WATER ELECTROLYSIS SYSTEM

OPTIMIZATION IN A

MICROGRID

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A Project

Presented

to the Faculty of

California State University, Chico

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In Partial Fulfillment

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Professional Science Master's

in

Environmental Science, Sustainable Development

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by

Ryan G. Stoltenberg

Spring 2017

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WATER ELECTROLYSIS SYSTEM OPTIMIZATION IN A MICROGRID

ABSTRACT

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In the past ten years, increases in distributed renewable generation (mostly wind and solar) have complicated normal grid operations. Careful engineering can effectively eliminate the potentially adverse impacts that distributed resource penetration could impress on the electric delivery system. When renewable generation technologies are paired with well-scaled, high efficiency, energy storage systems, they have the potential to meet a much more consistent level of demand. Pilot scale projects can demonstrate the viability of localized energy production and usage. This project revolves around the ongoing microgrid venture happening at the campus of Stone Edge Farm and Vineyard. Quantifying the inputs and outputs of the hydrogen electrolyzer component in different operation scenarios to determine its efficiency is the focus of this project. Hydrogen is an extremely energy dense molecule but does not occur in the desired H2 gaseous form under natural, atmospheric conditions. Measuring the component's electrical consumption and fuel production allows for real time and historical monitoring to quantify the system's efficiency variability based on control and operational adjustments.

# CHAPTER I

# INTRODUCTION

The United States electrical grid is comprised of power plants, transmission lines, transformers, substations, relay switches, and millions of metered consumer site connections. While it is one of the great engineering triumphs of the 20th century, the grid infrastructure separates consumers from the generation and control aspects of the grid. These steps have permanently been contracted to a small number of investor-owned utility companies who were tasked with maintaining a centralized electrical generation and distribution system to reach all American citizens. This rapid infrastructure construction grew the grid to reach customers in the early and mid-1900s, but has not been modernized extensively since. Incentivizing construction and not maintenance has left the electrical generation and distribution infrastructure facing significant deterioration. In the past ten years, increases in distributed renewable generation (mostly wind and solar) have complicated normal grid operations. Careful engineering can effectively eliminate the potentially adverse impacts that distributed resource penetration could impress on the electric delivery system.

Grid failures due to weather, transmission line cut offs, and electrical voltage peaks and valleys leave many customers vulnerable to extended power outages. More than 70% of the grid's transmission lines and transformers are 25 years or older while the power plants are on average, 34 years old (Bakke, 2016). The US, on average, withstands the most blackout time of any developed nation: about 6 hours per year not including outages due to extreme weather (Bakke, 2016). According to industry expert Peter Ausmus, “We rely on twice as many power plants as we actually need because of the massive inefficiencies built into the system.” (Bakke, 2016). Centralized generation and vast distribution infrastructure requires transformers to step up voltage for long distance transmission only to be stepped back down at the substation level and down again at the customer meter (Figure 1). Each point of voltage adjustment comes with energy losses and further decreases efficiency. A recent British Petroleum (BP) report

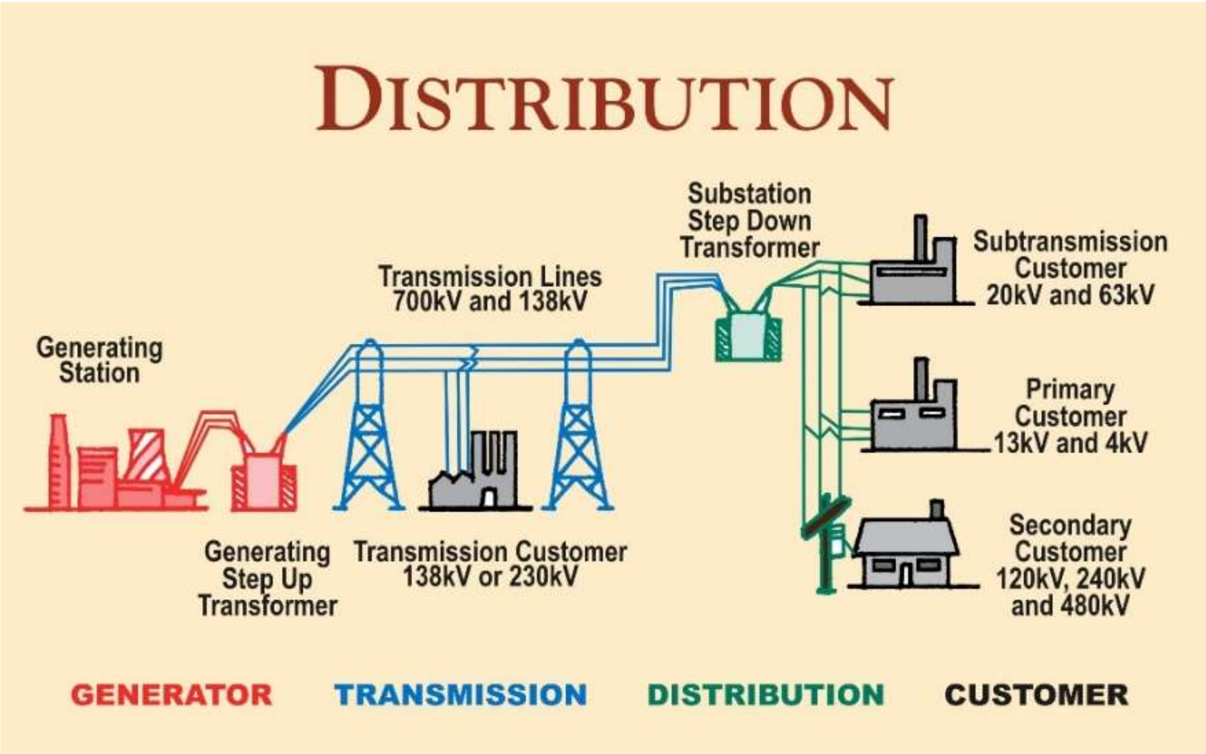


*Figure 1: Simplified distribution steps with voltages through the electrical grid system*

on the worldwide energy outlook predicts that an additional 1.3 billion people will become new energy consumers by 2030 (Chen et al., 2015.) Future population growth will further strain the grid's outdated ability to meet demand. Improving infrastructure proficiency is crucial to ensure America's energy security.

Increasing renewably generated energy on the grid has been a heavily debated topic for federal, state and local governments. California is leading the United States in renewable energy usage (Figure 2). In a 2015 senate bill, California set a goal of 50% renewable energy mix by 2030 (CA Energy Commission, 2015). A 2015 comprehensive study by the Department of Energy's National Renewable Energy Laboratory (NREL)

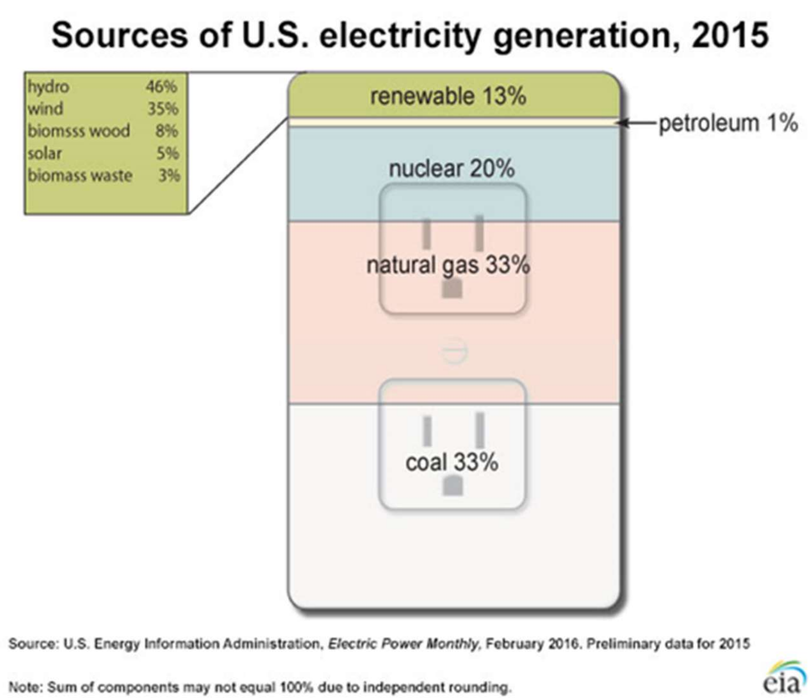


*Figure 2: Sources of electricity generation for the United States. Source; Energy Information Agency (EIA.gov).*

reported that the U.S. could potentially generate over half of its electricity from renewable energy by 2050 (NREL, 2015). Current technology and resources are available to continue to deploy distributed solar and wind generators but advanced, 21$^{st}$ century control and distribution techniques need to be implemented and managed effectively. Renewable resource characteristics, specifically geographical distribution, seasonal and daily variability pose challenges to the operability of the nation's electric system. However, these difficulties can be overcome with better understanding and more effective management of infrastructure and resources.

