Hybrid Microgrid Model based on Solar Photovoltaics with Batteries and Fuel Cells

system for intermittent applications

by

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ABSTRACT

Microgrids are a subset of the modern power structure; using distributed generation (DG) to supply power to communities rather than vast regions. The reduced scale mitigates loss allowing the power produced to do more with better control, giving greater security, reliability, and design flexibility. This paper explores the performance and cost viability of a hybrid grid-tied microgrid that utilizes Photovoltaic (PV), batteries, and fuel cell (FC) technology. The concept proposes that each community home is equipped with more PV than is required for normal operation. As the homes are part of a microgrid, excess or unused energy from one home is collected for use elsewhere within the microgrid footprint. The surplus power that would have been discarded becomes a community asset, and is used to run intermittent services. In this paper, the modeled community does not have parking adjacent to each home allowing for the installment of a privately owned slower Level 2 charger, making EV ownership option untenable. A solution is to provide a Level 3 DC Quick Charger (DCQC) as the intermittent service. The addition of batteries and Fuel Cells are meant to increase load leveling, reliability, and instill limited island capability.

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DEDICATION

To my amazing and loving wife, Barbara De Decker

ACKNOWLEDGMENTS

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CHAPTER 1

INTRODUCTION

Microgrids, as defined by the Microgrid Exchange Group (MEG), "A microgrid is

a group of interconnected loads and distributed energy resources within clearly defined

electrical boundaries that acts as a single controllable entity with respect to the grid. A

microgrid can connect and disconnect from the grid to enable it to operate in both grid-

connected or island-mode." [1] Microgrids use Decentralized Generation (DG), usually

serving tens to thousands of users, and embodying a plurality of smaller generators,

usually in the sub Megawatt range. The key advantages are found in power source

flexibility, security, reliability, and improved power quality. The cost per Watt

perspective is difficult to apply to microgrid systems because their benefits touch on so

many areas. That being said it should be noted that the upfront cost of a microgrid is

often a barrier to entry, which is why it is best applied as a community endeavor. Once in

place the cost of upgrading or replacing one or more of the power sources is significantly

less capital intensive when contrasted to a centralized power grid generator. As they

generally do not send power over vast distances, microgrids can make better use of low to

medium voltage systems requiring less metal involved in heavy lines and switching

equipment to accommodate the load. This is a key need for reducing pollution and

resource consumption, thus microgrids are ideal for renewable energy generation

integration. Another advantage is that it is possible to have dissimilar forms of

generation. For example, a microgrid power system can use wind and solar [2], to gain

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the advantages of both and fortify generating ability. The fuel for renewable generation is usually less toxic and has dramatically lower costs, both are very desirable traits. Microgrids offer a higher level of security, and the limited body of affected, making them a less appealing target for hostile intentions. A microgrid system can be installed into a pre-existing community to address the current power needs. Techniques such as Particle Swarm Optimization allows for maximum power management and predictive future planning as the community grows [3]. These advantages are not possible on a large central power grid system mainly because of logistics and capital required. More than one Microgrid can be interconnected to act as a "cluster" allowing for the sharing of resources while maintaining its own security and independence [4-7]. With respect to greenhouse gasses Microgrids utilizing renewable energy production have been shown to generate significantly less CO_2 emissions even in partial capacity [8].

1.1 Statement of Purpose

This document explores the viability and responses of a PV, batteries and fuel cells system based hybrid microgrid model for intermittent Level 3 EV charging services. This concept differs from other microgrid models in that the system remains grid-tied with limited autonomy, striving to reduce strain on the central grid when power is at a premium, and reduce the carbon footprint of the community. Where this concept is unique is that it purposes that each home is equipped with a generating capacity greater than its need, and this excess generated power is shared within the footprint of the microgrid community. The connected central grid is treated as an optional power source.

1.2 **Constraints**

This study was designed with some key objectives to provide the greatest compromise between cost and benefit. The first was to have renewable energy content (Renewable Fraction) of at least 45% of the total consumed energy. Next, maximum annual grid purchase should not exceed 120 megawatt hours (MWh) annually. Lastly, it must have an annual carbon dioxide reduction of at least 50% for the village.

CHAPTER 2

LITERATURE REVIEW

2.1   Microgrids

Microgrids are in essence an evolution to the modern central power grid, sometimes called a macrogrid [3] . Microgrids are not fully defined, as they cross into the domains both as societal needs as it relates to power generation, and the political entomic realm, ruled by policy and regulation [10] .

2.2   Protocols and Standards

Microgrids are still evolving; however, they are governed and shaped by various industry groups. These standards and guidelines can be found in IEEE 1547.4 (Planned Island Systems) with expansion support in IEEE P 1547.8 to broaden the coverage. They also are governed by IEEE 1547.6 that sets guidelines for Secondary Network Distributions Systems (SNDS). Microgrid interoperability for central power grid interaction is covered in IEEE P2030. These standards and guidelines are focused around areas of Power Flow, Short Circuit, Power Quality, Quasi-Statics, Dynamic Stability, and Transient Stability.

Microgrids incorporate one version or another of Supervisory Control and Data Acquisition (SCADA) to regulate power flow to the needed areas and handle communication interoperability between multiple power systems [1]. Figure 1 is a chart

taken from IEEE P2030 showing the complexity for allowing a microgrid to communicate with other power system entities.

These protocols are the driving rules that turn the chaos of conflicting community's needs into a pulsing intelligent system supplying power from source to user.
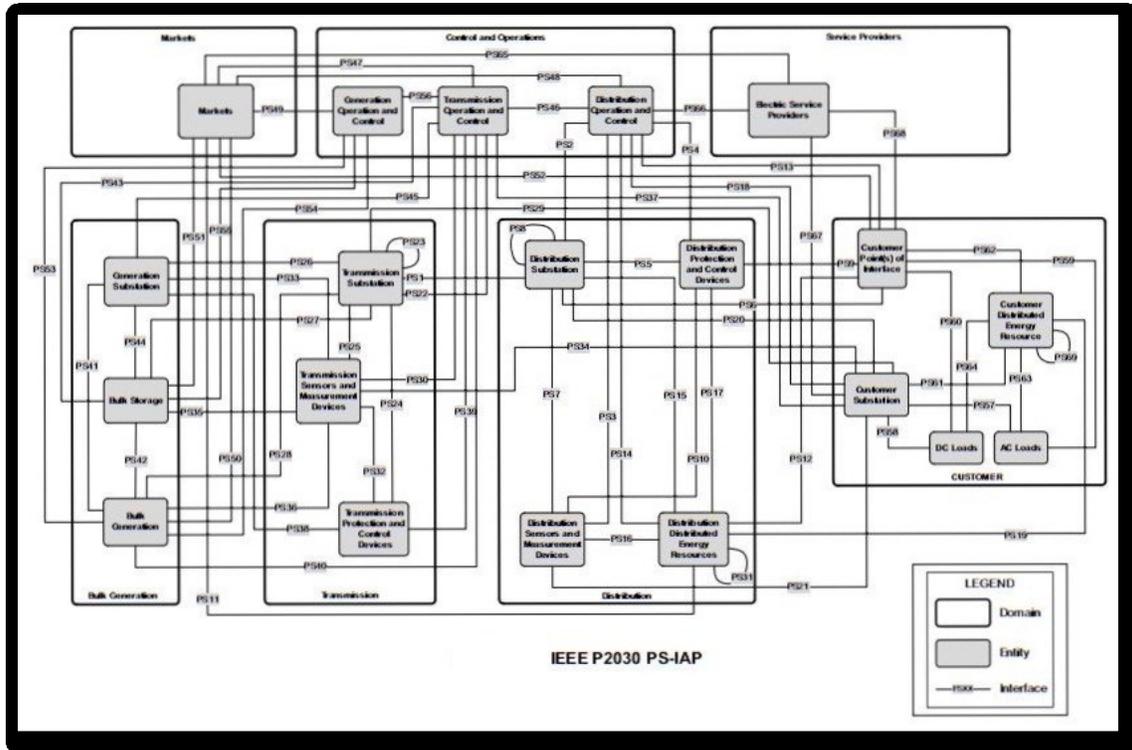
Figure 1: Smart Grid Implementation Chart [10].

2.3   Fault Vulnerability

Microgrids are generally smaller than arms of the centralized grid, 10 Megawatts or under, servicing communities instead of vast regions. This means greater flexibility and precision can be devoted to how the power in the microgrid is handled. A centralized grid must apply a blanket policy from millions to hundreds of millions of homes, a one size fits all perspective, and sometimes power quality suffers for it. This can be seen in a central grid brownout, where the

power is still there but the grid voltage drops, causing lights to flicker or sensitive electronics to react negatively. Sometimes it is more extreme where an entire area will experience complete power failure, this is called a blackout. For example, poor policy and bad planning caused a blackout that originated in the southern region of Arizona resulting in much of San Diego California being left in the dark [11]. Conversely, a microgrid policy or system failure would only affect the microgrid. If a failure similar to the one that happened in Arizona occurred, it would only affect that system. It is likely that non-conformance discovery and containment would occur more rapidly. Microgrids do not take perturbation as well as the central grid given they lack the enormous size, but they do recover much faster. Many are connected to the central grid, so the variance in behavior of the microgrids must be conditioned to work with the utility networks [7, 12-14].
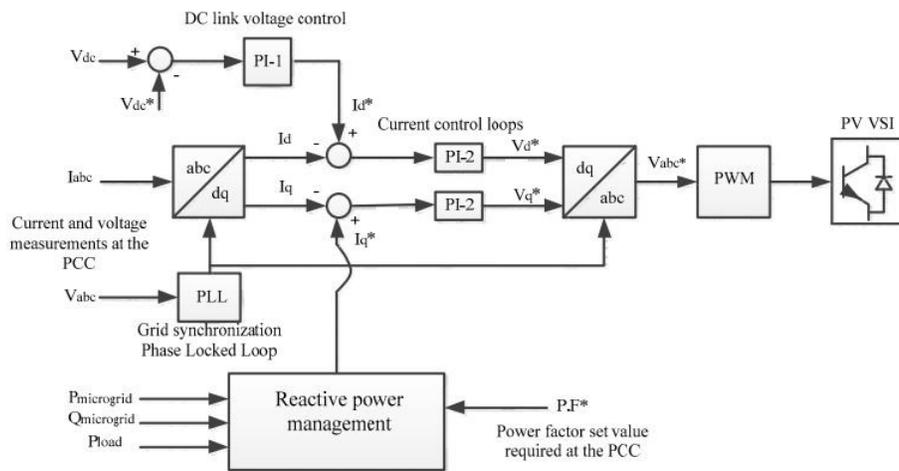
Figure 2: Schematic diagram of proposed control strategy [12].

2.4   Interconnectivity of Systems

Microgrids usually use more than one power source, allowing for higher reliability and greater efficiency. The generating sources do not have to push power over

enormous distances; as a result, they have more effective feedback and response through their Energy Management System (EMS) [15, 16]. By contrast the central grid must rely on substations and power up peak plants when demand is elevated. The peak plants are often multi-hundred kilowatt to multi-megawatt given the distance and population they must address. Microgrids are something of a different story; the expected output is in the tens of megawatts or less. This makes them ideal for renewable power systems, as shown in case studies [6, 12]. As different power generation solutions will have advantages in different conditions this presents a "cost possible" scenario where a microgrid community could look at resources that normally would be ignored because of a non-megawatt capacity.
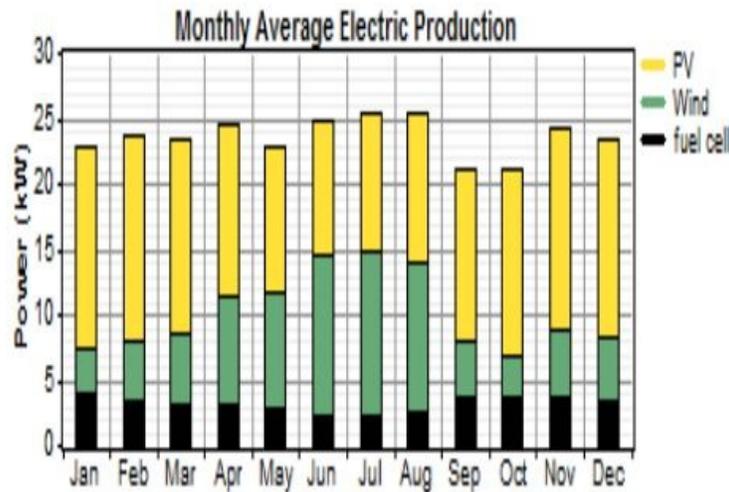
Figure 3: Decentralized Generation annual electrical production [6].

2.5   Carbon Footprint

Another benefit seen in microgrid implementation is the reduction in carbon dioxide emissions. As mentioned, microgrids use power sources more efficiently, and

the opportunity to use renewable power is appealing, as the cost of fuel is significantly lower. When a microgrid runs cleaner the entire community supported runs cleaner. The effect of the whole is greater than the sum of its parts. Further, if renewable fuels are being used, the conventional fuels are not. Case studies have shown a significant reduction in CO_2 by the inception of microgrid power systems [17].

2.6   Micro Power Sources

Photovoltaic arrays are a collection of panels, pulling a small Wattage level output from each panel, culminating to kilowatts and above. Once the panels are created they are very low maintenance, and continue to function for 25 years. The production of power is clean, safe, and quiet. This makes them an obvious choice for microgrid involvement. By happenstance, it seems that PV arrays are most effective at medium scale, which is a commonality for the microgrid model [18]. PV enhanced microgrids are a good solution, but there is an obvious drawback. The sun does not shine twenty four hours a day, further, cloud disruptions can cause heavy production loses [19]. A stand alone microgrid for a modern human habitat is ideal, but implausible. To navigate this issue other power sources must be included. Microgrids that exclusively function in, what is termed Island mode, i.e. completely disconnected from the grid, will usually have some other form of generation. Diesel is the most common. However, even with this solution, there are issues of power up and power off time, reducing the effectiveness of the system. If the microgrid is not islanded then it is called grid-tied, meaning that it pulls power from the central power grid. In this function the grid is treated as one of the

power sources, like the PV [20]. To enhance the robustness of the microgrid power systems, batteries are often introduced as ballast, and can greatly improve performance. The battery provides instant power on demand allowing for drops in power production from other sources to go unnoticed as it gives the other power systems time to start up or the perturbation in the grid to subside greatly, improving reliability and power quality [14, 21-23].

2.7   Grid-Tied and Island Mode

Island, also called "stand alone" or "autonomy" is the ability of the microgrid to function autonomously without support from an exterior centralized grid. Grid-tied means that the system is connected to a central power grid and uses power from a plurality of sources. Many microgrids can function as a hybrid, shifting between grid-tied or island mode [12, 24].

The ability to transition from grid-tied mode to island mode can be indispensible. This was seen on March 11th 2011, when the earthquake measuring 9.0 on the Richter scale sent tsunamis to Sendai Japan. The ensuing damage decimated the regions and dependent power structure. Power was down for weeks throughout the entire urban region except for Tohoku Fukushi University. The University was testing an experimental microgrid that used three types of generation (PV, Fuel Cells, and Gas Micro Turbines). This one MW system did not have to send power over great distances, significantly reducing losses. As a result, it was able to power the northwest part of town including the hospitals [25].

