Energy Research and Development Division
FINAL PROJECT REPORT

CAMP PENDLETON FRACTAL GRID DEMONSTRATION

Prepared for: California Energy Commission
Prepared by: Specialized Energy Solutions and CleanSpark (for Harper)

DECEMBER 2014
CEC-500-2016-013

PREPARED BY:

Primary Authors:
Art Villanueva

Specialized Energy Solutions
A Harper Construction Company
2241 Kettner Blvd, Suite 300
San Diego, CA 92101-1769
www.harperconstruction.com

Victor Fung
Jennifer Worrall
Jeff Trueblood

CleanSpark LLC
13000 Gregg Street, Suite C
Poway, CA 92064
www.cleanspark.com

Contract Number: PIR-12-033

Prepared for:

California Energy Commission

Prab Sethi
Contract Manager

Aleecia Gutierrez
Office Manager
Energy Generation Research

Laurie ten Hope
Deputy Director
ENERGY RESEARCH AND DEVELOPMENT DIVISION

Robert P. Oglesby
Executive Director

DISCLAIMER

This report was prepared as the result of work sponsored by the California Energy Commission. It does not necessarily represent the views of the Energy Commission, its employees or the State of California. The Energy Commission, the State of California, its employees, contractors and subcontractors make no warranty, express or implied, and assume no legal liability for the information in this report; nor does any party represent that the uses of this information will not infringe upon privately owned rights. This report has not been approved or disapproved by the California Energy Commission nor has the California Energy Commission passed upon the accuracy or adequacy of the information in this report.

ACKNOWLEDGEMENTS

The authors acknowledge the California Energy Commission (PIR-09-004) and Marine Corps Base Camp Pendleton and wish to express thanks for their support of this incredible project.

PREFACE

The California Energy Commission Energy Research and Development Division supports public interest energy research and development that will help improve the quality of life in California by bringing environmentally safe, affordable, and reliable energy services and products to the marketplace.

The Energy Research and Development Division conducts public interest research, development, and demonstration (RD&D) projects to benefit California.

The Energy Research and Development Division strives to conduct the most promising public interest energy research by partnering with RD&D entities, including individuals, businesses, utilities, and public or private research institutions.

Energy Research and Development Division funding efforts are focused on the following RD&D program areas:

- Buildings End-Use Energy Efficiency
- Energy Innovations Small Grants
- Energy-Related Environmental Research
- Energy Systems Integration
- Environmentally Preferred Advanced Generation
- Industrial/Agricultural/Water End-Use Energy Efficiency
- Renewable Energy Technologies
- Transportation

Camp Pendleton Fractal Grid Demonstration is the final report for the project (contract number PIR-12-033) conducted by Specialized Energy Solutions and CleanSpark (for Harper). The information from this project contributes to Energy Research and Development Division's Renewable Energy Technologies Program.

All of the tables/figures are provided by the authors.

For more information about the Energy Research and Development Division, please visit the Energy Commission's website at www.energy.ca.gov/research/ or contact the Energy Commission at 916-327-1551.

ABSTRACT

Recent years have seen the rapid development of energy technologies such as advanced energy management systems. One such energy management system is the microgrid, a local energy grid with the ability to disconnect from the main grid and operate autonomously. In this project, the research team investigated the utility of a unique microgrid architecture concept called the FractalGrid, in which multiple microgrids are strategically arranged in a fractal, or recursive, pattern. The FractalGrid configuration has the potential to deliver clean, secure, and affordable energy security in localized areas throughout California by managing energy sources and storage and by distributing energy efficiently to identified use cases. This concept has peak shaving and load management capabilities, and has the ability to maintain critical loads at times of low energy availability, as well as the ability to shift energy use in order to level out energy use profiles during peak hours of utility-grid energy pricing. The Camp Pendleton FractalGrid Demonstration project is a proof of concept that realizes much of the promise of FractalGrid architectures and serves as a basis for further microgrid-enablement of the entire base. The project integrates energy storage and distributed renewable energy sources with an advanced software system to create a sustainable solution for utility-scale establishments that require a stable energy input. The research team installed and successfully tested four fractal microgrids with the capacity to operate autonomously as well as in concert with a parent microgrid at Camp Pendleton. The microgrids enhanced stability and reliability throughout the power network, demonstrating a new method for California energy management.

Keywords: microgrid, FractalGrid, clean energy, renewable, military, energy storage, affordable energy, energy management, solar power, photovoltaic

Please use the following citation for this report:

Villanueva, Art; Victor Fung; Jennifer Worrall; Jeff Trueblood. (CleanSpark LLC and Harper Construction). 2014. ***Camp Pendleton FractalGrid Demonstration.*** California Energy Commission. Publication number: CEC-500-2016-013.

TABLE OF CONTENTS

Acknowledgements i

PREFACE ii

ABSTRACT iii

TABLE OF CONTENTS iv

LIST OF FIGURES vii

LIST OF TABLES viii

EXECUTIVE SUMMARY 1

Introduction 1

Project Purpose 2

Project Results 3

Project Benefits 5

CHAPTER 1: Objectives 6

1.1 Program Objectives 6

1.2 Use Cases 7

1.2.1 Use Case 1: Islanding 7

1.2.2 Use Case 2: Local generation 8

1.2.3 Use Case 3: Peak-shaving 8

1.2.4 Use Case 4: Load-shifting 9

1.2.5 Use Case 5: Load-leveling 10

1.2.6 Use Case 6: Robust data collection 10

1.2.7 Chapter Summary 11

CHAPTER 2: Architecture 12

2.1 Architecturally Significant Requirements 12

2.1.1 Galvin Electricity Initiative 12

2.1.2 Institute of Electrical and Electronics Engineers (IEEE) 1547.4 12

2.1.3 US Department of Energy (DOE) 12

2.1.4 Conseil International des Grands Réseaux Électriques (CIGRE) C 6.22 WG: (in English, the International Council on Large Electrical Systems) 12
2.2 Solution: The FractalGrid 14
2.2.1 Fractals 14
2.2.2 FractalGrid 14
2.3 Microgrid/FractalGrid Operational Modes 15
2.4 Camp Pendleton-Specific Architecture 17
2.5 Summary 17
CHAPTER 3: Design & Implementation 18
3.1 Constraints and Restrictions 18
3.1.1 Budget 18
3.1.2 Technical & Programmatic 18
3.2 Electrical and Physical Network 21
3.2.1 Description 21
3.2.2 Design for Reliability 24
3.2.3 Design for Sustainability 25
3.3 Information Network 26
3.3.1 Description 26
3.3.2 Design for Reliability 31
3.3.3 Design for Security 33
3.3.4 Design for Affordability/Sustainability 36
3.3.5 Other Design Decisions 38
3.4 Other 40
3.4.1 Physical Security 40
3.4.2 Protocols 41
3.4.3 Summary 41
CHAPTER 4: Demonstration and Test Results 42
4.1 Objective Analysis 42
4.1.1 Islanding Use Case 42

4.1.2 Consumption Reduction Use Case 43
4.1.3. Peak Load Management Use Case 49
4.1.4 Carbon Management Use Case 51
4.1.5 Other Use Cases 53
4.2 Performance and Current Limitations 56
4.2.1 Number of Points 56
4.2.2 History 56
4.2.3 Server Hardware 57
4.2.4 Switching Speed 57
4.2.5 Flywheel 57
4.2.6 Summary 57
CHAPTER 5: Conclusions 58
CHAPTER 6: Partners 59
6.1 SES 59
6.2 CleanSpark 60
6.3 Power Generation Services 61
6.3.1 Services 61
6.3.2 Energy Management Capabilities 61
6.3.3 Analytics, Reporting, and Compliance 61
6.4 ETAP 62
6.5 IPKeys 62
6.5.1 Management Philosophy 63
GLOSSARY 64
REFERENCES 66
APPENDIX A: Specs for FractalNodes and Other Components A-1
APPENDIX B: Definitions B-1
APPENDIX C: Energy Markets C-1
APPENDIX D: Organization Chart D-1

LIST OF FIGURES

Figure 1: Area 52 Community Map—Camp Pendleton, California 2
Figure 2: Camp Pendleton FractalGrid Layout 4
Figure 3: Fractal Patterns 14
Figure 4: Microgrid State Machine 16
Figure 5: NREL's Renewable Integrated Microgrid Model 19
Figure 6: Example Dashboard/Home Screen 28
Figure 7: Example Flywheel Screen 29
Figure 8: Redundant Connections 31
Figure 9: DNP3 Overview Diagram 34
Figure 10: Lynx User Interface (Courtesy of Power Generation Services) 38
Figure 11: Weather Station Widget 41
Figure 12: PV Generation Plotted With Battery System Voltage 44
Figure 13: Energy and Power Consumption at mComm on December 6, 2014 45
Figure 14: PV Generation (Left y-axis) and Battery Voltage (Right y-axis) as a Function of Time 46
Figure 15: m5.2 Energy and Power Consumption on December 5, 2014 47
Figure 16: Maximizing Local Energy Generation Usage 48
Figure 17: m52 Energy and Power Consumption Reduction 48
Figure 18: mBarr Microgrid Peakshaving to 0kW (From Utility) 50
Figure 19: Offsetting Fossil-Fuel Usage 53
Figure 20: Charging During Off-Peak Hours 54
Figure 21: Discharging During Peak Hours 54
Figure 22: Load Leveling to 0kW at mBarr 55
Figure 23: Load-Shifting 55
Figure 24: Adjustable Load-Leveling 56
Figure 25: Specialized Energy Solutions 59
Figure 26: CleanSpark Logo 60

Figure 27: Cleanspark 60
Figure 28: Power Generation Services, Inc. 61

LIST OF TABLES

Table 1: Demonstration Results Compared to Objectives 4
Table 2: Mapping of Objectives to Use Cases 7
Table 3: Summary of Microgrid Definitions 13
Table 4: Critical and Non-Critical Loads and Child Microgrids for CPFD 19
Table 5: Grid Services 37
Table 6: Demonstration Results Compared to 42
Table 7: Carbon Reduction Given Monthly 52 Area Generation and Load Data 52

EXECUTIVE SUMMARY

Introduction

In the United States, the aging electrical grid is becoming increasingly unstable and unreliable due to load (electricity demand) increases combined with a lack of new large-scale generation facilities. This inherent instability is compounded by the push to integrate a growing number and variety of renewable energy generators into the nation's electrical system. Simultaneously, military installations, communities, and campuses across the nation are turning to *microgrids*—small-scale, localized electrical systems that include multiple loads and distributed energy resources that can be operated independently from or in parallel with the main electrical grid—as a means to 1) increase their independence from grid instabilities, 2) use cleaner power, 3) enhance energy security, and 4) provide energy assurance.

The convergence of these factors—growing grid instability, increasing presence of renewable power generation, and the development of microgrids—has created a need for incorporating higher levels of renewable generation and enabling technologies in the power supply optimization and energy management arena. However, California must first address the challenge of efficiently operating the current electrical grid while maximizing the use of clean energy to produce affordable, stable, predictable, and reliable power on a large scale.

To meet this challenge, the research team embarked on the Camp Pendleton FractalGrid Demonstration project to investigate the efficacy of a unique microgrid architecture concept called a *FractalGrid*. This concept for managing distributed energy infrastructures offered the advantages of:

- The enablement of organic microgrid growth in a measured and gradual cadence.
- Rapid response times due to local control.
- The elimination of a single point of failure.
- Increased efficiency.
- The proliferation of sustainable power.

The Camp Pendleton FractalGrid Demonstration Project site is located within Marine Corps Base Camp Pendleton is at the School of Infantry, 52 Area. Camp Pendleton has hosted a wide variety of renewable energy conversion systems. The sun shines abundantly and there are few cloudy days, making the location advantageous for efficient solar energy production. The multitude of existing photovoltaic systems and newly constructed recruitment barracks buildings can easily accommodate a microgrid. The research team decided to test the FractalGrid microgrid on a pre-existing 530 kW (300-kW PV & 230-kW concentrating photovoltaic) photovoltaic generator at a nearby parking garage structure (see Figure 1). While this photovoltaic generator successfully harvests solar energy while providing shading and cooling to parked vehicles it lacks energy management and storage procedures, making it a perfect candidate for the microgrid testing

Figure 1: Area 52 Community Map—Camp Pendleton, California

Project Purpose

The purpose of the Camp Pendleton FractalGrid Demonstration Project is to pilot an innovative electrical grid architecture that integrates multiple intelligent and self aware microgrids,

community scale renewable energy generation resources, and energy storage systems to meet the demands of a community, as well as high-risk clients such as governments, mines, campuses, and large industrial institutions. The FractalGrid, which can be described as a "system of systems," features the following:

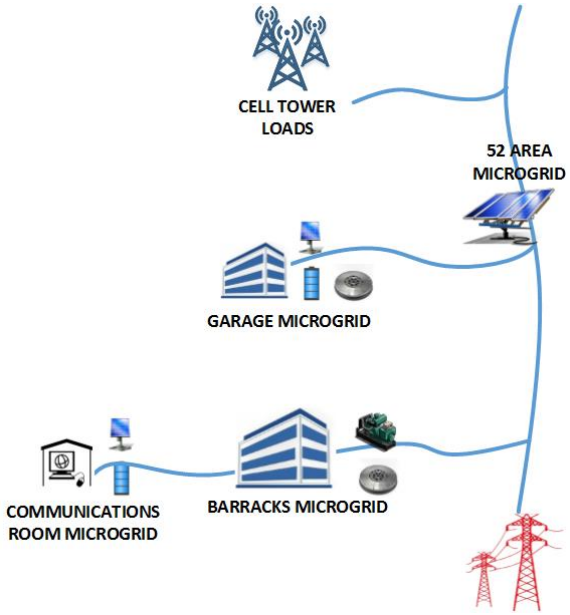
- Multi-facility microgrid infrastructures with concentrating photovoltaic renewable energy integration
- Grid-tied sub-systems with islanding capability (the ability to operate autonomously from the main electrical grid)
- Energy management and maintenance interfaces, both manual and autonomous
- Localized energy storage
- Prioritized load shedding (interruption of electricity supply to avoid excessive load on the electrical grid) and critical facility emergency demand response (reduction in electricity use to offset peak loads on the electrical grid)
- Energy production and usage optimization
- Scalable, open systems architecture-based, commercial off-the-shelf-preferred architecture

The Camp Pendleton FractalGrid Demonstration Project illustrates interoperability among multiple microgrids and indefinite scalability due to the *self-similar* nature of the subsystems and components. Self-similarity, or the property of a whole object being similar to a part of itself, is a typical property of fractals, hence the name *FractalGrid* for this microgrid. Each microgrid in the FractalGrid is a system in itself; while working independently for self-preservation, it participates in the larger mission of the FractalGrid community, making the whole of the system more than the sum of its parts. These highly interoperable systems, subsystems, and components function in harmony, supporting each other to fulfill the demands of the consumers.

Project Results

The research team tested an integrated system of four intelligent and self aware microgrids at the community scale with a combination of renewable energy generation and energy storage technologies. These variously sized microgrids interacted with each other and the utility grid to provide highly secure available power to critical assets (see Figure 2). To realize certain capabilities, the Camp Pendleton FractalGrid Demonstration project necessitated the development of a supervisory control and data acquisition system and energy management systems that used existing open source software coupled with a proprietary code, but always using standard protocols and interfaces such as XMPP, OpenADR 2.0b, JSON, and others.

Figure 2: Camp Pendleton FractalGrid Layout



Four categories of use were identified as end-objectives for the system: islanding, consumption reduction, peak load management, and carbon emissions management. The research team's efforts were successful (see Table 1). While there was insufficient time and budget for the largest microgrid, m52, CleanSpark is currently self-funding the completion of its islanding objective

Table 1: Demonstration Results Compared to Objectives

	mComm	mBarr	m5.2	m52
Islanding	Success	Success	Partial Success (10 minutes via batteries)	Insufficient Time/Budget
Consumption Reduction	Success	Success (via m52)	Success (via m52)	Success
Peak Load Management	Not applicable	Success	Success	Success (Extrapolated)
Carbon Management	Success	Success (via m52)	Success (via m52)	Success

The success of this project indicates a positive future for the FractalGrid concept. Camp Pendleton is currently working with CleanSpark to integrate additional fractal microgrids to into the FractalGrid architecture.

Project Benefits

The success of the Camp Pendleton FractalGrid Demonstration Project is a very relevant milestone in demonstrating organic microgrid growth enabled by a standardized inter-microgrid communications. The theory of a fractal topology has been successfully shown to support all the use cases to make sustainability sense—affecting people, planet, and profit. FractalGrid architecture will save the United States Marines, one of the largest ratepayers in the state, an average of $71,500 per year with the equivalent of a five-year payback if such a system and solution was procured through traditional commercial means. The results of this project can therefore now be used as a blueprint for future microgrid developments throughout the United States and worldwide.

CHAPTER 1: Objectives

This chapter summarizes the high-level use cases to be demonstrated by the project. Each of the use cases fall into one of two Program Objective categories – Energy Management and Security. (In systems engineering, use cases are a list of steps representing missions or "user stories.")

1.1 Program Objectives

The high level objectives of the Camp Pendleton FractalGrid Demonstration project are twofold

- **Energy management:** understand energy sharing within multi-microgrid settings using integrated community-scale renewable systems and enabling technologies; and
- **Security:** demonstrate security (including cybersecurity) solutions with renewable system integration and distributed generation control systems. The energy generation and demand will be optimized by installing power controllers, distribution and isolation switches, and local energy storage in addition to analyzing critical mission priorities.

For energy management, there are three technical objectives:

- **Utility Footprint Energy Reduction:** Reduce kilowatt-hours per day by 10 percent during the demonstration period by optimizing generation and load resources.
- **Utility Footprint Power Reduction:** Reduce Peak Demand kilowatts by 10 percent during the demonstration period using energy storage to optimize generation resources and load demands. This can be done via peak-shaving, load shifting, and load-leveling.
- **Carbon Management:** Reduce the carbon footprint by at least 5 percent against the baseline by locally producing zero-emission energy with renewable resources coupled with solar forecasting.

For security, the following is the technical objective:

- **Islanding:** Demonstrate the grid-independence of multiple distributed microgrids (from the local utility grid as well as from other microgrids) with FractalGrid architecture. Islanding will be a demonstration of reliability, security, and sustainability.

These objectives can be satisfied by a handful of use cases as outlined in Table 2 below.

Table 2: Mapping of Objectives to Use Cases

Program Objective	Technical Objective	Relevant Use Cases
Energy Management	Utility Footprint Energy Reduction	1: Islanding 2: Local Generation
Energy Management	Utility Footprint Power Reduction	3: Peak-Shaving 4: Load-Shifting 5: Load-Leveling
Energy Management	Carbon Management	2: Local Generation 3: Peak-Shaving 4: Load-Shifting 5: Load-Leveling
Security	Islanding	1: Islanding 6: Robust Data Collection

1.2 Use Cases

1.2.1 Use Case 1: Islanding

- Disconnecting from utility power, establishing voltage and power locally

Energy security is increased when the dependence on utility power is minimized. One primary function of a microgrid is the capability of operating off-grid. Breaking away from the grid is useful: if the grid experiences an outage, if power quality is poor, or if an equipment damaging voltage and or frequency event occurs. In such a case, a microgrid could establish a reference voltage and continue to feed loads while disconnected from the grid.

There are also scenarios when a short outage or *blink* in the power system can either damage sensitive equipment or cause critical computer data loss. A microgrid could endure the utility's temporary power loss by maintaining power flow to feed loads without a blink. This is considered a seamless transition to island. Due to the nature of AC power, this is typically complex and expensive to achieve, especially when synchronizing back with the utility grid.

Another case when islanding is useful is during a planned utility outage. The microgrid could gracefully break away from the utility and planned maintenance can be strategically scheduled to conclude before the system runs out of energy from storage and local generation. An islanded microgrid usually disconnects noncritical loads that would normally be fed while connected to the grid. The cost of the microgrid system can be substantially reduced if the load to be fed is limited to critical loads.

A recent utilization of microgrids is to participate in demand-response programs. For example, the California Public Utilities Commission (CPUC) developed demand-response programs that

will decrease customer utility rates or provide incentives for load reduction during planned events that a customer may participate in. With a microgrid, the customer could meet a demand response event requirement and reduce their overall utility energy consumption by activating the island mode of their microgrid.

1.2.2 Use Case 2: Local generation

- Store energy when PV generation is larger than circuit loads and discharge when PV is no longer available.
- Provide energy to microgrid circuits using PV power when utility power is not available and prevent reverse power flow outside of a microgrid. The UL1741 requirement to de-energize the grid when utility power is lost is still maintained.

A utility company might impose restrictions that a renewable energy generation system cannot flow into their grid for safety or regulatory reasons. In this case, standard renewable generation would require curtailment when local loads do not meet available generation. To avoid wasting available generation, a control system with monitoring of local load, local generation, and local storage, could intelligently store any excess generation for use when generation is unavailable.