Grid scale power plants shape the energy mix state by state. These producers are resource dependent with many coal fired plants on the east coast in the Appalachian Mountains and northwest in the Powder River Basin where mines continue to exploit anthracite, bituminous and subbituminous coal seams. Hydroelectric and natural gas power plants are very common on the west coast due to geographical features. Vermont has been an outlier state as far as energy mix with over 70% of their total use in 2015 derived from nuclear plants while West Virginia uses 94% coal derived electricity (U.S. Energy Information Administration, 2016). The fact remains that over 67% of electricity used in the US is produced from carbon sources (predominantly coal and natural gas) (Figure 3) (U.S. Energy Information Administration, 2016). However, electricity itself is neither renewable nor nonrenewable, it is only as clean as its source.

The largest inhibitor to grid-wide renewable generation deployment has been generation intermittency and therefore, production management. The way the grid was originally designed and built does not allow for voltage variability. The original model is functional when electricity is generated at centralized plants using stock-resources, such as coal and natural gas, that keep line voltages consistent (Figure 4). These steady outputs are what the twentieth century grid was built for. Renewable resources such as wind, solar, and waves are too unpredictable and variable to directly replace a

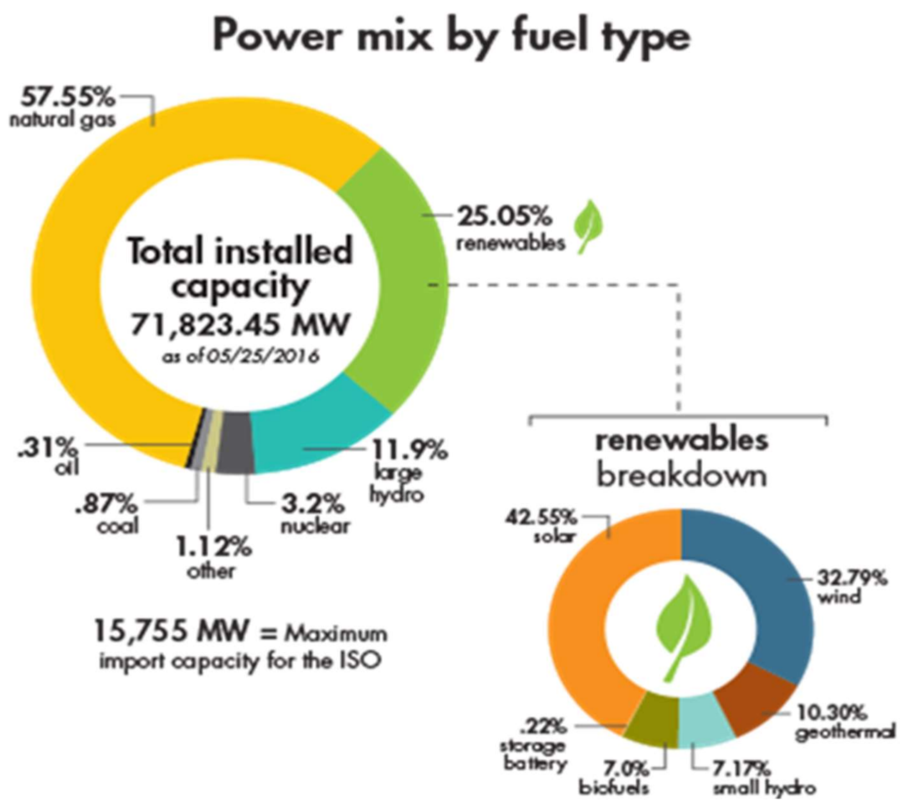


*Figure 3: Sources of electricity generation for California.*
*Source: California Independent System Operation (CAISO.gov).*

coal or natural gas fired plant capable of generating consistent voltage and amperage 24 hours a day. When renewable generation technologies are paired with well-scaled, high efficiency, energy storage systems, they have the potential to meet a much more consistent level of demand (Nasri et al., 2015). With integrated monitoring and control capabilities, this idea could be applied to a 21st century grid utilizing distributed energy resources accessed by customers variably based on localized generation and demand information (Figure 4).

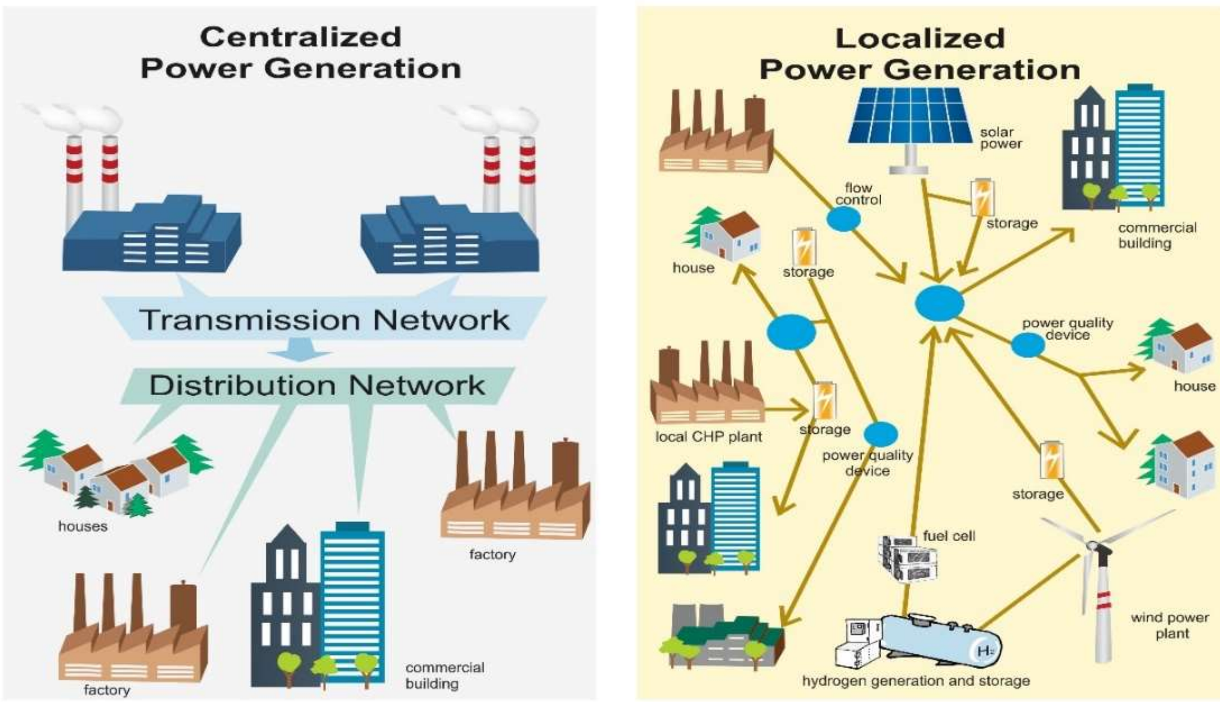


*Figure 4: Centralized distribution (grid) and Localized distribution (smart grid).*

Stone Edge Farm Microgrid Project

Pilot scale projects can demonstrate the viability of localized energy production and usage. The Stone Edge Farm Microgrid project located in Sonoma, CA, arose with the intent to see how far a 16-acre urban farm's carbon footprint could be reduced and to demonstrate what may be possible with current technological solutions and creativity. An interconnected network of electrical services has been designed to be capable of providing emergency power in the event of a macro-grid failure or, by choice to intentionally island the microgrid and ultimately, run in parallel operation with the macro-grid. The project internally connected seven metered PG&E services together as an isolatable electrical grid (Figure 5). In order to accomplish this goal, various forms of distributed generation and storage with real time monitoring and control were integrated and controlled to work together.

The research reported here revolves around the ongoing microgrid venture happening at the campus of Stone Edge Farm and Vineyard. An important facet of the project is the Distributed Energy Resource system that includes a solar array, hydrogen electrolyzer, vehicle fueling station, and fuel cells, as well as a high voltage battery bank (Figures 5 and 8). Quantifying the inputs and outputs of the hydrogen electrolyzer component in different operation scenarios to determine its efficiency is the focus of this project. Hydrogen is an extremely energy dense molecule but does not occur in the desired $H_2$ gaseous form under natural, atmospheric conditions. The electrolyzer is a piece of equipment designed to break the bonds of water ($H_2O$) using electricity, purify the two products ($H_2$ and $O_2$), and compress the gaseous hydrogen to high pressure for storage. This system required the design of a comprehensive sensor scheme capable of recording and logging the inputs and outputs of the system. Measuring the component's electrical consumption and fuel production allows for real time and historical monitoring to quantify the system's efficiency variability based on control and operational adjustments.

