required and hydrogen system configuration, that additional generation capacity would need to be brought on line to support certain FCV infrastructures.

[21] EPA study on CO_2 emissions 8,887 gCO2/gal
http://www.epa.gov/otaq/climate/documents/420f11041.pdf
[22] 21.4 mpg, as supplied by HNEI

3.4 System Costs

A high level cost evaluation was completed. The evaluation included the three largest cost elements of a hydrogen production and dispensing facility, namely, the initial capital expenditure, system operation & maintenance (O&M) expenses, and electricity costs. Consideration was not given to costs associated with anticipated depreciation, equipment replacement, utilities other than electricity, engineering design, equity financing, taxes, land, permitting and fees, decommissioning and profit[23]. Anticipated prices for 2020 were used.

3.4.1 Storage Capital Costs

The capital cost of storage systems were determined based on the "Hydrogen Storage Cost Analysis, Preliminary Results" report published by Strategic Analysis for DOE[24]. A storage system capital cost of $468/kg was taken from the Strategic Analysis Sensitivity Analysis, given an assumption that 500,000 units will be produced in 2020.

To support the number of vehicles detailed in Tables 6 and 7 (Referencing Table 8 - storage requirements for maximum number of vehicles) storage capital costs would range from $30.5Million (Base 2, 50 MW) to $261.7 Million (Base 4, 200MW), as shown below in Table 13.

Table 13. Total Storage Capital Costs to Support Maximum Number of Vehicles for Each Base Case

Case	Total Storage Capital Costs ($ Million)			
	50MW	100MW	150MW	200MW
Base 1	46.9	104.4	154.4	192.7
Base 2	30.5	58.7	85.2	114.5
Base 3	39.2	94.1	156.2	212.8
Base 4	49.8	103.6	182.9	261.7

3.4.2 Electrolyzer Capital Costs

The largest electrolyzer available on today's market is 3.5 MW and although currently priced at $1.3 Million/MW, is expected to fall to ~$1 Million/MW by 2020. Therefore a 200 MW capacity will require an approximate $200M capital outlay, as shown below in Table 14. Maximum electrolyzer size is not expected to increase substantially. Due to the relatively large amount of electrolysis capacity required to capture the quantities of curtailed energy analyzed in this report, the systems would need to be modular (in the form of multiple 3.5 MW units). Since centralized and distributed (forecourt) systems will

[23] Further in depth financial analysis would be required before investment.
[24] http://www.hydrogen.energy.gov/pdfs/review12/st100_james_2012_o.pdf

be composed of the different amounts of the same components, they are not expected to be largely different in cost per MW. This was confirmed via comparing DOE models of both centralized and distributed systems that resulted in less than 1% cost difference[25] in costs.

Table 14. Total Electrolyzer Capital Costs

Case	Total Electrolyzer Capital Costs ($ Million)			
	50MW	100MW	150MW	200MW
All	50	100	150	200

3.4.3 Total Storage and Electrolyzer Capital Costs

Table 15 below shows the total storage and electrolyzer capital costs for the maximum number of vehicles that can be supported.

Table 15. Total Capital Costs (Storage + Electrolyzer only)

Case	Total Capital Costs ($ Million)			
	50MW	100MW	150MW	200MW
Base 1	96.9	204.4	304.4	392.7
Base 2	80.5	158.7	235.2	314.5
Base 3	89.2	194.1	306.2	412.8
Base 4	99.8	203.6	332.9	461.7

Table 16 below shows the storage and electrolyzer capital costs per year amortized over a 40 year expected plant lifetime.

Table 16. Storage and Electrolyzer Capital Costs per Year (Amortized Over 40 Years)

Case	Capital Cost/Year ($ Million - Over 40 Years)			
	50MW	100MW	150MW	200MW
Base 1	2.4	5.1	7.6	9.8
Base 2	2.0	4.0	5.9	7.9
Base 3	2.2	4.9	7.7	10.3
Base 4	2.5	5.1	8.3	11.5

[25] http://www.hydrogen.energy.gov/h2a_prod_studies.html - It is noted that this comparative analysis did not consider location specific factors that may impact the economic attractiveness of each option on Oahu (i.e. costs associated with land purchase, road transport, piping installation, electrical supply system enhancements, etc.), because the required information is not readily available.

3.4.4 Electricity Costs

A PPA between Maui Electric Company and a wind farm company[26] was used to determine the cost of electricity. Typical PPAs of this nature define a price for a set amount of energy. If more than this set amount of energy is purchased, a reduced rate is then offered on future energy purchases. For this analysis, the rates for 2020 from the PPA were used. The first 83 GWh of energy delivered will cost $225.30 per MWh and any additional energy will cost $57.17 per MWh. Shown below in Table 17 are the total electricity costs per year, again based on the maximum number of vehicles supported.