Many current and future PV customers are under the impression that locally installed PV systems can act as a backup generator when the local power grid goes out. This is not typically the case due to the Public Utility Commission rulings that grid-tied renewable energy/generation sources must shut down at the time that utility voltage is lost. This is upheld by the Authority Having Jurisdiction (AHJ) verifying that equipment coupled to the utility is a UL1741 listed product and has been tested to shut off when voltage on the grid connection is lost.

A microgrid with islanding capabilities will allow generation equipment to remain in operation when the utility power is lost. In this case, any control or relay equipment at the Point of Common Coupling (PCC) for the microgrid must be verified to ensure that power generated by the microgrid cannot be connected to the utility system while the utility voltage is absent, out of phase, or otherwise out of range. The control system design includes this protection equipment that isolates the system from the utility prior to re-energizing the microgrid and protects the utility equipment, maintenance personnel and the microgrid equipment during power failure and reconnection. Once island voltage is established, the load-flow scheme described above can be implemented to manage storage and generation and continue to feed microgrid loads.

1.2.3 Use Case 3: Peak-shaving

- Reduce utility peak demand (kW) charge by discharging energy storage to reduce peak power draw from utility grid.

The utility company maintains their distribution system and runs their generation systems based on revenues from customer billing. One of the advantages for a customer is that energy on their site is available at any given time. However, the utility company rate structure is strategically set-up with different rates during specific times in a day to more closely mimic real time market electricity pricing. In addition, utility companies often impose a peak demand

charge set for the highest peak power draw seen on the utility meter over any single-month time period. Utility company demand charges are, for example, nearly $20 per kW in the SDG&E territory for Commercial Time of Use Customers (AL-TOU).

The benefit of renewable energy systems is that locally produced energy can replace or reduce grid demand and kWh consumption. Due to the variable and inconsistent nature of renewable generation, generated energy is not necessarily suited to minimize power consumption when rates are high. To best utilize this renewable energy, a control system with local energy storage could manage the energy by storing it when utility demands are low and dispatching it when utility demands are high.

Peak-shaving can be extremely advantageous for customers with large demand loads that occasionally or periodically turn on and raise the monthly peak demand value well above the average demand for the month. This is evident with many customers when a time clock system is used to initiate building loads in an occupied state, resulting in lighting and mechanical HVAC loads that extensively increase the demand for the first 15 minutes and settling as thermostat temperature set-points are reached. An extreme case would be an example of a magnetic resonance imaging (MRI) machine turning on that could cause a peak demand value as high as 100 times the average demand of medical clinic building's consumption.

To minimize a consumer's peak demand, the control system utilizes a complex forecasting algorithm to set a predicted peak demand value for each month. The energy storage and load management control sequencing is activated to keep the utility meter from receiving an average 15-minute demand larger than the prescribed set-point. This is done by storing grid energy when the load does not exceed the prescribed set-point and dispatching power from the energy storage unit when the load does exceed the set-point such that the peak demand from the utility is not exceeded.

1.2.4 Use Case 4: Load-shifting

- Load-shifting: storing energy during off-peak hours to feed loads during peak hours.

In addition to peak demand charges, utilities will often charge customers more for energy, or kilowatt-hour (kWh) use during on-peak periods compared to off-peak periods. To minimize costs, customers are incentivized to use energy during off peak times. The peak rates are typically 30 percent to 50 percent higher than off-peak rates and can be as high as 200 percent more in some cases.

There are many consumers that may not have much control of their on-peak energy use throughout the day, but may consume most of their energy during peak times. A control system can predict the consumption during peak time periods and, with energy storage, manage the power flow such that most if not all peak consumption is moved to an off-peak period. The process completely charges the energy storage in off-peak hours and discharges the energy storage during peak hours.

1.2.5 Use Case 5: Load-leveling

- Microgrids can throttle the kW demand at a meter for a specified time to validate a demand-response event has been met.

An underutilized set of programs created by utility companies and required by the Public Utility Commission (PUC) is demand-response. To generalize, the utility company will incentivize a customer with annual rate changes or event-driven payment/credit incentives to reduce power consumption during a specified time period. These programs require a response from the customer ranging from 15 minutes to 1 day in advance depending on the event.

One solution is to have a load-shedding (load management) process implemented that will satisfy the program's requirements. However, a possibility exists wherein customers might override a load shedding scheme and continue to use noncritical loads when demand response events occur, thereby eliminating any participation in the event.

With a control system and local energy storage, these events can be managed, automated, and optimized to benefit the customer's involvement. The control system can monitor the customer power usage, predict the consumption during the requested event and schedule energy storage charging and discharging to meet the demand-response requirement without any customer impact to non-critical loads. Should the customer elect to curtail any loads, priority levels can be included in the control algorithm and set by the customer; customizing and catering to the customer's energy requirements

A unique benefit has been found with the use of microgrids and load-leveling that can benefit demand-response. When a microgrid is implemented, an energy storage system within the microgrid can be "throttled" to establish a flat utility load profile while the customer's loads are turning on and off, causing the load demand to fluctuate. Load consumption under and above the set point would charge and discharge storage to match the set point. A client can continue to utilize energy as normally would and when the energy storage is near fully discharged, it would need to load-shed, or curtail a load, such as mechanical HVAC equipment. This would allow a customer to avoid the inconvenience of load-shedding procedures.

1.2.6 Use Case 6: Robust data collection

- In normal circumstances, data is stored locally and transmitted in real-time to both a local aggregator and the Microgrid Operations Center (MOC), both of which store sensor data, alarms, and events indefinitely.
- If network latency is experienced, the system will begin to accumulate files that will automatically backfill the local aggregator and the MOC server once the necessary bandwidth is restored.
- If the local network or the connection to the MOC is unavailable, the data is held in memory by the fPS system until the internal data store is full. At that point, files will be written as above. Once the connection is restored, the internally stored data will be sent, followed by the accumulated files.

An important aspect of Operations and Maintenance is the protection of raw and derived data that is generated by each FractalNode. In the event that the system experiences a fault, referring to logged data is important for determining both the cause of the anomaly and whether appropriate measures should be considered to resolve the issue.

In the event that either the local aggregator or the MOC are undergoing maintenance or the network is unreachable between locations, the data has been stored locally and the aggregator node(s) that are missing the data can be reconciled. Rather than relying on manual mechanisms to perform the reconciliation task, the local FractalNode will automatically write files to the disk once its internal buffers have been filled. When the connection to the aggregator server has been restored, the system sends the recent data from its internal memory buffers and will attempt to transmit all files to the aggregator servers. Each aggregator server has a module that accepts these data files and fills in the history to provide the complete data picture during an event. This allows the servers to be self-healing when planned or unplanned maintenance activities occur.

The ability to have a complete data history is also important for other analysis activities. In both cases, having data during both normal operating conditions and unusual circumstances allows for the system to better recognize such events in the future by implementing alarm conditions and automated processes.

1.2.7 Chapter Summary

While there are several essential use cases, all fall within the Energy Management or Security domains. By being so, the vast majority of the needs of users have been covered. Energy Management use cases include Islanding, Local Generation, Peak-Shaving, and Load-Shifting, and Load-Leveling. Security use cases include Islanding and Robust Data Collection.

CHAPTER 2: Architecture

This chapter describes the confluence of requirements and architecture as they related to describing a solution for the use cases described in Chapter 1. The architecture described as a FractalGrid is necessary to satisfy the non-functional requirements as derived from various definitions of a microgrid as well as unique requirements for inter-microgrid communications.

2.1 Architecturally Significant Requirements

General microgrid requirements are universally defined, albeit somewhat different depending on the origins of the definitions. Some of the more common definitions are the following:

2.1.1 Galvin Electricity Initiative

(www.galvinpower.org/microgrids**):** Microgrids are modern, small-scale versions of the centralized electricity system. They achieve specific local goals, such as reliability, carbon emission reduction, diversification of energy sources, and cost reduction, established by the community being served. Like the bulk power grid, smart microgrids generate, distribute, and regulate the flow of electricity to consumers, but do so locally.

2.1.2 Institute of Electrical and Electronics Engineers (IEEE) 1547.4

A Distributed Resource (DR) Island System or Microgrid is used for electric power systems (EPS) that

- Have DR and load
- Have the ability to disconnect from and parallel with the area EPS
- Include the local EPS and may include portions of the area EPS, and
- Are intentionally planned

DR island systems can be either local EPS islands or area EPS islands

2.1.3 US Department of Energy (DOE)

[A microgrid is] 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 enable it to operate in both grid-connected or island mode.

2.1.4 Conseil International des Grands Réseaux Électriques (CIGRE) C 6.22 WG: (in English, the International Council on Large Electrical Systems)

Microgrids are electricity distribution systems containing loads and DER, (such as distributed generators, storage devices, or controllable loads) that can be operated in a controlled, coordinated way either while connected to the main power network or while islanded.

A summary of these microgrid definitions is established in Table 3.

Table 3: Summary of Microgrid Definitions

Microgrid Definition	Requirement							
	Local	Renewable Power	Storage	Distributed Energy Resource	Islanded Capability	Connected Capability	Demand-response	Intentional Islandability
Galvin	Yes	No	No	No	No	No	No	No
IEEE 1547.4	Yes	No	No	Yes	Yes	Yes	Yes	Yes
DOE	Yes	No	No	Yes	Yes	Yes	No	No
CIGRE C 6.22 WG	Yes	No	No	Yes	Yes	Yes	No	No

Microgrids are not new. In years past, most of them simply satisfied the Galvin definition. More recently, stricter definitions have been utilized and have come to encompass the following considerations from the DOE[1]:

- Power flow
- Voltage, Frequency
- Single Point of Common Coupling (PCC) or Multiple PCCs (need coordination)
- Fault protection
- Load requirements
- Reserve margins
- Adequate Demand-response (DR)
- Power quality
- Transients

As any number of microgrid architectures may satisfy these requirements, we focused on non-functional requirements to develop an ideal architecture not just for microgrids but for a network of microgrids, considering first and foremost, *reliability*, *security*, and *sustainability* of the entire enterprise. In addition, we strongly consider the requirements of *modularity* and *scalability*.

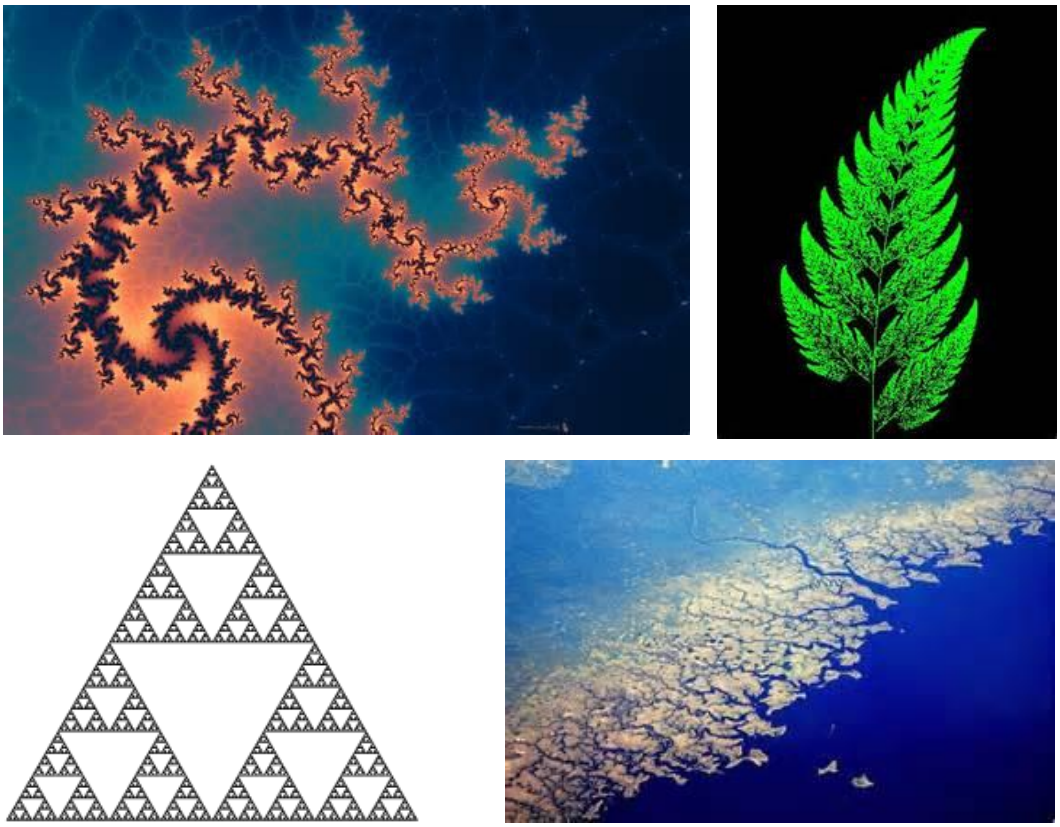
[1] http://e2rg.com/microgrid/standards_breakout2.pdf

2.2 Solution: The FractalGrid

2.2.1 Fractals

A fractal is a mathematical set that, having a Hausdorff dimension, exhibits a repeating or closely-repeating pattern that displays the same architecture at every scale. In computer science, fractals can be defined through recursion and are often used for rapid and realistic modeling of graphical objects. In nature, fractal characteristics are exhibited by fern fronds, clouds, and lung alveoli. Figure 3 shows several examples of both natural and computer generated fractals.

Figure 3: Fractal Patterns



2.2.2 FractalGrid

CleanSpark's unique FractalGrid™ architecture is a type of distributed and networked microgrid architecture in which a larger microgrid is comprised of smaller microgrid nodes or "fractal units". Fractals, or self-similar patterns, can be seen in nature. Clouds, river networks, and lightning bolts are a few examples of natural phenomenon that display fractal features. These features revolve around the mathematical principle that larger components of a system (river system, cardiovascular system, neurological system, etc.) are comprised of multiple subsystems with a similar design.

This solution leverages renewables combined with advanced energy storage (such as advanced energy storage flywheel and flow battery technology) to provide a renewable solution for the

critical infrastructure power system. On-site renewable generation provides greater energy reliability through triple redundancy achieved via integration with legacy assets while interconnected with the local utility network through existing points of interconnection.

The Camp Pendleton FractalGrid implementation is one of the first OpenADR 2.0b-compliant systems in the world and the first in a military base setting; able to respond instantaneously to demand-response events as well as interact with energy markets based on pricing signals. It provides a resilient electrical grid that is fully capable to interoperate at a local and utility level.

Revolving around the integration of locally-available community-scale renewable resources, the FractalGrid provides a reliable source of electricity generation and reduces stress on the aging US grid. If available, the system takes advantage of localized renewable resources for electricity generation and integrates renewable energy with the local utility grid via semi-autonomous controls that directly enhance the ability of the customer to maintain energy delivery during outage events or shortfalls in energy availability. This capability, combined with a cyber-secure-information sharing platform, greatly enhances energy security and reliability.

The fundamental goals of the FractalGrid are to ensure energy security to critical facilities and functions of the local area while reducing overall cost. This requirement of energy assurance drives the confidence that energy can be relied upon where and when it is needed. The energy reliability and security benefits of this system ensure uninterrupted power to support critical processes.

2.3 Microgrid/FractalGrid Operational Modes

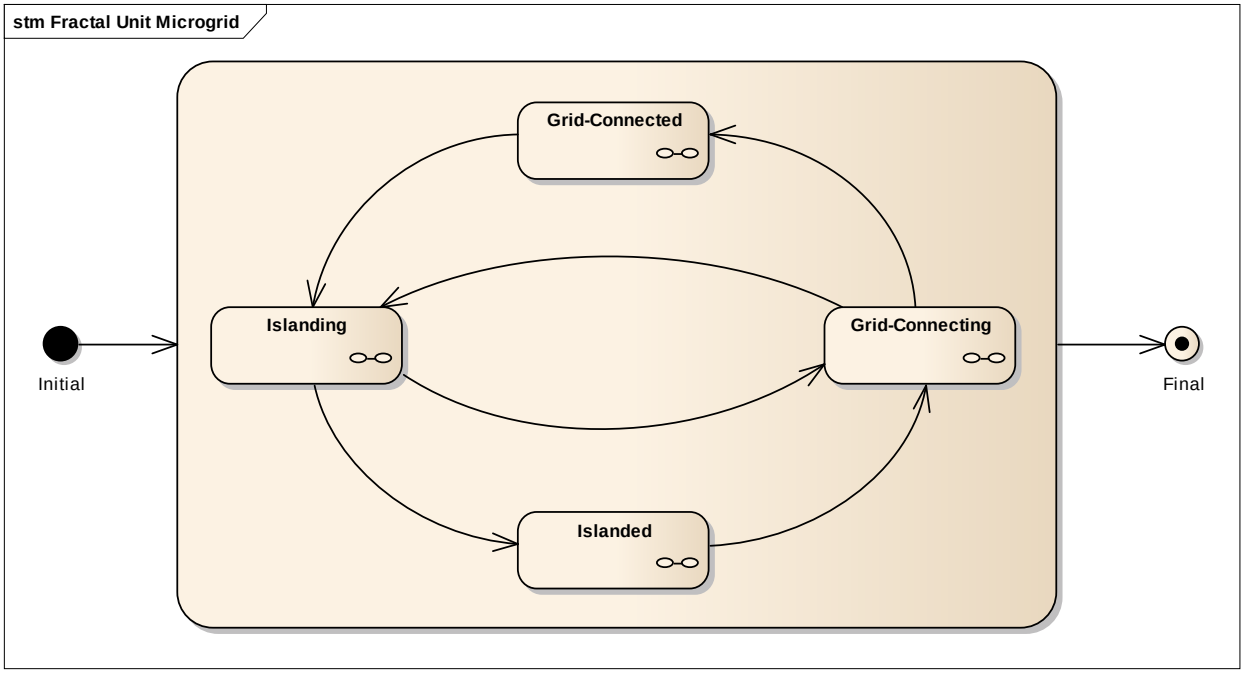
An advantage of a microgrid is the associated reliability and resiliency to adverse grid conditions such as voltage and frequency anomalies and power outages. When detecting such events, the microgrid is capable of disconnecting from the utility grid and autonomously sustaining power for minutes to weeks depending upon local distributed resource generation, energy storage, and intelligent energy management strategies. Consequently, the microgrid can detect the recovery of normal grid behavior and reconnect for normal parallel operation after syncing reference voltage and frequency.

Microgrids have four distinct states or operational modes (see Figure 4) according to the National Renewable Energy Laboratory. Additional operational sub-modes (peak-shaving, load-shifting, and load-leveling as described in “use cases”) allow end-users to offset energy and power consumption from the utility through locally produced renewable energy and energy storage, which helps to increase US grid stability (via Demand-response) and consequently, reduce electricity bills for participating customers.

- Grid-connected mode
    - Distributed resource and microgrid operate in IEEE 1547 standards
    - Operational sub-modes can be enabled to reduce peak load and energy demand from utility
    - Sub modes:

        - Load-shifting
        - Peak-shaving
        - Load-leveling
- Islanding mode
    - Transition from grid-connected mode to islanded mode
- Islanded mode
    - Operate disconnected from main grid
    - Sub-modes:
        - Load-leveling
        - Load-shedding
- Grid-connecting mode
    - Only reconnect within correct voltage, frequency, and phase angle windows specified in IEEE 1547

Figure 4: Microgrid State Machine



2.4 Camp Pendleton-Specific Architecture

To illustrate the architecture, m52 at the 12kV line was chosen as the single-entity microgrid that connects to the utility. There are two immediate, smaller microgrids, identified as mBarr and m5.2. While mBarr is a child of m52, m5.2 can be thought of as the degenerate form of the polymorphic m52 microgrid (see 0 3.2.3.1 Polymorphic Microgrids (m5.2 ←◎ *m52)*). The smallest microgrid, known as mComm, is a child microgrid to mBarr and supports the critical communications infrastructure for the entire m52.

2.5 Summary

The FractalGrid architecture has been described as the ideal topology in which to implement self-sufficient microgrids, satisfying all of the desired non-functional requirements including reliability, security, sustainability, modularity, and scalability. The architecture takes advantage of "self-similarity properties" and standard interfaces for maximum interoperability. The architecture grows with linear complexity, much more tenable than dealing with microgrids with non-standard interfaces.

CHAPTER 3:
Design & Implementation

This chapter describes the detailed design and implementation of the FractalGrid architecture described in Chapter 1, taking into consideration project-specific (such as budget and schedule) and technical constraints such as available equipment and existing technology to be integrated.

3.1 Constraints and Restrictions

3.1.1 Budget

While several of our subcontractors provided total matching funds (in equipment, software, and labor) exceeding that of the grant itself, there remained budget constraints for the four targeted microgrids. But while not every microgrid exhibits all the same desired requirements, all requirements were satisfied by at least one of the four microgrids.