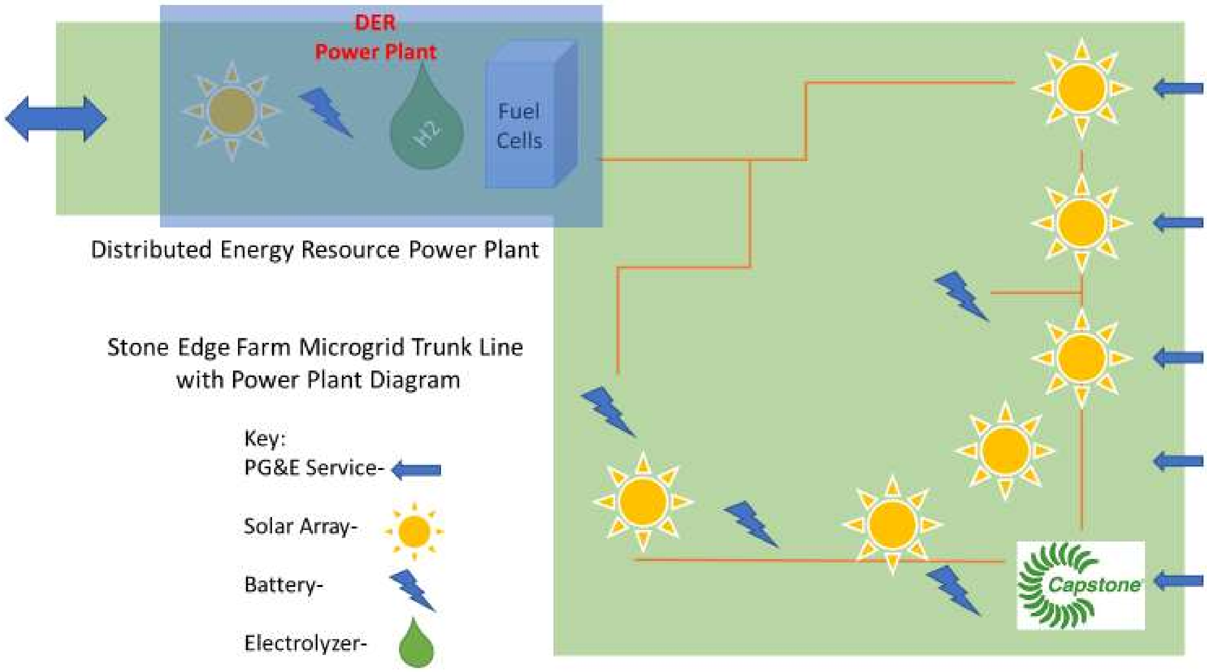


*Figure 5: Overview of Stone Edge Farm asset layout and power plant location.*

# CHAPTER II

# BACKGROUND

## Renewables

The grid isn't just a wired together contraption, it is also a massive cultural system with powerful stakeholders, including the utilities, investment firms, power plant owners, mining firms, and "too big to fail" multinational conglomerates (Bakke, 2016). Substantial push-back from fossil fuel and utility stakeholders is ongoing but steps are continuing to be taken to improve macro-grid-level legislation. These steps include the Public Utility Regulatory Policy Act (PURPA) and The Energy Policy Act (EPACT) of 2005. PURPA was originally passed in 1978 as part of the National Energy Act that aimed "to encourage the conservation and efficient use of energy resources and to promote the development of alternative power supplies capable of displacing the inefficient use of oil and natural gas by electric utilities," (US Office of Electricity Delivery and Energy Reliability, 2005). EPACT passed in 2005 and requires electric utilities, when they need power, to purchase power from Qualified Facilities (QF) (under Department of Energy guidelines) at the utilities' avoided cost, provide back-up power to QFs, interconnect with QFs, and operate with QFs under reasonable terms and conditions (US Office of Electricity Delivery and Energy Reliability, 2005). These two historic documents started the turn from the utilities' natural monopoly that had been in place since the inception of America’s grid system and have opened the grid infrastructure for publicly owned utility companies who can now legally buy and sell power to customers.

Solar energy is a decentralized and inexhaustible resource. The magnitude of the available solar power striking the earth’s surface at any instant is equivalent to the power capacity of 130 million, 500 megawatt power plants (Chen et al., 2015.) Hawaii has been the first state to encounter a statewide solar capacity issue. Over 12% of homes on the island have installed solar arrays that can produce more electricity than what is being used occasionally, causing some parts of the grid to go into emergency shutdown mode (DOE, 2016). This issue of overgeneration and under generation at different times of the day has been named the “duck curve” (Figure 6). The output fluctuations have caused the state to cap solar installations to mitigate these issues. Batteries, flywheels, or hydrogen can be used to level the generation and the consumption variability through load shedding and balancing to “cut the head off the duck.” This refers to overgeneration storage during the daily peak solar hours to be reclaimed during the peak usage hours in the evening. This avoids over-populating the grid with electrons and also reduces stress on the grid to ramp up for peak usage hours. Control and monitoring technology is needed grid wide to better manage the dynamic nature of the electrical system.

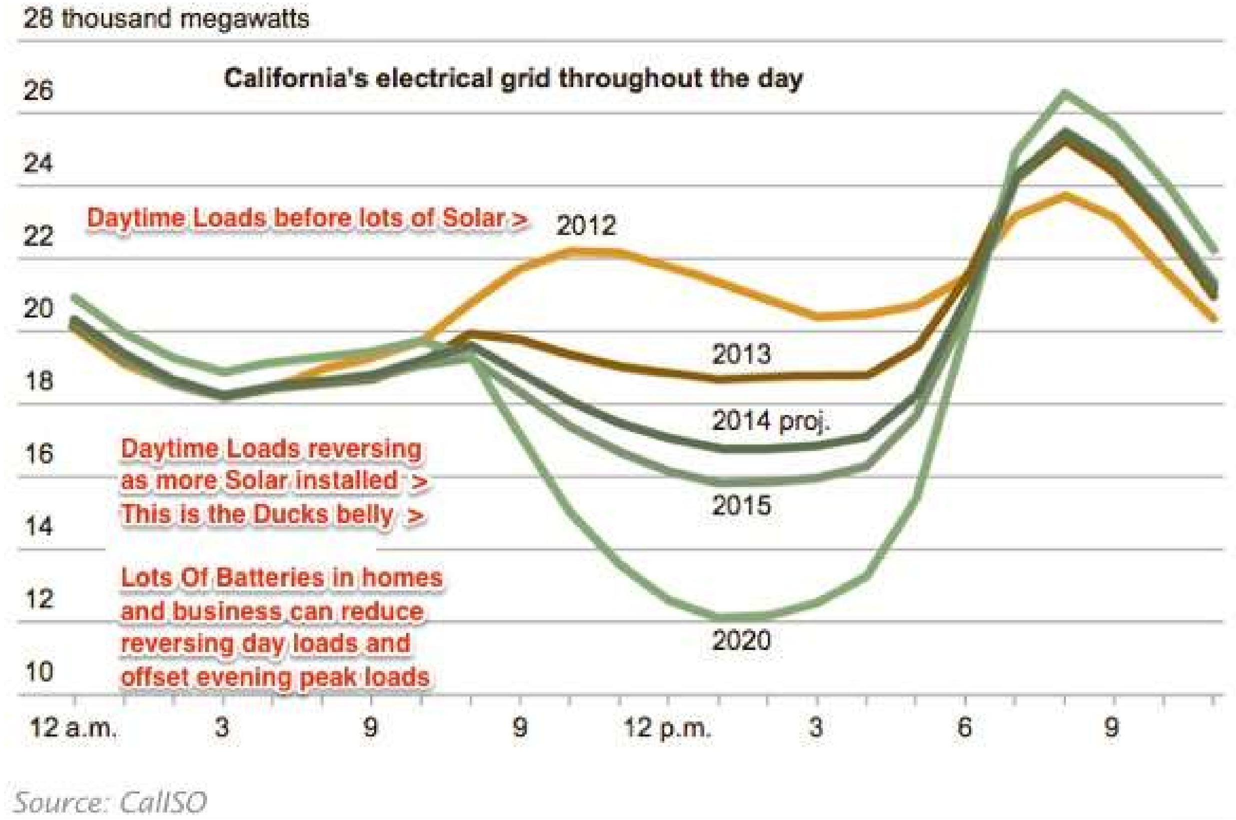


*Figure 6: The Duck Curve  Source: California Independent System Operator (CAISO.gov)*

## Microgrids

Losing lights is the least of the problems associated with power system crashes, which are becoming more and more frequent. America runs on electricity. Electricity has become so essential that using the word “blackout” to refer to a power outage is something of a misnomer. The age of information has revolutionized the ways citizens communicate, socialize and even learn into electricity dependent processes (Bakke, 2016). Public health and hospitals are intensely dependent on electric power as are factories, ports, police, and military operations. According to the Secretary of Defense, “over 40 DOD military bases either have currently operating microgrids, planned microgrids, or have conducted demonstrations of microgrid component technologies,” (PR Newswire, 2013).