Table 17. Electricity Costs Using Maui PPA for 2020

	Electricity Costs/Year ($ Million)			
	50MW	100MW	150MW	200MW
Base 1	17.3	21.4	23.4	24.7
Base 2	24.8	33.7	40.7	46.0
Base 3	21.7	27.5	31.5	34.1
Base 4	19.6	23.5	26.0	27.5

3.4.5 Operation & Maintenance Costs

A rough approximation of operating costs is shown below in Table 18. O&M costs were assumed to be 10% of capital (plus electricity) costs and although not a standard method of calculation, it represents a reasonable proxy.

Table 18. Estimated O & M Costs per Year

Case	Estimated O & M Costs /Year ($ Million)			
	50MW	100MW	150MW	200MW
Base 1	2.0	2.7	3.1	3.4
Base 2	2.7	3.8	4.7	5.4
Base 3	2.4	3.2	3.9	4.4
Base 4	2.2	2.9	3.4	3.9

3.4.6 Total Yearly Costs

Shown below in Table 19 is the total yearly costs for electrolyzers and storage (amortized over 40 Years), electricity and estimated O & M.

[26] MECO and Auwahi Power Purchase Agreement #2011-0060; June 15, 2011.

Table 19. Total Costs per Year for Electrolyzer and Storage Capital (Amortized over 40 Years), Electricity and Estimated O & M.

Case	Total Costs / Year ($ Million)			
	50MW	100MW	150MW	200MW
Base 1	21.7	29.2	34.1	37.9
Base 2	29.5	41.5	51.2	59.3
Base 3	26.4	35.6	43.1	48.9
Base 4	24.4	31.5	37.8	43.0

3.4.7 Costs per Kilogram Hydrogen and Vehicle Miles

Table 20 below shows costs per kilogram of hydrogen using total costs above and amount of hydrogen produced in a year as per Table 8.

Table 20. Costs per Kilogram of Hydrogen

Case	$/Kilogram			
	50MW	100MW	150MW	200MW
Base 1	22.6	17.9	16.5	16.2
Base 2	12.4	9.6	8.8	8.5
Base 3	15.5	12.0	11.2	11.1
Base 4	19.6	15.1	14.4	14.5

Table 21 below shows costs per mile for light duty FCVs, noting that Base 2 (100, 150 and 200 MW) are below average conventional vehicle costs at $0.19/mile.

Table 21. Energy Cost per Mile for Light Duty FCVs

Case	$/Mile -- Light Duty FCVs			
	50MW	100MW	150MW	200MW
Base 1	0.41	0.33	0.30	0.29
Base 2	0.23	0.17	0.16	0.15
Base 3	0.28	0.22	0.20	0.20
Base 4	0.36	0.27	0.26	0.26

Table 22 below shows energy costs per mile for heavy duty FCVs.

Table 22. Energy Cost per Mile for Heavy Duty FCVs

Case	$/Mile -- Heavy Duty FCVs			
	50MW	100MW	150MW	200MW
Base 1	2.83	2.24	2.07	2.03
Base 2	1.56	1.20	1.10	1.06
Base 3	1.94	1.50	1.40	1.39
Base 4	2.45	1.88	1.79	1.81

4.0 Conclusion

This study evaluated the installation of hydrogen production, storage and dispensing infrastructure on Oahu, to reduce the amount of curtailed renewable energy from four theoretical electricity generation cases:

- Base 1 - 500 MW wind, 100 MW Solar PV,
- Base 2 - 700 MW wind, 300 MW Solar PV,
- Base 3 - 500 MW wind, 500 MW Solar PV, and
- Base 4 - 500 MW wind, 300 MW Solar PV.

It was shown that operating a hydrogen production infrastructure can significantly reduce the amount of curtailed renewable energy when 1 GW of renewable capacity is added to the Oahu grid. Hydrogen produced from curtailed renewable energy also serves to reduce air pollution by displacing petroleum based fuels that generate harmful tailpipe emissions. When stored as a compressed gas, the hydrogen can be used to fuel FCVs, as well as materials-handling vehicles, backup power systems, unmanned aerial vehicles, etc. Large capital investments are required to capture a useful amount of the curtailed energy. These capital investments are greater than would be required for hydrogen generation systems that run solely on grid power, due to the variable availability and the requisite additional storage. Although the initial investment is greater, when preliminarily[27]evaluated over a 40 year cycle, the costs per mile driven for an FCV are less than an average gasoline vehicle ($0.19/mile) for Base Case 2, 100, 150 and 200 MW installed electrolyzer capacity.

The analysis resulted in several key conclusions regarding:

1) electrolyzer capacities,

[27] Using only capital costs, PPA electricity prices and estimated O & M costs. This does not include anticipated deprecation, equipment replacement, utilities other than electricity, engineering design, equity financing, taxes, land, permitting and fees, decommissioning and profit etc.

2) storage capacities,
3) supported FCVs, and
4) system costs.

1) **Electrolyzers**: Analysis of various electrolyzer sizes specifically showed the following.

- For an aggregate electrolyzer capacity between 1 and 50 MW, the number of vehicles supported and energy captured was approximately linear. This was not the case above 50 MW installed capacity. Consequently, calculating the best strategies for electrolyzer capacity required the use of stepwise, iterative evaluation techniques.