3.1.2 Technical & Programmatic

3.1.2.1 Generation

52 Area at MCB Camp Pendleton had a total of 530 kW (300 kW PV and 230 kW CPV) solar generation prior to the FractalGrid integration, but lacked energy management and storage to parse generation and deliver energy to specific loads within the area. Excess generation beyond local loads was by default pushed into the grid. Without energy storage to act as a buffer, solar intermittency induced variable electricity generation and contributed to macrogrid instability.

In order to effectively use the existing solar generation for the FractalGrid, the pre-existing grid-tied Satcon inverters had to be controlled. Satcon Technology Corporation filed for bankruptcy in October 2012 and was eventually purchased by Great Wall Energy; so finding technical support to adjust the existing system proved to be difficult.

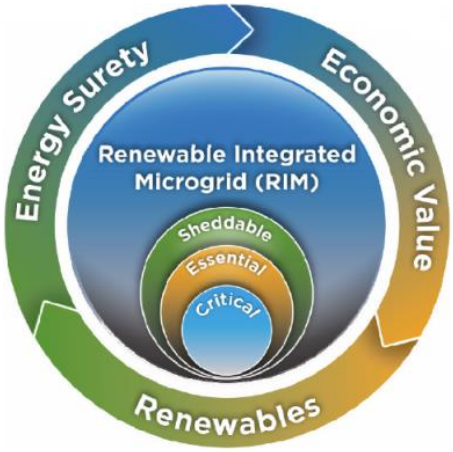
Additionally, after finally reaching technical support, an attempt was made to integrate a communications and controls module (CCM) for adjusting the power output of each inverter during mid-project timeframe. The hardware was installed and safely mounted within each inverter, but time constraints of the project prevented software integration to control ramping of the inverter output as desired, correspondingly affecting the formation of the m52 microgrid.

At the time of this writing, the m5.2 microgrid can retrieve data from the inverters via the CCM but Satcon support for establishing controls is pending.

3.1.2.2 Loads

The National Renewable Energy Laboratory (NREL) identifies three types of load criticalities to define a microgrid's procedure to sustain, control, and shed based on importance in the event of a macrogrid failure: critical, essential, and sheddable (see Figure 5).

Figure 5: NREL's Renewable Integrated Microgrid Model



In the case of CPFD, however, we chose to limit the loads to only two types: critical and non-critical. The constituents of each are in Table 4 and described in the following subsections.

Table 4: Critical and Non-Critical Loads and Child Microgrids for CPFD

	Critical	Non-critical	Child Microgrids
m5.2/m52	Emergency lighting 480VAC panel	HVAC 208VAC panel Cell Towers Receptacles	mBarr
mBarr	Emergency lighting Armory security system Armory HVAC	Elevator Fire System	mComm
mComm	Server Racks Routers, Modems, Switches Computers Flywheel power electronics	AC condenser AC fan coil	None

Critical Loads

One objective of microgrids is to ensure good power quality and energy surety to *critical* loads where it is necessary. *Critical* loads are imperative to remain online in the event of energy shortfall by the macrogrid. Operating rooms and ERs at hospitals, door entry systems, or water treatment and distribution systems are typically categorized as critical loads. An uninterruptible

power supply (UPS) allows a seamless transition to an auxiliary power source that can support critical loads once the main grid fails and will continue to support until the utility restores normal operation.

Traditionally, diesel generators act as backup emergency power supply during grid failure or grid support for voltage and frequency stabilizing; in other words, they provide standby power. These generators have short start-up time and can restore power to homes within seconds of utility blackouts. However, diesel generators do not last extremely long and can only maintain power to large areas for several hours. Backup generators also require fuel to operate and consequently emit large amounts of greenhouse gases into the atmosphere. Microgrid systems can mitigate the disadvantages of conventional standby generators and produce reliable and clean energy to homes, businesses, and facilities.

At the Camp Pendleton demonstration site, critical loads at each location were pre-determined prior to FractalGrid installation. Within the mComm microgrid, all devices and systems are critical loads since telecommunication is a necessity in the event of an emergency or grid power failure. A 2kW PV generation and 24V 840Ah energy storage supports mComm's electrical infrastructure; so the critical loads can remain active indefinitely given sufficient solar resources.

For mBarr, the critical loads consist of the barracks standby (as opposed to emergency) lighting, armory security system, and armory mechanical (HVAC) system. (The fire system is surprisingly not classified as critical.) The barracks construction included a predetermined critical load circuit, which makes microgrid integration a convenient task.

At m5.2, standby lighting and the 480VAC panel constitutes as critical loads. The m5.2 microgrid also possesses its own PV generation (2kW) and batteries (48V 500Ah) to support loads.

Essential and Sheddable Loads (Non-Critical Loads)

Microgrids are capable of disconnecting individual loads that are not "critical" to the building's minimal functionality during periods of abnormal macrogrid characteristics or emergencies. Generally, smart buildings on backup generators have control procedures that can shed *essential* and *sheddable* loads during grid downtime such that critical load uptime can increase.

Essential loads are secondary support services and may be required for health and safety reasons to preserve the building's basic function such as maintaining ambient temperature, air-conditioning, heating, and lighting. These loads do not require an uninterruptible power supply and are allowed to temporarily power off during the startup period of a standby generator.

Unlike critical loads where tight voltage and frequency regulations are required for sensitive medical or scientific equipment, essential loads are not concerned with quality of the supply and can be powered by a generator directly. *Sheddable* loads are demands that are not necessary for minimal building operation and do not require power protection unlike critical and essential loads. Loads such as general lighting, non-essential printing services and certain household appliances are sheddable and can be temporarily curtailed until the supply profile recovers.

Consequently, uptime for critical loads will increase by reducing the overall load on the microgrid. Eliminating loads from the microgrid will also mitigate fluctuation in overall load demand and increase the stability of the microgrid.

For the FractalGrid implementation at Camp Pendleton, each microgrid has several non-critical loads including its "child" microgrids. Each microgrid, with the exception of mComm, has a child that can be detached during a utility outage.

m52 grid is the parent grid of mBarr and will abandon the child as it anticipates or detects that the child's load can no longer be supported. Likewise, mBarr will release mComm as it cannot sustain the two combined without sufficient generation. Currently, a 12kV transformer is prohibiting the connection between all microgrids to form the m52 microgrid; therefore the microgrids act independently and self-sustain their loads when the utility drops.

Further research is required to cold/warm start the transformer without the need for utility power, which allows for energy management implementation (monitor / shed / reconnection schemes).

3.2 Electrical and Physical Network

3.2.1 Description

The design of the electrical system and interconnection of resources is a key component to this project. The overall basis of design is to have multiple microgrids that are self-sustaining to some extent, but interconnected as a whole to take advantage of any unique resources. The selected site presents an optimal opportunity to demonstrate this because there is a typical building with load that cannot be powered by renewable generation strictly due to a lack of space, and an excess of renewable generation some distance away with little load to use it.

3.2.1.1 m5.2/m52 Microgrid (Community Scale)

The electrical infrastructure in this area branches from a single 12kV overhead circuit routing along a street with step-down transformers feeding one or more buildings along the street. A key requirement of a microgrid is the ability to disconnect and island from its parent grid (oftentimes, the utility company). Therefore, the topmost device added is an automated 12kV switch capable of break away and reconnecting to the utility grid under the right conditions.

Since a community scale microgrid was needed within the middle of an existing CP circuit, a new switched "branch" was constructed in parallel to an existing overhead line to isolate specific loads from the original circuit. This branch was set up so that future loads can be added by relocating the current attachment from the non-switched circuit to the switched circuit without major reconstruction.

> *NOTE: This layout assumed that the design is not for public utility company power distribution, but that the owner of the medium voltage equipment will allow this type of modification. In the case of utility company owned power lines, this equipment would be part of unmetered distribution and the utility would typically not allow a control device to be installed that is not within their control.*

The 12kV branch circuit feeds two transformers (750 kVA and 100 kVA) that cover the buildings with critical loads, the renewable generation (PV), and the remote loads (cell towers). Several internal building loads are fed by other transformers from the 12kV non-switched circuit.

With the separation of the buildings and generation between the microgrids, each building needed to be electrically configured to share energy to prevent overloading or underloading conditions. Once the branch circuit is disconnected, a generation system must be controlled to provide generation matching the loads attached without importing or exporting on the grid. In this case, since renewable energy resources (PV/CPV) were used as the major generation source, these resources must be controlled in coordination with fluctuating loads using energy storage as an available buffer.

The smaller child microgrids at the building level can connect and disconnect themselves from m52. It is advantageous to be able to disconnect the loads from the renewable resources and have this main branch (or bus) be capable of energizing or de-energizing without interrupting the child microgrid critical loads.

m52 Electrical Power Controls: The main controlling device for the 12kV circuit is a recloser that matched the local utility company standards. The 2-way recloser switch is typically used to disconnect a branch from a circuit and may be used as an automated branch circuit protection device. The device opens in a fault condition and attempts to close after the fault condition has cleared with configurable times for disconnection and reconnection. Automatic reconnection avoids the need for a repair/maintenance crew to reset the tripped circuit at the site location.

The other controlling devices in m52 are connected to load circuits and the PV/CPV generation. The loads consist of the non-critical circuits at the barracks and the cell towers. When these loads and child microgrids are disconnected, the 12kV circuit will not have any load or voltage sources attached and the inrush of connecting the parent voltage source will be minimized. The loads and child microgrids are staged to reconnect when their individual programs detect the proper conditions.

The PV/CPV system control is set to variable output which will change according to load changes. This allows for strict load-flow control in microgrid mode.

3.2.1.2 mBarr Microgrid (Building Scale)

The microgrid with the greatest resemblance to a typical industrial or commercial situation is the barracks building. The barracks building contains multiple floors of corridors with beds, restrooms, showers, and laundry facilities. Also included are training rooms and elevator systems, established for this demonstration project as critical loads. This building load is too large for the local renewable generation source to sustain alone, but could have sufficient energy storage installed to support critical loads for a set period of time. Since there is a larger renewable generation source attached to the overarching m52 microgrid with energy sharing capabilities, this could be used to recharge the energy storage when available.

The barracks building consists of a 1200A 480Y/277V service fed by a 750kVA transformer attached to the overarching m52 12kV circuit. The non-critical loads are fed by several circuit

breakers and the critical loads are fed by one 400A circuit breaker. Due to the existing equipment layout, space availability, and circuit breaker configuration, the non-critical loads could be shed and the 1200A bus along with the one critical branch can remain connected to the m52 (parent) microgrid.

When the renewable resource is available, the energy could flow into this branch without the shed loads interfering with the power flow characteristics. (Another option that can apply to other building designs may be to feed the critical branch with a feeder directly from a service transformer and a contactor that will disconnect all other loads with one device.)

To form the microgrid, an energy storage device was installed to feed critical loads for about 10 hours. (The size of this energy storage has many factors that may have been different if this were not a demonstration project.) Also a control system, network equipment of the microgrid and any aggregation equipment was installed to interconnect the other microgrids that intertwine the system in a fractal manner. This control and network equipment is installed within the microgrid labeled mComm.

> *NOTE: Although the diesel generator is able to establish a microgrid on the 400A distribution board, this generator can only be connected to the loads when the "Grid" side of the ATS is disconnected, making energy sharing with the parent microgrid impossible. For this reason, the energy storage device should not be connected to a standard ATS as an interconnection with a larger parent microgrid.*

mBarr Electrical Power Controls: The main electrical power control for mBarr is the contactor to isolate mBarr from its parent grid (m52). In this case, all critical loads have already been isolated in the mBarr distribution board so no other load-shedding procedure is necessary. The last control device of the energy storage is to avoid accidental discharge onto the mBarr distribution board while the diesel generator is creating the voltage source for mBarr.

3.2.1.3 mComm Microgrid (Room Scale)

In this demonstration project, the lowest level microgrid system, mComm, is the most important and contains more than one generation source to keep it energized. Because mComm is a branch of mBarr it is fed from a parent microgrid that has an overarching parent microgrid. mComm is fed via a 30A circuit of mBarr that routes directly to a transformer to provide 208Y/120V to mComm.

Initially, a 3-phase 208Y/120V hybrid inverter system was installed to feed mComm load directly from the utility. In this case, inverted battery power would only be utilized when the utility is lost. Equipment connected to this hybrid inverter source turns off during the brief switching time from on to off grid and this loss of power is undesirable. This configuration was eventually re-arranged so two inverters provide power to a DC bus and a third inverter feeds the total AC load from the DC Bus. The configuration avoided the switching sequence of the inverters when the parent power drops by continuously feeding loads from a battery, battery charger, and PV maintained DC bus.

The hybrid inverter system allows for a charge controller to be integrated with the DC bus, incorporating PV energy into the DC system. 2kW of PV generation was installed on the building roof generating an average of 10kWh of energy each day. The overall load averages to 0.5kW, meaning 10kWh could feed the load for approximately 20 hours. Since the PV generation returns within 20 hours of the last charge cycle and mComm exhibits steady load consumption, the PV system can feed the load without the need for the parent power connection. It would not be prudent to keep the parent power from charging the DC batteries because this would cause larger depth of discharge on the batteries than necessary and thus, reduce the life of the batteries.

mComm Electrical Power Controls: The electrical power controls in the mComm microgrid are programmed and automated with the hybrid inverter configuration and do not need intervention from the SCADA system. The SCADA system monitors the results and set points of the inverters and will alarm when parameters are outside a nominal range. For example, the charging inverters measure the DC bus voltage and pull power from the parent grid when charge is needed. SCADA will monitor both the DC bus and the inverter temperature to confirm that the inverter continues to operate within the set range and that the inverter temperature is maintained at a safe and reliable level. Future optimization and commissioning may include refinement of these set points with forecasting inputs of PV generation and fluctuations in load.

3.2.2 Design for Reliability

3.2.2.1 Existing Circuitry with Generator

When retrofitting a building with a microgrid, there will be instances when an existing life-safety generator or lighting system needs to be integrated. In the case of the mBarr microgrid, an existing 200kW diesel generator was integrated. The microgrid supplies the emergency distribution board with power such that the generator senses the voltage as if the normal power source is available, preventing the generator from turning on. When our microgrid energy storage is depleted, the voltage source will disconnect and the generator will support the loads as intended.

This specific generator was not intended as a life-safety system, but individual battery packs within the building lighting satisfy the building critical power system. If the building was designed to have the generator satisfy the code requirements for life-safety systems in the building (such as egress lighting), then the energy storage equipment would need to be accepted by AHJ. The equipment must be UL listed for emergency system use certifying that the system would not interfere with the life-safety power source.

3.2.2.2 FractalNode for mBarr powered by mComm

For microgrid control systems, it is possible that a microgrid fails or the power flow is interrupted for a period of time. In such cases, it is important to keep the FractalNode control systems powered so data can be retained, mechanical switches can remain operational, and autonomous decisions can be evaluated and initiated. These control systems do not require much energy, but the primary backup system for DC voltage controls to remain fully charged at all times is a requirement.

In this project design, mComm microgrid is similar to a small data center model. Within close proximity to mComm microgrid is the parent microgrid, mBarr. Since mBarr does not have any critical loads that must remain running without a *blink*, power transitions to and from island mode will experience temporary losses of voltage. In this case, it was decided to additionally secure the power to the controls for mBarr with the mComm microgrid since mComm is always on line.

3.2.3 Design for Sustainability

3.2.3.1 Polymorphic Microgrids (m5.2 ←→ m52)

The Camp Pendleton FractalGrid architecture allows a microgrid to migrate its primary components into and out of its sphere of influence. For instance, this has been designed into the m5.2 microgrid which feeds a very specific load, has PV generation, and contains two forms of energy storage capable of sustaining its load for longer than 24 hours. Only minimal PV generation was included in m5.2 because it was designed to connect with a larger distribution service with excess renewable generation, namely the 540kW PV/CPV system previously described.

Connecting m5.2 to the larger distribution provides its parent microgrid, m52, with voltage and frequency. With this functionality, the sphere of m5.2 can grow, allowing other resources to be integrated. As an example, with m5.2 connected to m52, the grid-tied PV/CPV inverters can come online to provide additional generation to m5.2 or any other children of m52, even with the utility removed.

Conversely when the PV/CPV system on m52 connects to m5.2, m52 can take advantage of the m5.2 energy storage to store or dispatch power to the m52 children.

> *NOTE: At the time of this writing, the interconnection of the m52 microgrid has not been demonstrated due to equipment constraints and existing transformers connected on the m52 12kV line. The equipment constraint is that the hybrid off-grid/grid-tied inverter product used to create the voltage signal for the grid-tie inverter and the energy storage inverter are not electrically compatible to work together in an island. Further research with both inverter manufacturers is required.*

3.2.3.2 Microgrids as UPS (mComm)

A microgrid typically consists of an energy source, an energy storage system, and loads. A self-sustaining microgrid provides local generation of energy. A microgrid acting as a UPS will not (or cannot) share this energy generation with the parent grid.

At mComm, an inverter system that converts DC to AC acts as a generator to feed a load. Energy originates from locally installed PV or the parent grid (when grid-connected), passes into a battery energy storage system, then inverts back to AC to feed any load. The batteries can be charged with the parent grid if the PV alone is insufficient. When the parent grid is not available, the microgrid sheds non-critical loads and is self-sustained by the PV and batteries. The parent grid treats this microgrid as a load and not as a generation resource because no excess renewable generation can be shared with external microgrids. This would be considered

a UPS microgrid because the system is self-sustaining but not sized to share with its parent microgrid.

3.2.3.3 Microgrids as Primarily Generation (m5.2)

In many cases, microgrids will be installed in non-ideal environments. Due to space or accessibility constraints, a microgrid configuration may have minimal critical loads and an excess of generation. In some cases, such as with m52, establishment of the microgrid is still advantageous as the excess generation may be shared with neighboring microgrids.

With CPFD, it was not feasible to connect a voltage source directly to the feeding bus of the PV/CPV generation, or m52. The intended solution for bringing m52 online was to leverage a smaller microgrid, m5.2, to provide voltage to its parent. Once the parent is energized, the PV/CPV generation can come online prepared to provide generation, provided sunlight is available. With the solar inverters available, the fractalgrid controls can adjust their output to manage the load changes as the child microgrids join or separate from the parent m52. Effectively the child microgrids can use their parent as a resource when they need it and separate from it when they don't.

The m52 combined with its "kick starter," m5.2, is an example of a *generator microgrid*. The loads directly attached to the microgrid will only draw a small portion of the available generation capacity, but if this microgrid expands in scope to all its children a greater proportion of the generation will be required.

3.3 Information Network

3.3.1 Description

The IT network allows for the flow of electrons from generation to storage to loads. And as the IT network is dependent on the electrical network to function, a dependency loop is created. As such, it was important to classify the FractalNodes as critical nodes. In fact, two of the FractalNodes and one of the FractalNode Synapses were specifically designed to be powered by the most robust microgrids developed within this grant.

To maximize the applicability of the IT network of the widest array of devices for cost control and maintainability, great care was exercised in using standard protocols and interfaces.

3.3.1.1 Command, Control, Communications, Computers, and Intelligence (C4I)

Overview

The SCADA Master server at each FractalNode contains several off-the-shelf and proprietary applications that compose the flex Power System software.

SCADA System

The fPS Energy Management System (EMS) is developed as a series of modules that serve a very specialized purpose. The EMS incorporates the REEF SCADA system, which is a group of similar modules that serve as the core of the SCADA system of the EMS. REEF bundles communicate internally primarily via message queues. Although REEF exposes an API that can

be used for both request/response and data subscription mechanisms, the combination did not scale well.

Initially, the alarm processing within REEF was heavily utilized, but did not meet the needs of the EMS and was replaced. There are several utility bundles that are part of the EMS system unrelated to the SCADA system: user maintenance and verification allows the system to add and remove users as well as authenticate and authorize actions; the health monitor collects status from each of the nodes, alerting as necessary and reporting to the aggregator nodes for O&M support; and the configurator package, which helps build the data points used within SCADA. The configurator package will play a large role going forward in developing new FractalNodes.

External Communications

The EMS provides middleware capabilities as part of the software implementation. Multiple protocols and data transfer mechanisms are in place based on the source and destination of the data messages and the type of communications.

Request/response (web services)

- Web services are primarily used by the user interface to have direct interaction with the SCADA system to retrieve data and execute commands (based on specific user privileges).
- The flex Power System provides a variety of REST-style web services over HTTPS.
- All services require certificate based authentication and some additionally require LDAP authorization.

3.3.1.2 User Interface (UI)

The User Interface provided by the fPS Energy Management System is web-based and is developed in Java. This framework provides a reference architecture that can be used to create more consistent views, and speed up development by reusing portions of data views. Additionally, it has built in support for server-side events, which allow the client to receive information on a near real-time basis without having a great deal of network congestion.