Microgrids can also serve as an asset to surrounding communities and systems. To this point, the University of California San Diego (UCSD) had been researching microgrids for some time. Their microgrid infrastructure entails solar, wind, wave, and stand-alone generators all in an effort to reduce carbon footprint and reduce draw from the region power grid. In 2007 California was ravaged by wild fires that eventually damaged the southern California power grid and began to fail. UCSD responded to the crisis by dropping its power consumption and maximizing its generation, supplying power to the City of San Diego. Figure 4 shows the UCSD microgrid response timeline. This case gives strong evidence to the advantage of having hybrid grid-tied systems embedded throughout urban communities.
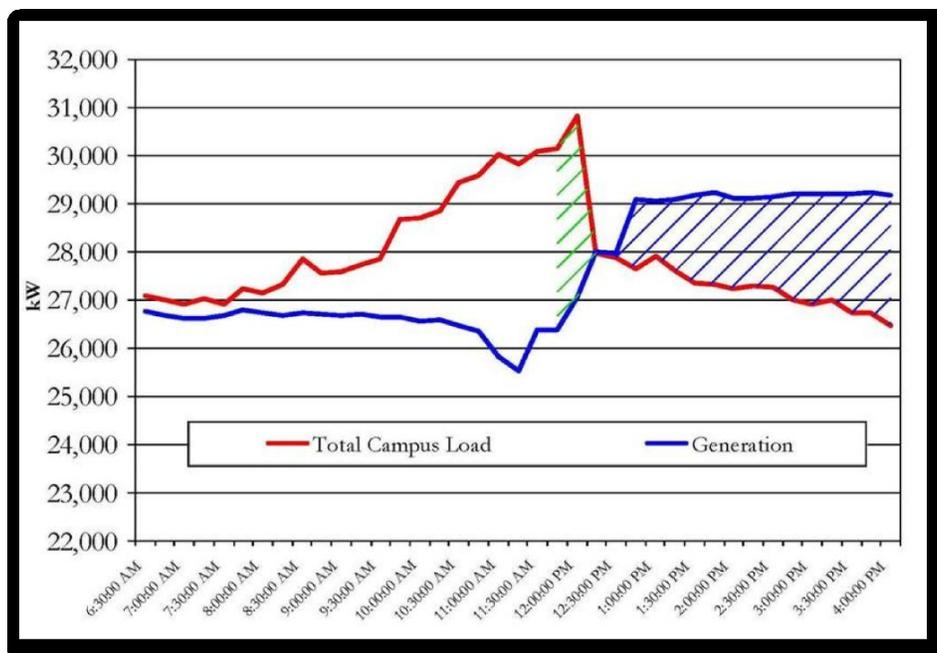
Figure 4: UCSD Load vs. Generation Plot for Oct. 2007 [26].

CHAPTER 3

MODEL DEVELOPMENT

3.0 Source Data and Component Modeling
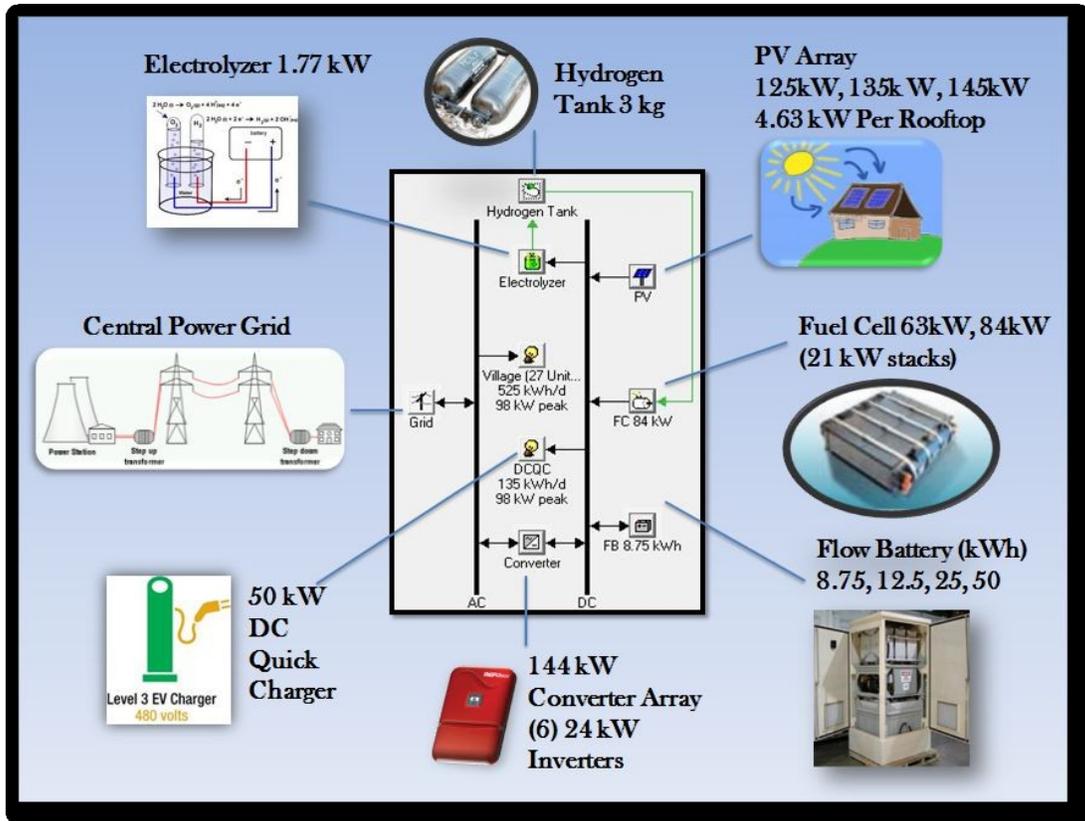
Figure 5: Schematic of Modeled Village Microgrid.

3.1 Biosphere 2 Village

Biosphere 2 is a research facility just north of Tucson Arizona (Lat 32.35 N, Long W 110.50). The model is based on data from Biosphere 2's Village (Figure 6) as part of

the Future Cities project. There are 28 housing units, labeled 1 to 28, each having 3 to 5 bedrooms depending on the unit. All units have two refrigerators, a stove, microwave, water heater, TV and centralized heating and cooling. There is a private shower and washroom in each bedroom. The rooftops are a flat level design with roughly 1000 to 1200 square feet per unit, of which at least 800 square feet is usable for PV, more with modified racking.

Figure 6: Google map view of Biosphere 2's Village.

The base data for modeling was taken from the Biosphere 2 Village and was recorded month to month from each unit for the span of 17 months, of which the first 12

months will be used for this simulation. A Energy Map of the community usage is shown in Figure 7.
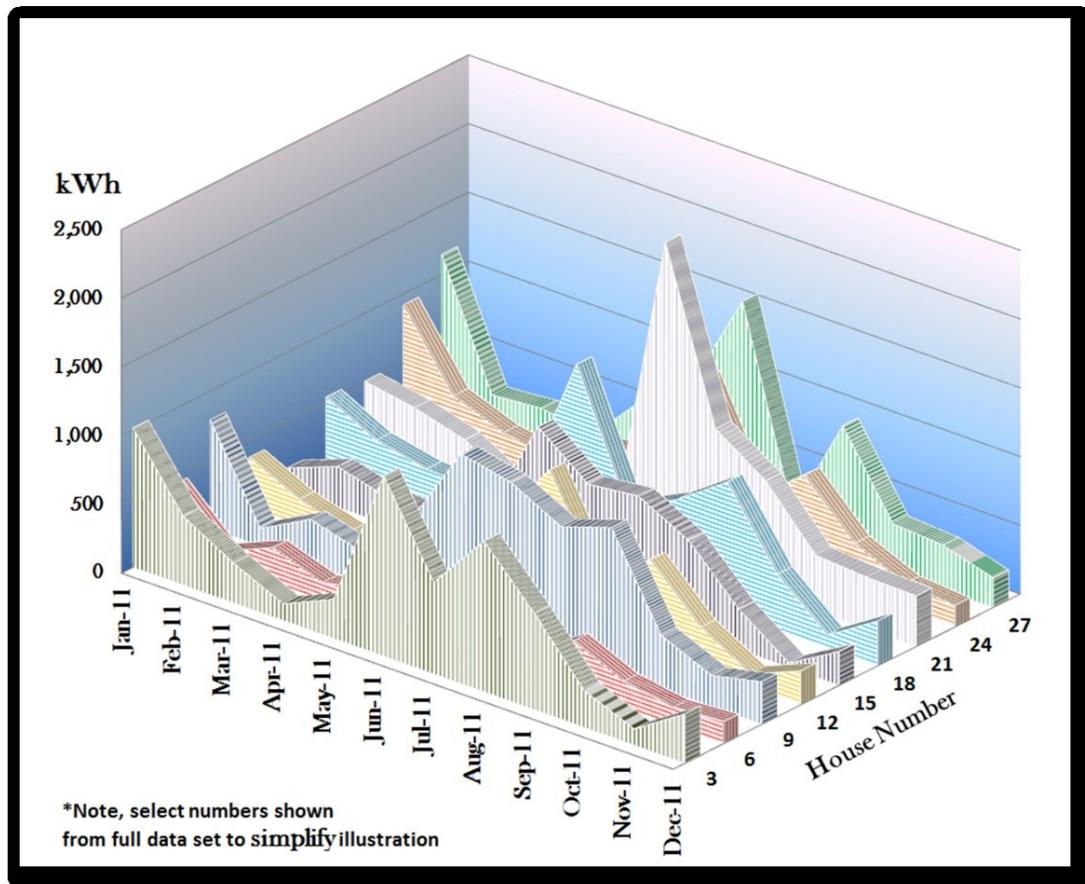
Figure 7: Village Energy Map.

Figure 7 shows a sample of the village data to illustrate how each home has different peaks and valleys. The model data was collected in monthly intervals. This needed to be analyzed and transposed to hourly data points to be loaded into HOMER. Two random variability filters were applied; 18 percent for Day-to-day, and 20 percent for Time-step-to-time-step. Day-to-day variability changes the shape of the load on a day to day, in similar fashion Time-step-to-time-step variability creates changes to the time blocks assigned. This adds variability to the level of power used and when, but does not

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change quantitative value of the original data. The average load was 21.9 kW, with a peak load of 98.5 kW giving Load factor of 0.222. The average power usage is 525 kWh per day for the community. This number is the Core Target Need (CTN) illustrated in Figure 8. It was hypothesized that in a microgrid system the CTN is the point where the excess energy generated by a portion of the homes would balance the deficits consumed by other homes. The CTN was used to base the starting point for the sizing of the PV array and support power systems.
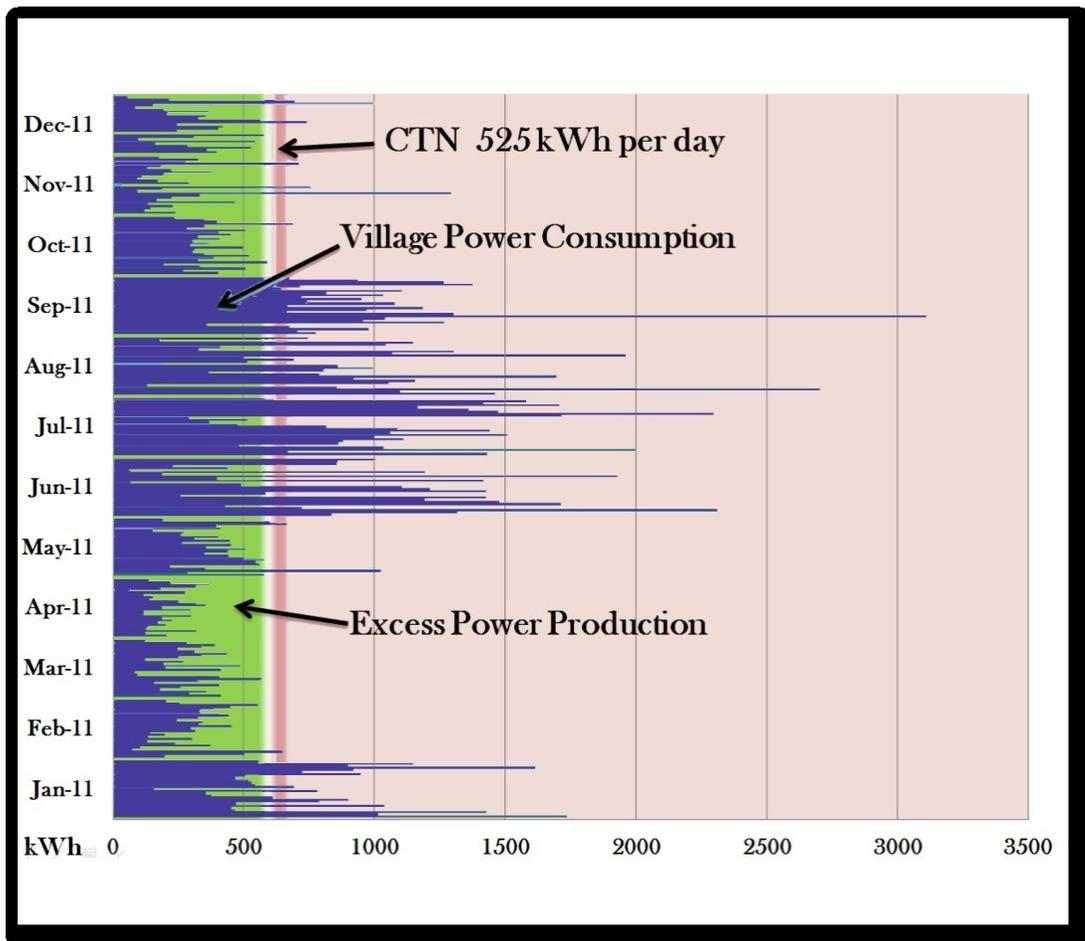
Figure 8: Village Core Target Need.

3.2 Solar Photovoltaic Array

The rooftop PV array is the bulk of the community's power supply system and one of the most cost effective sources of sustainable power as Arizona receives more than 320 sunny days in a year. It was found that the target constraints (or energy mix) could be obtained with 125 kW array, broken up into 4.63 kW per rooftop, 19 PV panels at 245 Watt rating. This works out to about 361 square feet, plus 15 percent for racking, leading to 415.15 square feet which is well under the estimated 800 square feet of usable area per roof. This study revolved around the PV array size of 125kW which was found to be optimal for target objectives, but testing was also done against arrays of 135 and 145 kW for depth discovery and comparison. Figure 9 illustrates the solar insolation for the region; this data is imported from the National Renewable Energy Laboratory (NREL).
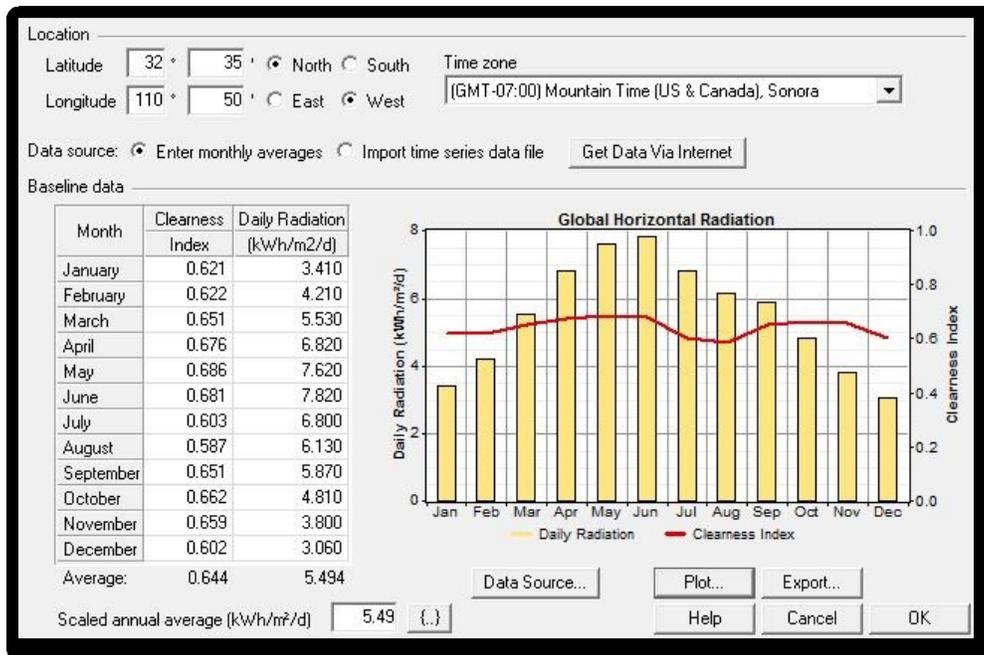
Figure 9: Insolations for the Biosphere 2 Village.