- 200 MW of installed electrolyzer capacity will capture approximately 90.7% of the curtailed energy for Base 4 (highest) and 76.3% for Base 2 (lowest). This fact is important because it is the reason that 200 MW capacity was used as an upper limit for the analysis.

- To capture at least 25% (considered an acceptable amount to justify investment) of the available curtailed energy for each Base Case (lowest, Base 2), at least 50 MW of electrolyzer capacity is required.

- The highest amount of curtailed energy that can be captured with a 50 MW electrolyzer capacity is 38% (Base 4).

- A 1 MW electrolyzer will capture less than 1% of all curtailed energy for all Base Cases.

- Utilization efficiency of curtailed energy captured above 50 MW electrolyzer capacity does not scale linearly. The best efficiency is Base 4, 50 MW (at 0.76%/MW) but this will support only 4,700 light duty (or 229 heavy duty) FCVs with 62% of the available energy unused[28].

- Not considering storage and consumption limitations (number of vehicles), 200 MW of installed electrolyzer capacity would result in the highest hydrogen production (7,013,680 kg in Base 2) and lowest (2,338,269 kg in Base 1).

2) **Storage**: Analysis of various storage capacities specifically showed the following.

- It made essentially no difference when the FCVs were refueled with regards to time frame on a daily/weekly basis. Actual refueling times have minimal effects on

[28] (100% - (0.76%/MW x 50MW)).

required storage levels of hydrogen (maximum 3% change among all refueling schedules evaluated) and thus associated costs to accommodate higher refueling frequencies for the same number of vehicles is minimal.

- The reduction of available curtailed energy for all Base Cases in the September - November time frame (most severe in November) has a significant effect on the size of storage required and consequently the number of vehicles that can be supported in the first year[29]. Unused hydrogen remaining in storage at the end of the yeardoes not increase the number of vehicles that can be supported.

- Storage requirements[30] ranged from 244,670 kg to 100,240 kg for the highest (Base 2, 200MW) and lowest (Base 1, 50MW) evaluated scenarios.

- The least amount of storage required to support the maximum number of vehicles for a given electrolyzer size is consistently Base 2, with an average of ~9 kg/vehicle. This is less than half the requirement of Base 3, the next lowest at average ~21 kg/vehicle. The highest is Base 4 at average ~33 kg/vehicle. This is important when evaluating capital costs.

3) **Fuel Cell Vehicles**: Analysis of the overall results from the various configurations showed the following.

- At 200 MW electrolysis capacity, supported vehicle numbers ranged from 4,025 (Base 1, 50MW) to 23,620 (Base 2, 200MW) for light-duty FCVs and 196 to 1,152 for heavy-duty FCVs.

- A "perfect tracking" scenario where all hydrogen and curtailed energy is used yields 45,975 light-duty FCVs or 2,240 heavy-duty FCVs, but requires 553 MW of electrolyzer capacity and 766,560 kg of storage (Base 2), which is not considered a feasible approach as a large amount of electrolyzer capacity would sit idle for extended periods and capital costs would be extreme.

- It was found that increasing the electrolyzer capacity does not yield a one-for-one increase in the amount of vehicles supported because less curtailed energy is available at the highest power magnitudes. When electrolyzer capacity was doubled in the various Base Cases, the number of FCVs able to be supported only increased by 1.7.

[29] This was not an artificial constraint as the curtailed energy data supplied by GE was calculated from real world, location specific irradiance and wind data, gathered over an extended time period.
[30] Storage requirements are a result of the maximum number of vehicles that could be supported using the given electrolyzer capacity and curtailed energy fluctuation so that the station would not run out of hydrogen in the lull periods.

- If storage levels are reduced and vehicle fueling requirements remain the same, the resulting energy gaps that require additional energy from the grid to produce hydrogen do not have a linear relationship with the reductions in storage. A larger installed electrolyzer capacity (and thus larger number of vehicles supported) results in storage levels being more sensitive to changes in curtailed renewable energy and thus can lead to larger requirements for additional energy. For a 25% reduction in storage capacity, the highest amount of additional energy from the grid is 7.9% (Base 1) of the total energy required to produce the hydrogen. For a 50% reduction in storage, the highest amount of additional energy from the grid is 18.4% (Base 4) of the total energy required to produce the hydrogen. This amount[31] of energy would likely come from thermal energy generators such as petroleum fired power plants. If additional capacity were installed for this purpose only, it would sit idle 2/3 - 3/4's of the year.

- By simply replacing fossil fuel powered vehicles on the road with FCVs[32], CO_2 emissions could be reduced per year by approximately 22.5 million[33] to 131million[34] tons for the analyzed scenarios. Gasoline reduction for the analyzed Base Cases ranges from approximately 2.5 million gallons (Base 4)[35] to approximately 12.1 million gallons (Base 2)[36].

4) **System Costs:** Analysis of the resulting costs of these hydrogen production, storage and dispensing facilities showed the following.