A web client is available on each FractalNode on a touchscreen on the front of the panel. Additionally, the site is accessible via the local network and the VPN network. There is no data collected directly by the UI; it receives data pushes in near-real-time from the EMS and uses available web service calls to query history or perform commands.

The UI requires a login/password for authentication, and access to various pages on the site may be limited by a user's role. This is performed by calling a web service in the EMS system that queries the User Management package.

Currently implementations for each microgrid are customized through a JSON-based configuration file, providing a summary of site data on its primary dashboard page. Additional pages specific to devices are also available. All sites include a link to the local data historian

which allows users to query any point in the system for a 30 day period. A link to view alarms and events are also included for each local site.

Dashboard Screen

Each dashboard screen provides an overview of the power sources and load for the particular microgrid at the current time (see Figure 6). On the left side of the screen, a stacked area chart provides a view of how much each particular energy source (in the case of this implementation: solar power, energy storage, and utility power) makes up the current load. The load is indicated with a dotted gray line. The load line is frequently below the top of the various energy sources; this indicates that the microgrid is not utilizing all of the power being generated, and all power above the line is flowing back into the utility power grid.

Figure 6: Example Dashboard/Home Screen

On the dashboard, the left menu of icons allows the user to view more detail of various devices or energy sources. In the upper left, users can get to more administrative screens such as the data historian or alarms page.

Solar Screen

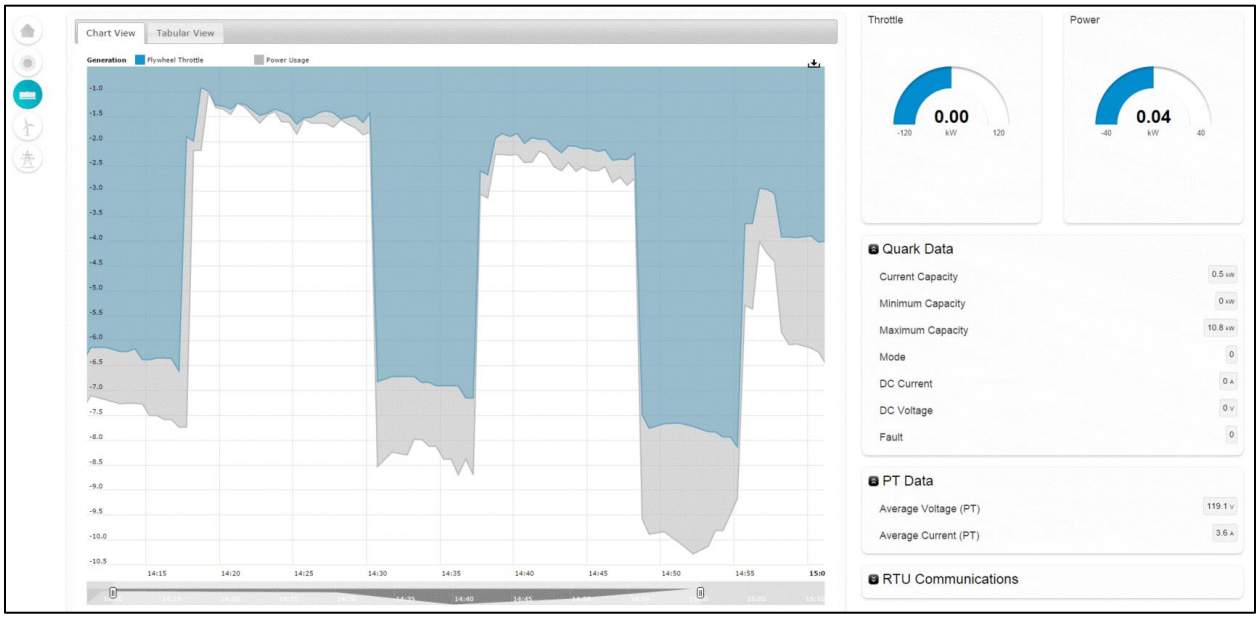
The solar screen is a configurable screen where users can see the output of specific PV generation for each microgrid.

The stacked area graph of the left represents the source of the solar generation. The gauge to the right represents the current total of all solar generation. Underneath, data groups provide additional access to data relevant to the specific generation source.

Flywheel Screen

The flywheel screen represents the control of the energy storage device (see Figure 7). On the chart (left), the blue indicates the requested power, and the gray shows the immediate response of the flywheel to deliver power in response. The values to the right are individual sensor measurements that are updated on change, or 500ms.

Figure 7: Example Flywheel Screen



Utility Screen

The utility screen allows the user to view the power requested from the utility. The screen illustrates the history for the previous 1-hour and individual sensor data.

History Screen

Below is an example of the History screen that is available on each FractalNode. The user can search for points of interest and both a chart and the raw data will appear in the left frame. Users can also: choose which colors to use to display each data point, add axes to the graph, stack the charts, and perform simple calculations on the data presented.

Alarms and Events Screen

The user can view the most recent alarms and events by clicking on the appropriate tab on the "Alarms and Events" page. Within each tab, the user is able to search by start and end date, for specific points, and by the type of alarm. The alarms of type fPS Data allow the user to click to go directly to the history view, with any supporting data included.

Flywheel Controls Screen

Manual control of the flywheel is performed via the Flywheel Controls screen, which is restricted to very limited personnel. The Flywheel may also receive automated controls via OpenADR requests or energy market requests. Basic control information is presented on the left side of the screen. On the right side, users choose from various modes and schedule the flywheel as needed.

Custom Screens

Additional custom screens can be defined within the configuration file that allows users to display a chart and data fields of their choice. One particular usage of this page is in the m52 Microgrid. Different measurements are needed when the microgrid is in islanded mode, and this page allows users to see the appropriate data when needed.

Data Aggregator and Monitor

All data that is collected by each of the FractalNodes is transmitted to a local aggregator server for longer term storage and monitoring. The user interface for the aggregator simplifies each node into its power sources and load data and presents it to the user in a unified manner. The screen below shows a map with indicators for each of the tree nodes. The size of the map markers increases as the usage of renewable energy increases. On the right, each site is represented by two bar graphs. The top bar is a stacked graph with one color indicating each source of power. Below that is the current load for the microgrid. Below that are statics for all microgrids combined.

Clicking on the bar graphs brings aggregator users to a mirror of the local UI as seen above, with very similar screens available.

A health monitor for the nodes is also included as part of the aggregator user interface. The node map allows users to see each aspect of the running instance and monitor disk space, queue sizes, CPU usage, etc. When a value is out of range, the node turns red which allows the user to immediately spot the area of concern.

There are similar history screens available as part of the Aggregator UI that allow the user to search for points in all microgrids for longer than the 30 days supplied locally. Additionally, alarms and health monitoring for the entire FractalGrid are available via this UI.

Status and Alarms

The fPS Energy Management System processes each data point for status changes and out of range values on each scan. All unsolicited status changes are logged as events in the system,

and any value that is outside of the configured normal range will generate an alarm. Because the system receives several point scans each second, alarms are recorded only once in a five minute period. Configured users are notified via email when an alarm is generated. The alarms can be inhibited by administrative users of the system during known outages or while a fix is being implemented.

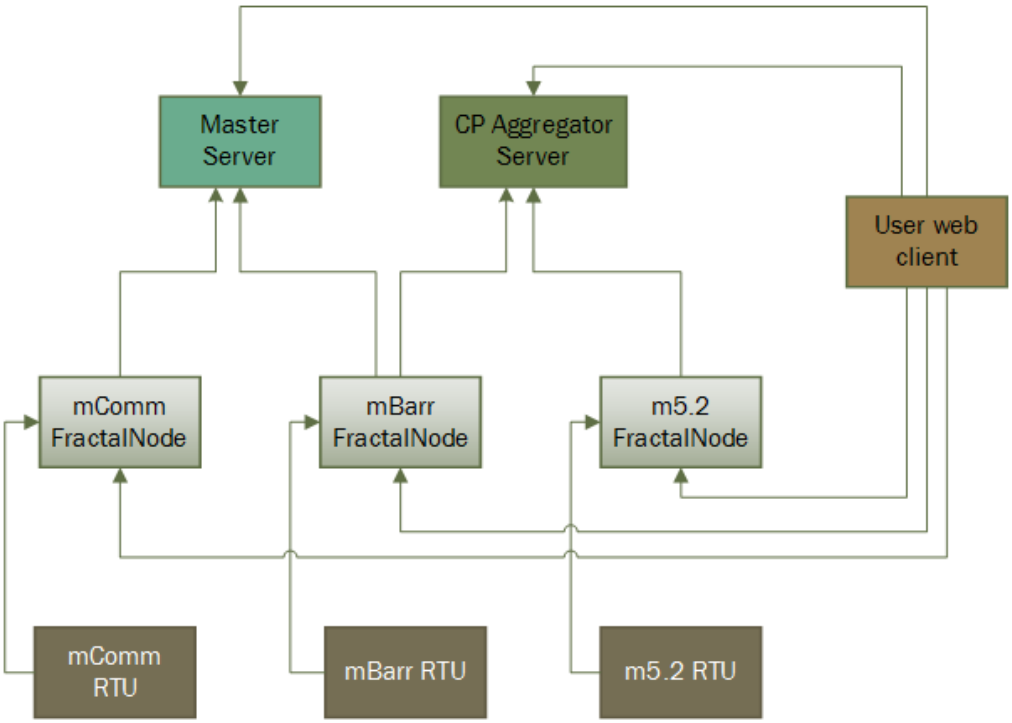
Alarms and Events are also visible and searchable in the local UI as well as in the Microgrid Operations Center (MOC) interface. In the alarm view, some types of alarms can be expanded to provide data that is related to the alarm. The "View History" link below can be clicked to go directly to the historical view at the time of the alarm with each recorded instance of the alarm clearly marked.

3.3.2 Design for Reliability

3.3.2.1 Redundant Connections

A fully redundant system is often perceived as more reliable, but often the complexities introduced by the redundancy result in less desirable results. For example, one issue is the "split brain" condition where communications are not currently possible between the redundant devices and both determine the need to perform controls that are not consistent with one another. For this reason, redundancy was introduced into the system in limited ways with strong mitigation in others. Figure 8 shows these redundant connections.

Figure 8: Redundant Connections



Remote Terminal Unit (RTU)

The RTU is not redundant due to complexities in managing the controls of multiple devices. A split brain condition could be especially detrimental in the RTU since it is rapidly making decisions based on incoming information. The mitigation for redundancy in the RTU is the use of an industrial-grade commercial PLC product.

SCADA Master

Similarly to the RTU, the SCADA system is responsible for making macro decision about the operation of the grid based on real time information and the system could be impacted poorly by a conflict of control. In the future, redundancy may be added to allow a secondary master to control the RTU when needed, but this would be implemented in a non-automated active/passive control model, where only one server is active at a time and a manual change is required to move to a secondary server.

Data

Multiple data paths send the near real time data to the aggregator and CleanSpark master servers for long-term storage and as a backup. Multiple paths ensure that in the case of an outage on a single server, the collection of data will not be interrupted.

User Interface

Because of the Service Oriented Architecture in place in the system, the user interface for each site can be hosted simultaneously from any server with the ability to connect to the SCADA Master. Historical queries for any data point can also be completed at the aggregator and master nodes.

3.3.2.2 Decentralized Controls

FractalNodes

Rather than a centralized system, a fractal hierarchy concept has multiple levels of control for different areas based on local conditions. Each microgrid, controlled by a FractalNode, governs smaller areas and can join together to form an overall larger microgrid. The hierarchy allows parents to detect a child's health and can logically reason whether to provide support if needed.

Each FractalNode is protected inside a 36 x 30 in. NEMA 4x enclosure with a touchscreen user interface display mounted on the front to show real-time measurements of the microgrid. Incoming AC power is filtered before converting to DC power and is the main energy source for the system. The FractalNode consumes approximately 40W to 60W and has a backup battery pack (24VDC, 36Ah) that can last for more than 7 hours with an uninterruptible power supply unit to seamlessly switch if the primary source fails. A 24VDC bus energizes a series of electronics including a remote terminal unit (RTU), onboard computer (SCADA system), touchscreen monitor (User Interface), managed switches, sensors, and remote contactors. The measurements are then transferred to the SCADA system for transmission to other FractalNodes or Synapses as well as to the Microgrid Operations Center (MOC) via managed switches and fiber-optic.

FractalNode Synapse

A FractalNode synapse is a smaller FractalNode system and only serves to transmit locally collected data via fiber optic connections to its parent node; in other words, the FractalNode synapse is an extension to a FractalNode. Unlike the FractalNode, a synapse contains the minimal necessary components for functionality (therefore power consumption is reduced to 10W to 15W) and does not provide a graphical UI to display measurements since the parent node will display real-time synapse measurements. The parent node can control mechanical relays linked to the synapses, which enables load shedding features during times when available energy is limited. However, the synapse cannot read data or control mechanical relays on the parent node nor does it contain self-logic schemes.

Aggregator

Aggregator nodes collect data from multiple FractalNodes and monitor the health of connected nodes. Data collected at the local aggregator node is maintained for 1 year, while data at the Microgrid Operations Center is kept indefinitely. This longer data retention allows for medium- and long-term analysis for forecasting and preventative maintenance needs. Each aggregator requests status from each connected FractalNode at a configured interval (currently 60 seconds) and alarms CleanSpark staff when the node is unreachable. The aggregator node also examines the data sent from each node regarding: disk and CPU usage, current memory footprint, and time of last update, to ensure the successful working operation of each node.

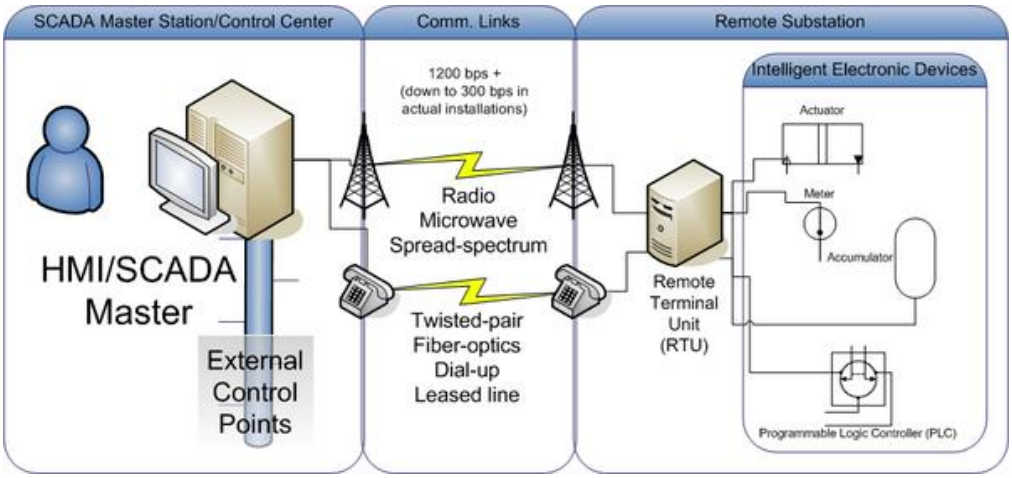
In the aggregator's user interface, it is possible to query the history and alarm events across multiple sites. Additionally, aggregator user interfaces provide multiple screens to quickly deduce the status of each FractalNode within the system so that problems are quickly identified.

3.3.3 Design for Security

DNP3 vs Modbus

One of the very first design decisions to be made for the FractalGrid architecture was the choice of protocol between the SCADA system and the RTU, and between the RTU and configured devices. Both the DNP3 and Modbus protocols have wide support in the utility industry, although the Modbus standard is much more widely implemented. The Modbus standard has been in use since 1979, while the DNP3 protocol is newer, developed in 1993 by Harris systems. The decision made by CleanSpark considered the Modbus TCP version of the standard rather than the original serial standard. See Figure 9 for an overview of the DNP3 protocol.

Figure 9: DNP3 Overview Diagram



**When the source of a table, figure or photo is not otherwise credited, it is the work of the author of the report.*

While the Modbus protocol was supported by nearly every device in the field, several disadvantages were apparent, including register-based addressing which made device configurations considerably more difficult, and an inefficient polling method at regular intervals in which data for all points are returned regardless of status or value change since the previous poll. Securing data communications for Modbus is also an issue as security features are virtually nonexistent within the standard Modbus TCP domain.

In contrast, while DNP3 is not as widely supported, it allows for easy index-based addressing for configuration and allows for multiple types of data retrieval: data can be pushed to the caller, data polling can be done by exception, and/or a full data poll can be executed. Choosing unsolicited data (for Level 3) or exception polling greatly reduces the amount of network bandwidth required to communicate with devices. Also, for those devices that support Level 3 implementations, security is paramount with the support of encrypted data.

To this end, the FractalGrid implementation uses DNP3 as a rule to take advantage of the security and reduced bandwidth requirements. The RTU we chose is capable of communicating via both protocols, and is DNP3 Level 3 compliant. The SCADA system in place uses DNP3 but supports only integrity polling and exception scans and does not support data encryption. At a later date, the SCADA system will be modified to use a Level 3 compliant DNP3 data provider. Communication with devices in the field is mixed: the flywheel supports limited DNP3 connectivity while the majority use Modbus.

3.3.3.1 RTUs

In order to secure the microgrid control system (MCS) especially among the IP capable devices the RTUs were ordered with DNP3-SA security and three of the five RTUs have an additional encryption capability known as AGA12.

DNP3-SA (Secure Authentication) is a security protocol implemented at the application layer of DNP3 that allows DNP3 capable devices to securely communicate with each other. Before the advent of TCP/IP based communications much of the data communicated across devices within an industrial control system was serial in nature. This made remote accessing to those devices highly difficult if not impossible.

AGA12, much like DNP-SA makes it difficult to spoof, modify or reply messages flowing between AGA12 enabled devices. For CPFD, AGA12 will be used to secure communications between FractalNode 1 and Synapse 1a & 1b. Further, it would be prudent to look into encryption packs, like the ones made by Sequi, Inc., that allow system integrators to encrypt data between devices that don't have any encryption capabilities with minimal down time.

3.3.3.2 SCADA and Middleware System Security

There are several data paths using TCP/IP communications within the server, and externally from the server to other nodes. These data paths are secured as follows:

- All protocols in use are encrypted
- Web services and publish/subscribe communications require client certificate authentication. Only trusted certificates can be used to authenticate against a particular server.
- Logins to the web user interface require LDAP-based authentication and appropriate authorization to see data and issue commands.

3.3.3.3 FractalNode server security

- The server's internal firewall limits access to a limited number of ports. All open ports require encryption.
- All standard ports were changed to high port numbers, all custom selections.
- Security patches and virus signature updates are performed on each server regularly.
- No privileged users can log in externally; users must first log in as themselves.

3.3.3.4 Single Point of Entry to Camp Pendleton

In order to limit the possibilities of a remote attack on the CPFD FractalGrid it was determined that a Fortinet Unified Threat Management (UTM) appliance needed to be installed at the network boundary of the FractalGrid. A UTM is capable of monitoring network traffic in real time for viruses, network intrusions and other malicious activity. To further secure the network, the FractalGrid network is split into two architectures. The microgrid control system (MCS) is completely separated from the outside world and no remote access is allowed. The inter FractalNode network has VPN access back to a central database and command center at CleanSpark's headquarters; this VPN tunnel is anchored at both ends by Fortinet UTM appliances.

3.3.4 Design for Affordability/Sustainability

3.3.4.1 Energy Markets

Electricity is by its nature difficult to store and has to be available on demand. Consequently, unlike other commodity products, it is not possible under normal operating conditions to: keep it in stock, ration it or have customers queue for it. Furthermore, demand and supply vary continuously creating a physical requirement for a controlling agency, the transmission system operator (AKA independent system operator (ISO) or Regional Transmission Operator (RTO)), to coordinate the dispatch of generating units to meet the expected demand of the system across the transmission grid. If there is a mismatch between supply and demand, the generators speed up or slow down causing the system frequency (either 50 Hz or 60 Hz) to increase or decrease. If the frequency falls outside a predetermined range, the system operator will act to add or remove either generation or load (Demand-response). The scope of each electricity market consists of the transmission grid or network that is available to the wholesalers, retailers, and the ultimate consumers in any geographic area.

Microgrids are unique in that they are one of the only demand-response products that can provide all types of DR. Microgrids can provide capacity to fast acting frequency response. Finally in the extreme case, microgrids can completely disconnect from the grid and can independently operate. When looking at the different types of demand-response capabilities and how they generally translate into energy markets, microgrids can span nearly all market types; see Table 5 for details.