Hybrid power systems consisting of a generation and storage component have a main goal of ensuring electricity production and delivery without any interruption (Nasri et al., 2015). A microgrid takes the hybrid system approach a step further allowing the site to operate with no grid inputs. The Department of Energy defines a microgrid as, "a group of interconnected loads and distributed energy resources (DER) with clearly defined electrical boundaries that acts as a single, controllable entity with respect to the grid [and can] connect and disconnect from the grid to operate in both grid-connected or island mode.” (DOE.gov, 2016). This model could be utilized in a number of destinations such as an apartment complex, office building, school campus, hotel, farm, or vineyard to name a few. A microgrid requires three main components; generation source, storage capacity, combined with monitoring and control capabilities. Increased adoption of localized generation and storage capacity would substantially decrease the generation demanded from the macro-grid and reduce electricity outage times.

The United States Department of Defense's (DOD) interest in microgrid technology and energy security stems from its heavy reliance upon all forms of fossil fuels, often imported from regions of the world hostile to U.S. interests (PR Newswire, 2013). Microgrids can enable military bases to sustain operations, regardless of what is happening on the macro grid or in the lack of one in remote, non-industrialized areas. At the same time, microgrids can reduce the amount of fossil fuels burned to create electricity by networking generation sites as a system to maximize efficiency (DOE.gov, 2016).

Aggregating microgrids into a network of localized generation and exporting assets can utilize existing infrastructure to make the grid system more intelligent. A smart grid is a modernized electrical grid that uses analog or digital information and communications technology to gather and act on information (Marcon et al., 2015). Information about the behaviors of suppliers and consumers allow for improvement of efficiency, economics, reliability, and sustainability of the generation and distribution of electricity (DOE.gov, 2016) (Figure 7). The use of microgrid and smart grid technologies can effectively manage community demand loads while increasing user awareness of energy (Parra et al., 2016). These monitoring and control concepts can be built into the existing grid structure. There have been billions of dollars spent on growing the grid to the scale it now exists. It is necessary to utilize the existing infrastructure and using localized power sharing can shape the future of the United States electricity market.

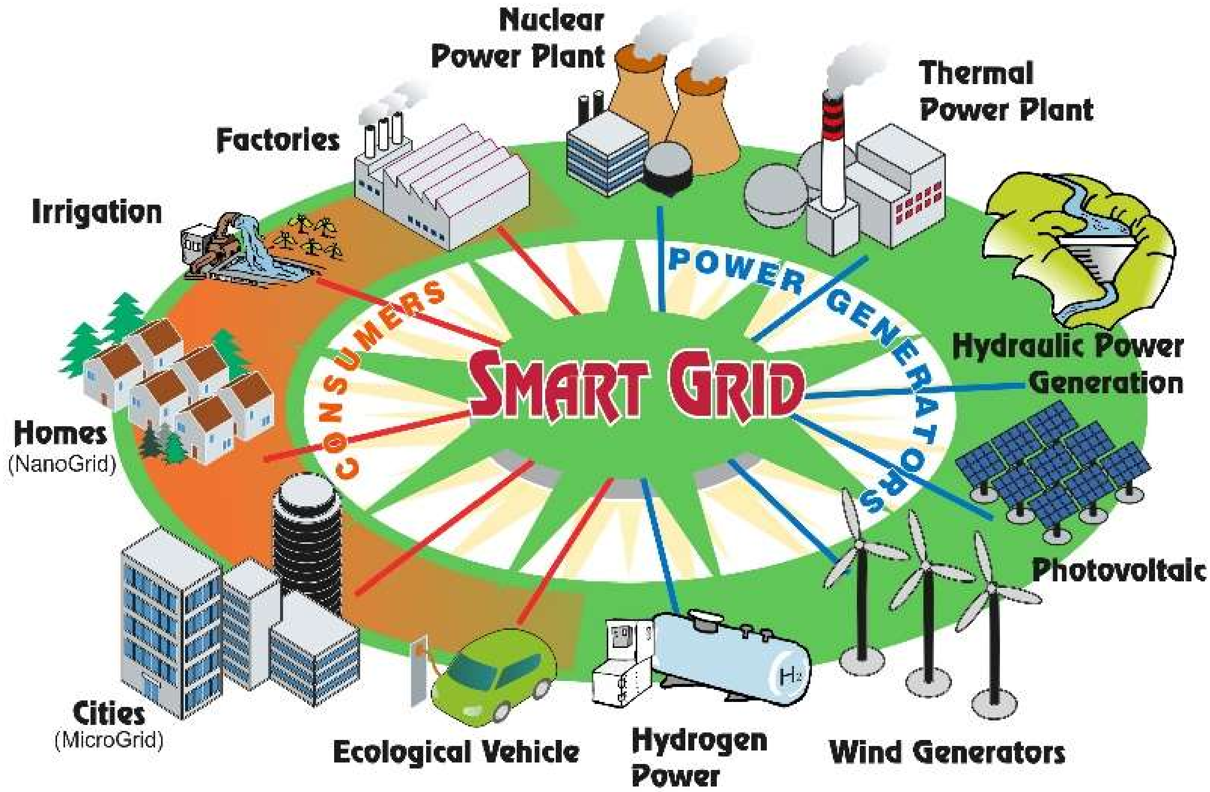


*Figure 7: Depiction of Smart Grid consumers and generators.*

Hydrogen

On-site electricity generation paired with energy storage can revolutionize the outdated, centralized power paradigm that has existed since the grid was constructed.

This understanding has driven energy storage technology to diversify chemistries, physical scale, and storage capacity. Efficiency and capacity have increased but fundamental problems remain such as heat loss as well as degradation with charge cycling. There are technologies that fill niches in the small-scale market however, a new approach needs to be taken to achieve effective residential, industrial, and even grid scale energy storage. Using hydrogen systems as energy storage mediums paired with batteries and fuel cells has the potential to meet a wide range of energy needs.

Like electricity, hydrogen is a carrier of energy and it must be produced from a natural resource (Crabtree et al., 2004). Unlike electricity, however, hydrogen does not have to be generated and used simultaneously, it can be stored effectively and returned to electricity on demand. Generating hydrogen from electrical overproduction can allow for large storage of energy using the bonds of water as an energy medium.

Using an electrolyzer (hydrogen generator) to strip two water molecules into two hydrogen and one oxygen ($2H_2O + \Delta \leftrightarrow 2H_2 + O_2$) ($\Delta$ denotes energy) takes a known amount of energy and can be scaled to be feasible for a number of uses. “Under ideal circumstances, it requires 39.4 kWh of electricity and 8.9 liters (2.35 gallons) of water at normal conditions (25 °C and 1 atm.) to make 1 kilogram of hydrogen,” (Saur, 2008). This represents the total amount of energy to dissociate water at atmospheric conditions. The maximum efficiency can never be reached because the process is never perfectly ideal due to thermodynamics as well as material limitations (Saur, 2008). Storage of the pressurized $H_2$ can be tailored for intended use from small to large scale: individual home to industrial manufacturing plant. This process would occur while solar or wind turbine production is exceeding demand. When the sun or wind resource goes away, the process can be reversed in a hydrogen fuel cell to return the hydrogen to the electrical form or used in fuel cell vehicles. A fuel cell is effectively the reverse reaction from electrolysis. While an electrolyzer uses electricity to break the bonds of water, a fuel cell uses hydrogen gas as fuel and reintroduces it to atmospheric air in the presence of a catalyst to exploit the released energy as electricity with water vapor being the only other byproduct. Pairing renewable resources such as wind or solar with a hydrogen generation and reclamation system can allow for 24-hour energy availability. This depends heavily on understanding of system dynamics and efficient engineering and optimized scaling.