- Due to the large amount of electrolysis capacity required to capture the quantities of curtailed energy analyzed in this report, the systems would need to be modular. Consequently, centralized and distributed systems are not expected to be largely different in cost; this was confirmed via DOE models which demonstrated a less than 1 % difference in costs between the two. It is noted that the models do not take into consideration Oahu specific land, electric supply infrastructure and transportation cost differences, but do consider capital, deprecation, equipment replacement, energy, utilities, engineering design, equity financing, taxes, land, permitting fees, O & M, decommissioning, profit, and expected planned and unplanned downtime.

[31] 18.835 and 43.673 GWh respectively
[32] 21.4 mpg, as supplied by HNEI
[33] 200 MW electrolyzer capacity and 244,000 kg's of hydrogen storage - Base 2

[34] 50 MW installed capacity and approximately 100,000 kg's of storage - Base 1

[35] 50 MW installed electrolyzer capacity
[36] 200 MW installed electrolyzer capacity

- Based on the maximum number of vehicles that can be supported for each Base Case and electrolyzer capacity, storage capital costs range from a low of $30.5 Million (Base 2, 50 MW) to a high of $261.7 Million (Base 4, 200 MW).
- Electrolyzer costs are expected to be $1 Million/MW by 2020.
- Total capital costs for electrolyzer and storage range from a low of $80.5 Million (Base 2, 50 MW) to a high of $461.7 Million (Base 4, 200 MW).
- Electricity costs per year range from $17.3Million (Base 1, 50MW) to $46Million (Base 2, 200MW).
- Capital (amortized over 40 years), electricity and O & M costs per year range from $21.7 Million (Base 1, 50MW) and $59.3 Million (Base 2, 200MW).
- Base 2 is consistently the most favorable Case in costs per mile driven for light-duty FCVs, ranging from $0.15/mile (200 MW) to $0.23/mile (50 MW). The highest cost is $0.41/mile (Base 1, 50 MW).
- The cost analysis shows that energy cost per FCV mile driven decreases as installed electrolyzer capacity increases due to a reduction in electricity rates and an increased number of FCVs supported.

Overall, 6,000 and 23,620 FCVs can be supported with the use of the curtailed energy resulting from the addition of 1 GW of renewable energy (Bases 2 and 3). This, in-turn, will displace up to 131 Million tons of CO_2 and other tailpipe emissions. Although Base 2 scenarios utilize the least amount of total energy available (25.8% for 50 MW and 76.3% for 200 MW), it is the configuration that supports the greatest number of vehicles with the least amount of storage, and is thus the most cost efficient. Although an estimated capital investment of between ~$80.5 and ~$315 Million would be required for this optimized configuration, the price per mile over a 40-year plant life (including electricity and estimated O & M costs) ranges from $0.15 to $0.23, which is in the range of an average conventional fossil fuel powered vehicle ($0.19/mile).

5.0 Appendix A

Hydrogen production from electrolysis is an electrochemical process in which an electric current is passed through water using electrodes. The electric energy splits the chemical bonds in the water molecule producing pure oxygen at the anode and hydrogen at the cathode.

$H_2O \rightarrow \frac{1}{2} O_2 + H_2$

The process can be scheduled such that it is synchronized with the excess renewable energy that would have normally been curtailed. Hydrogen is also easily stored and dispensed and thus can be made available for future use. The two commercial methods of electrolysis are Proton Exchange Membrane (PEM) and Alkaline. Regardless of the method, the overall electrochemical reaction is the same.

PEM Electrolysis

PEM technology is mature in small capacities but several companies are presently scaling up their units in order to produce larger scale output electrolyzer units (up to 2 MW). In a PEM electrolyzer, the electrolyte is a solid ion conducting membrane, as opposed to the aqueous solution in the alkaline electrolyzers. The membrane allows the H+ ion to transfer from the anode side of the membrane to the cathode side, where it forms hydrogen. The membrane also serves to separate the hydrogen and oxygen gasses, as oxygen is produced at the anode on one side of the membrane and hydrogen is produced at the cathode on the opposite side of the membrane.

PEM Hydrogen Production at the Cathode

$2\ H^+ + 2e^- \rightarrow H_2$

PEM Oxygen Production at the Anode

$H_2O \rightarrow \frac{1}{2} O_2 + 2\ H^+ + 2e^-$

Alkaline Electrolysis

Alkaline electrolysis is the most mature electrolysis technology available. Electrolyzers, which can be either unipolar or bipolar, can be obtained in large sizes (up to 3.5 MW). Unipolar alkaline electrolysis involves submerging electrodes connected in parallel in an aqueous electrolytic solution, such as potassium hydroxide (KOH). The electrolyte is used because of its high conductivity which improves hydrogen and oxygen production. A membrane is placed between the cathode and anode electrodes that serves to separate the hydrogen and oxygen molecules during electrolysis, but allows the transfer of ions. The bipolar design resembles a filter press where electrode cells are connected in series and separated by a membrane. Hydrogen is produced on one side of the cell, oxygen on the other. The potassium is not used in the reaction.