3.3   Inverter

Inverter is an energy converter used to translate power from DC to AC and in rectifier mode AC to DC. The inverters involved in the simulation are modeled after the RefuSol 024-UL 24kW product [27]. As with the PV, the inverter selection was static. Six inverters, each a 24 kW rating, provided a maximum conversion of 144 kW as an array. The intent was for the inverters to be evenly distributed throughout the community for sub-microgrid distribution control. The even number was selected to allow for hypothetical parallel placement throughout the Village community.   It has been demonstrated in simulation that a parallel inverter scheme has a higher reliability, better load management, and greater efficiency [13]. Figure 10 shows the simulation of the output for the inverter configuration (PV 125 kW/Fuel Cell 63 kW/ Battery 8.75 kWh).
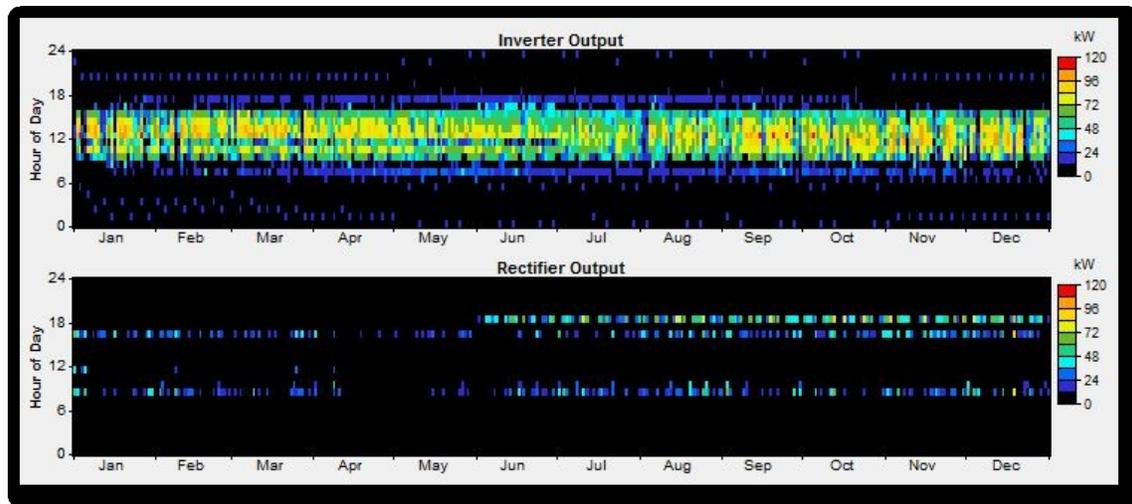
Figure 10: Converter Output for Hybrid Configuration FC63kW+FB8.75kWh.

3.4   Intermittent load

An objective component of this simulation is to have the excess power produced collected to power an intermittent community service within the footprint of the microgrid. In this scenario it is decided that a clean microgrid community should have the option of allowing its members to own and use Electric Vehicles (EV). However, EV ownership means charging at home. To do this there needs to be a parking spot adjacent to the home to install Level 2 Electric Vehicle Supply Equipment (EVSE). The average required charge time for a level 2 is around 5 hours. The Village does not have adjacent parking so a solution is to install a community use 50 kW Level 3 DC Quick Charger (DCQC). This technology provides DC power directly to the EV's battery, reducing charge times to as little as 30 minutes. Level 2 charging systems have been integrated into PV arrays for some time; however, recent research has proven that DC charging can be effectively integrated into battery supported PV systems [28].

To determine DCQC usage and required power it is assumed that there are two cars per household giving 54 total cars. Charger use was modeled at an EV population of 10% as the mandated need, as well as 15% and 20% to explored configuration range. It was estimated that the drivers will travel 16 miles one way to work, with an additional 8 miles added for miscellaneous travel, giving an expected daily travel of 40 miles. The EV has a range of 100 miles and would require a 30 minute charge every two days, yielding a community daily power load of 135, 202, and 270 kWh respectively. Three time ranges were grouped to simulate charging habits; before work (8 to 9am), lunchtime

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(11 am to 12pm), and after work (4 to 5pm). Further, a Day-to-day variability of 40% and Time-step-to-time-step were applied giving more realistic user variation.
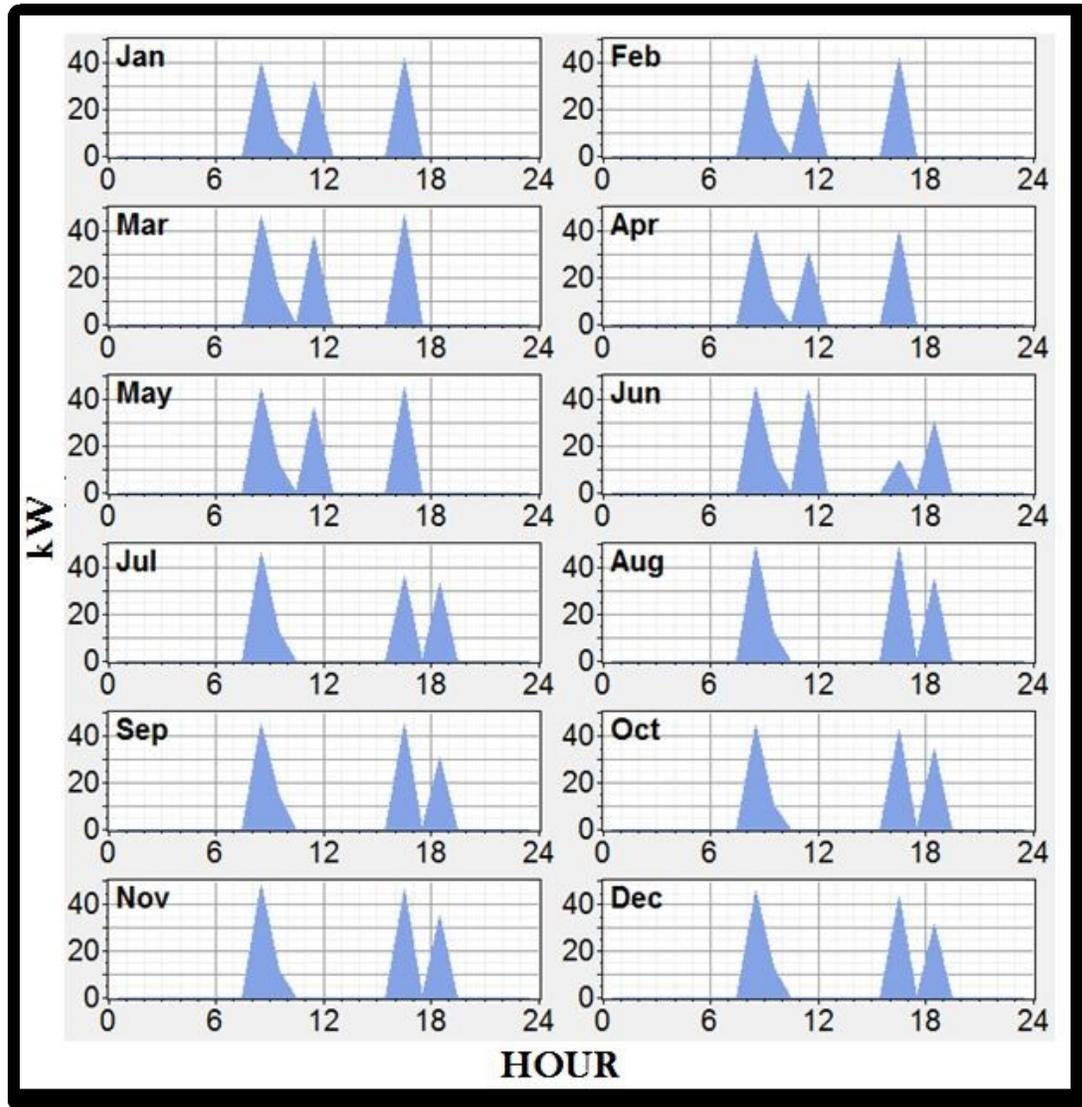
Figure 11: Intermittent Load Profile.

3.5   Fuel Cells

Fuel cells, first developed in 1839 by William Grove, work by combining Oxygen with Hydrogen to create water, and by doing so, extracts electrons to do work (Figure 12).
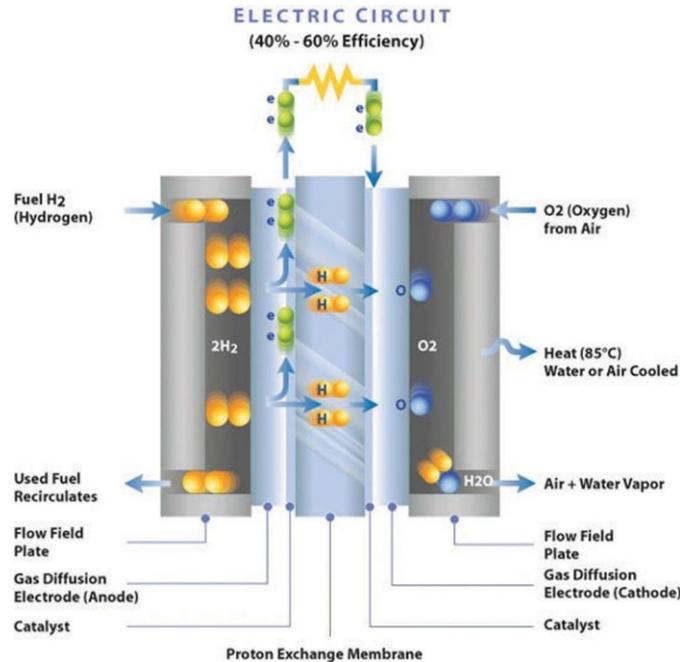
Figure 12: Fuel Cell Schematic.

The advantage of using this technology is its use of non-hydrocarbon fuel to produce clean power.   The hydrogen fuel can be generated on site through an electrolyzer. The fuel cells used in the simulation are composed of 21 kW stacks, with 10,000 hours operation life at an efficiency of 52 percent. They are modeled after the Ballard FCvelocity-9SSL [29]. These models are Proton Exchange Membrane (PEM) fuel cells and were selected because they are powered by pure hydrogen. Figure 13 illustrates fuel cell operation schedule as it relates to the modeled utility rate schedule. It

was decided that the fuel cell should have forced operation during hours of no sun with exception given to the most expensive months as determined by the utility rate schedule.
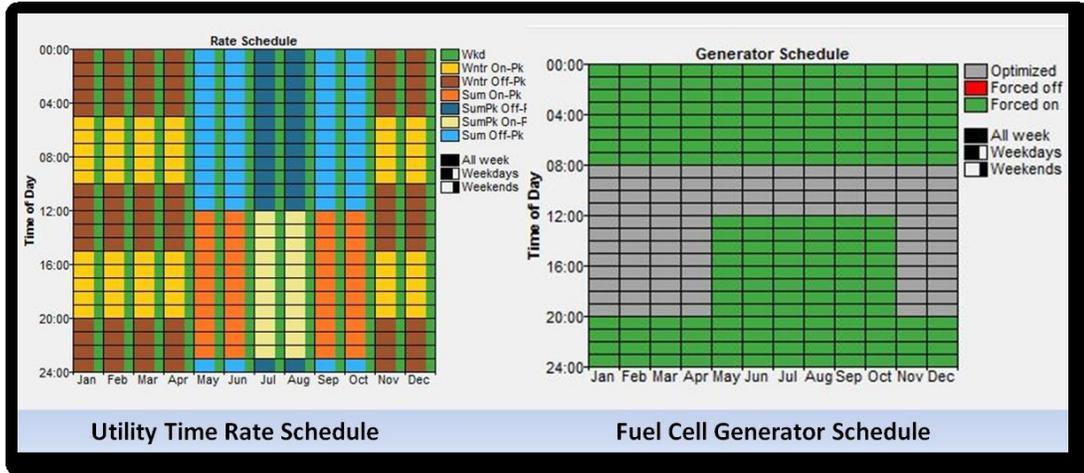
Figure 13: Utility Rate Schedule vs. FC Generation.

Figure 14 shows the simulated behavior of the fuel cell as it relates to time. Notice that the expected operational lifetime of the stacks exceeds the simulation life of 25 years.

Quantity	Value	Units	Quantity	Value	Units	Quantity	Value	Units
Hours of operation	278	hr/yr	Electrical production	5,627	kWh/yr	Hydrogen consumption	326	kg/yr
Number of starts	278	starts/yr	Mean electrical output	20.2	kW	Specific fuel consumption	0.058	kg/kWh
Operational life	36.0	yr	Min. electrical output	18.9	kW	Fuel energy input	10,879	kWh/yr
Capacity factor	1.02	%	Max. electrical output	27.4	kW	Mean electrical efficiency	51.7	%
Fixed generation cost	5.83	$/hr						
Marginal generation cost	0.00	$/kWh						

Figure 14: PEM 63 kW - Output vs. Time.

3.6   Hydrogen Production

Hydrogen production is modeled after the Proton-Onsite HOGEN S10.   This model consumes 1.77 kW to produce 0.57 kg of hydrogen every 24 hours. There were two main reasons for choosing onsite hydrogen production in spite of the additional projected cost of the equipment.   The first was to mitigate greenhouse gas emissions. Assuming that the delivery Semi-Truck comes from central Tucson, this means a one way travel distance of about 60 miles, at 7 miles per gallon the truck produces an estimated 1.36 kg of CO_2 per mile. Every delivery to Biosphere 2 would contribute 162 kg of carbon dioxide.   Even if the tank size was increased to allow for a monthly delivery, this would still generate 1.9 metric tons per year. The second reason for onsite production is that Biosphere 2 has a water storage capacity of 500,000 gallons on site. The electrolyzer has a projected consumption of 0.065 gallons of water per hour, or 567.6 gallons per year.   Production of Hydrogen at point of use is an economic and environmentally responsible option that is viable.

3.7   Batteries

Batteries use a chemical process to store electricity. A chief advantage is that power access is instantaneous. A drawback is the limited duration of energy output. For this experiment a Zinc Bromide Flow Battery (FB) is selected. Unlike conventional batteries the electrolytes are stored in separate tanks and pumped to the cell stack (Figure 15). The batteries used in the simulation are modeled after the ZBB EnerStore for ZESS battery.   Capacities are 8.75, 12.5, 25, and 50 kWh [30].   The electrolyte solutions are pumped through the battery stack and reconstituted through a chemical process.   These

batteries can be fully discharged without capacity degradation with cycling. Only the cell stack needs replacing every 4 to 5 years. The replacement cost of the cell stack is roughly 18% of the battery cost, and has been incorporated into the model over 5 years as the yearly O&M cost.
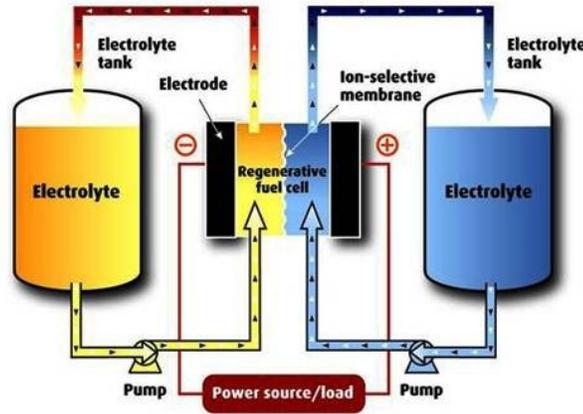
Figure 15: Flow Battery Schematics.