Not only can hydrogen be utilized as an energy storage medium, but it also has the potential to replace hydrocarbons in the transportation market. Most hydrogen powered transportation technologies require high pressure compressed hydrogen gas in the range of 500 to 10,000 psi while output from an electrolyzer stack is typically less than 500 psi (Saur, 2008). In December 2006, the U.S. DOE published the “Hydrogen Posture Plan” which outlined goals of President Bush’s Hydrogen Fuel Initiative (Saur, 2008). One of the plan’s goals was a delivered hydrogen target of $2.00 to $3.00 per kilogram of hydrogen per gallon of gasoline equivalent (gge). One kilogram of hydrogen contains the approximate energy equivalent to one gallon of gasoline assuming the same end-use conversion efficiency (Saur, 2008). Hydrogen fuel cell vehicles are becoming more prevalent but the infrastructure for the fuel resource needs to be in place to really allow for the market to thrive. The first step in bringing hydrogen into everyday use is to prove a model that can be adjusted and scaled to fit various needs and applications. Quantifying these systems’ efficiencies is a main hurdle to making this technology an option for consumers. The main challenges of renewable electrolysis are designing and implementing systems that can cost-effectively produce hydrogen from renewable sources using efficient, and streamlined processes (Harrison et al., 2009).

In 2004, a group at MIT funded by the US Department of Energy (DOE) developed a framework for the future of a “hydrogen economy” (Crabtree et al., 2004). The proposed model involves a network composed of three functional steps: production, storage and use. The DOE estimates that by 2040 cars and light trucks powered by fuel cells will require about 150 megatons of hydrogen per year (Crabtree et al., 2004). The US currently produces about 9 megatons per year, almost all of it by steam reforming natural gas. This process uses high temperature steam to break the bonds of natural gas ($CH_4$) into hydrogen gas ($H_2$) and a combination of carbon and carbon dioxide ($CO_2$). It takes energy to split the water molecule and release hydrogen but that energy can be later recovered during oxidation. Non-carbon sources such as solar, nuclear, wind, or hydropower must be the source of generation to eliminate fossil fuels from the cycle.

Single cell organisms such as algae and microbes can produce hydrogen efficiently at ambient temperature and pressures by molecular level processes (Crabtree et al., 2004). With time and resources, researchers can potentially capitalize on natures efficient manufacturing processes by mimicking molecular structures and functions using artificial materials in applications such as fuel cell anodes and cathodes. Storing hydrogen in a high-energy density form that links its production and eventual use is a key element of the hydrogen economy model. Unlike electricity, which must be produced and used at the same rate, stored hydrogen can be stockpiled for much later use, or as a buffer to bridge the differing temporal cycles of energy production and consumption.

Industrial facilities and laboratories are already accustomed to handling hydrogen in its two traditional storage mediums: cylinders of liquid or highly pressurized gas. For on-vehicle use, hydrogen storage needs only about half of the energy that gasoline provides because the efficiency of fuel cells can be greater by a factor of two or more than that of internal combustion engines (Crabtree et al., 2004). This efficiency difference- about 60% for fuel cells compared to 22% for gasoline or 45% for diesel internal combustion engines- would dramatically improve the efficiency of future energy use (Crabtree et al., 2004). Coupling fuel cells with electric motors, which can be up to 90% efficient, converts the chemical energy of hydrogen to mechanical work without heat as an intermediary. Internal combustion as well as jet engines can be rather easily modified to run on hydrogen instead of hydrocarbons (Crabtree et al., 2004). Internal combustion engines run as much as 25% more efficiently on hydrogen than on gasoline with no carbon emissions. Stationary hydrogen power plants scaled to supply neighborhood electrical power are practical. Such plants could connect to the electrical grid to share power locally but are independent of the grid in cases of failure.

The approach of generating hydrogen through the electrolysis of water and the use of stored hydrogen in a fuel cell or internal combustion engine to produce electricity during times of peak demand or as a transportation fuel is hindered in part, by the difficulty of $H_2$ production in a cost-competitive manner (Schug, 1998). Renewable electrolysis systems must be optimized and tailored to realize the most competitive option for electricity and $H_2$ production. Electrolysis hydrogen production is highly dependent on the delivered cost of electricity. However, if the electricity used by these systems is recovered from overproduction of solar or wind generation that would otherwise be spilled back onto the grid for free, the model becomes more feasible (Harrison et al., 2008). Experimental testing provides feedback to the analysis to verify system efficiency improvements. This all aligns with the nations interest in developing and demonstrating advanced hydrogen technologies to reduce America's dependence on foreign energy resources, improve air quality, and ultimately support the nation's long-term economic viability (Harrison et al., 2008).

The hydrogen economy has enormous technical and societal appeal as a potential solution to the fundamental energy concerns of abundant supply and minimal environmental impact. The ultimate success of a hydrogen economy depends on how the market reacts. The government must also play a key role in moving away from a fossil fuels-based economy. Research and development as well as infrastructure costs will be high, so early investment, established clear goals, research support, and sharing realized risk is necessary to prime the emergence of a vibrant, market-driven, hydrogen economy.

## Hydrogen Case Studies

A study done in 2013 under the framework of Project Carbon Reduction Technologies (CARETE) explored a Polymer Electrolyte Membrane (PEM) electrolyzer system that is now implemented in the framework of the Fuel Cells and Hydrogen Joint Undertaking Electrohypem Project (Briguglio et al., 2013). The hydrogen production system mainly consists of an electrolysis stack, and a power conditioning unit. A large number of studies have been carried out concerning materials investigation and modeling in a single cell scaling up from cell to stack. A large range of operating management conditions including temperature, pressure, and water circulation have been investigated for modeling purposes. However, it is very difficult to find research focusing on the whole production system such as studies on integrated effects of the electrolysis cells with ancillary components (or Balance of Plant, BoP) (Briguglio et al., 2013). The overall management of BoP contribution to the system efficiency loss is not insignificant.

Depending on the stack and system design, ancillaries' energy consumption can influence the optimal operating point providing the best system efficiency. In this context, by evaluating the BoP contribution to the performance of a complete electrolyzer system, this research aimed to provide a contribution to the adjustment of the electrolysis system design (Briguglio et al., 2013). Electrolyzers converting electricity produced by renewable energy resources into chemical energy stored in the bonds of water, combined with fuel cells transforming hydrogen back into electricity may lead to efficient energy storage for renewable energy sources and prompt a wider penetration of distributed generation systems (Briguglio et al., 2013).

Electrolysis is still only a minor generation process compared to the total amount of hydrogen produced and used in the world. “Two factors are mostly responsible for the underutilization of electrolysis in the hydrogen market. First, the low cost of hydrocarbon sources for hydrogen and second, the fact that most of the world-wide hydrogen production is used as feed in the chemical industry at the same place where it is produced from hydrocarbon sources," (Briguglio et al., 20013). The environmental demand for "Zero Emissions Vehicles" and "Regenerative Energies" will soon be reason enough to change the economical weighting of hydrogen from electrolyzers against generation from hydrocarbons. There are three main target groups for high-pressure electrolyzers: users who want to produce a constant amount of hydrogen per time unit over a long period; users who want to couple the electrolyzer to an energy source of variable power such as photovoltaic field or wind generators; and users who want to smooth changes in energy consumption of power plant networks (Briguglio et al., 20013). The constant production group is mostly interested in a maintenance free, automated operation with high volume output. The variable output energy sources case has two additional aspects. First is the energy production depends on external influences which might result in unpredictable phases of low and high current. Second, there will be times where there is no current at all and the machine will be in a standby mode. Using electrolysis as a network peak shaving device has the most possible complications and more work and research needs to be done to realize the possible techniques to fill this niche.

In 2007, a cooperative research and development agreement (CRADA) was created between Xcel Energy and the U.S. National Renewable Energy Laboratory (NREL) "to investigate possible ways to improve the system efficiency of producing, delivering, and using hydrogen from renewable resources," (Harrison and Martin, 2008). The wind-to-hydrogen (Wind2H2) demonstration project aimed to quantify system-level efficiency improvements and cost reductions by designing, building, and integrating dedicated renewable energy-to-electrolyzer stack power electronics (Harrison and Martin, 2008). The goal of the project was to enable closer coupling of renewably generated electricity and the electrolyzer stack to produce hydrogen, which is then compressed and stored or future use to produce electricity via a hydrogen-fueled internal combustion engine for grid-connected peaking power applications, or, as a vehicle fuel. The Wind2H2 construction project began normal operations in 2007 focused on baseline testing (utility or grid tied operation). Since then, it has been enjoying success as a demonstration project, producing hydrogen directly from renewable energy sources (Harrison et al., 2009). The stored hydrogen is being used both as a transportation fuel and as an energy storage medium, effectively allowing renewable energy to be stored and converted back to electricity at a later time. Future work will include sensor calibrations and hardware to allow communications with the various devices for automated unattended operation (Harrison et al., 2009).