Alkaline Hydrogen Production at the Cathode

$4\ H_2O + 4e^- \rightarrow 2H_2 + 4OH^-$

Alkaline Oxygen Production at the Anode

$4OH^- \rightarrow O_2 + 2H_2O + 4e^-$

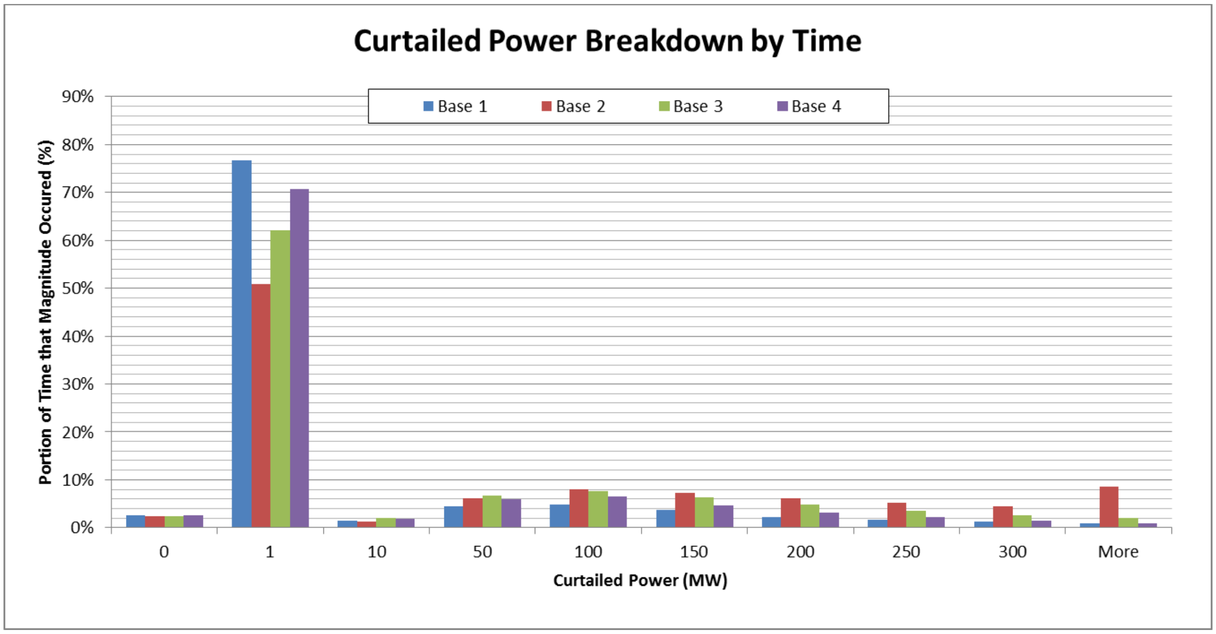
Electrolysis Method Comparison

Alkaline electrolysis is by far the most mature technology having been in commercial production since the 1920's. Although mature, proven and readily available in the marketplace, the technology has some drawbacks. These include requiring corrosive potassium hydroxide to operate, along with operating at a reduced efficiency to PEM electrolyzers (up to 16%[39]). Large alkaline electrolyzers have not typically been used in an environment where rapid hydrogen production rate changes are required and thus, have previously been designed with a slower ramp rate than PEM's, but research and development in this area is ongoing. The world's leading manufacturer of large electrolyzers, NEL Hydrogen (Norway), now advertises a 3 second ramp rate which, for the purpose of this study, would be sufficient.

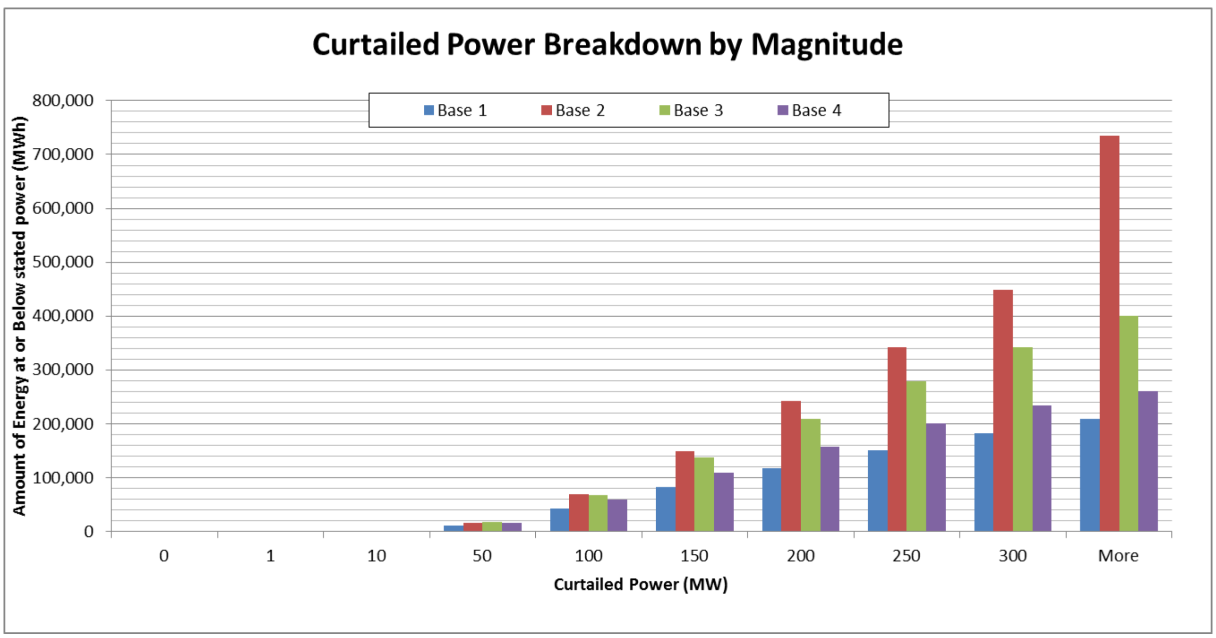
PEM electrolyzers are a far less mature technology than alkaline (at large scales, i.e. MW sizes) but can be load following to the millisecond and a 50 millisecond ramp rate has been demonstrated at the United States National Renewable Energy Laboratory (NREL)[40]. A PEM electrolyzer producing the same amount of hydrogen as an alkaline electrolyzer will typically have a smaller footprint, which can have practical implications when selecting a certain technology.