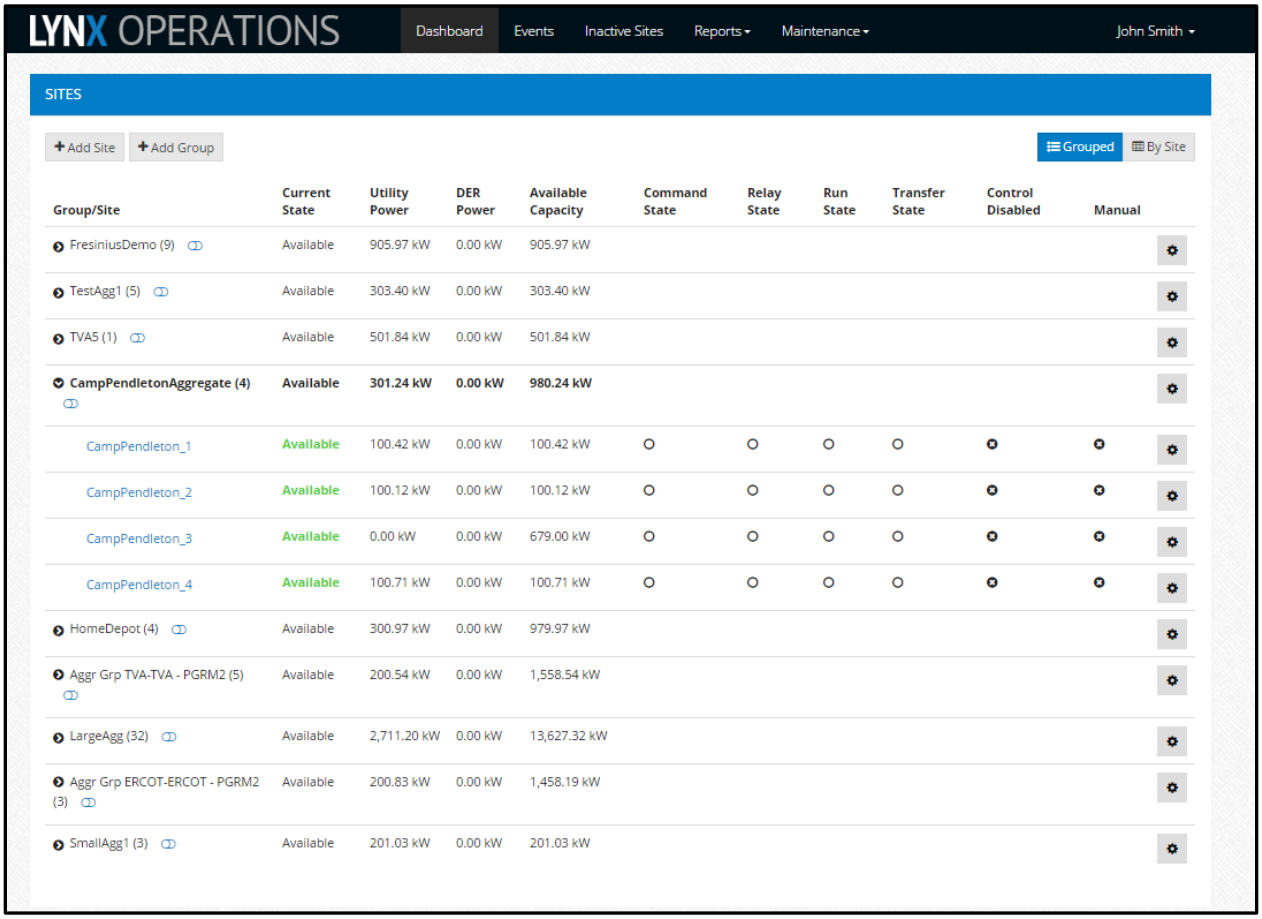
Table 5: Grid Services

Grid Service Type	Response Speed	Minimum Response Duration	Description	Demand Response
Capacity	Minutes	Few hours	Used to meet demand plus reserve margin requirements.	DLC, FA-DLC, DC-DLC, LT-DR, PS-DR
Ancillary Services Contingency Reserve	<15 minutes	Minutes to Hours	Reserves used to replace sudden loss of power, or major system changes.	FA-DLC, DC-DLC, LT-DR
Ancillary Services Regulation or Reserve	Seconds	Minutes to Hours	Used to maintain system frequency.	FA-DLC, DC-DLC, LT-DR
Ancillary Services Non-Spinning Reserve	10-30 Minutes	Minutes to Hours	Used to augment/restore regulation and reserves. Slower response than Reg or reserve.	DLC, FA-DLC, DC-DLC, LT-DR
Ancillary Services Inertial Response	Seconds	Seconds	Local response to mitigate transient stability issues (e.g. solar or wind)	LT-DR
Black Start	Seconds	Time to restore system	Standby generation or storage units which can keep power on local areas.	LT-DR
Energy Price Response (peak reduction)	Minutes	Minutes	Ability to increase generation or reduce load during high price peak demand events.	DLC, FA-DLC, DC-DLC, LT-DR, PS-DR
Energy Price Response (turn down)	Minutes	Minutes	Ability to decrease generation or increase load during high price valley demand events.	FA-DLC, DC-DLC, LT-DR, PS-DR

The value of microgrids is inherent not only to the owner, but also to the energy market it interconnects. The monetary value can greatly vary based on grid service type and real time-pricing. One of the keys to microgrid success is the ability to take advantage of energy market revenue in addition to kW/kWh savings to the customer. In general, this could increase the returns to the customer by 2 to 10 times.

Working with Power Generation Services (PoGens™), we integrated the CPFD microgrids with the Lynx system. Lynx is Power Generation Services' market-facing aggregation solution that interfaces with distributed energy resource management systems (DERMS). The system manages multiple DERMS individually or in an aggregated group. Figure 10 is a screenshot of the Lynx application showing multiple sites, including Camp Pendleton microgrid resources.

Figure 10: Lynx User Interface (Courtesy of Power Generation Services)



Group/Site	Current State	Utility Power	DER Power	Available Capacity	Command State	Relay State	Run State	Transfer State	Control Disabled	Manual
FresiniusDemo (9)	Available	905.97 kW	0.00 kW	905.97 kW						
TestAgg1 (5)	Available	303.40 kW	0.00 kW	303.40 kW						
TVA5 (1)	Available	501.84 kW	0.00 kW	501.84 kW						
CampPendletonAggregate (4)	**Available**	**301.24 kW**	**0.00 kW**	**980.24 kW**						
CampPendleton_1	Available	100.42 kW	0.00 kW	100.42 kW						
CampPendleton_2	Available	100.12 kW	0.00 kW	100.12 kW						
CampPendleton_3	Available	0.00 kW	0.00 kW	679.00 kW						
CampPendleton_4	Available	100.71 kW	0.00 kW	100.71 kW						
HomeDepot (4)	Available	300.97 kW	0.00 kW	979.97 kW						
Aggr Grp TVA-TVA - PGRM2 (5)	Available	200.54 kW	0.00 kW	1,558.54 kW						
LargeAgg (32)	Available	2,711.20 kW	0.00 kW	13,627.32 kW						
Aggr Grp ERCOT-ERCOT - PGRM2 (3)	Available	200.83 kW	0.00 kW	1,458.19 kW						
SmallAgg1 (3)	Available	201.03 kW	0.00 kW	201.03 kW						

3.3.5 Other Design Decisions

3.3.5.1 SCADA Software

CleanSpark continually evaluated SCADA products from the start of the CPFD project and throughout design and a large part of development. The early stages of doing a trade study included considering Power Analytics' Paladin DesignBase and Live software packages. Actual design and implementation, however, involved the following packages.

ETAP (www.etap.com)

The ETAP 12.5 is Operation Technologies, Incorporated's (OTI) latest electrical power system design and operation software. Since Camp Pendleton already had a project underway that consisted of using ETAP to map out its entire electrical network infrastructure to the individual meters, using ETAP was a logical choice with which to model and simulate the Camp Pendleton FractalGrid Demonstration but we ran into some limitations:

- ETAP is a heavy system best suited for relatively powerful computers. Since the microgrids were small in size, using ETAP would have been overkill for what we needed it to do.

- As ETAP is written for Microsoft Windows platforms, OPC (Object Linking and Embedding for Process Control) is the predominant communications protocol and is best suited for Windows systems. CleanSpark decided to use the Linus operating system along with a variety of protocols other than OPC
- Cost considerations

In the end, we continued to use ETAP for modeling but decided a different route for real-time SCADA operations.

Ignition (www.inductiveautomation.com)

Ignition is a commercial SCADA system produced by Inductive Automation. The system bills itself as "The most capable, scalable, and affordable SCADA system in the world." Ignition was initially selected for use on the Camp Pendleton FractalNodes and was fully implemented at the CleanSpark Headquarters Building. After a period of running on the Ignition platform, some shortcomings for our application were encountered including:

- Lack of batch configuration. Maintainers of the system were required to manually set up each point to record to data historian, alarm, etc. Additionally, there was no way to look at all point configurations via a report to ensure that the configuration was consistent across each of the data points.
- Lack of insight into code. Because this is a commercial and not an open source product, it was not possible to diagnose and fix issues within the code. The Inductive Automation support team could assist and enter defect or enhancement requests, but immediate solutions were not quickly forthcoming.

REEF (https://github.com/gec/reef)

REEF is an Open Source SCADA application developed by GreenBus Technology on the Apache Karaf platform. The REEF system was designed to work with renewable energy sources and to easily scale and federate, which potentially made it an excellent fit for the CleanSpark flex Power System architecture. However, several issues were encountered including:

- Licensing. The REEF product is built on two licenses, AGPLv3 and Apache 2.0. The AGPLv3 license is not commercially friendly, and changes to bundles with this license require CleanSpark to divulge the code for that bundle when requested.
- Scala programming language. The vast majority of REEF is developed in the Scala language, a relatively new variant of Java. There is little expertise in Scala within the CleanSpark software development team, and less in the development community in general, which often makes debugging and diagnosing issues somewhat time consuming.
- User Interface. There is no user interface provided with REEF. Its sister project, Coral, provides very limited functionality. As a result, an entirely custom web based user interface system was developed by CleanSpark.

3.3.5.2 Replacing Existing Dashboard

The existing dashboard provided an overview of the system at a very high level. However, there were many shortcomings that were overcome by the replacement with the CleanSpark custom UI.

- Drilldown capability. There was no ability to see the power generated and loads for each microgrid since the dashboard was created prior to dividing the site into smaller microgrids.
- Outdated UI. The UI provided was outdated and provided a great deal of unnecessary data for the casual user. The UI developed by CleanSpark is cleaner and allows the user better visibility at each node and overall.
- Lack of real-time data. The UI provided did not contain real time or near-real time data. All data presented was accumulated in 15 minute intervals.

Using a simulator

Initially, four microgrids were slated to be part of the m52 FractalGrid. Due to budgetary and design constraints, the number of microgrids was reduced to three with the intention of adding a simulator as a fourth grid. The creation of a simulator is still slated to be completed prior to the close of the CPFD project and can be run as part of the m52 Fractalgrid if desired. However, in order for the power calculations to be unaffected at the other nodes, it would be required to maintain complete equilibrium between the simulated generation and load, or exist in an islanded mode.

The simulator would replace the RTU in a standard FractalNode with a model developed based on real system data. The SCADA master would run as normal using the simulated data.

The model would contain the following:

1. Solar generation curve for an average day relative to the time of year.
2. Multiple energy storage charge and discharge profiles for each OpMode (Peak-shaving, Load Shifting, and Manual)
3. Configurable critical and sheddable non-critical loads

Future benefits of having a simulator are using it alongside forecasts to determine how the system might react to over the next 24 to 48 hours and allow optimization and enhanced prioritization of loads.

3.4 Other

3.4.1 Physical Security

The layer of physical security is designed for each FractalNode, including a padlock on the door. Additionally, security cameras monitor each QESC flywheel system and live feeds are recorded locally on a hard drive and streamed to headquarter for redundant recording. Future

security implementation at CPFD includes security cameras for each MCS enclosure and motion sensors in critical electrical, communication and mechanical rooms.

3.4.2 Protocols

3.4.2.1 Atmospheric/Weather from weather service

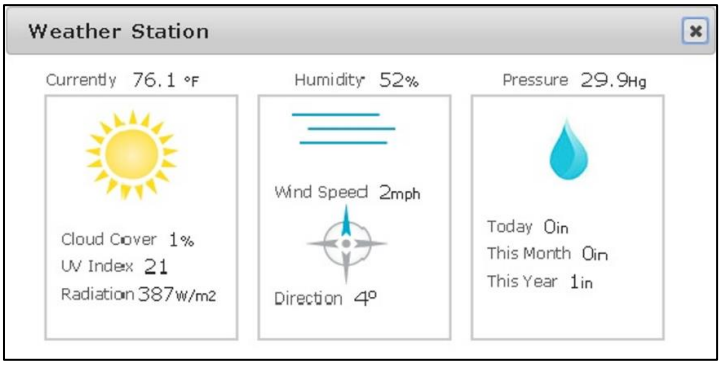
The fPS has the ability to connect via the Internet to access current and forecasted weather from weather stations. In the future, this information can be useful for the system to forecast upcoming generation and load.

Currently, the weather feature is not enabled at the Camp Pendleton FractalNodes due to lack of an outside Internet connection to the nodes. However, if an external weather service is needed, one could be added by developing a proxy service to retrieve weather information from weather services and provide that data to the nodes at Camp Pendleton.

3.4.2.2 Local Weather

A weather station (Figure 11) can be added to provide localized current weather conditions, but this was beyond the out of scope for the project. In the future, this information will be used to forecast upcoming generation capabilities and load.

Figure 11: Weather Station Widget



3.4.3 Summary

To implement the FractalGrid concept, detailed design decisions and implementations had to be executed. The FractalGrid consists of two distinct but very interrelated networks – the electrical and the information networks. While the electrical network implements a lot of currently existing technologies is different configurations, it is the information network that truly enables the multi-microgrid capabilities such as advanced security and standards-based communications.

CHAPTER 4:
Demonstration and Test Results

This chapter describes the resulting tests of all four microgrids for each use case. Table 6: Demonstration Results Compared to Table 1: Demonstration Results and summarizes the results of the testing as desired objectives. While virtually all microgrids successfully demonstrated all use cases, there was insufficient time and budget to island the largest microgrid, m52. CleanSpark, however, is self-funding the completion of the islanding.

Table 6: Demonstration Results Compared to Table 1 demonstration Results

	mComm	mBarr	m5.2	m52
Islanding	Success	Success	Partial Success (10 minutes via batteries)	Insufficient Time/Budget
Consumption Reduction	Success	Success (via m52)	Success (via m52)	Success
Peak Load Management	Not applicable	Success	Success	Success (Extrapolated)
Carbon Management	Success	Success (via m52)	Success (via m52)	Success

4.1 Objective Analysis

4.1.1 Islanding Use Case

Islanding at *mComm* was accomplished consistently. All loads are fed from a battery storage system which is maintained at a high state of charge by PV power and Grid power. When grid power is unavailable the loads are sustained until stored energy and PV are unavailable.

Islanding at *mBarr* was accomplished in two ways using the following priority. First, an off-grid inverter discharges the energy storage and feeds the load. Next, after the energy storage system depletes, an existing diesel generator activates to continue feeding the loads. If the energy storage system fails to provide a nominal voltage within 5 seconds of loss of utility, the generator ATS will transition from the main feeder to generator power and the island will be carried by the generator.

Note that the off-grid inverter connected to the energy storage unit has not been tested to be fully successful. At the time of this writing, this form of islanding by the microgrid control system is not available and the generator provides the islanding of mBarr.

The island capability at *m5.2* has achieved partial success using its hybrid off-grid/grid-tie inverter system to keep controls powered, maintain battery charge, allow a 2kW PV system to sell power to the grid, and provide voltage during island events to power some loads. However, the hybrid inverter had compatibility issues with the energy storage inverter. Acting alone, without support from the energy storage, the hybrid inverter was incapable of energizing the larger m52 grid. Additional equipment and development will be needed to achieve this goal. See section 0 for more detail on this configuration.

The *m52* microgrid was completely setup for island capability, but the equipment installed was determined to be inadequate when black-starting the higher voltage power lines. Because a necessary reconfiguration of the equipment may be seen as disruptive to military officials, the island activation on this circuit will be postponed until additional energy storage and a more proven UL listed and off-grid capable inverter system can be installed.

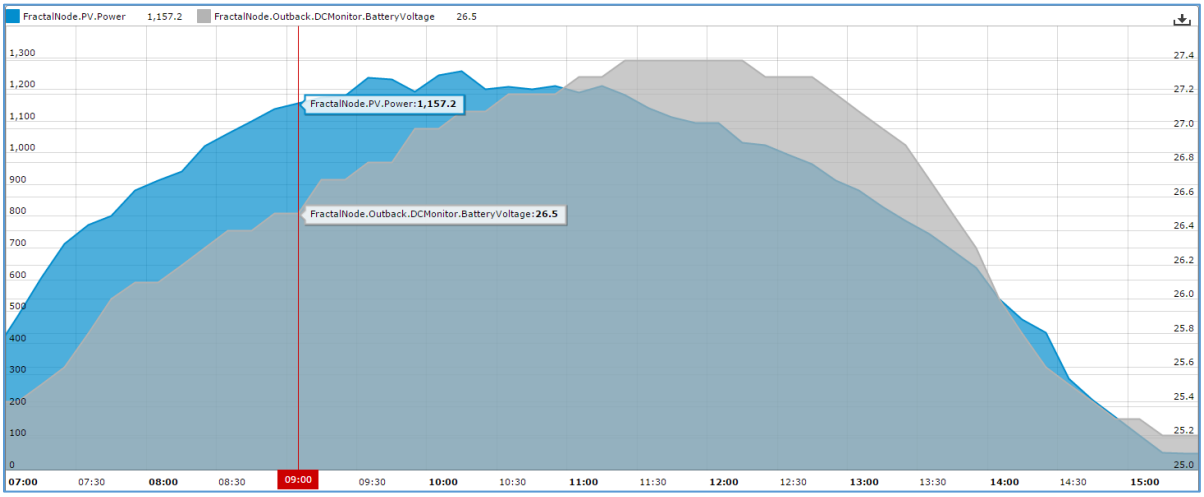
4.1.2 Consumption Reduction Use Case

A major incentive of our microgrid is the ability to replace consumption of grid-produced energy with locally generated renewable energy from solar, wind, geothermal, etc. During the demonstration period, the FractalGrid concept is targeted to reduce daily energy consumption (kWh/day) from the utility by 10 percent or more. Energy reduction (*ER*) expressed as a percentage.

The ER is underestimated since it does not account for line losses during electric power transmission, which can vary over distance travelled. Total ER will also translate to the amount of carbon emission reduced since energy is generated locally and with zero carbon emission sources. At the time of this writing, the testing and integration of QESC flywheels was not complete and therefore, cannot be included into the computations.

In the Figure 12, PV generation in Watts (left y-axis) is graphically displayed alongside battery voltage in Volts (right y-axis) as a function of time (x-axis) on Dec 6. Figure 12 shows power generation increasing as the sun rises with little-to-no clouds hindering production. Once production exceeds the total load consumption, the PV charges the battery system, raising the battery voltage. This surplus generation is stored in the battery causing the battery voltage to rise until it plateaus around 11:00. Once the PV generation tapers off for some time, the battery voltage begins to retreat as the load uses the stored energy. This effectively demonstrates the local use of generation by storing and using locally produced energy when it's needed.

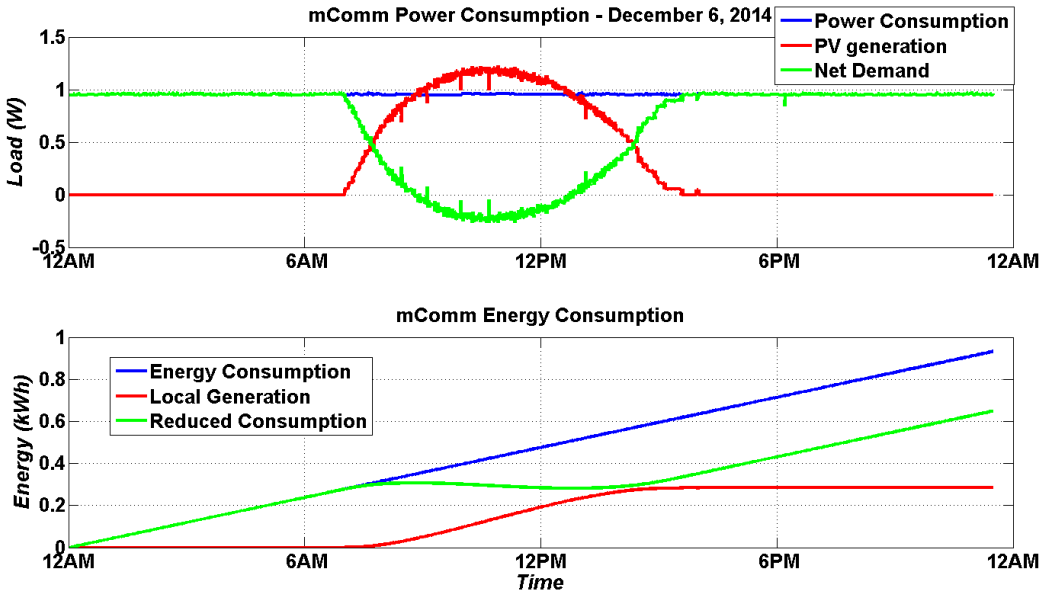
Figure 12: PV Generation Plotted With Battery System Voltage



For *mComm*, one use case, "using locally generated PV energy," is accomplished by connecting the PV to the battery system which stores excess generation locally before backfeeding excess to the load upstream.