# CHAPTER III

# METHODOLOGY

The Stone Edge Farm Distributed Energy Resource Power Plant consists of a 123-panel solar array, a six-stack Polymer Electrolyte Membrane (PEM) Hydrogen Electrolyzer, a low and high stage piston compressor, 24 gas storage bottles configured in four six-packs with 225 Liters of storage at 6000 psi, vehicle fueling station, Relion E-2200x Hydrogen Fuel Cell "hive" (stack of 12 Cells), and a 30 kW Ideal inverter that is controlling two banks of 14 Aquion batteries (each 48 volts wired in series for a total bank voltage of 672 volts nominal). Eventually these five components will work together

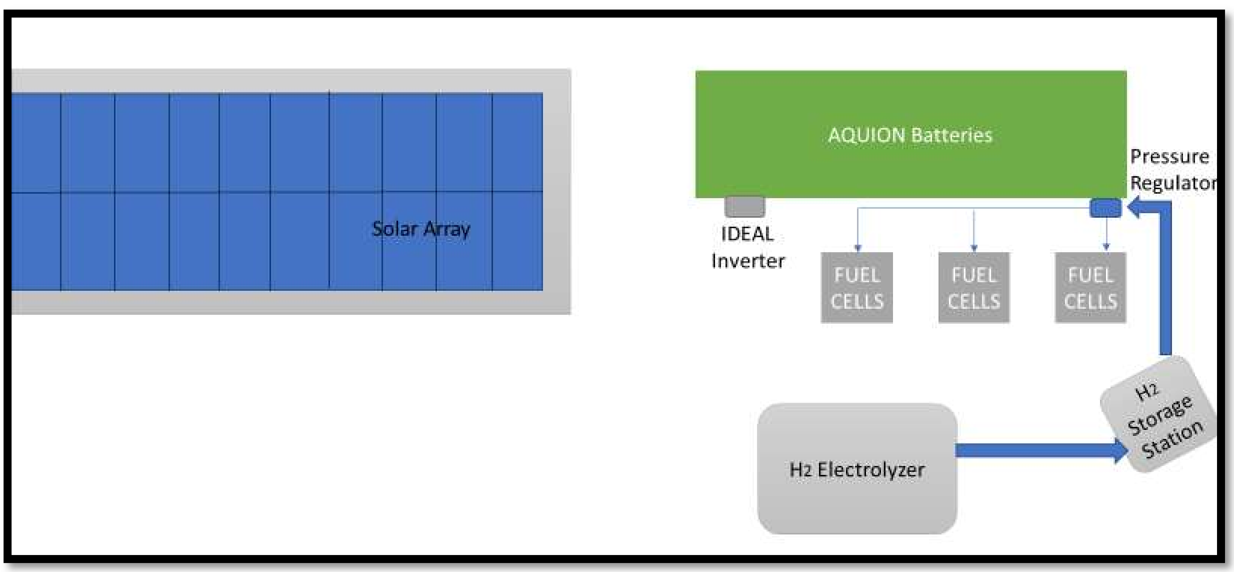


*Figure 8: Aerial view of DER Power Plant layout.*

as a localized power plant (Figure 8). Using the electricity generated by the solar to charge the batteries and offset power used by the electrolyzer, the gas produced by the electrolyzer to run fuel cells or fuel vehicles. The output electricity from the fuel cells is then used to charge the batteries and energize other loads on the microgrid campus. The purpose of this project is focused on quantifying the main component: the PEM electrolyzer. This system was monitored and adjusted using data loggers and a central controller. The understanding of this machine is crucial to the control of the whole power plant, so understanding its performance under variable conditions is essential.

The electrolyzer itself was designed to be monitored and adjusted by an operator. Factory sensor readings and adjustment valves were all analog configuration. The first step was to design and implement a digital sensor scheme to monitor the machine's operation processes. These included, electrical consumption, gas production, system and storage pressures, water intake, water temperature, heater temperature, and gas temperature (Table 1). Each of these sensors needed to fit the machine's operating ranges and be compatible with the chosen data logger/controller. The data acquisition tool used was an easyIO FG 32+ logger/controller. The electrical consumption was logged to the easyIO by an eGuage model EG30xx reading four 200 amp Accu-CT current transformers at the dedicated electrolyzer 240 volt, split phase panel. The eGuage was calibrated and the accuracy was confirmed by a second monitoring system: an Asco Emerson 5221 power quality monitor mounted on the same panel. All sensors were terminated at the easyIO logger and controlled through an ethernet cord connected laptop where monitoring and settings changes were made.

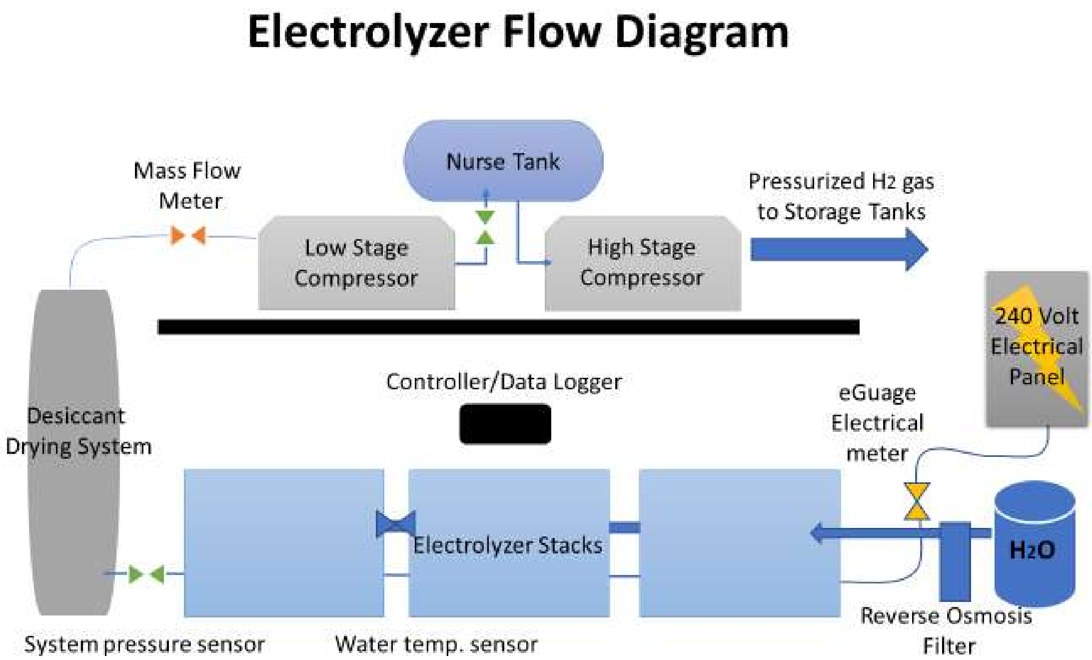


*Figure 9: Diagram of Electrolyzer with sensor sites.*

These sensors were custom ordered from various companies and took nearly 10 months until they were received, installed, and tested. Testing was done to provide calibration and baseline information. After 100+ hours of baseline operation and trend monitoring, tests were designed to measure the machine's performance in multiple operating scenarios. The relevant summary statistics were calculated for each test: total time, overall electrical consumption, overall grams of gas produced, average gas flow, average electrical consumption, standard deviation of gas and electricity, gas and electricity produced/used per hour, grams of gas produced per kilowatt, kilowatt hours (kWh) per kilogram of gas produced, kilograms of gas produced per day, as well as price per kilogram of gas The statistics that provided the most insight to system functionality were kilograms per day, kWh per kilogram, and price per kilogram. The price statistic was calculated based on an average of $0.13 per kilowatt (PG&E average based on billing history). Hydrogen fuel prices range from $12.85 to more than $16 per kilogram (kg), but the most common price is $13.99 per kg (equivalent on a price per energy basis to $5.60 per gallon of gasoline) (CAFCP, 2016). These price derivations can be adjusted when the electrolyzer operates using sources other than the grid such as the microturbine or solar. An example can be found at TABLE 2.

| Sensor Type/ Part Number | Input | Output | Location(s) |
|---|---|---|---|
| | | | |
| Pressure (10,000 PSIG) Omega PX309-10kg | 12-28VDC | 4-20 mA | After High Pressure Compressor, After Storage T to Fuel Cells |
| Pressure (1000 PSIG) Omega PX309-1kg | 12-28VDC | 4-20 mA | Low Pressure Compressor Output |
| Pressure (200 PSIG) Omega PX309-200g | 12-28VDC | 4-20 mA | Storage Gauge, System Gauge, Low Pressure Compressor Input |
| | | | |
| Flow (water) 1/2 in. (Omega FLR D Series) | 10-30 VDC | 4-20 mA | Between Storage Bucket and Circulation Pump |
| | | | |
| Mass Flow (H2 gas) (SmartTrack 100) | 12-24 VDC | 4-20 mA | Behind Purification/Dessicant System Before Low Pressure Compressor |
| | | | |
| Temperature Probes (SA1-TH-44000 Series) | 5 VDC | 3000 Ohms | On each Heater/Dryer (4) and on Low and High Stage Compressors (2) |