Figure 16 shows the simulated Zinc Bromide flow battery response in contrast to Figure 17, which is a deep cycle lead acid of comparable size. (PV 125 kW, FC 63 kW)
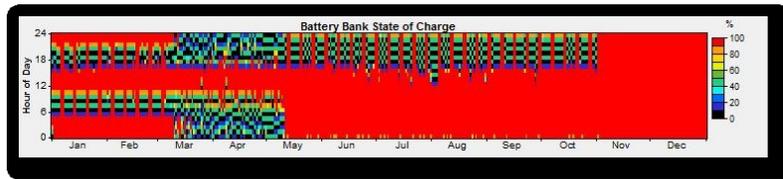
Figure 16: Flow Battery SOC vs. Time.
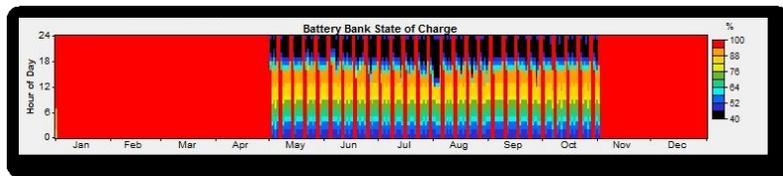
Figure 17: Deep Cycle SOC vs. Time.

3.8   Software

The modeling software is HOMER (Hybrid Optimization Model for Electric Renewables), Version 2.81 from Homer Energy LLC. HOMER's development can be traced back to NREL and is currently used by more than 80,000 people in 193 countries. HOMER works by performing energy balanced calculations including aspects of cost and efficiencies against the constraints applied by the user. It ranks all successful results by Optimizations, i.e. net present cost to determine best configuration. It also makes use of Sensitivity Analysis using inputted variables running repeated simulations against these inputs [31].
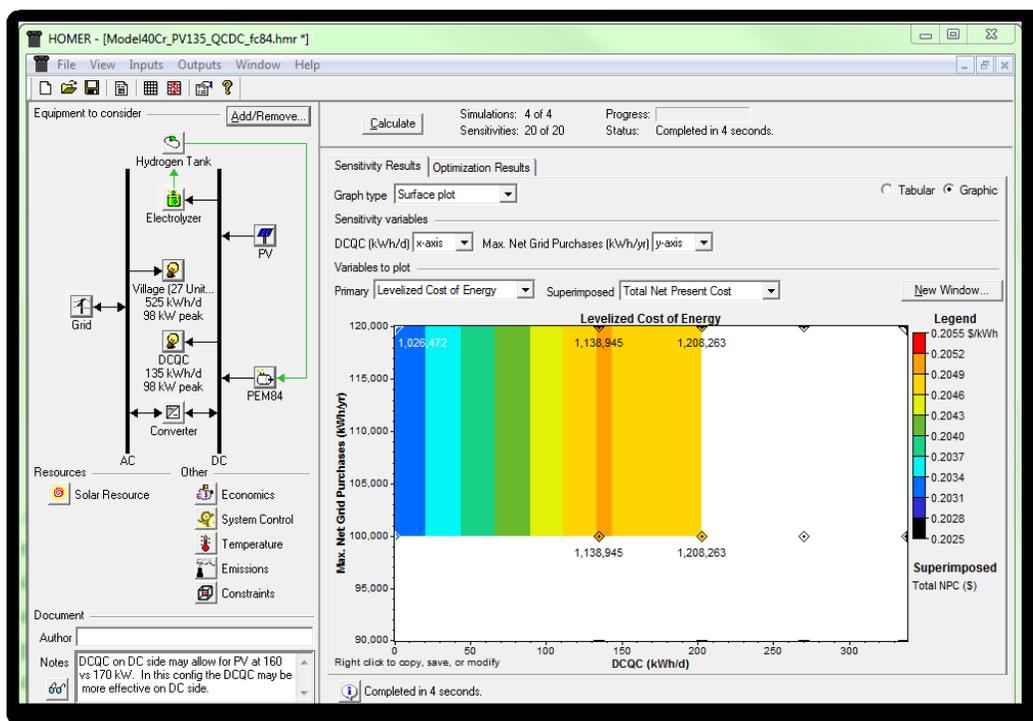
Figure 18: HOMER system interface.

CHAPTER 4

MODEL DEVELOPMENT

4.0   Model Development

The modeling process was conducted in progressive stages, building in complexity with each stage requiring up to 37,632 simulations with 35 sensitivities, as much as 20 hours per run. These numbers dropped as optimized selections rose to the top removing inferior combinations. Each simulation is a calculation on how energy flows from each component throughout the life cycle of the system. Sensitivity variables are ranges that are specified for a given component, such as PV efficiency. The initial model development was of the village alone, then with the addition of the DCQC. This was useful in determining minimal PV need to achieve the 45% or above renewable fraction constraint. PV array and Inverter capacities were determined and set as a static value then tested against each version of battery, fuel cells, and then individual combinations of each. The process was repeated for two other PV array capacities, resulting in 69 configurations, tested at three different load conditions.   To synthesize how one configuration modeled was relative to another it was important to look for meaningful commonality. Five key metrics were selected to as to embody the most impactful data. In sum, how much does it cost now and completely, what type of environmental impact can be expected, which configuration has the more applicable autonomy to the expected operational conditions.

4.1 Five Key Metrics

When looking at a complex system it is difficult to select any one parameter metric to determine best outcome. For this model five key metrics were selected as they align strongest with the thesis.

4.1.1 Net Present Cost (NPC) is the cost of all components for install and operation over the lifespan of the model minus the value created during operation.

4.1.2 Cost of Energy (COE) is the average cost per kWh of useful electricity produced.

Equation 1: Cost of Energy

$$COE = \frac{C_{ann,tot} - c_{boiler} H_{served}}{E_{served}}$$

where:

$C_{ann,tot}$ = total annualized cost of the system [$/yr]

c_{boiler} = boiler marginal cost [$/kWh]

H_{served} = total thermal load served [kWh/yr]

E_{served} = total electrical load served [kWh/yr]

4.1.3 Grid Purchased per Year (kWh/yr) is the amount of power purchased from the centralized grid per year and does not include energy generated by the other microgrid power sources.

4.1.4 CO2 (kg/yr) is the approximated quantity of carbon dioxide gas produced by non-renewable power production.

4.1.5 Autonomy is the amount of time that the system can function without power from the grid. In this document, this term is used in place of "island" or "stand alone" because it is representative of the individual components being tested. When both Fuel Cells and Battery are present the number given is a summation of the two.

Equation 2: Autonomy of Battery

$$A_{batt} = \frac{N_{batt} V_{nom} Q_{nom} \left(1 - \frac{q_{min}}{100}\right)(24\,h/d)}{L_{prim,ave}(1000\,Wh/kWh)}$$

where:

N_{batt} = number of batteries in the battery bank

V_{nom} = nominal voltage of a single battery [V]

Q_{nom} = nominal capacity of a single battery [Ah]

q_{min} = minimum state of charge of the battery bank [%]

$L_{prim,ave}$ = average primary load [kWh/d]

Equation 3: Autonomy of Hydrogen Tank

$$A_{htank} = \frac{Y_{htank} LHV_{H_2}(24\,h/d)}{L_{prim,ave}(3.6\,MJ/kWh)}$$

where:

Y_{htank} = capacity of the hydrogen tank [kg]

LHV_{H_2} = energy content (lower heating value) of hydrogen [120 MJ/kg]

$L_{prim,ave}$ = average primary load [kWh/d]

Net Present Cost and Cost of Energy are grouped together as they provide a total and present time value of the system. Grid Purchase per Year (kWh/yr) and CO_2 (kg/yr) are also grouped together because they give perspective of impact to the exterior

environment. The last metric Autonomy is a selection metric and should be used to determine what configuration is most suitable for a given condition, i.e. available sun hours and grid reliability.

CHAPTER 5

DATA AND ANALYSIS

5.1   **Stage One**

The first stage in modeling allowed for multiple numbers of each type of battery to be used, giving a greater range of storage capacity options. It was originally thought that the metric of cost combined with the other 4 metrics would allow for detectable divergence to determine superior configurations. Table 1 shows configuration and level of intermittent load is achievable. The fields with numbers indicated that a battery is part of the configuration, and the number batteries of that type used. Configurations not using batteries will have a "Yes" or "No" to indicate if the design is optimally viable for the represented intermittent load. All configurations were able to support up to a 15% EV population with drop off at 20% for all non battery supported systems and the two smaller battery supported configurations under the PV 125 kW platform.   This information is useful in selecting configurations as for the size and number of components needed, but the picture is incomplete. Stage 2 will apply the five metrics giving a clearer understanding.

FB = Flow Battery (kWh)		FC = Fuel Cell (kW)			
	EV 0 %	EV 10%	EV 15%	EV 20%	EV 25%
Congfiguration PV125 kW	0 kWh	185 kWh/day	202 kWh/day	270 kWh/day	887 kWh/day
FB8.75	1	1	1	4	No
FB12.5	1	1	1	4	No
FB25	1	1	1	2	No
FB50	1	1	1	2	No
FC63	Yes	Yes	Yes	No	No
FC84	**Yes**	**Yes**	**Yes**	No	No
FB8.75+FC63	1	1	1	No	No
FB12.5+FC68	8	2	6	No	No
FB25+FC63	2	1	3	6	No
FB50+FC63	1	2	2	3	No
FB8.75+FC84	2	8	8	10	No
FB12.5+FC84	1	8	8	4	No
FB25+FC84	1	8	8	2	No
FB50+FC84	5	1	2	No	No
Congfiguration PV185 kW	0 kWh	185 kWh/day	202 kWh/day	270 kWh/day	887 kWh/day
FB8.75	1	1	1	4	No
FB12.5	1	1	1	4	No
FB25	1	1	1	2	No
FB50	1	1	1	2	No
FC63	Yes	Yes	Yes	No	No
FC84	Yes	Yes	Yes	No	No
FB8.75+FC63	1	1	8	5	No
FB12.5+FC63	2	1	2	8	No
FB25+F68	1	1	1	4	No
FB50+FC63	1	2	2	2	7
FB8.75+FC84	2	3	3	6	No
FB12.5+FC84	1	8	8	4	No
FB25+FC84	5	4	2	2	No
FB50+FC84	8	1	1	2	7
Congfiguration PV145 kW	0 kWh	185 kWh/day	202 kWh/day	270 kWh/day	337 kWh/day
FB8.75	1	1	1	4	No
FB12.5	1	1	1	4	**No**
FB25 EV	1	1	1	2	No
FB50 EV	1	1	1	1	5
FC68	**Yes**	**Yes**	**Yes**	No	No
FC84	Yes	Yes	Yes	No	No
FB8.75+FC68	1	1	1	5	No
FB12.5+FC63	2	2	2	8	No
FB25+F63	1	1	1	4	No
FB50+FC68	2	2	8	2	6
FB8.75+FC84	2	3	3	5	No
FB12.5+FC84	1	3	8	5	No
FB25+FC84	1	8	8	4	No
FB50+FC84	5	2	2	2	No

Table 1: Optimized Configuration vs. Intermittent Load - No Battery Limit.

5.2   Stage Two

The five metrics in sets were applied to each of the three platforms with one of each configuration at an EV population of 10 percent. For this analysis EV 10% makes sense as the EV population is unlikely to grow beyond 10 percent at a rate that would prevent installment of additional equipment; however, in the event of such a case Table 1 provides sufficient guidance for system upgrades. The grid-tie + DCQC are added to illustrate a baseline with no renewable power enhancement. The baseline is meant to give perspective benefits in relation to the five metrics. The graphs for stage 2 and stage 4 are for an EV 10% population.