In Figure 12, the blue line shows a steady load from the communication room and red represents the 2kW PV generation. Around solar noon, the net demand seen by the utility becomes 0 and excess energy generation was pushed into the electric grid after refilling the battery system. What would have equated to a total 22.32 kWh consumption had been reduced to 6.72 kWh, which is a 30.4 percent reduction. Considering the mComm load is relatively constant, a day of more than 2.2kWh generation (which is one-third generation compared to this particular day) would produce enough energy to reduce consumption by greater than 10 percent. Therefore, the ER goal was achieved in the case of mComm microgrid.

Figure 13: Energy and Power Consumption at mComm on December 6, 2014

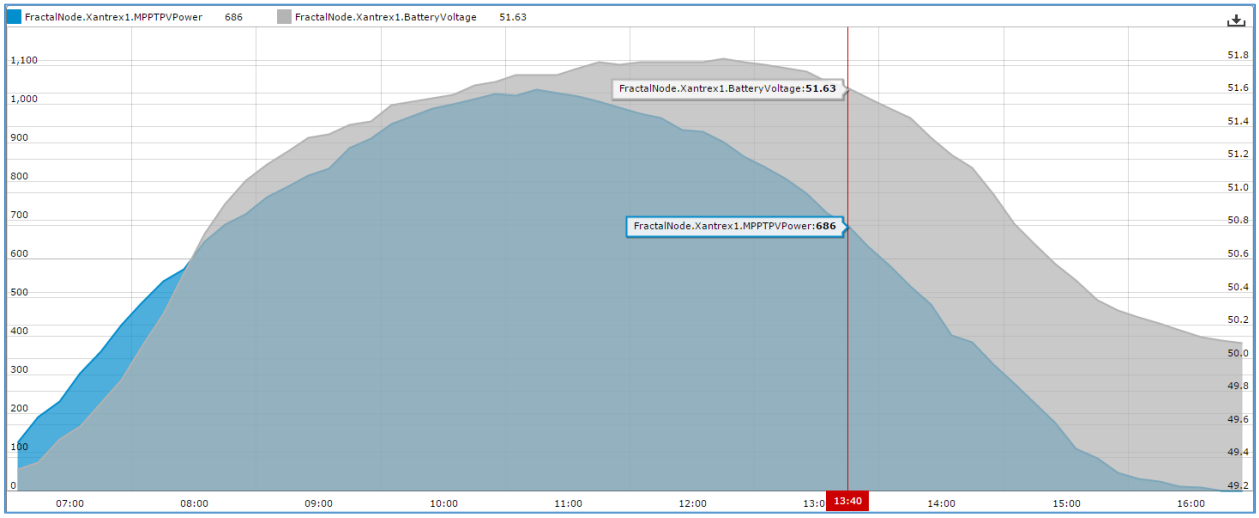


From a sample of nine days in December, only one day did not meet the 10 percent energy reduction requirement. An 88.9 percent success rate with 23.1percent average energy reduction is astonishing considering the sample set consists of some cloudy days, all during winter.

For mBarr, the use case, "using locally generated PV energy," is achieved at mBarr by the large CPV/PV system connected on the m52 microgrid. Since the m52 microgrid is parent to mBarr, mBarr is removed from island mode (connected to m52) to access the PV generated energy when m52 is islanded. Therefore, mBarr can only use PV generation locally when it is not islanded. The overall m52 microgrid generated sufficient energy from CPV/PV such that mBarr loads are compensated at the utility-microgrid PCC meter without the need for mBarr self-generation and storage. No energy reduction analysis was included since the mBarr microgrid did not have local generation. Analysis was performed for the m5.2 and m52 microgrid instead.

For *m5.2* the use case, utilizing PV generated energy locally, is accomplished at m5.2 with the local PV connected to the battery system (Figure 14)Table 7, charging the battery locally prior to exporting excess generation. Only if there is excess PV generation will the hybrid inverter system backfeed the load upstream. In this case, the only load is the m5.2 main lighting which is always larger than the local PV generation.

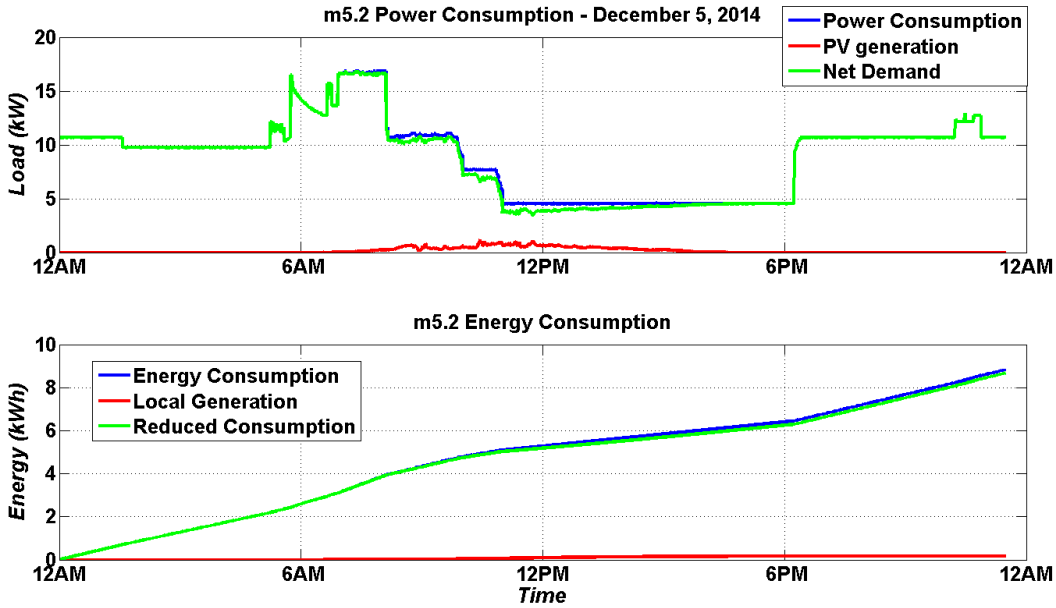
Figure 14: PV Generation (Left y-axis) and Battery Voltage (Right y-axis) as a Function of Time



The 2kW PV generation was not sufficient to support the entirety of m5.2 microgrid and was only able to cover a small fraction of the total m5.2 load as shown in Figure 14.

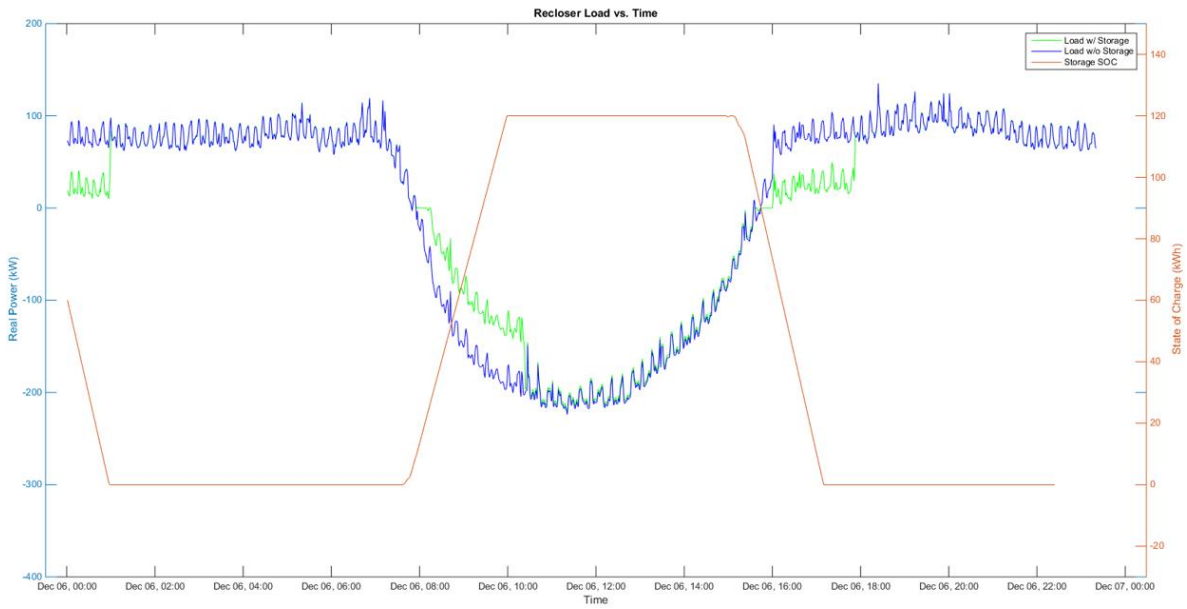
As seen in Figure 15, the overall load changes appear as steps. The timing of the steps, 10AM and 11AM likely indicate lighting loads being turned off. The PV system generated 3.84kWh of energy while the total m5.2 load consumption was 211.92kWh on this particular day. Total energy reduction was only 1.8 percent given fairly cloudy weather conditions. However, even with a full sun day such as the one encountered on Nov 27th and 28th, generation is insufficient to offset load demand to meet the 10 percent energy reduction requirement.

Figure 15: m5.2 Energy and Power Consumption on December 5, 2014



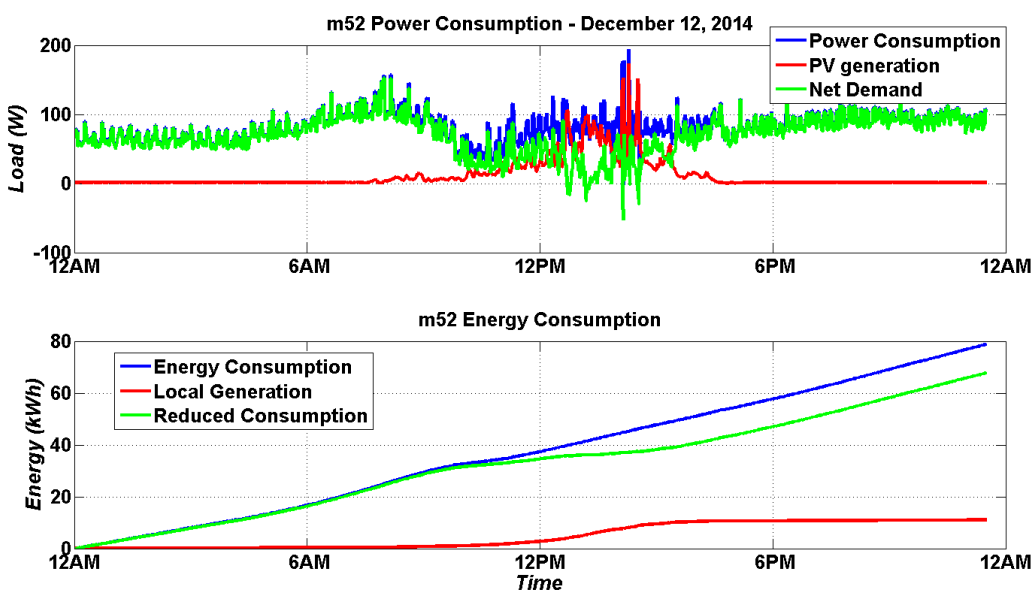
Generation used locally could not be tested directly at **m52** since the QESC flywheel integration is not complete. Instead, a simulation was run using actual load and PV generation data. In this simulation the two QESC flywheels are charged in the morning using available excess PV generation. The energy is stored for the day to potentially mitigate large swings in PV production and dispatched at the end of the day to minimize the load beyond the time PV is available. With the net load or generation higher than the maximum charge and discharge rates of the wheels, the wheels will generally operate at or near their maximum power. Figure 16 shows the results of the simulation using December 6th load data. The blue line is the original load and the green line shows the net load with energy storage. When the storage unit is not running, the two lines overlap.

Figure 16: Maximizing Local Energy Generation Usage



For energy reduction calculations a worst case scenario was calculated using December 12th data. Shown in Figure 17, the 52 Area consumed a total of 1.89 MWh of energy and generated 0.27MWh of renewable energy. Normally, the CPV and PV produces an extreme surplus amount of energy to deliver into the grid (Figure 17), but this particular day was very cloudy and resulted in little PV generation. Even on this low generation day, energy reduction was 14.0 percent, exceeding the requirement for a 10 percent reduction.

Figure 17: m52 Energy and Power Consumption Reduction



4.1.3 Peak Load Management Use Case

The ability to reduce instantaneous power draw and 15-minute interval peak demand from the grid is a beneficial feature of a microgrid. The demonstration target is to reduce the peak demand kW by 10 percent or greater, which can be accomplished given operational modes such as load shifting or peak shaving set by the fPS energy management system. With the QESC flywheels large storage capacity and rapid response capabilities, large load demands can be satisfied without grid involvement. Power Reduction (*PR*) throughout the day can be expressed as:

$$PR(i) = \frac{kW_{pre}(i) - kW_{post}(i)}{kW_{pre}(i)}$$

and

$$kW_{post}(i) = kW_{draw}(i) + kW_{FW}(i) - kW(i)_{gen}$$

where kW_{FW} represents the power used to charge the flywheel, kW_{draw} is the power draw from the grid to support loads, kW_{gen} is power generated by renewables, and kW_{pre} and kW_{post} indicates the instantaneous power consumption from the utility prior to and after the microgrid operations, respectively. "i" denotes the time of the demand measurement within the day.

During evening and early morning periods, kW_{post} will become greater than kW_{pre} since additional energy from the utility grid is required to charge the FW after the microgrid installation. Consequently, the value of *PR(i)* will vary between [-1 , 1] as a function of time, but with respect to each day, the overall *PR* is positive since free energy from renewables is produced to offset power draw. PR(i) can also be translated to total cost reduction and savings over time since the intelligence of fPS energy management can schedule to reduce high cost energy purchases during macrogrid peak hours and use low cost energy acquired and stored when utility energy prices are lowest.

Although individual microgrids were installed, tested and in operation by the time of this writing, the m52 microgrid could not be formed. Therefore, the use of two QESC flywheels to reduce the peak demand on m52 could not be demonstrated.

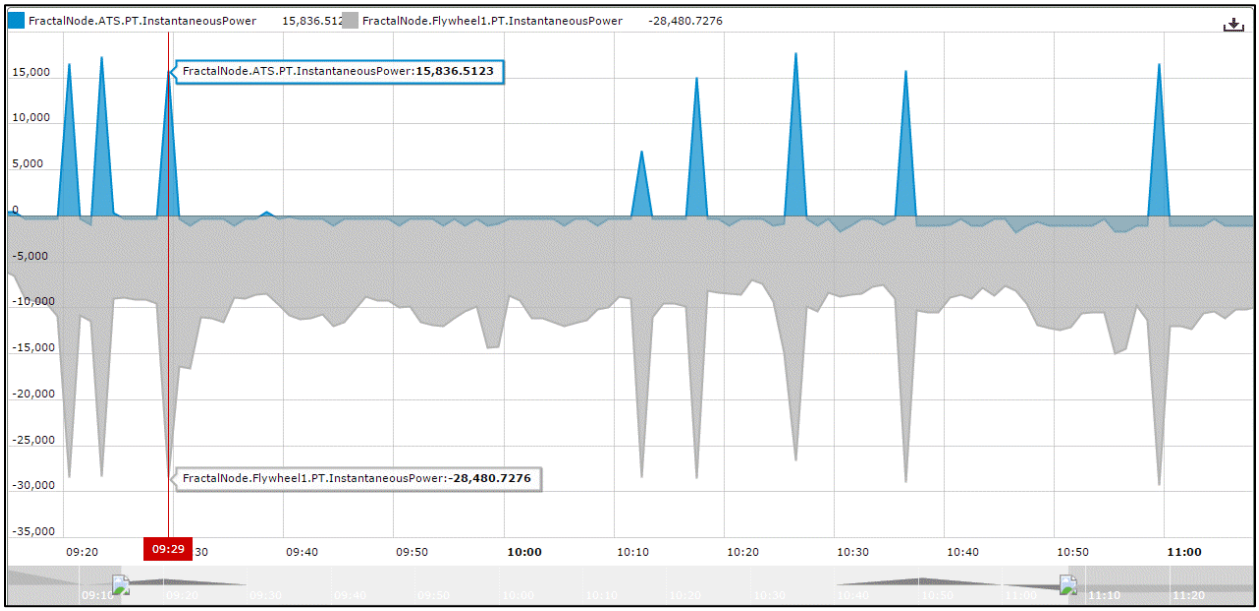
The use case of peak-shaving to minimize peak demand charges at **mComm** is not relevant in this microgrid since the load is relatively constant throughout the day and small enough to be negligible on the upstream utility meter. If the load size was 10 times greater than observed demand, the peak demand could be managed by limiting maximum amperage through the grid-connected inverters to ensure the demand would not exceed a set value. Generally peak-shaving is more useful for loads with occasional or frequent fluctuations because energy can be stored when load is low without increasing the overall peak demand. Other energy management strategies such as load shifting will be more applicable and beneficial for constant loads where the focus becomes a reduction in on-peak energy consumption rather than

reduction in the relatively constant demand. This technique can be achieved by using generation, load forecasting, energy storage and proper management.

Unlike mComm, peak-shaving to minimize peak demand charges is applicable to the **mBarr** microgrid since there are large power spikes from the elevator loads. The control system is set to bound power demand from the utility under a specific kW value and compensates using the energy storage. The energy storage will not allow the total load seen at the meter to exceed this maximum. Future improvements to the fPS intelligence will dynamically set the kW threshold based on historical and forecasted loads.

Figure 18 shows the flywheel operating to peak-shave the mBarr load to nearly 0kW. The flywheel reacts to the dynamic load profile by adjusting its power output to offset and maintain a constant load. The grey area, Flywheel1.pt, represents the total flywheel output used to reduce the demand from the utility to the blue. ATS.PT represents the upstream utility power meter which is observed through the Automatic Transfer Switch. The occasional spikes seen in the ATS.PT load profile are caused by elevator loads which cannot be damped completely by the limited 30kW storage inverter.

Figure 18: mBarr Microgrid Peakshaving to 0kW (From Utility)[2]



Similar to mComm, peak-shaving for m5.2 is not relevant in this microgrid because of minimal load fluctuations. The bulk of the overall load is lighting which is either turned on 24 hours/day or only turned on during the evening hours. Utility demand management can still be performed

[2] Negative values indicate power draw from the energy source. ATS.PT does not show exactly 0kW due to minor sensor calibration errors.

using energy storage, but reducing the monthly demand charges will be difficult without more load variations.

The use case of peak-shaving to minimize peak demand charges can be used in the **m52** microgrid since there are load fluctuations observed at the point of common coupling (PCC). To perform peak-shaving in this microgrid the mBarr microgrid must be set to load-level on the barracks load, thus eliminating power fluctuation contributed by the barracks circuit. Meanwhile, the energy storage at m5.2 could be setup to peak-shave or load-levelize to a specific kW value at the m52 point of connection. Reducing fluctuations and flattening demand in the m52 grid from its constituents would effectively control the total peak demand seen at m52.

4.1.4 Carbon Management Use Case

In order to meet California and nationwide GHG emission reduction goals set the state and federal officials, a significant change in the existing power infrastructure is required. This national electricity transmission and distribution system is inefficient in providing electricity to its customers and is the largest source of carbon pollution. The flex Power System reduces energy dependence from the local utility anywhere from 10 to 100 percent depending on the quantity of renewable energy generation and storage devices connected. Consequently, local energy generation from renewable sources and energy management would mitigate these issues and result in reduction of GHG emissions.

San Diego Gas & Electric (SDGE) is the primary provider of electricity for MCB Camp Pendleton. According to SDG&E's *Greenhouse Gas Emissions Reporting*, the utility company generated 3,048 MW (or 26.7 TWh) and produced 1.57 million metric tons (or 1.57 x 10^{12} grams) of CO2 equivalent in 2011. The amount of emissions reduced by local renewable generation can be expressed as:

$$CP\ local\ energy\ generation * \frac{1.57 * 10^{12}\ \mathrm{g}\ CO_2}{26.7\ TWh} * \frac{1\ TWh}{10^9\ kWh} = \mathrm{g\ CO_2\ Reduced}$$

To analyze the FractalGrid's carbon offset, the PV generation data acquired late November to mid-December 2014 will be used. The difference between the total CO_2 emitted from the load with and without PV generation will result in CO_2 reduction. Carbon Emission Reduction (*CER*) *c*an be expressed as a percentage:

$$CER = \left(\frac{Carbon_{pre} - Carbon_{post}}{Carbon_{pre}}\right) * 100\%$$

where $Carbon_{pre}$ *and* $Carbon_{post}$ represents the carbon emission without and with PV generation. However, CER = ER percentages since calculations to obtain these percentages remain the same, but with the addition of a scaling factor to convert kWh to CO_2 emission for CER; thus, no additional computation is required. The carbon offset requirement for this project is automatically satisfied given energy reduction requirement being met.