*Table 1: List of sensory types and models with inputs, outputs, and install locations in the electrolyzer system.*

Nine tests were designed based on operation scenarios that would vary the machines controllable components. Controls settings, electrical source, storage pressures and volumes were all adjusted to represent realistic generation scenarios. Data was collected to identify baseline as well as optimized operation conditions.

| 1776 pts | G/min | Watts | Total Time (min) | Total Time (hour) | KWH used |
|---|---|---|---|---|---|
| Total | 7309.39 | 58305433 | 118.4 | 1.97 | 64.78 |
| Average | 4.12 | 32829.64 | | | |
| Standard Dev | 0.42 | 10473.73 | | | |
| per hour | 246.94 | 32829.64 | | | |
| G/KW | 0.0075 | | | | |
| KWH per KG | | 132.95 | | | |
| Grams Produced | 487.29 | | | | |
| KG/day | 5.93 | | | | |
| $/KG@$0.13/kWh | $17.28 | | | | |

*Table 2: Summary Statistics table example.*

- The first test was a warm up and purge of the system to represent a normal start up cycle of operation. This gave a baseline measurement for time to production as well as a calculated list of statistics that would be consistent with each startup and therefore be dismissed on following tests.
- Test two was initially a baseline grid-tied test that demonstrated two scenarios of compression inefficiency resulting in controls settings changes. This test also provided data on heater baseline temperature trends.
- The third test demonstrated the electrolyzer running on power generated on site by the Capstone C65 microturbine with the microgrid in island mode. Island mode is when the PG&E connections to the grid are closed off and all electricity

is being generated and used by on-site components. In this test, the Capstone was the master generator with no battery systems contributing to the microgrid trunk line power baseline test of microturbine generation to hydrogen production.

- Test four represented another baseline test connected this time directly to the macro-grid with the microgrid in connected mode drawing power directly from PG&E.
- The fifth test shows the result of the first control adjustments and efficiency gains. During this test, heat thresholds programed into the PLC were adjusted to increase run time between stack shut downs. The in-line sensors proved that this reduced the number of stack shut downs.
- The sixth test is representative of another grid connected test with the adjusted control settings. All of the factors shown in test two are the same to focus on the effectiveness of just the settings changes.
- Test seven shows the electrolyzer with a limited storage capacity. Instead of the full 24 bottles of storage open, just 5 bottles were open so this test was to show the variability that the compressors were facing with storage pressure increasing rapidly.
- The eighth test demonstrated the electrolyzer filling just one 37.5-liter bottle starting at approximately 500 psi.
- The ninth and final test was under the same conditions however, the single bottle stated at about 2000 psi to show the variable performance against different storage pressure levels.

# CHAPTER IV

# RESULTS

Test one was the first two hours (227 minutes) of run time from start up. Appendix one shows the warm up cycle with the electrical usage of the machine averaging 30,641 watts (30 kW) (Table A1). The electrolyzer took about 45 minutes to reach maximum electrical draw (Figure A1). The mass flow measurement floats around 4 grams per minute during production but averaged 3.3 grams per minute overall due to idle gas production during warm up (Figure A1). It took the electrolyzer about 25 minutes to warm up and gain pressure before the first compressor kicked on and the mass flow meter began reading (Figure A1). Based on PG&E's average electrical sales prices ($0.13) and the gas production, test one produced 418.77 grams of $H_2$ using 64.79 kilowatt hours (kWh) of energy. These results translate to a price per kilogram of $20.11 (Table A1).

Test two showed the first 32 minutes of run time after the purge cycle. Appendix two shows the tail end of warm up with the electrical usage of the machine rising from 400 watts to 35,000 (35 kW) (Figure A2). The mass flow measurement floats between 4 and 5 grams per minute during production but averaged 3.59 grams per minute overall due to the inconsistency of the compressors (Table A1). Figure A3 represents the purification heaters warm up trends. These heaters are activated by $H_2$ flowing through them so they gain heat as production and compression commences. This trend was proved consistent by multiple tests so the sensors remain in place to ensure ignition.

The system pressure reached 90 psi at 75 seconds into the test activating the low stage compressor drawing hydrogen through the mass flow meter (Figure A2). Test two produced 113.55 grams of H2 using 15.39 kilowatt hours (kWh) of energy resulting in $17.63 dollars per kilogram (Table A2).

Test three demonstrated the generator running in Microgrid Island mode using the Capstone C65 microturbine as the electrical input. When the microgrid is in Island mode, there is no electrical power being imported into the farm. All PG&E inlets are disconnected and the electricity on the farm is all generated and consumed by inside components. This test shows a lower peak watt usage than in test one. The generator consumption stayed pretty consistent at 32,000 watts. The gas production was similar to tests one and two floating at 4 grams per minute (Figure A4). This test ran for 98 minutes and produced 386.38 grams of hydrogen while using 49.13 kilowatt hours of energy. This translates to a price per kilogram of $16.53 (Table A3).

The fourth test was the final baseline with the electrolyzer connected directly to grid power. Wattage consumption was high peaking at 37,330 watts and averaging 31,126.88 (Figure A6, Table A4). Mass flow readings averaged 3.94 grams per minute and the compressors remained on throughout the 52-minute test. The test consumed 27.19 kWh while producing 209.59 grams of $H_2$ (Table A4). This translates to a price per kilogram of $17.11.

Test five was the longest recorded test with two changes demonstrated. This test was run while on grid power for 2.5 hours and then was switched to Island Mode for the final 20 minutes. Table A5 characterizes the entire 3193 data point summary where the generator averaged 30,629 watts and 3.88 grams of $H_2$ per minute. Controls adjustments were made after 71 minutes of generation and summary statistics are shown in Figures A6 and A7. These two tables represent the differences the logic modification made.

Test number six demonstrated the optimized controls settings for a 58-minute run time. This test produced the best price per kilogram number of any test at $15.54 (Table A8). The test showed that the stacks were shutting down while keeping the mass flow and compressors constant which resulted in a very efficient kWh per kilogram number of 119.5 (Figure A8).

The seventh test was based on limited storage space with only 5 out of 24 bottles open in the storage building. At the start of the test, the bottles were at 2100 psi and after the 107-minute test, they reached 2750 psi (Figure A9). According to Table A9, the test produced 482 grams of $H_2$ using 61 kWh of energy.

Tests 8 and 9 were both single bottle fills starting at different pressures. Test 8 had a starting pressure of 500 psi and an ending pressure of 3500 psi (Figure A12). Figure A11 demonstrates the inconsistency in both electrical consumption and gas production. This test only ran for 118 minutes producing 487.29 grams of $H_2$ gas (Table A10). This test resulted in a price per kilogram of $17.29 (Table A10). The final test ran for 89 minutes with a starting pressure of 1450 psi and a final pressure of 3700 psi (Figure A14).

## DISCUSSION

The data collection of the first four tests were intended to set baselines for normal running conditions. The system takes about 20-45 minutes to run warm up and purge cycles which bring the stack and dryer systems up to pressure (Test 1). The machines' Programable Logic Controller (PLC) and the compressors have threshold settings for system pressure, water temperature, as well as alarm and fault settings that had to be wired in parallel with the easyIO controller. The compressors have two different threshold settings. The low stage compressor engages at inlet pressures of between 90 and 116 psi. The high stage compressor has an inlet range of 500 to 625 psi. If the pressure falls outside of this range, the compressors kick off. These circumstances provide opportunities for optimization.

The first baseline test demonstrated the purge and warm up cycle. The stacks produce gas that stays in the system side of the machine before the compressors are activated. Test one took 27 minutes for the compressors to engage. This data is relevant because all other tests were data logged following the purge and warm up cycle. Due to the placement of the mass flow meter (after desiccant system before compressors) the stacks are consuming power with no gas flow through the system (Table A1). Even though the stacks were producing gas up to 90 psi for 27 minutes, the compressors were not on so no gas was drawn through the mass flow meter until that pressure is reached.

Test two established scenarios of inconsistent mass flow and electrical usage. With a minute and a half break from compression after only about 7 minutes of generation, there is obvious room for optimization. This data (Figure A2) reveals an under-production scenario. In this case, the stacks were not in full production yet because they were not fully warmed up. They were unable to satisfy the first stage compressor and the pressure fell below 90 psi. With the first stage compressor off, mass flow ceases until the stacks bring the system back into the pressure range. 24 minutes into the test, the pressure fell out of range again when the system pressure reached 116 psi and the generator went into a pressure fault that turned the stack consumption off (Figure A2). The PLC threshold setting of 116 psi indicates that the storage is full causing all 6 stacks power to be disconnected. It is a safety setting but happens frequently due to the compressor-to-stack output scaling.