In respect to Prime Cost (Figures 19 - 21), the battery only configuration costs come in at the lowest end; however, when comparing the fuel cells to the battery fuel cell combination there is a marginal flattening. In the area of Environmental Impact (Figures 22 - 24), there is a dramatic reduction in contrast to the baseline along with some marginal dips in the fuel cell combinations specifically the FC63 kW+FB8.75kWh, FC63kW+FB12.5kWh, and FC84 kW+8.75kWh. The last set deals with autonomy (Figures 25 - 27) and the combinations containing the FB50 kWh battery show strong advantage, but also cost more. These measurements are insightful for planning against budget and autonomous performance; however, these changes are not marginally definitive. It shows that the midrange configurations are ample for the job. A more thorough and restrictive approach is taken in stage 3
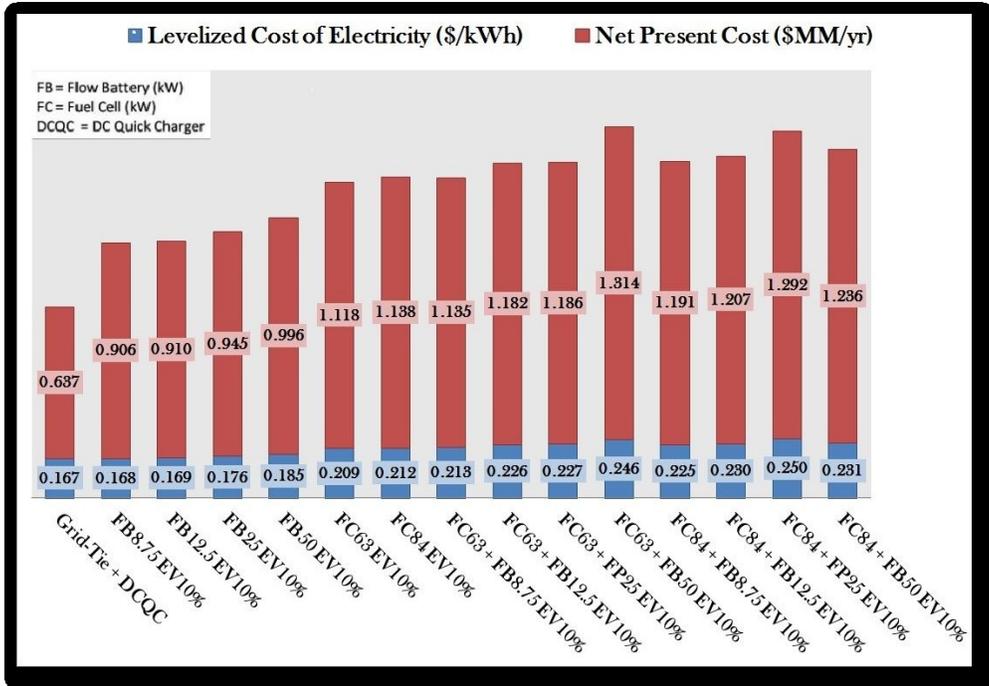
Figure 19: Prime Cost PV125 kW - No Battery Limit.
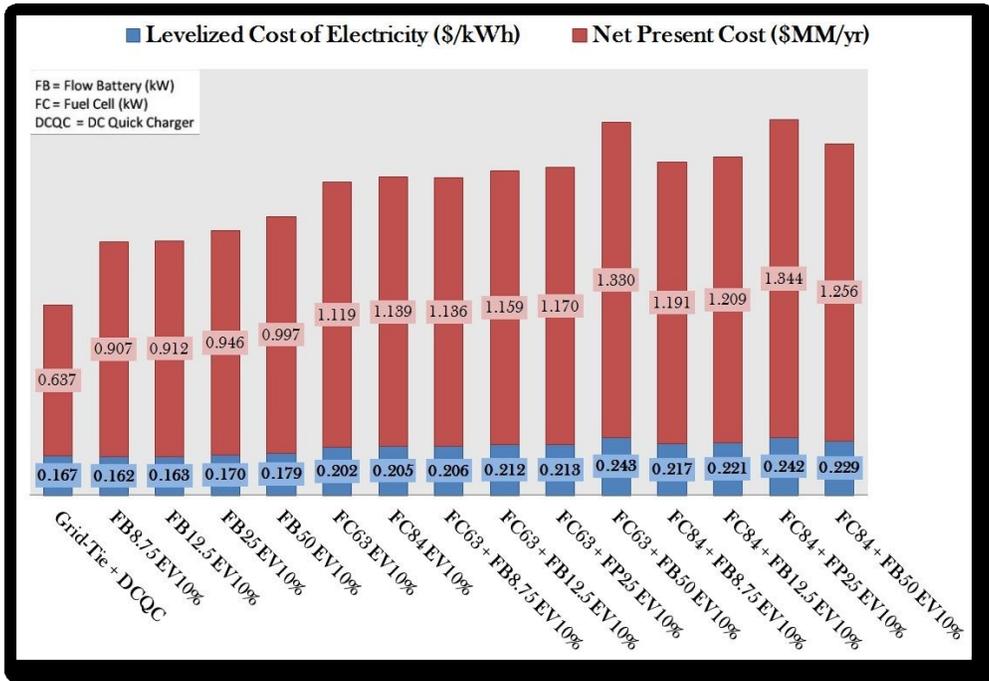
Figure 20: Prime Cost PV135 kW - No Battery Limit.
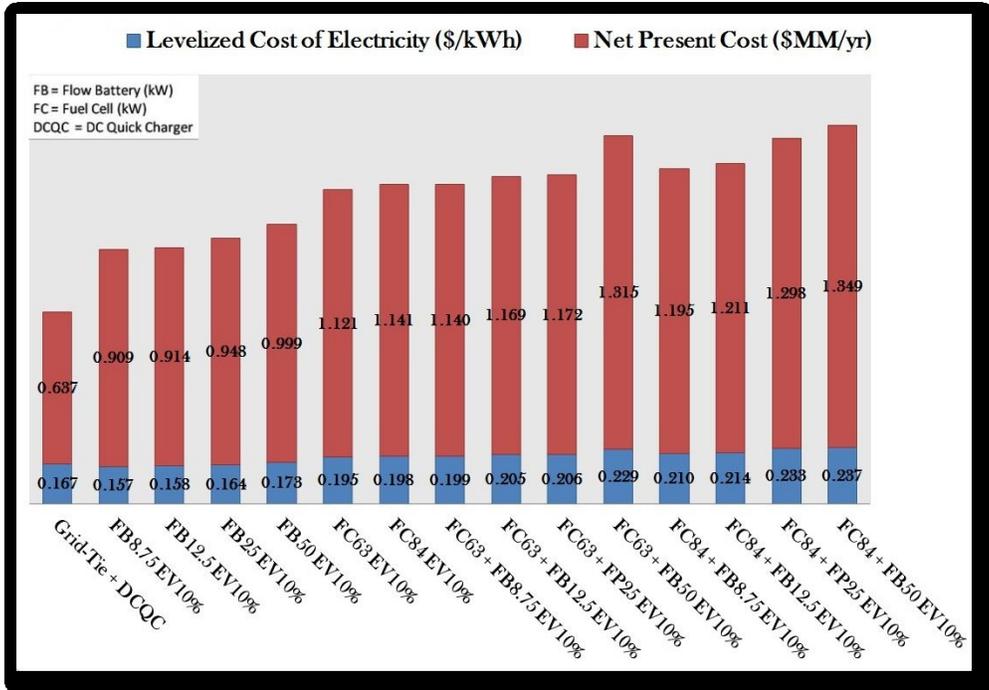
Figure 21: Prime Cost PV145 kW - No Battery Limit.
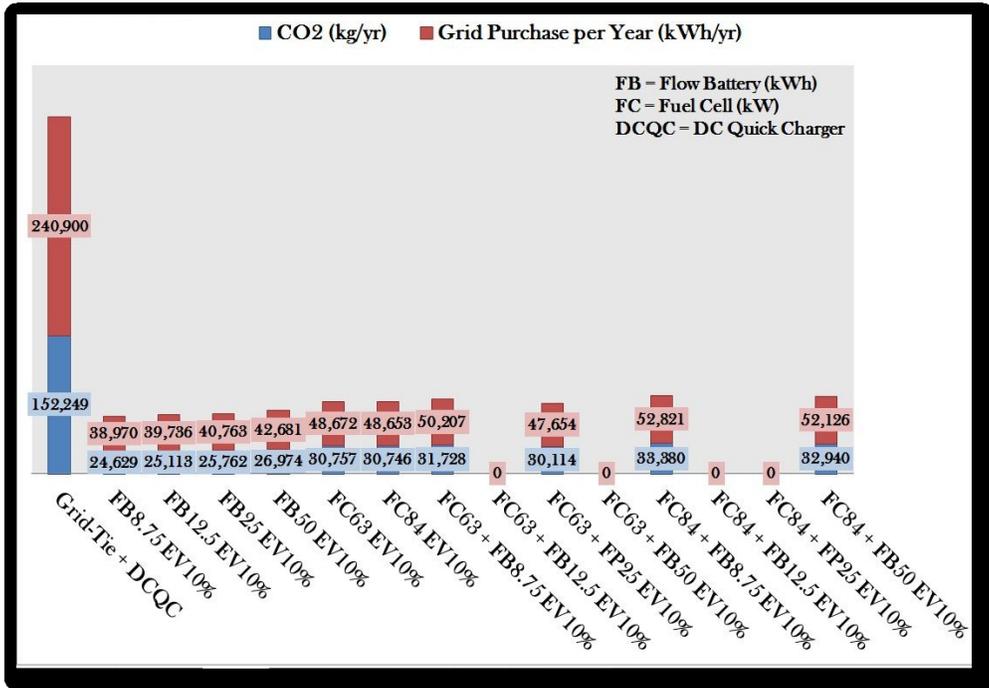
Figure 22: Environmental Impact PV 125 kW - No Battery Limit.

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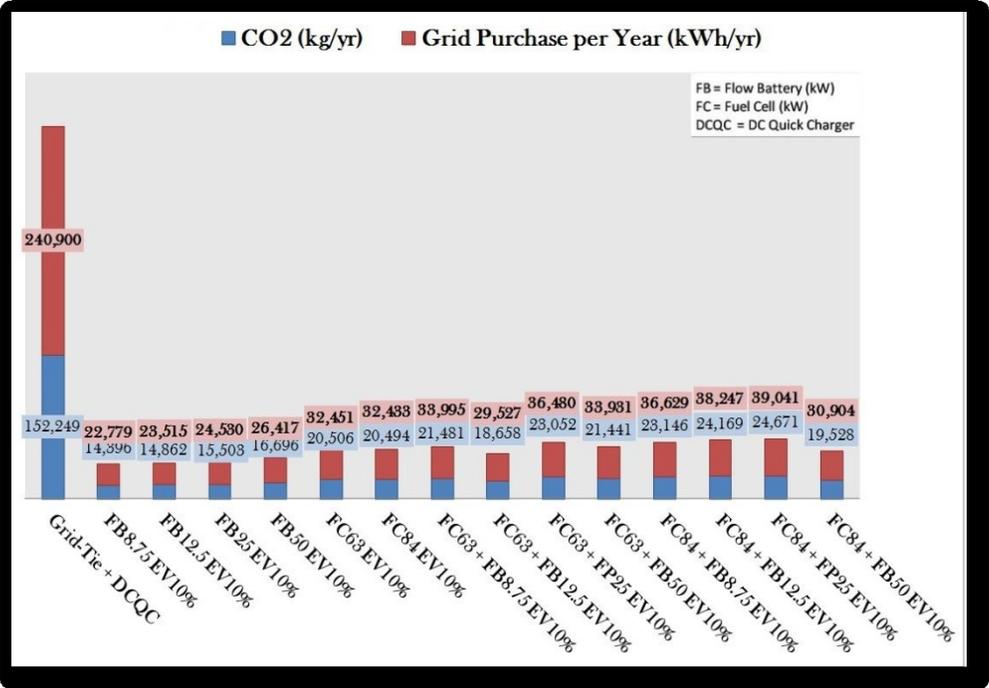
Figure 23: Environmental Impact PV 135 kW - No Battery Limit.
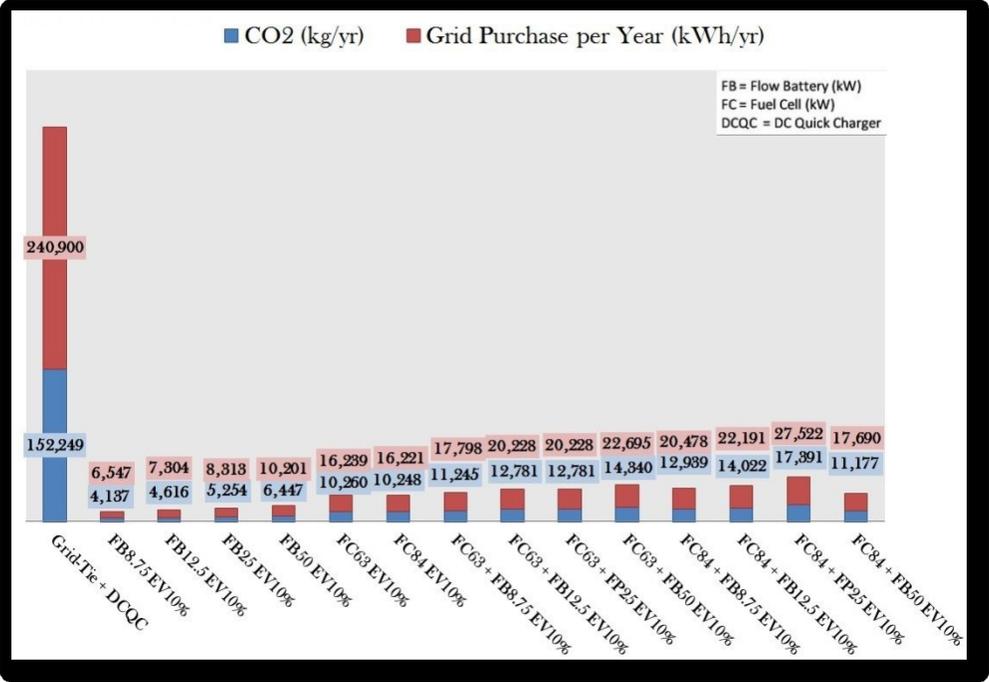
Figure 24: Environmental Impact PV 145 kW - No Battery Limit.

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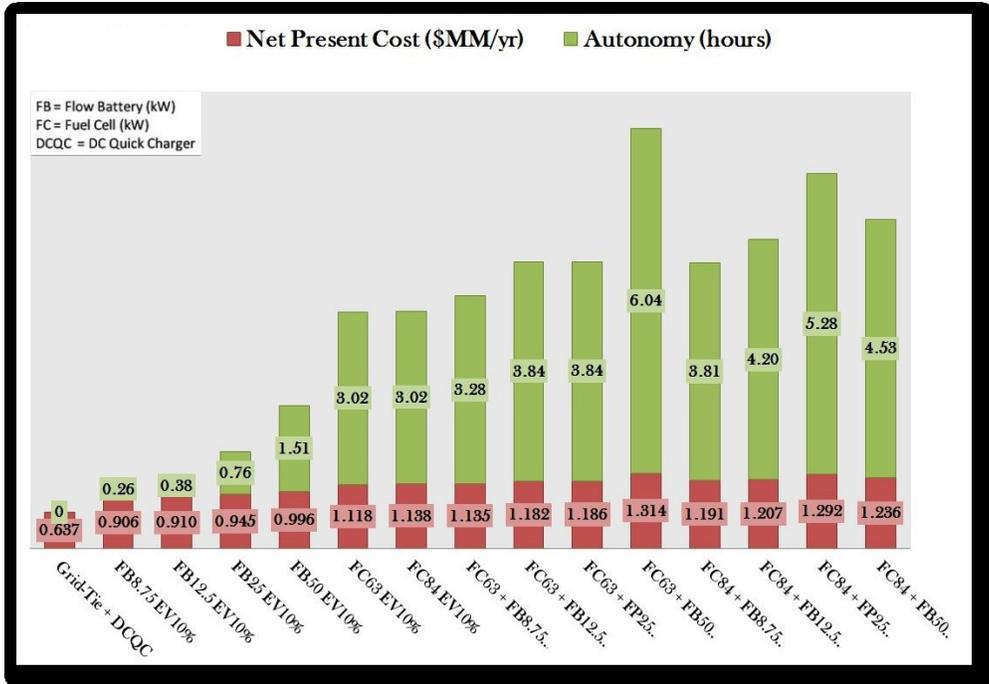
Figure 25: Autonomy and Net Present Cost PV 125 kW - No Battery Limit.
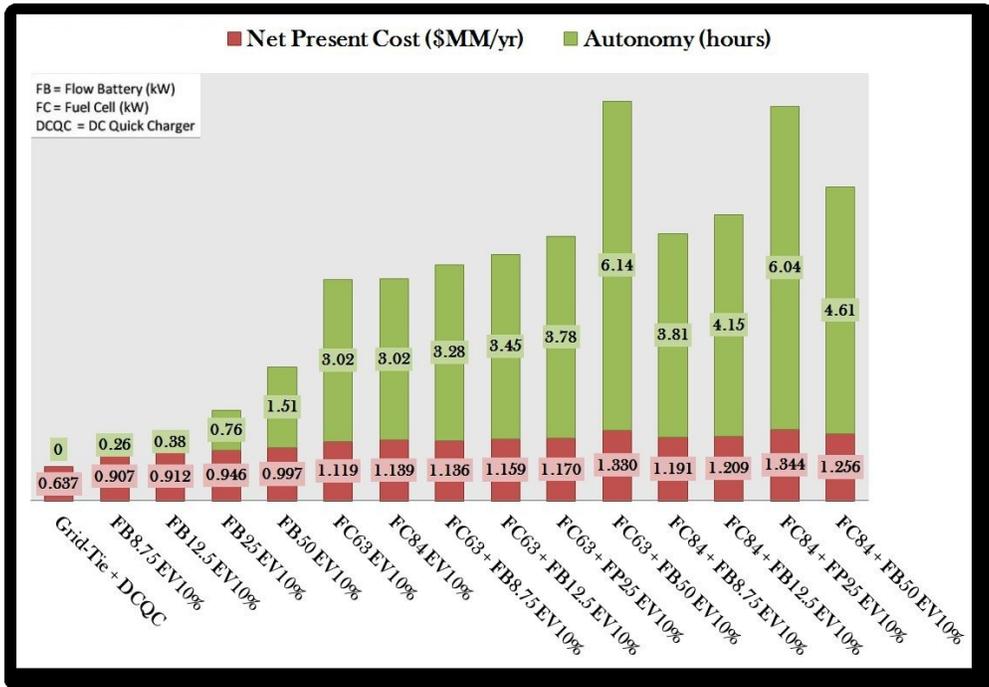
Figure 26: Autonomy and Net Present Cost PV 135 kW - No Battery Limit.