[39] K. Harrison (NREL), Hydrogen Works Conference, San Diego, CA, Feb 17-19, 2009
[40] PEM R & D Electrolysis Webinar (NREL), Dr. Katherine Ayers
http://www1.eere.energy.gov/hydrogenandfuelcells/pdfs/webinarslides052311_pemelectrolysis_ayers.pdf

6.0 Appendix B

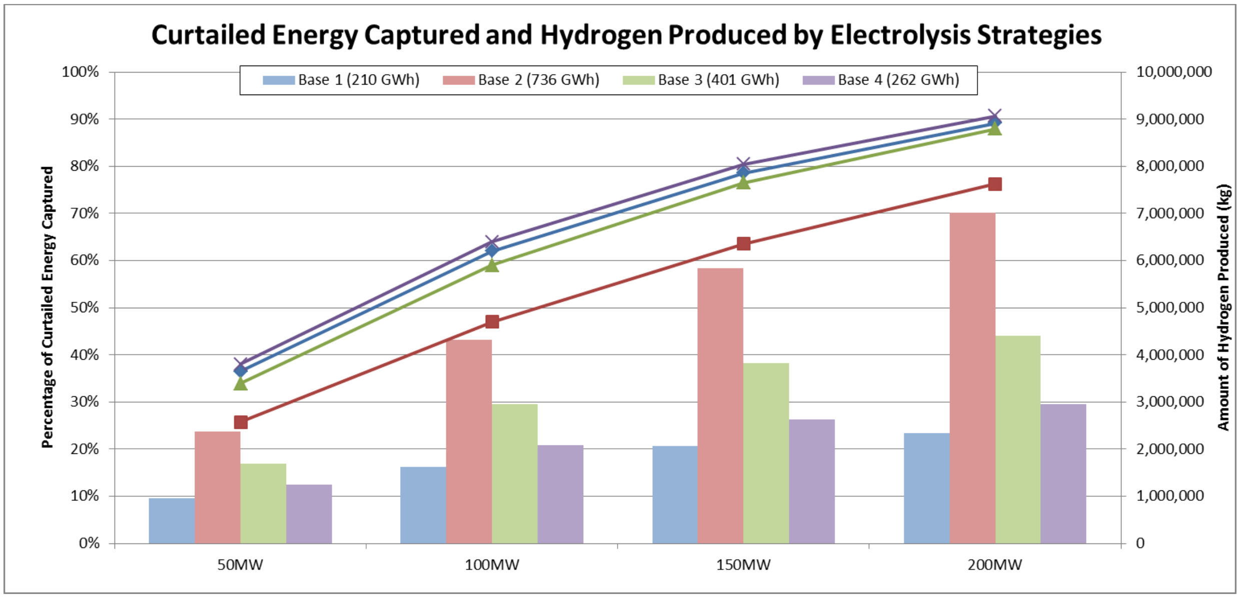


Portion of time that certain magnitudes of hourly curtailed power occur



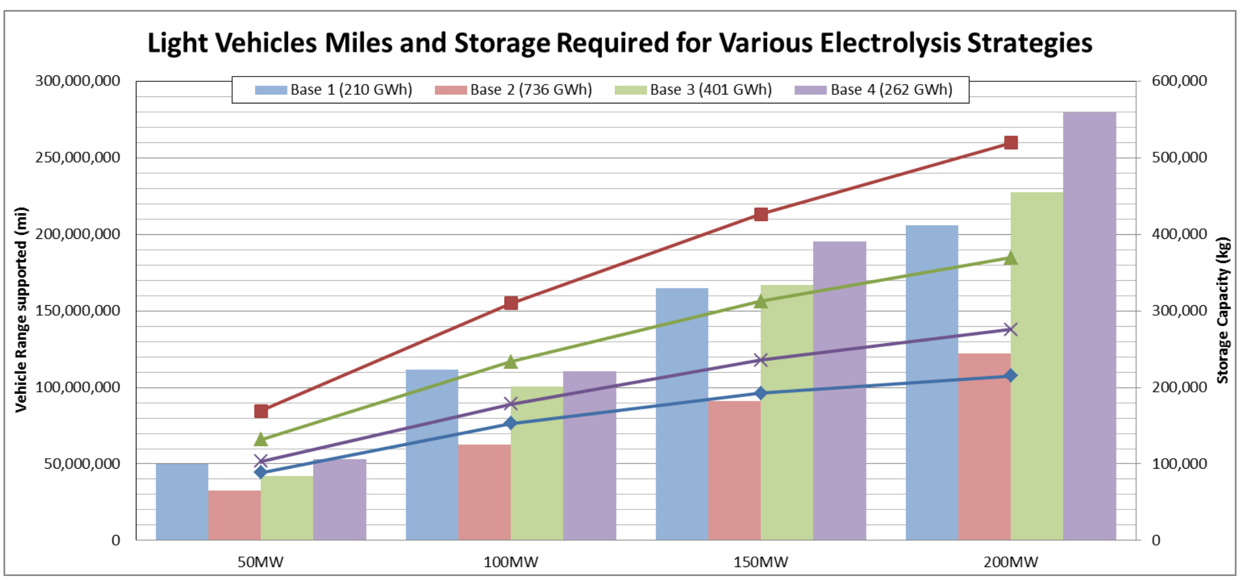
Amount of energy available at various power levels for curtailed renewables