Using data for PV&CPV generation given by the CP energy manager, the system offset a staggering 97,385 kg of CO_2 emission using renewable resources as shown in Table 7. This contributes significantly toward the strict GHG reduction policies set in California. With the fPS, CleanSpark will continuously monitor the facility's carbon footprint. This feature is key in tracking GHG emission trends and gradually helps meet the 2050's emission requirements.

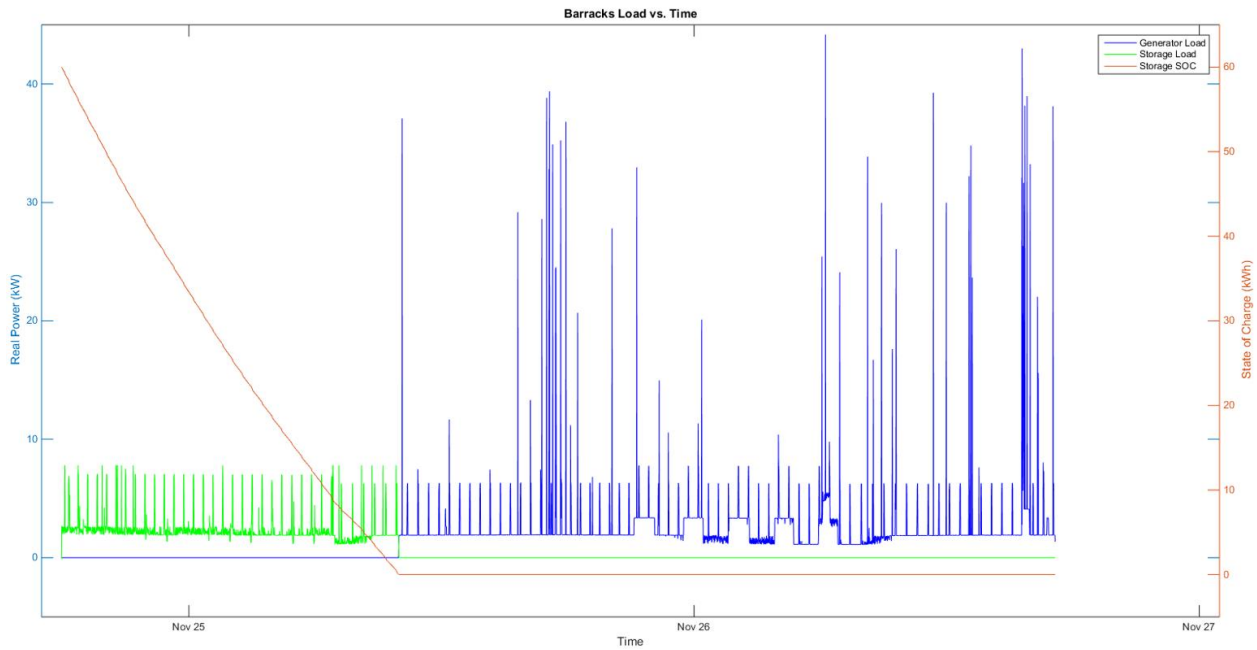
Table 7: Carbon Reduction Given Monthly 52 Area Generation and Load Data

	PV Generation	CO_2 Emission Reduction
CPV & PV System	738.14 MWh	97,384.9 $kgCO_2$

In addition to offsetting GHG emissions using PV, emissions from local standby generation can be offset using energy storage in an outage scenario. The simulation presented in Figure 18 shows the capability of using a charged QESC flywheel energy storage (assuming no PV generation available) to offset energy produced by a diesel generator to support mBarr loads during an outage. Data was gathered during a real outage experienced at CP from November 24th to 26th 2014. In the simulation, the fully charged energy storage system delays the need for diesel generation. Starting with the initial power loss, the load is maintained by the energy storage unit. Once the energy stored in the flywheel depletes to zero over roughly 16 hours, the generator turns on to power the microgrid. In the figure, the green line shows the load fed by the storage, the blue shows load fed by the generator, and the orange shows the energy available in the flywheel.

> *NOTE: The elevators are shown turned off while the energy storage system is carrying the load since the power required by the elevator exceeds the energy storage power limits. However, loads less than 30kW are sustainable by the flywheel.*

Figure 19: Offsetting Fossil-Fuel Usage



By convention, burning a gallon of diesel fuel would produce approximately 22.38 lbs of CO_2. The diesel generator controlled by the ATS is configured with standby fuel consumption at 25 percent load, which draws 5.2 gallons of diesel fuel per hour. Since energy storage replaced the usage of the generator, storage could have reduced 16 hours of CO_2 emission. Therefore, total CO_2 reduced in this simulation using the flywheel is:

$$16\ hrs * \left(\frac{5.2\ gallons}{1\ hr}\right) * \left(\frac{22.38\ lbs\ CO_2}{1\ gallon}\right) = 1862.0\ lbs\ of\ CO_2, or\ 844.6\ kgs\ of\ CO_2$$

4.1.5 Other Use Cases

Another use case, *Load-shifting*, could be implemented in the fPS energy management by scheduling the grid-tied energy storage inverters to only charge during off-peak hours. Complexity can be added in the future where backfeeding energy upstream can be scheduled for peak hours only. However, time constraints prevented development and testing of the opMode so the mode was not deployed.

The use case of load-leveling is implemented in mComm without specific control sequences because the load is connected to the UPS inverter and load fluctuation is handled by keeping the DC bus charged to hold the voltage above a certain threshold given PV generation. Load-leveling will reduce energy consumption at every hour of a given day, which will reduce energy draw from the grid and lower on-peak loads.

Load-shifting could be implemented in the *mBarr* microgrid by scheduling the energy storage to charge during off-peak hours and discharge during peak hours (see Figures 20 and 21). This is beneficial because the cost of energy is reduced by shifting loads to hours where energy is cheaper. Future implementations will include load forecasting and solar generation to allow for more precise control of load shifts.

Figure 20: Charging During Off-Peak Hours

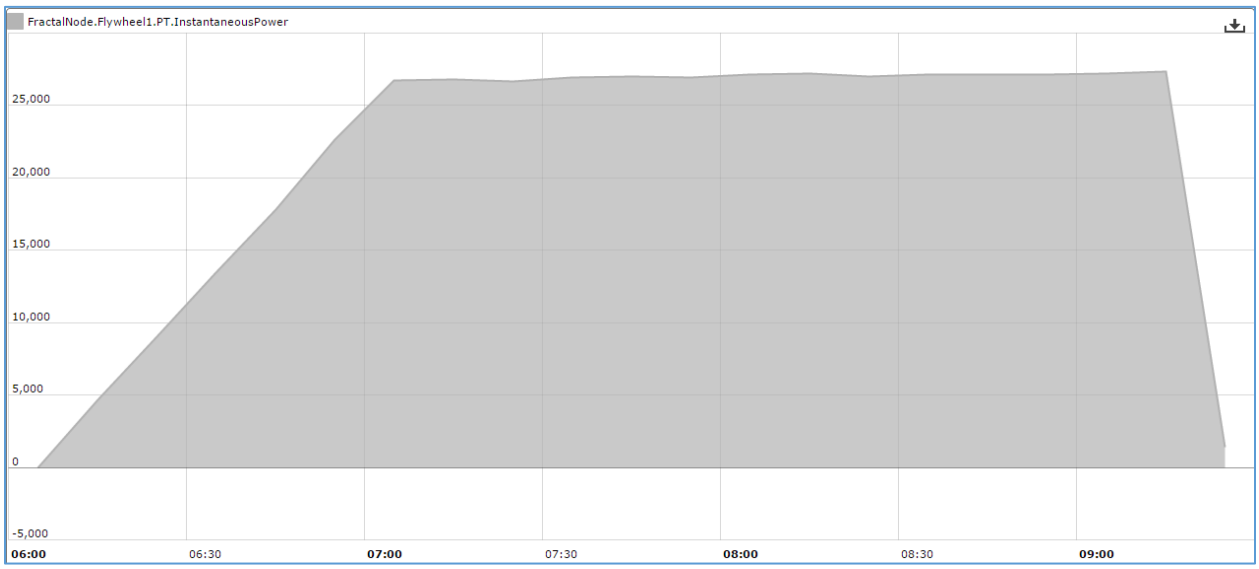
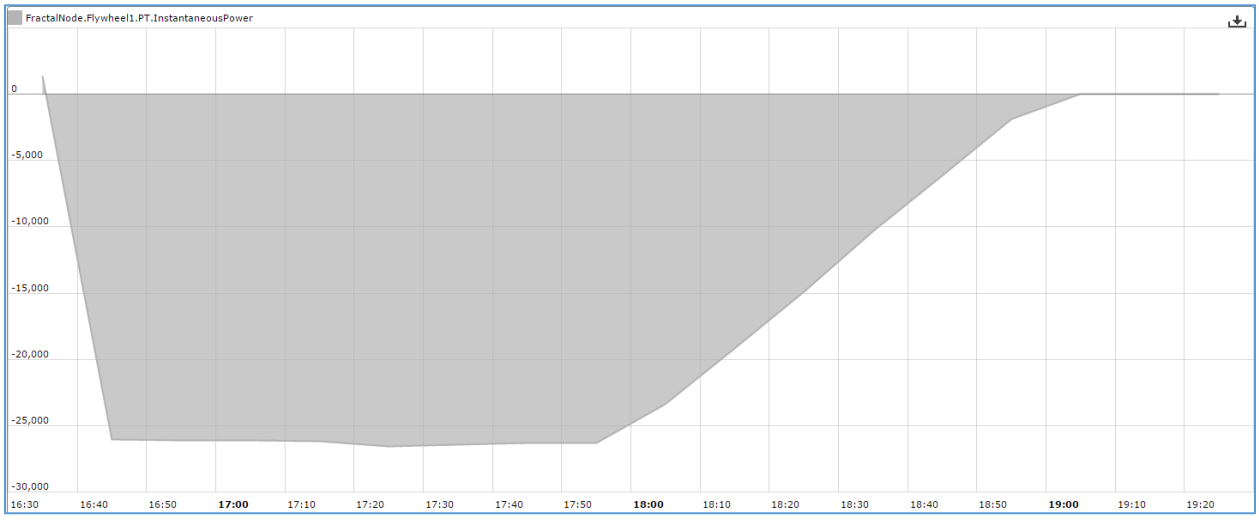


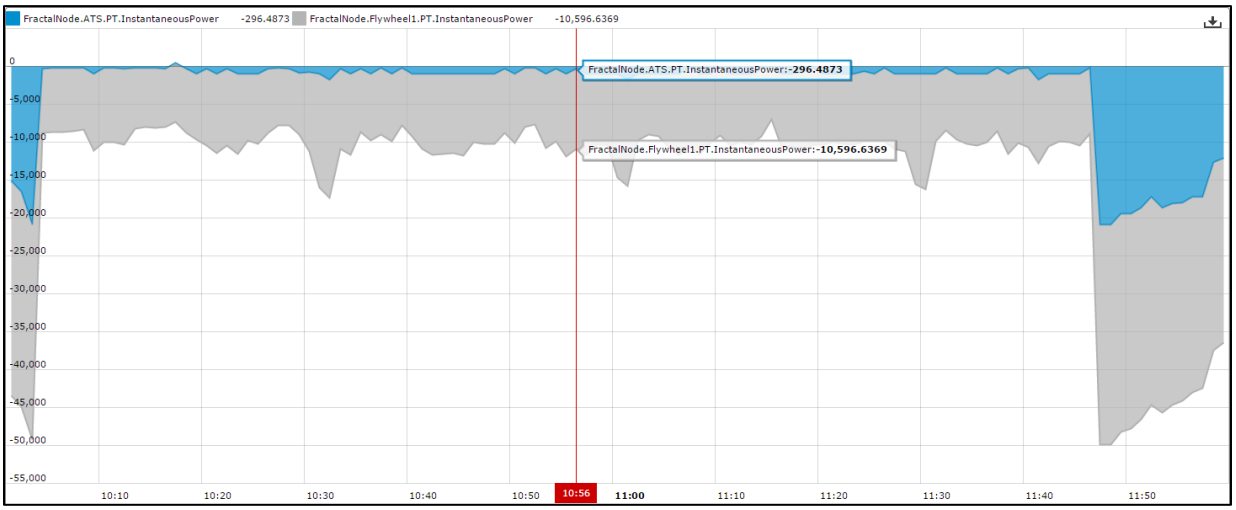
Figure 21: Discharging During Peak Hours



Load-leveling as shown in Figure 22 may also be demonstrated at mBarr. Similar to peak shaving, load leveling will discharge the energy storage unit when load exceeds a specific kW

threshold. However, load leveling will also charge the energy storage unit when the load is below the threshold. With this mode, the load is just maintained at the fixed value.

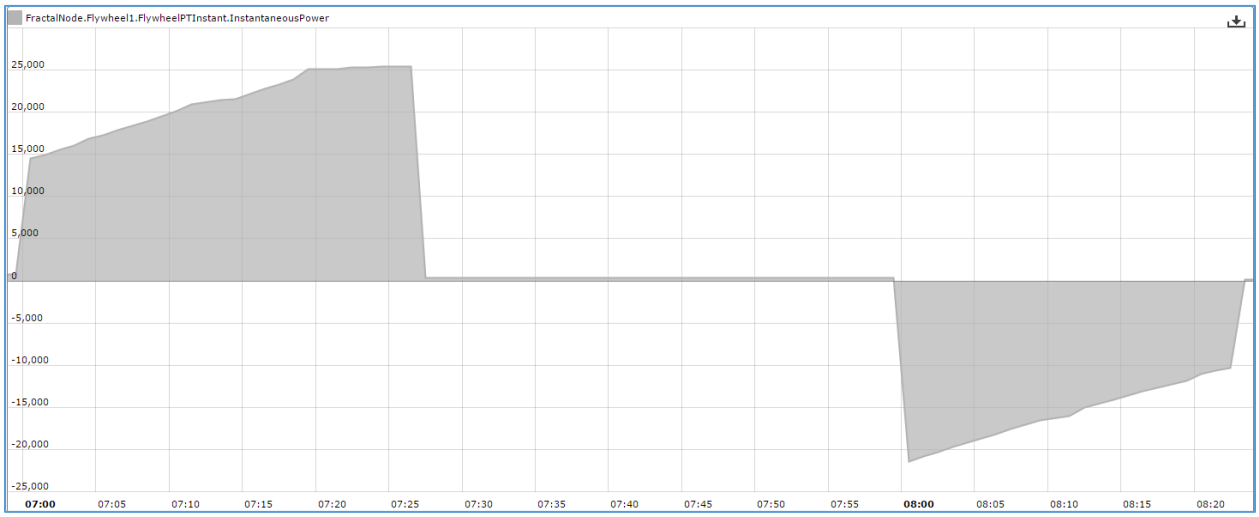
Figure 22: Load Leveling to 0kW at mBarr



Similar to *mBarr*, load-shifting can also be utilized at *m5.2* by scheduling the energy storage to charge during off-peak hours and discharge during on-peak hours. Other energy saving techniques such as peak-shaving can be integrated to prevent new peaks from occurring at night during storage unit charging. Future research and development will include cost of energy per time, allowing the system to autonomously decide the best feature to benefit both utility and customer.

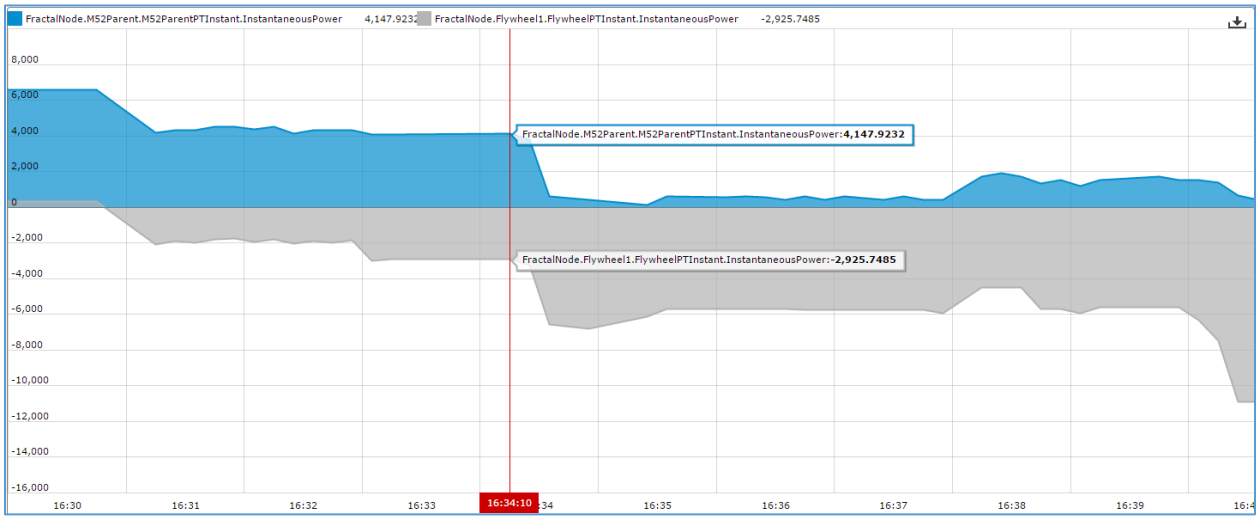
Figure 23 shows a shortened time between charge and discharge to provide a demonstration of charging during off-peak hours and discharging during peak hours. The flywheel unit is charged to 25 kWh and discharged fully at a later time.

Figure 23: Load-Shifting



The load-leveling mode was also run at m5.2 by maintaining a specific kW load using the energy storage unit. Figure 24 shows a case where multiple load-level (kW) setpoints were chosen in a short period of time. During each period, the flywheel adjusts its power output to maintain the requested m5.2 load. This could be a beneficial mode of operation for utilities or microgrids alike since eliminating the load variation locally will reduce variation on the parent grid.

Figure 24: Adjustable Load-Leveling



Load-shifting can be implemented on *m52* by scheduling the energy storage at mBarr and m5.2 to charge during off-peak hours and discharge during peak hours. In this case the child microgrids will combine to impact the parent microgrid.

Load-leveling is implemented on m52 by setting the energy storage unit at mBarr to load-level the mBarr load and setting m5.2 to load-level on the point of common coupling (PCC). This is possible because m5.2 can monitor the PCC load. Meanwhile, with this setup, mBarr will independently reduce its load variability to assist m5.2.

4.2 Performance and Current Limitations

4.2.1 Number of Points

The number of points that can be supported by a single FractalNode was limited by the usage of the REEF SCADA core of the Energy Management System. Depending on the hardware used, the system could support between 325 and 450 points, which was frequently less than desired. While the programming was able to accommodate the lower number, future versions of the fPS EMS will no longer run the REEF core and are expected to support a higher number of points.

4.2.2 History

The size of online history is limited to 30 days. Currently the history is kept in a database, and nearly 1M rows are added each day for a moderately sized 300 data-point system. Keeping the

size of history in check locally ensures that inserting records into the database are completed quickly and data queries return in a reasonable period.

4.2.3 Server Hardware

The fPS Energy Management System has adequate hardware to support the running processes. The current hardware minimum requirements are: dual core Intel Celeron processors or above, 4GB RAM, 250GB drive. The preferred architecture uses Intel i5 processors, 8GB RAM, and solid state hard drives (SSD).

4.2.4 Switching Speed

All critical and time-sensitive switching was performed at the RTU level for the Camp Pendleton implementation. Functionality such as peak shifting and load-leveling required less than 10 ms response rates, which are not possible with the SCADA system but the local RTU was able to meet these switching requirements easily. Non-critical switching such as that done in response to Automatic Demand-Response programs were performed by the Energy Management System via SCADA commands. These commands responded in a 500ms timeframe, which met the needs of most high-value utility programs, requiring a 4 second response rate.

4.2.5 Flywheel

The QESC flywheel energy storage system demonstrated in this project at both m5.2 and mBarr is an early version of a kinetic energy storage system that will outperform chemical battery systems in many aspects.

One performance outlier of this product is the life-cycle time of the main unit. The machine characteristics of this product will stay in operation for 20 years or more with only minimal periodic maintenance. Batteries on the other hand, chemically fail over a much shorter life-span and are not easily recyclable.

Another performance enhancement is the size per kWh of energy. A single 120kWh unit only consumes about half the space needed for a comparable battery. Since, the unit will not degrade with complete charge and discharge cycles, an equivalent battery system would need to up-sized to minimize degradation.