These two situations arose in less than 30 minutes of run time under normal operation conditions. This test provided enough feedback to make the first settings change on the machine. To prevent the machine from shutting down all of the stacks and therefore production, a logic setting was implemented. Instead of allowing the system psi to reach 116 psi, a pair of stacks were put on a shut-down threshold of 115 psi for sixty seconds. This allowed for 4 stacks to remain in generation while the compressors caught up with the produced gas and prevented the system psi from reaching the fault threshold of 116 psi.

The third test demonstrated the machine running off of the microturbine and logged the first logic addition made in the easyIO controller. 27 minutes into the test, the system pressure reached 115 psi and the generator switched from 6 to 4 stacks (Figure

A5). This prevented the system pressure from reaching 116 psi and after one minute, the 2 stacks kicked back on and continued to generate with all 6 stacks. This logic adjustment increased the grams per day value and the kWh value.

Test four showed the logic control setting in use again. After 2.5 minutes of run time, the system pressure reached 115 psi turning of the two stacks and reducing electrical consumption to 25,000 watts (25kW). This kept the generator and compressors running and returned to 6 stack production after sixty seconds. This situation occurred again 30 minutes into the test but the system pressure still reached 116 psi and the stacks were put into fault mode. This was manually rectified by opening a bleed valve on the compressor and the two stacks stayed off for one minute again to allow system pressure to fall below 115 psi a second time. This test indicated that the logic setting of 115 psi was too close to the 116-psi threshold.

The controls test demonstrated a longer run time than the first 4 tests and resulted in the highest peak watt consumption (38,100 watts) (Figure A7). The test also represented the second change in logic controls made 71 minutes into the test. The 115-psi threshold was being met constantly (13 times in 71 minutes) as the electrolyzer was in full production. It did not allow the system pressure to get low enough and as soon as the 6 stacks would go back on, the pressure would quickly reach 115 psi again (Figure A7). The logic defined two stack shut off point was changed to 114 psi so that the machine had a longer time in between stack shut offs to generate with 6 stacks. This controls change was aimed at keeping the electrolyzer in its “sweet spot,” or optimal setting, so that more gas can be generated. The results were immediate with the kilograms per day number rising from 5.73 (Table A6) to 6.25 (Table A7). Gas production numbers also rose after the adjustment from 3.98 to 4.34 grams per minute (Tables A6 and A7). This adjustment allowed for the stack shut-offs to become less frequent and the gas production numbers to rise (Figure A7).

The sixth test resulted in the best efficiency numbers of any of the tests. Producing at a price per kilogram of $15.54 based off grid connected pricing ($0.13). The results of test six were very consistent with the as production averaging 4.43 grams per minute (Table A8). The stacks reached 114 psi 9 times in the 58-minute run but never reached 116 psi resulting in lower consumption averages but constant production (Figure A8). This test did not however, have the highest kilogram per day number (6.39 KG/day) (Table A8).

Test seven produced very consistent gas production data. Staying very constant at 4.51 grams per minute, this test had the highest kilogram per day statistic at 6.49 KG/day (Table A9). The logic control was used just 10 times in the 107-minute test but never reached the 116-psi threshold (Figures A9 and A10). Staying below these limits and keeping gas production constant is key to successful operation of the generator.

Test eight was set up to demonstrate fueling a single low pressure bottle to calculate how many grams it took to fill a 37.5-liter bottle to 5000 psi. For this experiment, the single bottle was purged from 2000 down to 500 psi in the morning and the test was conducted in the afternoon so that the heat generated by the purge could subside. Meanwhile, the electrolyzer was running all day prior to the test so it was already up to full temperature and production when this test began. This data was kept due to the alarm thresholds met during the experiment.

About 17 minutes into data recording, the water temperature threshold of 140 degrees Fahrenheit was met and the stacks lost power for about 5 minutes (Figure A11). This did not turn off the compressors but the stacks' production was halted. After the cooling pump reduced the water temperature, the stacks regained power and ran for about 45 minutes until the temperature threshold was met again just after the system pressure reached 114 psi (Figures A11 and A12). This had the same effect as the first alarm and the stacks lost power for 5 more minutes. These two instances were out of the control of the logic settings in place in the easyIO but still had substantial influence on overall machine performance. The compressors never fell out of their ranges so gas production was still present throughout the test.

The ninth and final experiment was conducted to test again a single bottle fill. This bottle began at a higher pressure (1450 psi) than in test 8 (500 psi) (Figures A12 and A14). This test also ran into a separate logic issue about 13 minutes into testing. This alarm, which indicates an $H_2$ and $O_2$ mix in the plumbing cabinet between the stacks and desiccant system, indicates that some hydrogen had been detected on the oxygen side of the purge lines. This sensor was built by the electrolyzer manufacturer has since been replaced due to oversensitivity. After that was disarmed, the rest of the test was very clean and consistent with the system pressure reaching 114 psi only 3 times in the remainder of the 89-minute test (Figures A13 and A14). These final two experiments exemplify the many factors that can potentially impact the effectiveness of the system during normal operation.

# CONCLUSIONS AND RECCOMENDATIONS

This project has focused on the analysis of hydrogen production, compression, and storage providing valuable data that has led to system optimization. The tests and controls adjustments followed months of baseline machine run time. The electrolyzer was operated multiple times a week and hours of maintenance and upkeep was required to continue running. The compressors were both replaced after less than a year of installation. An updated dryer/desiccant system was installed based on our sites' testing and monitoring. Multiple safety updates were installed such as bleed valves and bypass solenoids to avoid fault conditions. Some of these upgrades and changes were made before the entire sensor scheme was installed, tested, and logging data but were still within the scope of the project. This project was tremendously influential in the product development of this machine. However, there are still upgrade possibilities for improvement based off of some options.

The main issue with this system is compression. The stacks consistently outproduced the compressor's capacity to draw gas through the system causing the stacks to shut down and lose efficiency (Figures A8 and A9). There are two apparent options to mitigate this issue. One is to add a second nurse tank before the low stage compressor with a 150-psi threshold and a controllable solenoid. This option would allow for the stacks to stay on when the compressors reached their fault pressure. In this case, the solenoid would be activated and gas from the stacks would fill the nurse tank until the compressor was back to lower pressure. This upgrade would also allow for gas production without compression and the low-pressure nurse tank gas could be plumbed to the fuel cells which do not need pressurized hydrogen (10 psi inlet currently achieved by regulators from high pressure storage).

A second modification option would be to place the compressors in the storage building with the storage tanks and add a large propane style tank near the fuel cells. This option would decouple the production and compression steps but could ultimately produce better resulting efficiencies. High pressure is only needed for vehicle fueling and could potentially be a step cut out of the generation system. If the gas produced by the stacks was kept at around 150 psi, there would be less of a chance for power loss. The compression system has consistently been the limiting factor in this system so using it only when necessary could be very beneficial to overall operations efficiency.

Electrolyzer efficiency was monitored over all nine tests by calculating price per kilogram based on average mass flow and electrical consumption with an assumed cost of $0.13 per kWh. Hydrogen cost statistics ($/kilogram) ranged from $15.54 to $17.65 per kilogram. These calculated costs did not take into account solar generated input which ranged between 4 and 28 kW during testing. This would have substantially reduce the price per kilogram if capital costs of solar were discounted (estimated $2-3 dollar per kg savings). A main takeaway from these tests is that price of electricity was factored in and calculated for each test. However, in future operation of this system, the marginal costs will not include power price. The marginal cost of a kilogram of hydrogen is the price of 2.35 gallons of unfiltered water. Smaller scale electrolysis systems are more heavily influenced by capital costs and larger systems are more influenced by feedstock prices. Effective scaling can eventually reduce both of these costs. Future system design and control optimization will eliminate feedstock costs routing overproduction to storable fuel.

## FUTURE WORK

The data collected from the sensor scheme has increased production and efficiency numbers from the machine. These can continue to be improved with more analysis and control adjustments. System integration can develop better understanding of component interactions and balances. Controlling the electrolyzer in parallel with the battery bank, solar array, and fuel cells in one logic scheme could further hone the power plant's potential to meet consistent power needs. More testing and research will continue to tailor the system to achieve practicality and functionality.

Ongoing testing will allow for further understanding of individual system components. Adding more granular energy monitoring sensors could identify further system inefficiencies such as compressor and heater electrical consumption and hydrogen losses. The key findings from this monitoring plan will improve understanding of the hurdles and potential areas for improvement in renewable electrolysis technologies.

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