7.0 Appendix C

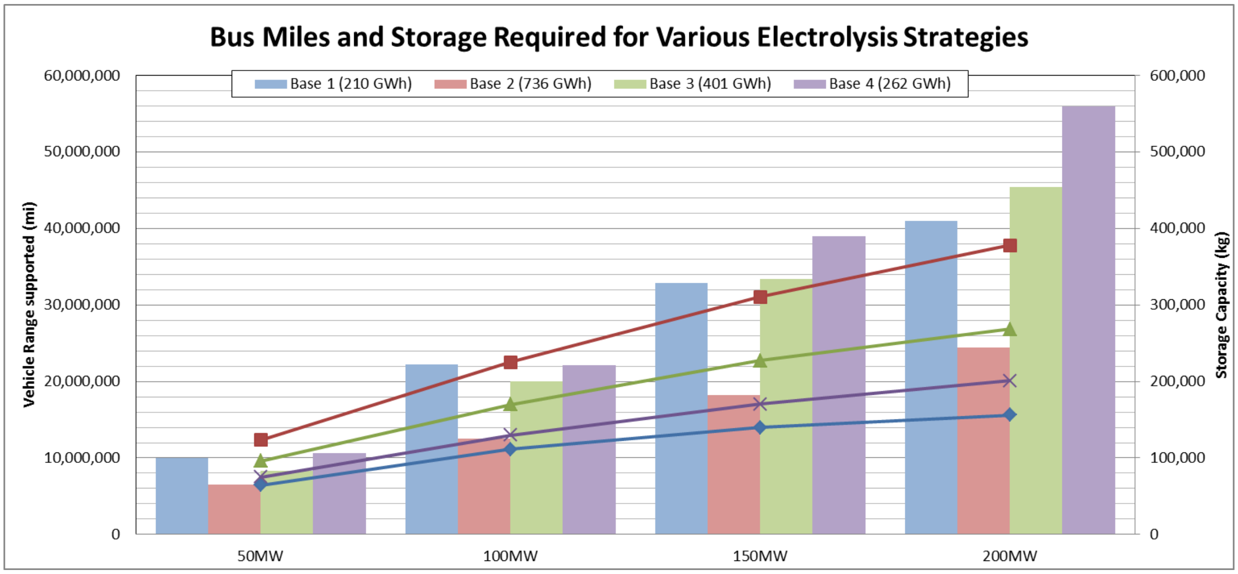


Maximum amount of curtailed energy captured as a percentage of total available (lines) and subsequent amount of hydrogen produced for each Base case and various electrolyzer capacities (bars)

8.0 Appendix D



The Amount of light-duty vehicle miles (lines) and corresponding minimum amount of storage required (bars) assuming consistent and evenly distributed hourly consumption of hydrogen for each Base Case with varying electrolyzer capacities