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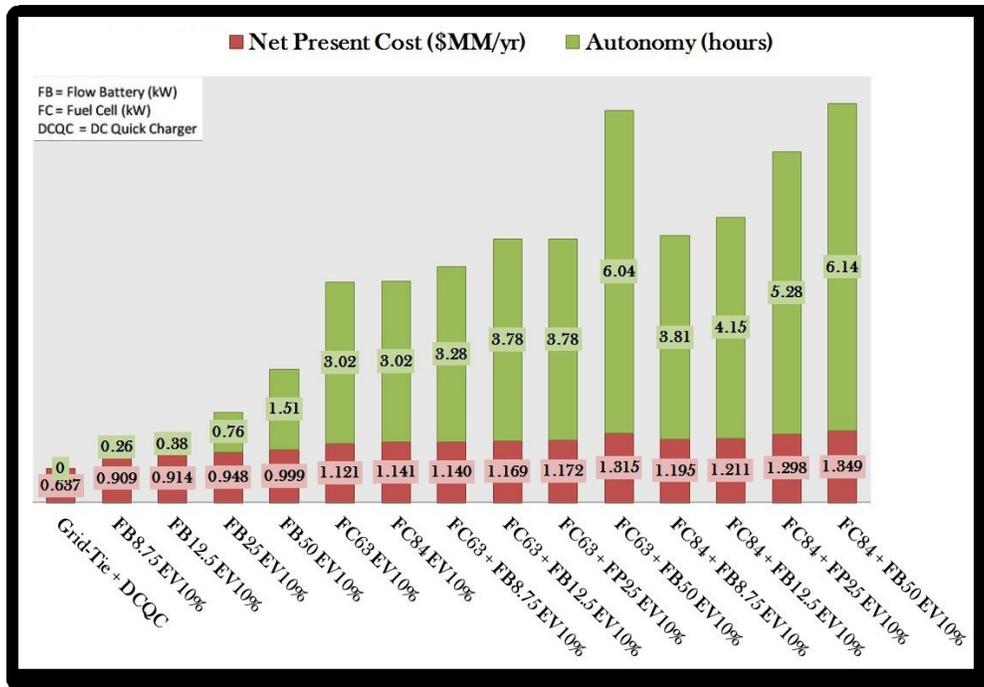
Figure 27: Autonomy and Net Present Cost PV 145 kW - No Battery Limit.

5.3   Stage Three

The third stage of modeling was more rigid, as with the fuel cell configurations, only one battery of any class was allowed. This is done to determine optimized viability against the set constraints. The results were much more definitive and can be seen in Table 2, where all configurations are shown as Yes, for optimally viable, or No, for non-viable, with respect to each intermittent load.

FB = Flow Battery (kWh)		FC = Fuel Cell (kW)			
	EV 0 %	EV 10%	EV 15%	EV 20%	EV 25%
Congfiguration PV125 kW	0 kWh	135 kWh/day	202 kWh/day	270 kWh/day	337 kWh/day
FB8.75	Yes	Yes	Yes	No	No
FB12.5	Yes	Yes	Yes	No	No
FB25	Yes	Yes	Yes	No	No
FB50	Yes	Yes	Yes	No	No
FC63	Yes	Yes	Yes	No	No
FC84	Yes	Yes	Yes	No	No
FB8.75+FC63	Yes	Yes	Yes	No	No
FB12.5+FC63	No	No	No	No	No
FB25+FC63	No	Yes	No	No	No
FB50+FC63	YES	No	No	No	No
FB8.75+FC84	No	No	No	No	No
FB12.5+FC84	Yes	No	No	No	No
FB25+FC84	Yes	No	No	No	No
FB50+FC84	No	Yes	No	No	No
Congfiguration PV135 kW	0 kWh	135 kWh/day	202 kWh/day	270 kWh/day	337 kWh/day
FB8.75	Yes	Yes	Yes	No	No
FB12.5	Yes	Yes	Yes	No	No
FB25	Yes	Yes	Yes	No	No
FB50	Yes	Yes	Yes	No	No
FC63	Yes	Yes	Yes	No	No
FC84	Yes	Yes	Yes	No	No
FB8.75+FC63	Yes	Yes	No	No	No
FB12.5+FC63	No	Yes	No	No	No
FB25+FC63	Yes	Yes	Yes	No	No
FB50+FC63	Yes	No	No	No	No
FB8.75+FC84	No	No	No	No	No
FB12.5+FC84	Yes	No	No	No	No
FB25+FC84	No	No	No	No	No
FB50+FC84	No	Yes	Yes	No	No
Congfiguration PV145 kW	0 kWh	135 kWh/day	202 kWh/day	270 kWh/day	337 kWh/day
FB8.75	Yes	Yes	Yes	No	No
FB12.5	Yes	Yes	Yes	No	No
FB25	Yes	Yes	Yes	No	No
FB50	Yes	Yes	Yes	Yes	No
FC63	Yes	Yes	Yes	No	No
FC84	Yes	Yes	Yes	No	No
FB8.75+FC63	Yes	Yes	Yes	No	No
FB12.5+FC63	No	No	No	No	No
FB25+FC63	Yes	Yes	Yes	No	No
FB50+FC63	No	No	No	No	No
FB8.75+FC84	No	No	No	No	No
FB12.5+FC84	Yes	No	No	No	No
FB25+FC84	Yes	No	No	No	No
FB50+FC84	No	No	No	No	No

Table 2: Optimized Configuration vs. Intermittent Load - 1 Battery Limit.

It can be seen that the outcome is much different than the prior results; there were random passes and failures dotted throughout the table in the configurations of fuel cell battery combination. The fuel cell only and battery only are consistently successful up to

an EV population of 15%. The combinations configuration data illustrates a relationship to the capacity of the PV platform. FC63kW+FB8.75kWh can accommodate up to EV 15% on platforms PV 125 and PV 145 kW, but only EV 10% on 135 kW PV platform. Similar behavior is evident with the other configurations. More information was evident, but again, not enough information for a detailed understanding. Stage 4 is a repeat of stage two.

5.4 **Stage Four**

The five metrics were applied in identical sets used for stage 2. The non-viable configurations were left in the graphs at value zero to show contrast, as was the configuration "Grid-Tie + DCQC".

Figures-28 - 30, Prime Cost illustrates both Net Present Cost and Cost of Energy. As both metrics are related to economics, this gives a fair and close perspective of needed financial expectations. Notice that the only two of the combo configurations remain present throughout all three PV capacities.
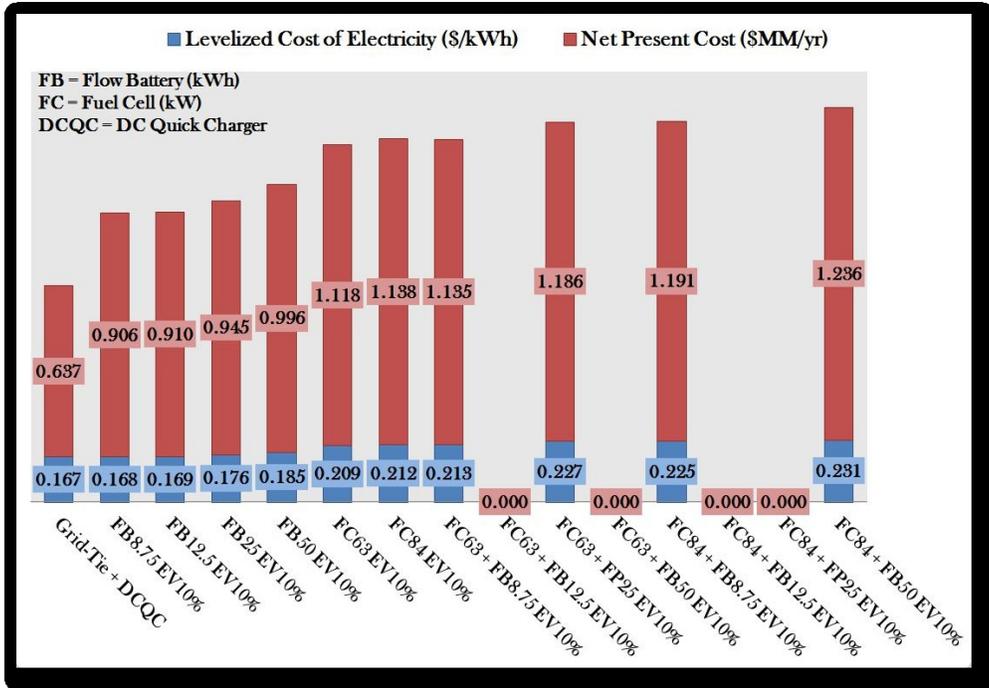
Figure 28: Prime Cost PV125kW / 1 Battery.
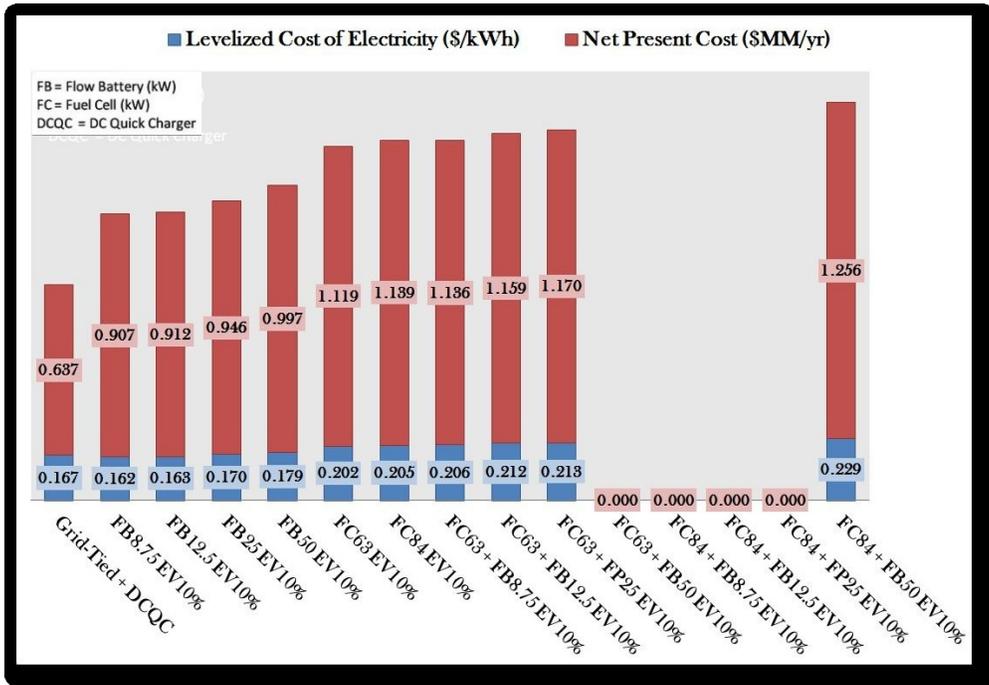
Figure 29: Prime Cost PV 135 kW / 1 Battery.
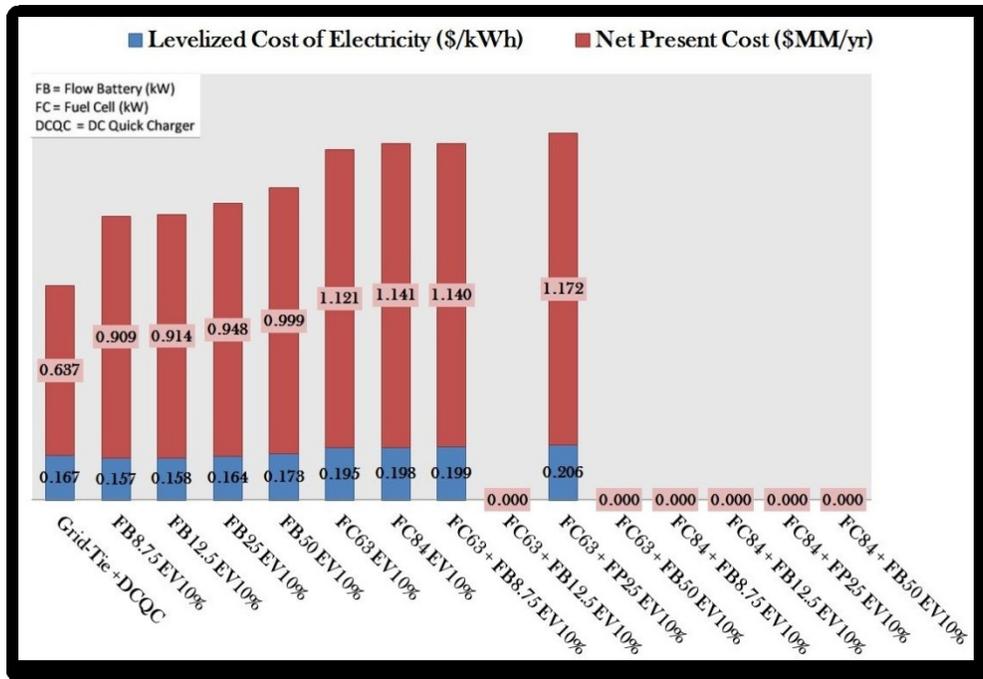
Figure 30: Prime Cost PV 145 kW / 1 Battery.

Figures 31 - 33, environmental impact illustrates a relation of kWh purchased from the grid annually and how it translates into the village's carbon footprint. This is also a relational value as it illustrates the expected load change on the connected centralized grid. Again, two of the combo configurations (FC63kW+8.75kWh and FC63kW+25kWh) are predominant through all three PV capacities.
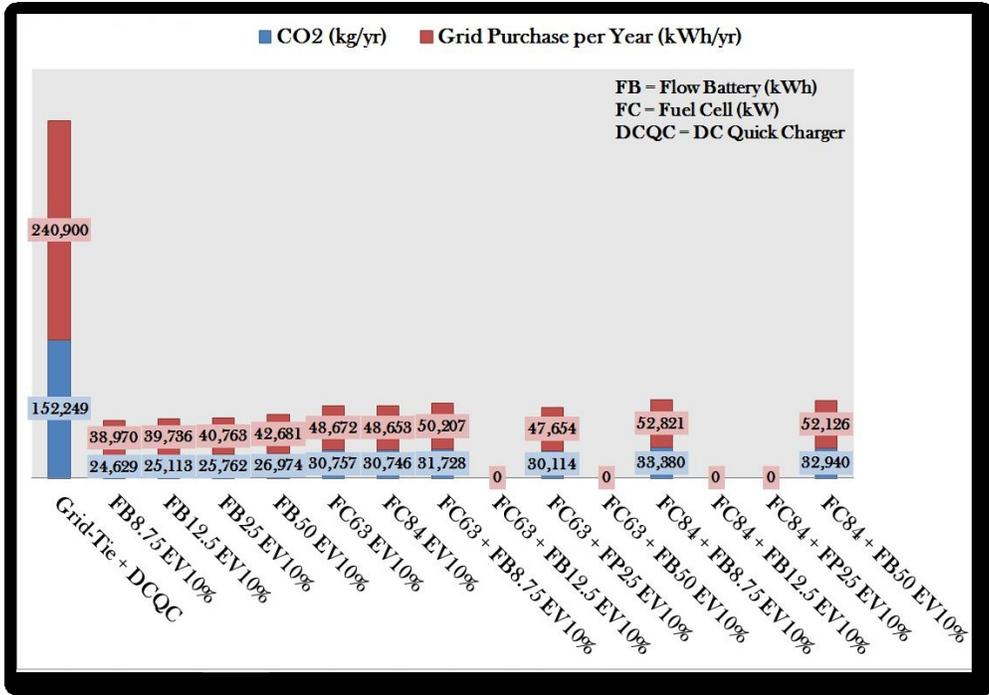
Figure 31: Environmental Impact PV 125 kW / 1 Battery.
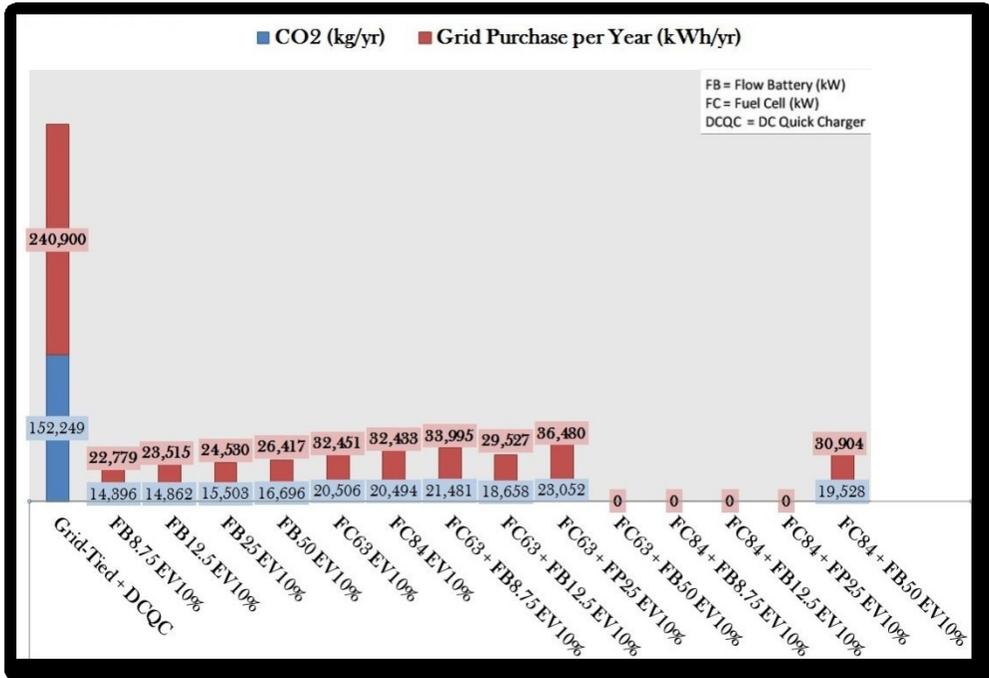
Figure 32: Environmental Impact PV 135 kW / 1 Battery.
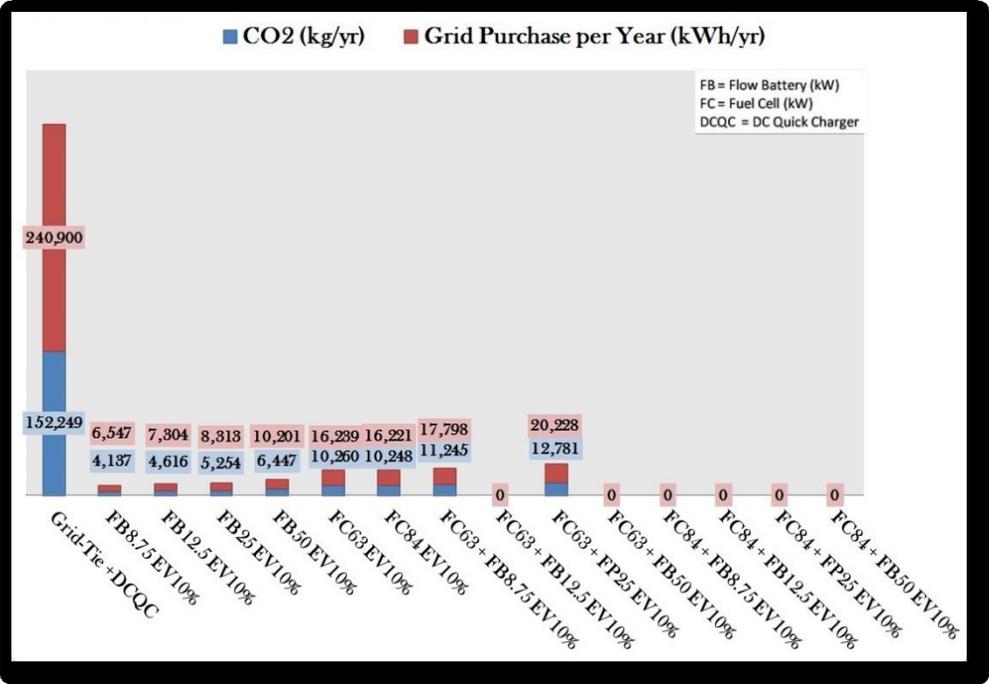
Figure 33: Environmental Impact PV 145 kW / 1 Battery.