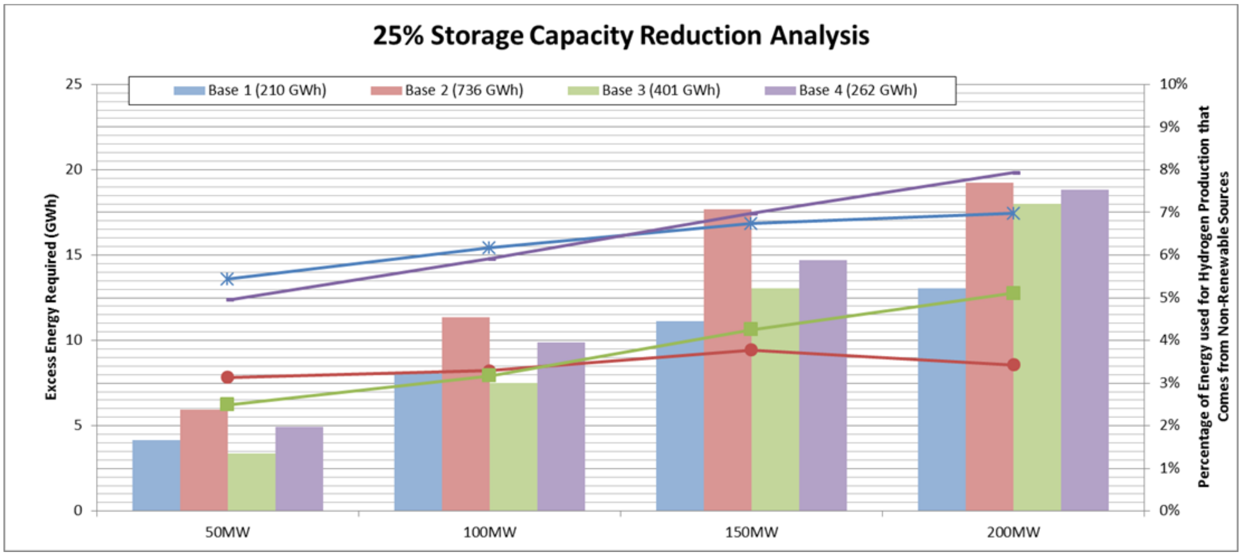
The Amount of heavy-duty vehicle miles (lines) and corresponding minimum amount of storage required (bars) assuming consistent and evenly distributed hourly consumption of hydrogen for each Base Case with varying electrolyzer capacities

9.0 Appendix E

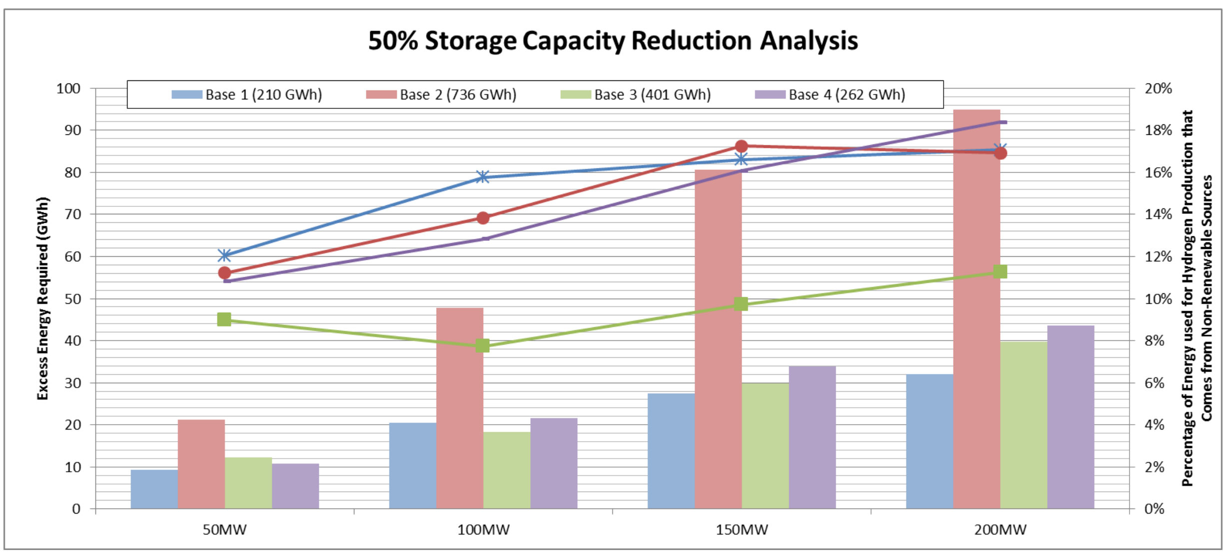
Case	Storage kg/vehicle				Average
	50MW	100MW	150MW	200MW	
Base 1	24.90	32.06	37.74	42.12	34.21
Base 2	8.45	8.90	9.39	10.36	9.27
Base 3	13.96	18.92	23.51	27.07	20.86
Base 4	22.66	27.34	36.49	44.58	32.77

Minimum required storage levels to support stated vehicle fleets for each Base Case. The amount of storage required per vehicle increases with electrolyzer capacity and vehicle fleet size.

10.0 Appendix F



Storage reduction of 25% analysis that gives the amount of excess energy from thermal generation required (bars) to maintain the same amount of vehicle miles as the strategy that uses only curtailed renewables. Lines show the percentage of energy used to produce hydrogen that is from additional sources.



Storage reduction of 50% analysis that gives the amount of excess energy required (bars) to maintain the same amount of vehicle miles as the strategy that uses only curtailed renewables. Lines show the percentage of energy used to produce hydrogen that is from additional sources.