Figures 34 – 35, Autonomy and Net Present Cost, these metrics were paired as they relate to decision making. Similar to the old engineer saying, "Fast, cheap, and good…pick two". Especially in microgrid systems a minimal autonomy of 15 minutes is expected, as this is considered a safe window for power source switching purposes [32]. Additionally, this information is vital, as the configuration autonomy could be very relevant to the site location. A site where cloud cover can be a problem or power is subject to frequent disruption may need a longer duration of autonomy. The battery only systems would be completely unsuitable for a region that frequently experiences 40 to 90 minutes of cloud cover degrading PV production and possibly nullifying the benefits of the renewable generation.

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The two combinations seen before, (FC63kW+8.75kWh and FC63kW+25kWh), show prevailingly throughout all three PV capacities, and it looks like either would be suitable for the task. Until the data from Table 2 is taken into account, the selection really is dependent on which PV capacity is installed.
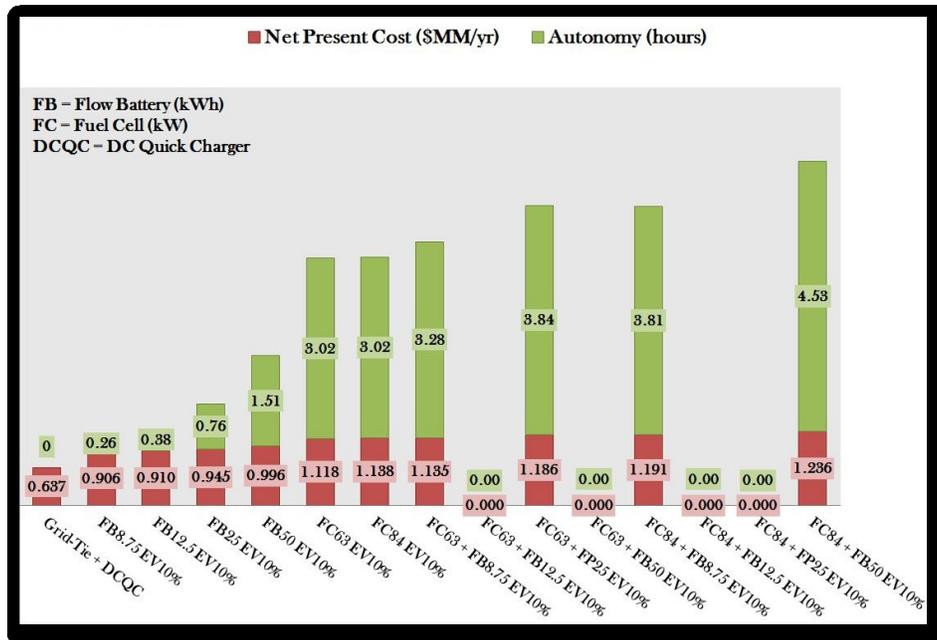
Figure 34: Autonomy and Net Present Cost PV 125 kW / 1 Battery.
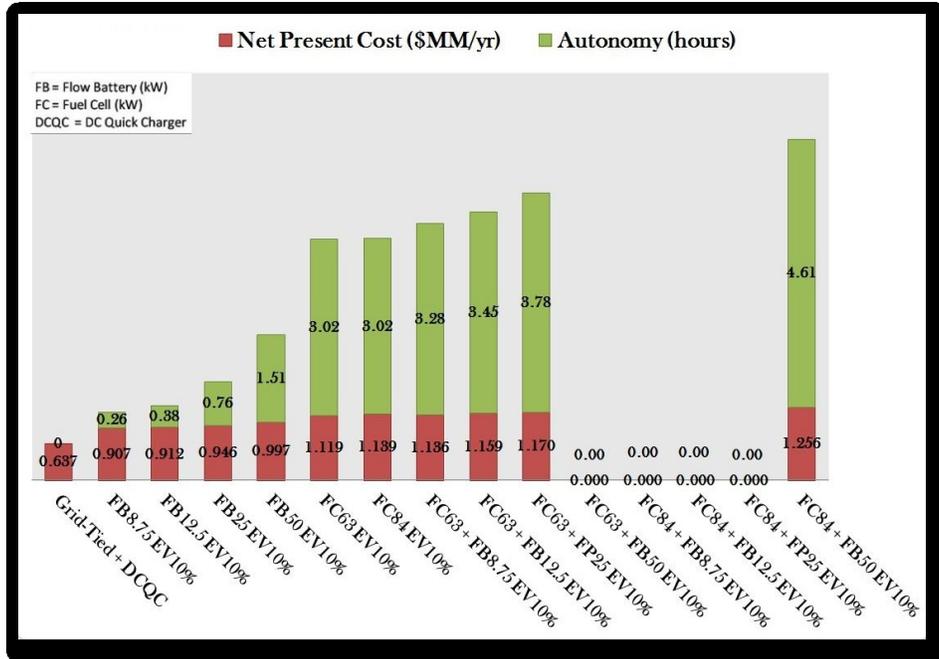
Figure 35: Autonomy and Net Present Cost PV 135 kW / 1 Battery.
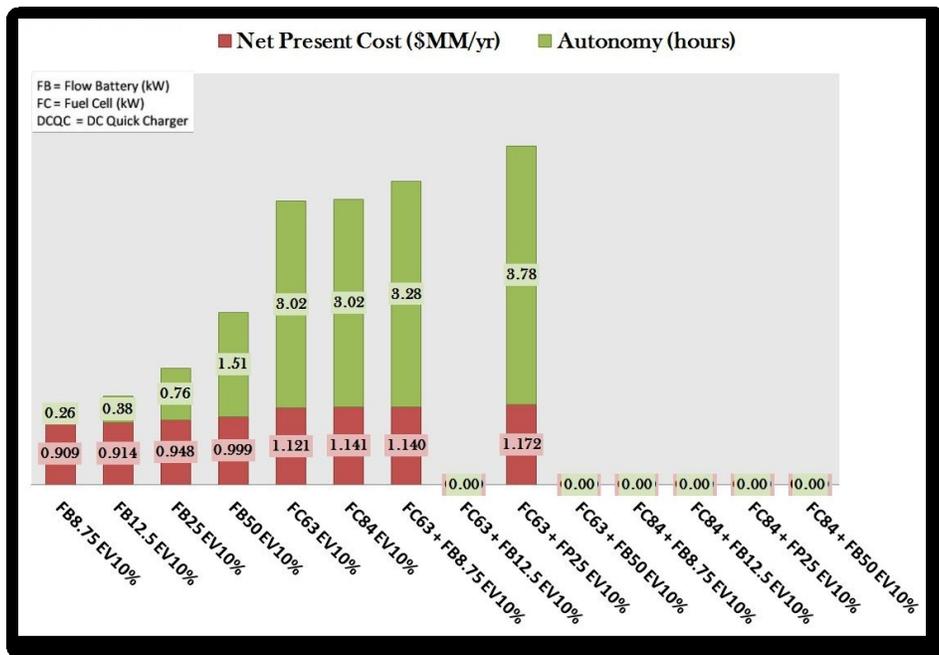
Figure 36: Autonomy and Net Present Cost PV 145 kW / 1 Battery.

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5.5   **Stage Five**

This stage is a deconstruction of the leading combination configuration, FC63kW+FB8.75 kWh on a PV 125 kW platform at an intermittent load of EV 10%.

5.5.1   Grid Power Purchase Density Map Analysis

Figure 37 represent density maps (DMAP) of the Net grid purchase. The strips are hour long time slices, and the color indicates power level respectively. Examining the DMAP of the combo configuration (Figure 37A), the power density is greatly reduced below the 32 kW level, and in many areas below the 16 kW level. There is a heavier consumption during the months of June to September, particularly at time slots of 9am and 6pm. By contrast, the grid-tie only configuration is a much more clouded picture with high levels throughout most of the graph. When the combo configuration is broken up into a PV fuel cell configuration (Figure 37C) and a PV battery configuration (Figure 37D), more information is available. It is still clouded with higher power consumptions, particularly along the later hours. The battery only configuration has a slightly lower consumption density than the fuel cell only, but the two configurations are very close. The take away is that the configuration combo requires less grid support than the individual components.
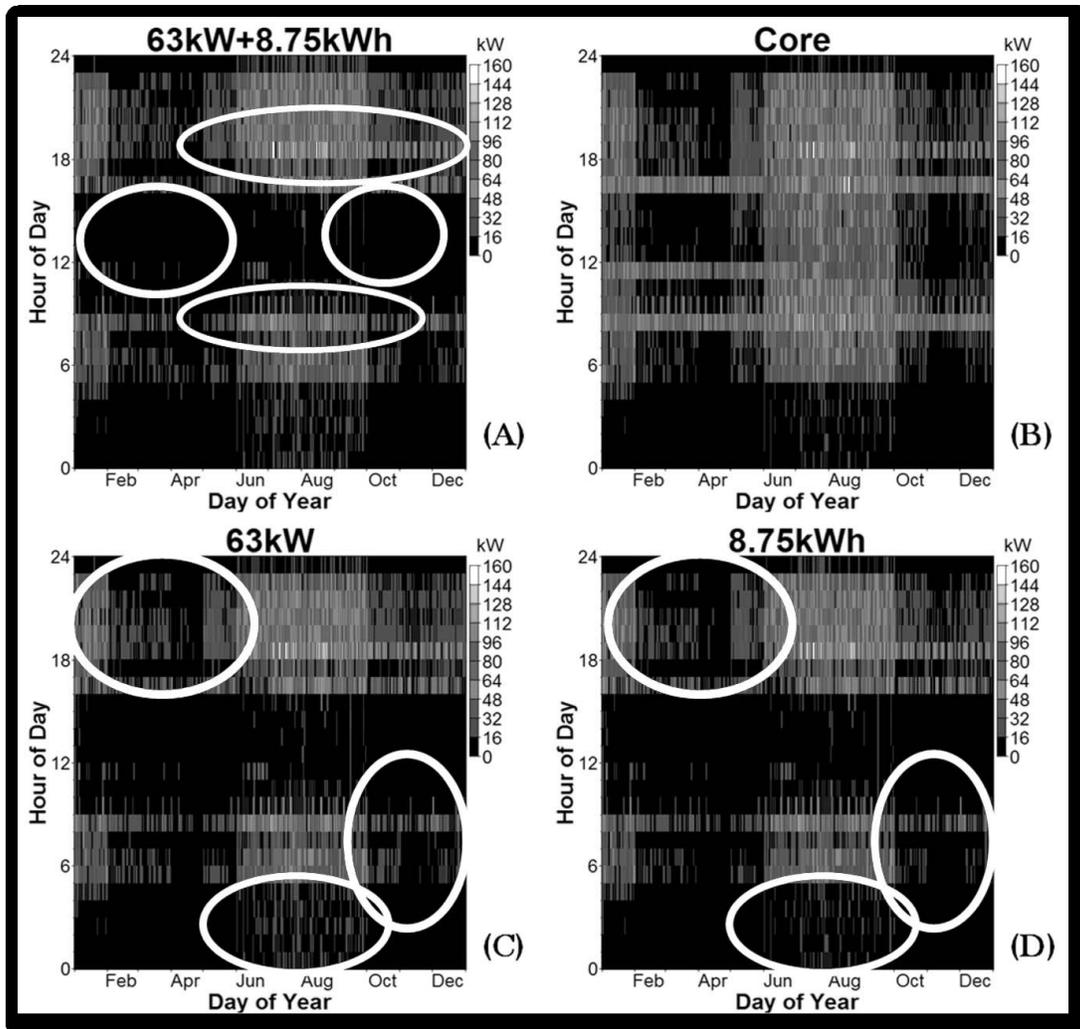
Figure 37 Purchased Grid Power DMAP (Hybrid, Grid-tie, FC, FB).

5.5.2   PEM Output Density Map Analysis

Fuel cells are generators utilizing the power stored in the provided Hydrogen fuel. Figure 39 illustrates the power output and duration. The pane on the left side is the combination configuration; the pane on the right is the fuel cell only configuration. The fuel cell only pane has heavy uniform regions of production; further, the output level is consistently higher.   The combo configuration (right side pane) output regions are staggered and at a lower output level.   The staggered output means a lower fuel cell

operation time giving a longer life to the fuel cell, hence reducing overall fuel cell operation costs while still supporting the system.
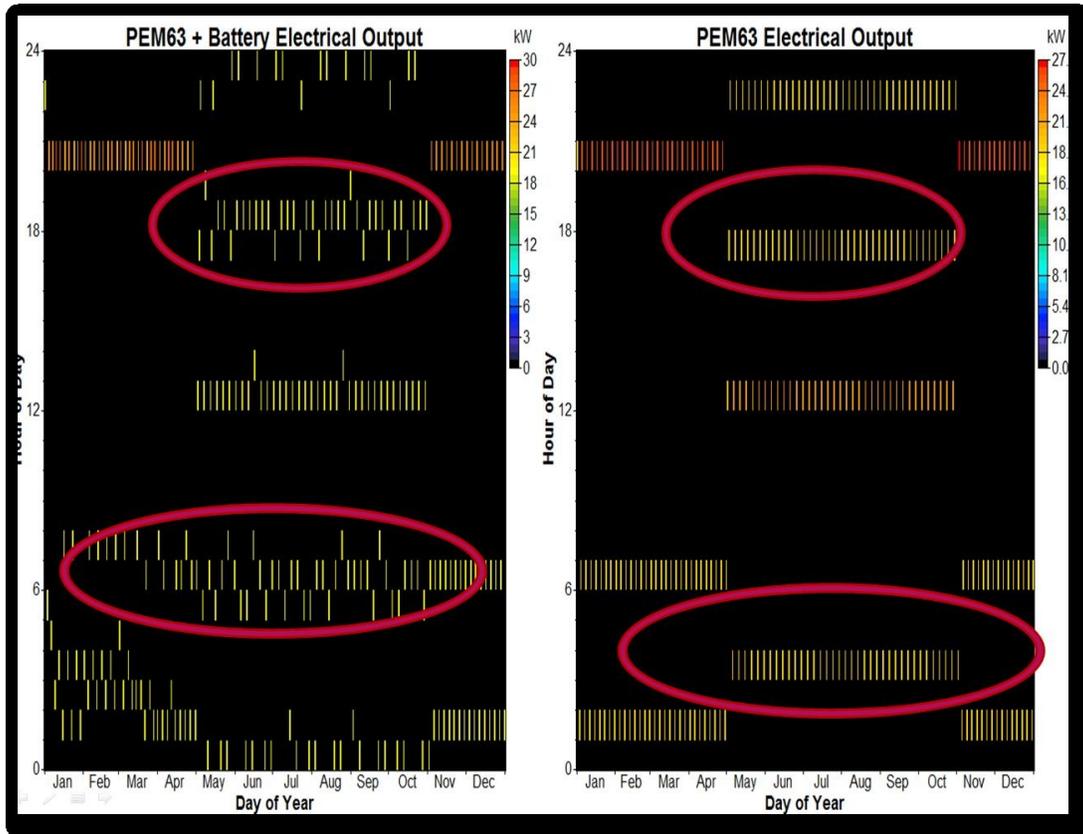
Figure 38 PEM Electrical Output (Hybrid, FC).

5.5.3 Battery Cost

Batteries are energy storage mechanisms. They provide power instantly to the system, but require a regular recharge and maintenance. All of which have influence on performance and cost. Figure 40 is a graphic of the Probability Density Function of the battery cost of energy as modeled over its lifetime. The battery of the combo configuration (left pane) has a significantly lower cost. It is evident that this is a benefit

of the other support systems, and gives credence to the reduced operation cost of hybrid
systems.
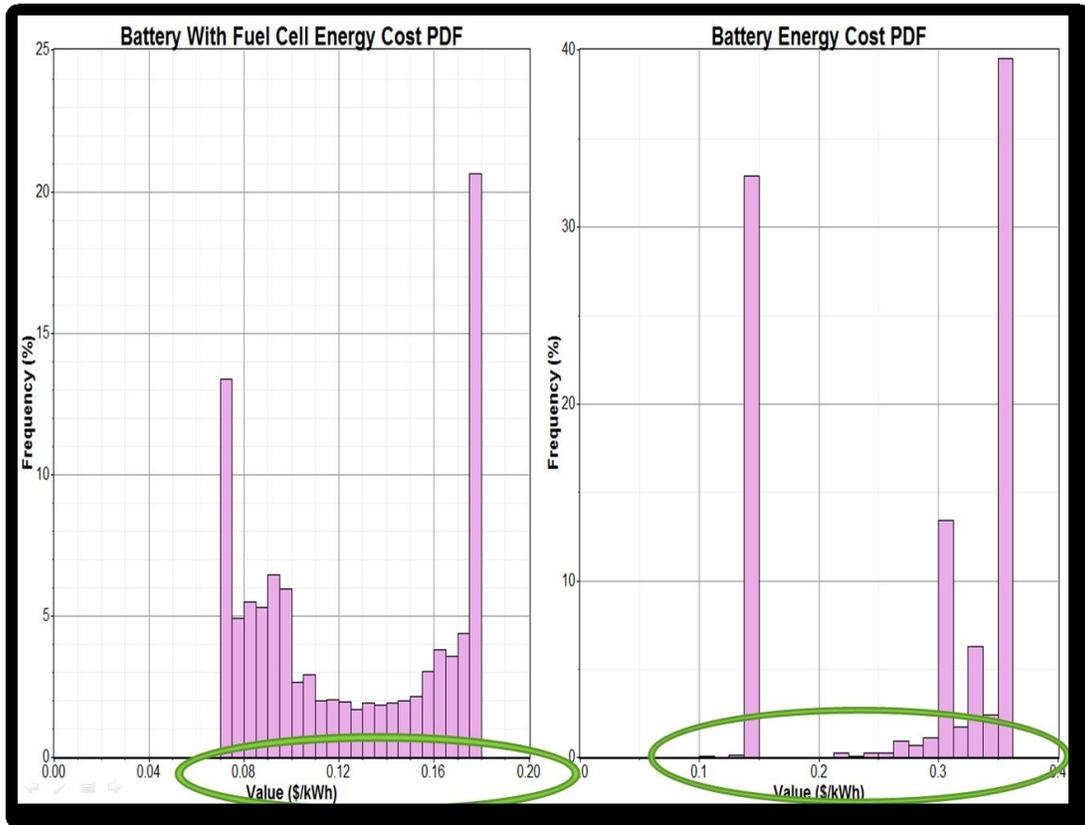
Figure: 39 Battery Energy Cost PDF (Hybrid, FB).

CHAPTER 6

CONCLUSION

6.0   Summary

This document examines the modeled costs and advantages gained by instituting a PV, batteries, and fuel cells system based hybrid, with excess production to run intermittent community DC quick chargers, while meeting the set constraints. Five key metrics were examined to determine the optimum configuration for the microgrid. The battery only configuration offers positives in the area of response time and economics, but has limited autonomy and must be charged. Of the 4 classes of batteries modeled, the 50 kWh is superior. Its NPC is only 5.1% higher than the next lower class, but has 98% more autonomy for an EV10% intermittent load. The fuel cell only solutions score well on autonomy, but have a slower startup time and a cost that is within 6 to 9% short of the next solution. A fuel cell and battery combination provides rapid response and longer sustained autonomy. The favored configuration is 63 kW PEM fuel cell, and an 8.75 kWh flow battery. This configuration shows optimized viability for both EV 10 and 15% populations. For autonomy, this configuration offers 8% greater time than the stand alone fuel cell configuration, and 117% greater than the stand alone battery capacity of 50 kWh. The NPC for this configuration is 14% above the 50 kWh battery and 3% above the fuel cell. The Cost of Energy of this configuration is 1 to 3 cents per kWh above the fuel cell options, which is not significant given the scope of the design. Concerning

environmental impact, the net grid purchases for the village at this configuration is estimated to be 54.8 Megawatt hours annually. This is dramatically less than if the community was grid-tied only, with the addition of the 50 kW DC Quick Charger translating to 240 Megawatt hours. This represents a considerable reduction in demand on the centralized grid, and much higher level of energy security for the Village community. In addition, this configuration represents a contribution of 31.7 metric tons per year, which is 20.8% of the 152.2 metric tons generated annually by the community without renewable power enhancements. Though not shown, there would be an additional reduction of 31 to 42 tons of CO_2 per year by the 10 percent EV population.

When sized correctly, a community microgrid can mitigate energy waste by using the excess generation where needed. This is a stark difference from the central grid concept and home mounted PV system. In a sense, this model is an energy community capable of doing more with less, utilizing energy toward community services, which would have been otherwise wasted. The results of stage five showed that the microgrid modeled is greater as a whole than the sum of its parts.

6.1   Future Work

The model shows how a microgrid can benefit the Biosphere 2 Village community, and through a collaborative power structure, solve other community needs. The next level of progression would be to move from theory to experiment for validation, and improve the model system. One of the goals of this undertaking was to develop a model that is transplantable to other communities in similar situations. With adjustments

this model could be applied to townhome communities within the urban regions of cities. It could also be applied to shopping centers comprising of many stores. Urban embedded microgrids, as pointed out in the literature review section, are potential resources in times of crisis; a point that should not be taken lightly. It should also be noted that this model could be modified to fit similar communities as the DC Quick Charger could be replaced with some other intermittent load such as a water pump system.

REFERENCES

[1] "DOE Microgrid Workshop Report 2011," vol. 2013.

[2] Jiangui Li, Xiaodong Zhang and Wenlong Li, "An efficient wind-photovoltaic hybrid generation system for DC micro-grid," in *Advances in Power System Control, Operation and Management (APSCOM 2009), 8th International Conference On,* 2009, pp. 1-6.

[3] A. K. Basu, A. Bhattacharya, S. P. Chowdhury, S. Chowdhury and P. A. Crossley, "Reliability study of a micro grid system with optimal sizing and placement of DER," in *SmartGrids for Distribution, 2008. IET-CIRED. CIRED Seminar,* 2008, pp. 1-4.

[4] R. Yokoyama, Y. Hida, K. Koyanagi and K. Iba, "The role of battery systems and expandable distribution networks for smarter grid," in *Power and Energy Society General Meeting, 2011 IEEE,* 2011, pp. 1-6.

[5] A. Burgio, D. Menniti, A. Pinnarelli and N. Sorrentino, "The reliability studies of a novel integrated configuration for micro-grids," in *Electric Utility Deregulation and Restructuring and Power Technologies, 2008. DRPT 2008. Third International Conference On,* 2008, pp. 2634-2639.

[6] K. M. Krishna, "Optimization analysis of microgrid using HOMER — A case study," in *India Conference (INDICON), 2011 Annual IEEE,* 2011, pp. 1-5.

[7] Anonymous "IEEE P2030™/D5.0 draft guide for smart grid interoperability of energy technology and information
Technology operation with the electric power system (EPS), and end-use applications and loads," IEEE Standards Association Department, IEEE Standards Store, Tech. Rep. D5.0, 2-23-2011. 2011.

[8] N. Saito, T. Niimura, K. Koyanagi and R. Yokoyama, "Quantitative evaluations of CO_2 reduction by microgrid with PV and battery," in *Power and Energy Engineering Conference, 2009. APPEEC 2009. Asia-Pacific,* 2009, pp. 1-5.

[9] Anonymous "SRP: Site search," vol. 2013.

[10] Stanley S. Reynolds, Professor of Economics, Public Policy and Markets, University of Arizona and and Andrew N. Kleit, Professor of Energy and Environmental Economics, Pennsylvania State University, "Opening the grid: How to recharge arizona's electricity system for the 21st century," Goldwater Institute, 500 East Coronado Road Phoenix, AZ 85004, Tech. Rep. 232, 07/21/2009. 2009.

[11] J. S. Hill, "Operator Error and Lack of Planning Key to 2011 San Diego Blackout - CleanTechnica," vol. 2013, May 7, 2012, .

[12] K. M. Abo-Al-Ez, X. Xia and J. Zhang, "Smart interconnection of a PV/wind DG micro grid with the utility distribution network," in *Industrial and Commercial use of Energy Conference (ICUE), 2012 Proceedings of the 9th,* 2012, pp. 1-8.

[13] M. N. Ambia, A. Al-Durra and S. M. Muyeen, "Centralized power control strategy for AC-DC hybrid micro-grid system using multi-converter scheme," in *IECON 2011 - 37th Annual Conference on IEEE Industrial Electronics Society,* 2011, pp. 843-848.

[14] E. A. Bakirtzis and C. Demoulias, "Control of a micro grid supplied by renewable energy sources and storage batteries," in *Electrical Machines (ICEM), 2012 XXth International Conference On,* 2012, pp. 2053-2059.

[15] S. A. Pourmousavi, R. K. Sharma and B. Asghari, "A framework for real-time power management of a grid-tied microgrid to extend battery lifetime and reduce cost of energy," in *Innovative Smart Grid Technologies (ISGT), 2012 IEEE PES,* 2012, pp. 1-8.

[16] J. D. Kueck, R. H. Staunton, S. D. Labinov and B. J. Kirby, "Microgrid energy management system," U.S. Department of Energy, Oak Ridge, Tennesee 37831, Tech. Rep. ORNL/TM-2002/242, 1/29/2003. 2003.

[17] U.S. Energy Information Administration (EIA), "Energy-related carbon dioxide emissions," vol. 2013, September 19, 2011, 2011.

[18] "Solar PV Makes Most Sense at Modest Size - CleanTechnica," vol. 2013.

[19] R. W. Andrew Mills, "Implications of wide-area geographic diversity for short- term variability of solar power," Ernest Orlando Lawrence Berkeley National Laboratory, 1 Cyclotron Road, MS 90R4000 Berkeley CA 94720-8136, Tech. Rep. LBNL-3884E, 9/2010. 2010.

[20] Zhao Dongmei, Zhang Nan and Liu Yanhua, "Micro-grid connected/islanding operation based on wind and PV hybrid power system," in *Innovative Smart Grid Technologies - Asia (ISGT Asia), 2012 IEEE,* 2012, pp. 1-6.

[21] A. M. Sharaf and A. A. El-Gammal, "A novel efficient PSO-self regulating PID controller for hybrid PV-FC-diesel-battery micro grid scheme for village/resort electricity utilization," in *Electric Power and Energy Conference (EPEC), 2010 IEEE,* 2010, pp. 1-6.

[22] D. -. Valcan, C. Marinescu and S. Kaplanis, "Connecting a PV supplied micro-grid to the public grid," in *Optimization of Electrical and Electronic Equipment, 2008. OPTIM 2008. 11th International Conference On,* 2008, pp. 369-374.

[23] Loc Nguyen Khanh, Dong-Jun Won, Sung-Eun Lee, Jae-Geun Jeon and Jae-Ho Choi, "Improvement of a PV-FC hybrid source operation in a microgrid," in *Power Electronics Conference (IPEC), 2010 International,* 2010, pp. 717-720.

[24] L. Mili, "Taxonomy of the characteristics of power system operating states," Bradley Department of Electrical and Computer Engineering, Northern Virginia Center, Virginia Tech Falls Church, VA 22043, 01/11/2011. 2011.

[25] ELIZA STRICKLAND, "A Microgrid That Wouldn't Quit
How one experiment kept the lights on after Japan's earthquake," *10/2011,* vol. 2013, pp. 1/20/2013, 10/26/2011, 2011.

[26] G. Mathews, "THE CAMPUS AS A LIVING LABORATORY FOR CLIMATE SOLUTIONS UC San Diego Learning Journey about UCSD," 2/4/2010.

[27] "REFUsol International: REFUsol 012K-UL - 024K-UL," vol. 2013.

[28] J. Traube, Fenglong Lu and D. Maksimovic, "Electric vehicle DC charger integrated within a photovoltaic power system," in *Applied Power Electronics Conference and Exposition (APEC), 2012 Twenty-Seventh Annual IEEE,* 2012, pp. 352-358.

[29] "Fuel Cell Products | FC Velocity Motive Power | FC Velocity 9SSL | Ballard Power Systems," vol. 2013.

[30] "ZBB Energy :: Advanced Energy Storage," vol. 2013.

[31] "HOMER Energy - Hybrid Renewable and Distributed Power Design Support," vol. 2013.

[32] "Remote Microgrids Pike Research," vol. 2013, 12/11/2012, .