4.2.6 Summary

All use cases have been addressed in this chapter as demonstrated by all four microgrids in the FractalGrid formation. While virtually all microgrids successfully demonstrated all use cases, there was insufficient time and budget to island the largest microgrid, m52. CleanSpark, however, is self-funding the completion of the islanding.

CHAPTER 5: Conclusions

An increasing global awareness about GHG emissions and energy supply security is acting as the main driving force behind a national requirement to transition towards cleaner forms of energy. Given our aging U.S. grid infrastructure and evidence of global warming activities, technological advancements and energy management strategies must evolve from the current status to uphold the aggressive suite of environmental policies imposed by state and federal order while sustaining our growing energy needs with renewable sources.

The entire Harper Construction team, including SES, CleanSpark, and various energy storage and device organizations, embraces these challenges by demonstrating a proof of concept at the Marines Corps Base Camp Pendleton (MCBCP) to promise an innovative *FractalGrid* network of microgrids architecture to provide reliable and secure energy generated and managed with minimal environmental impact. CleanSpark's flex Power System installation at the Camp Pendleton FractalGrid Demonstration (CPFD) interoperates and interconnects four microgrids of various sizes, each supplied with local renewable generation and storage, to create a topology that reduces common system-to-system complexity to a standard set of rules and protocols.

The main form of storage for CPFD were flywheel technology that were to be developed by Quantum Energy Storage. Although in research and development phase, the energy storage had much promise exceeds leading battery technologies and is highly-cost effective in production quantities. In the end, only a limited amount of kWh's were able to be provided by Quantum due to technology challenges, but metallic rotor flywheels show much promise and many firms such as Amber Kinetics are entering into the space with success.

Among the successfully demonstrated goals of the FractalGrid architectural approach was to reduce energy and power consumption by replacing grid-produced energy with locally generated renewables. Total energy production on the Camp Pendleton site in 2014 was 738.14 MWh, corresponding to 97,385 kgCO_2 emission reduction from the local utility company. These were accomplished through a combination of various techniques such as load-shifting, peak-shaving, load-leveling, and islanding. The implementation also provided additional energy surety and security through federated microgrids, substantially increasing uptime during planned and unplanned grid outages, while intelligent reporting and alarming systems captured system behavior and anomalies for operations and maintenance.

Future improvements to the FractalGrid system will allow for smarter controls and additional functionalities above the already accomplished features. Future systems will autonomously determine the best energy management strategies to maximize benefits to the customer given load demand and solar generation predictions. The system will learn the energy usage habits of the customer and apply its knowledge to schedule energy saving methods catered to their needs. An improved system UI will further increase awareness of energy usage and environmental impacts and provide a much simpler mechanism for enhanced performance.

CHAPTER 6: Partners

6.1 SES

Specialized Energy Solutions was established to expand the use of clean energy technologies and sustainable building infrastructure through innovative design-build solutions that harness the expertise of our highly skilled, cross-functional, engineering and construction teams. Our goal is to design, deliver, and operate high-quality sustainable infrastructure solutions that create value for our clients.

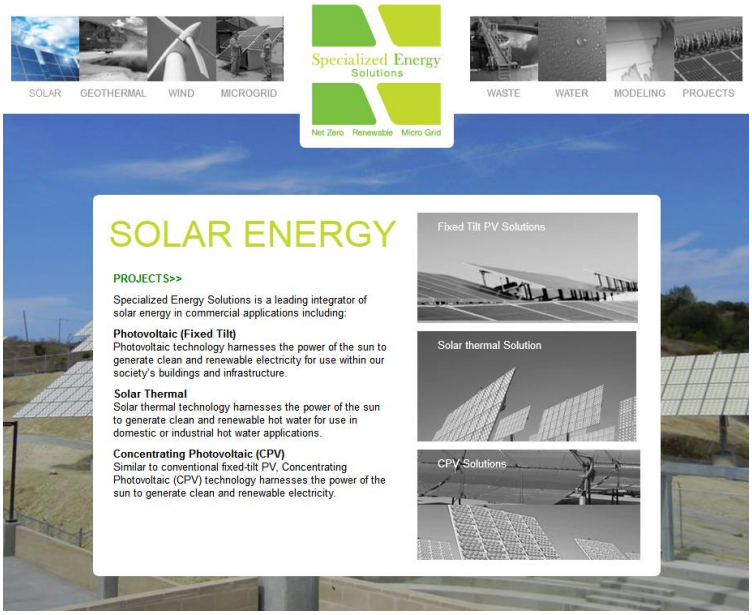
Specialized Energy Solutions is a leading integrator of solar energy in commercial applications including:

Photovoltaic (Fixed Tilt): Photovoltaic technology harnesses the power of the sun to generate clean and renewable electricity for use within our society's buildings and infrastructure.

Solar Thermal: Solar thermal technology harnesses the power of the sun to generate clean and renewable hot water for use in domestic or industrial hot water applications.

Concentrating Photovoltaic (CPV): Similar to conventional fixed-tilt PV, Concentrating Photovoltaic (CPV) technology harnesses the power of the sun to generate clean and renewable electricity.

Figure 25: Specialized Energy Solutions



6.2 CleanSpark

VISION: To empower communities through sustainable, secure, and reliable energy.

MISSION: Leading a revolution in transforming global energy into a clean, affordable, and sustainable infrastructure that promotes socio-economic upliftment.

CleanSpark provides clean, reliable, and secure energy solutions at a price that results in energy rates which are less than current utility grid operators.

CleanSpark provides integration, installation, and operations and maintenance products and services that specifically address the global microgrid and advanced energy storage market.

Figure 26: CleanSpark Logo

The team of world-class systems engineers and integrators utilize a system-of-systems approach developed to quickly and seamlessly incorporate any variety and number of physical devices and cyber-services. Coupled with the best information engineers, electrical engineers, and designers with a unique defense and critical power background, CleanSpark architects, engineers, and integrates its systems to be future-proof.

Figure 27: Cleanspark

The team of world-class electrical and controls systems installers draw upon decades of experience of fieldwork and leadership to build systems with unmatched workmanship. Coupled with utilizing state-of-the-art equipment and processes, CleanSpark's internal talent and understanding of advanced power systems build quality from the ground up.

The team of world-class operators, maintainers, and technicians are themselves accomplished technologists that achieve harmony with our autonomous monitoring systems. Led by military veterans, CleanSpark's O&M teams maintain and operate its installations with experience, skill, and discipline.

6.3 Power Generation Services

Power Generation Services, Inc. (PoGens™) is a turnkey provider of managed energy services for Distributed Generation and Distributed Energy Resources to commercial customers in North America. PoGens™ provides a complete energy management infrastructure that includes installation, monitoring, control, compliance and dispatch of our customers' emergency generation assets into deregulated power markets. In an increasingly complex and ever changing energy environment, our mission is to leverage our national energy services platform to assist customers in the transition toward cleaner energy, while enhancing profitability of generation assets.

Figure 28: Power Generation Services, Inc.

6.3.1 Services

Power Generation Services, Inc. has created a comprehensive ecosystem to provide our customers with an energy strategy, which can be leveraged to meet their reliability requirements and increase their bottom line revenue. Our services encompass a comprehensive list of Energy Management Services; Technology; Compliance, Analytics and Reporting; and Intellectual Property. Our goal is to provide our customers with a turn-key solution which provides peace of mind about their energy strategy.

6.3.2 Energy Management Capabilities

The core of the PoGens™ offering is turn-key energy management services. Our asset management solutions provide guaranteed reliability while introducing our customers to a new stream of revenue.

6.3.3 Analytics, Reporting, and Compliance

Our reporting and analytics provides real time updates to show our customers exactly how their assets are preforming as well as operational reports for daily or monthly reconciliation.

PoGens™ implements compliance and risk management practices for each customer. We manage your portfolio within federal and/or local regulatory statutes and also continuously analyze your portfolio for any risks that could adversely affect your goals. We track all our customers' asset parameters, providing reports for EPA compliance, GADS reports, operational compliance, and regulatory compliance and recommending to our clients solutions to minimize risk.

6.4 ETAP

ETAP is a full spectrum analytical engineering firm specializing in the planning, design, analysis, operation, training, and computer simulation of power systems.

ETAP is the most comprehensive power system enterprise solution. With more than 50,000 licenses in over 100 countries, ETAP serves the power system needs from generation to utilization.

ETAP employs a research and development team supported by a staff of engineers and scientists who have a combined knowledge of over 500 years of experience. ETAP is privileged to have a permanent staff of power system engineers, many of whom have been internationally recognized as experts in their field. ETAP is committed to providing quality solutions for electrical power systems.

Incorporated in 1986, ETAP released the first version of Electrical Transient Analyzer Program (ETAP) power system analysis and design software. Today, ETAP is recognized as the global market leader in providing solutions for power systems analysis, design, simulation, operation, control, optimization, and automation.

In 1996 ETAP released the first, true 32-bit, power system analysis program on the market for Windows. ETAP is designed for Microsoft Windows and contains many advanced features including ODBC, multidimensional database, composite network nesting, and more.

ETAP developed ETAP Real-Time to provide online (real-time) monitoring, simulation, control, and supervisory control capabilities. ETAP Real-Time uses real-time data and system topology (ETAP database) to estimate unmonitored power flows and voltages throughout the system.

Along with aggressive development and product maintenance, ETAP utilizes a highly specialized team of engineers to conduct research and development projects as well as system studies.

In recent years, ETAP has grown to include specialized consultants, design engineers, cutting-edge programmers, and an experienced sales staff. ETAP will continue to meet its clients' needs by incorporating the latest advances in technology into both software development and engineering services.

6.5 IPKeys

IPKeys, an SBA Certified 8(a) and women owned company, is an emerging strategic partner in the DoD Federal, Commercial and Energy sectors, delivering expertise in the definition, development, integration, and deployment of Internet Protocol ("IP") technology and communications systems. IPKeys expertise includes Network and Telecommunications Engineering; Systems Engineering and Integration; Cyber Security; Systems Acquisition, Production and Fielding; Modeling and Simulation; and Energy/Smart Grid Engineering Services.

Incorporated in March 2005, IPKeys is headquartered in New Jersey and has locations in California, Maryland, and Virginia. IPKeys' mission is to assist the customer in integrating the highest mission-appropriate level of secure information and communications systems. We enable users to efficiently access, communicate, integrate and apply data solutions to support their mission objectives. IPKeys provides mission relevant solutions grounded in our in-depth knowledge of current force systems, emerging technologies, present and developing standards, and Future Force infrastructure requirements.

Our expert staff possesses in-depth experience and knowledge with DoD enterprise systems and frameworks, strategic and tactical Warfighter communities, architectures, cutting-edge information, and security management technologies. We leverage this expertise and our corporate experience in the delivery of value added Enterprise Information Technology and information security solutions to the federal government.

6.5.1 Management Philosophy

IPKeys stands firmly on principles of integrity and ethics that reflect a deep respect for our clients and employees. Our company culture focuses on cultivating quality service and customer satisfaction, yet we consider our personnel "the heartbeat of the solutions we are hired to execute." By recognizing the individual strengths, needs, and contributions of our employees, IPKeys management fosters a positive corporate culture that is both challenging and rewarding. This constructive corporate philosophy in turn strengthens the deliverables and value we offer our clientele.

GLOSSARY

Term	Definition
AC	Alternating Current
ADR	Automated Demand-Response
AHJ	Authority Having Jurisdiction
ATS	Automatic Transfer Switch
CCM	Communications and Controls Module
CEC	California Energy Commission
CIGRE	Conseil International des Grands Réseaux Électriques
COTS	Commercial Off-the-Shelf
CPFD	Camp Pendleton FractalGrid Demonstration
CPUC	California Public Utilities Commission
CPV	Concentrating Photovoltaic
CS	CleanSpark
DC	Direct Current
DOE	Department of Energy
DR	Distributed Resource; Demand-Response
EMS	Energy Management System
EPS	Electric Power System
fPS	flex Power System
GHG	Greenhouse Emissions
HTTPS	Secure Hypertext Transfer Protocol
HVAC	Heating, Ventilation, and Air Conditioning
IEEE	Institute of Electrical and Electronics Engineers
JSON	JavaScript Object Notation
LDAP	Lightweight Directory Access Protocol
MCBCP	Marines Corps Base Camp Pendleton
MOC	Microgrid Operations Center
MRI	Magnetic Resonance Imaging
NAVFAC	Naval Facilities Engineering Command
NREL	National Renewable Energy Laboratory
O&M	Operation and Maintenance
OSA	Open Systems Architecture
PCC	Point of Common Coupling
PUC	Public Utility Commission
PV	Photovoltaic
QESC	Quantum Energy Storage Corporation
REST	Representational State Transfer
RTU	Remote Terminal Unit
SCADA	Supervisor Control and Data Acquisition

SES	Specialized Energy Solutions
SSL	Secure Sockets Layer
VPN	Virtual Private Network
XMPP	Extensible Messaging and Presence Protocol

REFERENCES

Asmus, Peter. Market Data: Microgrids - Forecasts for Commercial/Industrial, Community/Utility, Campus/Institutional, Military, and Remote Microgrids: 2013-2020. (2013). *Navigant Research*.

Grid Energy Storage. (2013). *United States Department of Energy*.

APPENDIX A:
Specs for FractalNodes and Other Components

Microgrid	m52	m5.2	mBarr	mComm
Critical Loads	3 cell towers and support components	Parking structure, emergency lighting	Arms rooms, lighting, elevators -- isolated with emergency circuit	Server and communications equipment
Energy Requirements for All Loads	21,325 kWh/mo	6,920 kWh/mo	77,280 kWh/mo	1,500 kWh/mo
Energy Requirements for Critical Loads	21,325 kWh/mo	500 kWh/mo	3,240 kWh/mo estimated	750 kWh/mo
Non-critical Loads	Barracks building except mBarr	Non-critical lighting and receptacles	None	None
Parent Microgrid	SDG&E Utility	m52	m52	mBarr
Child Microgrids	m5.2, mBarr	None	mComm	None
Renewable Energy	300 kW PV 233 kW CPV	2 kW PV	None	2 kW PV
Main Energy Storage	Child microgrids	1 QESC flywheel, Batteries (AGM)	1 QESC flywheel	Batteries (Gel)
Total Energy Storage	See child microgrids	118 kWh per cycle average	100 kWh per cycle average	10 kWh per cycle average
Emergency Power	None	None	250 kW Diesel generator	None
SCADA System	CleanSpark	CleanSpark	CleanSpark	CleanSpark

APPENDIX B:
Definitions

Demand-management: Also known as demand-side management (DSM), is the modification of consumer demand for energy through various methods such as financial incentives and education. These can be done via...

1. Energy efficiency
2. Demand-response
3. Dynamic Demand, which is the advancement or delay appliance operating cycles by a few seconds to increase the diversity factor (the ratio of the sum of the maximum power demands of the subdivisions of any electric power system to the maximum demand of the whole system measured at the point of supply) of the set of loads. The concept is that by monitoring the power factor of the power grid, as well as their own control parameters, individual, intermittent loads would switch on or off at optimal moments to balance the overall system load with generation, reducing critical power mismatches.

Demand-response (DR): According to the Federal Energy Regulatory Commission (FERC), DR are "changes in electric usage by end-use customers from their normal consumption patterns in response to changes in the price of electricity over time, or to incentive payments designed to induce lower electricity use at times of high wholesale market prices or when system reliability is jeopardized." In general, however, DR has taken on the more general process of balancing a user's need for electricity with the power company's output by shutting down loads.

Load-following: Load-following is process of varying power output as demand for electricity fluctuates throughout the day.

Load-leveling: A method for reducing the large fluctuations that occur in electricity demand, for example by storing excess electricity during periods of low demand for use during periods of high demand.

Load-shifting: Load-shifting is a load management technique that entails moving demand from daily peak hours to off-peak hours. Load-shifting is therefore a function of "time-of-use."

Peak-shaving / Peak-clipping: Peak-shaving is the process of reducing the amount of energy purchased from the utility company during peak hours when the charges are highest

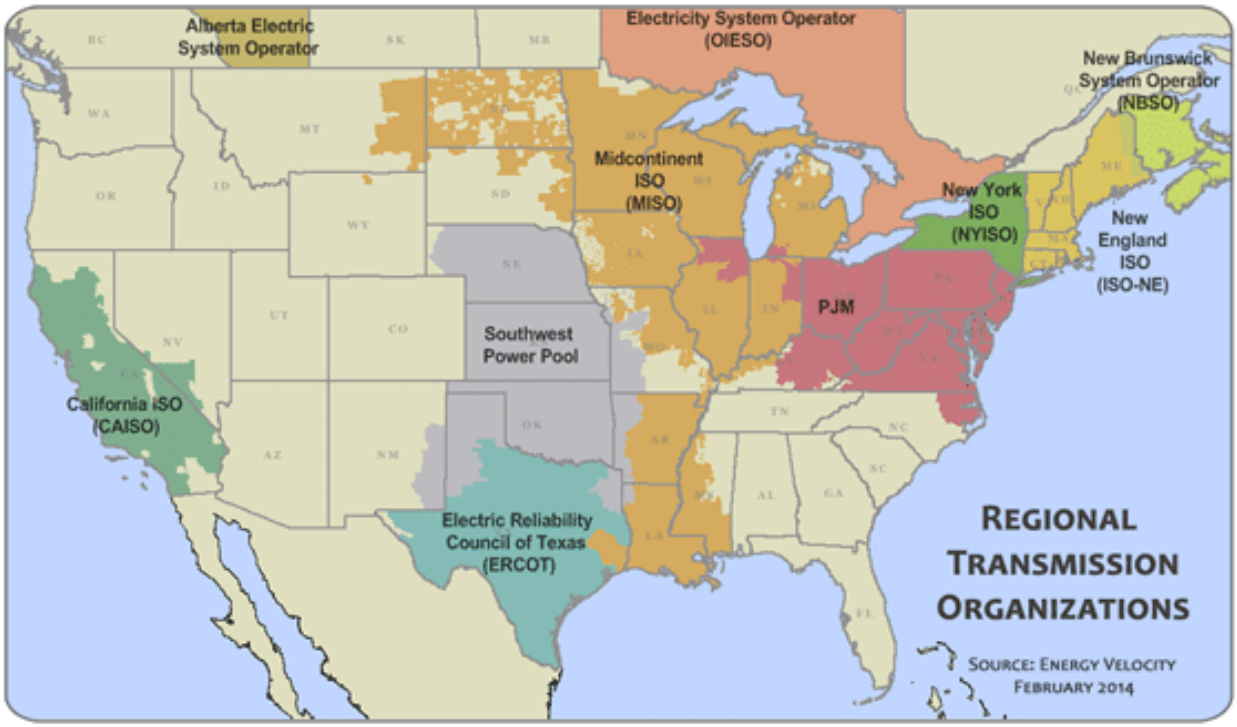
APPENDIX C:
Energy Markets

The Energy industry is the third largest industry in the United States with investments expected to exceed $500B over the next 10 years. Energy markets are commodity markets that deal specifically with the trade and supply of energy. Energy market may refer to an electricity market, but can also refer to other sources of energy. Typically energy development is the result of a government creating an energy policy that encourages the development of an energy industry in a competitive manner. In the United States the regulatory entities are known as the Federal Electric Reliability Commission ("FERC") and the National Electric Reliability Council ("NERC"). FERC is ultimately responsible for energy rules and regulations around energy markets and energy policy. NERC is ultimately responsible for energy reliability, energy security, and cyber security around energy in the United States.

Electricity is by its nature difficult to store and has to be available on demand. Consequently, unlike other commodity products, it is not possible, under normal operating conditions, to keep it in stock, ration it or have customers queue for it. Furthermore, demand and supply vary continuously. There is therefore a physical requirement for a controlling agency, the transmission system operator (AKA independent system operator (ISO) or Regional Transmission Operator (RTO)), to coordinate the dispatch of generating units to meet the expected demand of the system across the transmission grid. If there is a mismatch between supply and demand the generators speed up or slow down causing the system frequency (either 50 or 60 Hz) to increase or decrease. If the frequency falls outside a predetermined range the system operator will act to add or remove either generation or load (Demand-response). The scope of each electricity market consists of the transmission grid or network that is available to the wholesalers, retailers and the ultimate consumers in any geographic area.

Within the United States regulated energy areas are defined as non-tradable energy markets. These areas are defined by tariffs that dictate the cost of electricity and how it can be provided to the local grid manager. Generally, regulated markets follow legacy state lines and there are roughly 29 states.

The remaining 21 states are within deregulated markets. The picture below depicts the areas that are deregulated within the United States:



Each of the deregulated markets have specific rules that govern how electric power is traded, priced, and settled. In general, power prices are driven by specific energy market types, weather, and fuel costs.

Deregulated Eastern Interconnections

PJM Interconnection is a regional transmission organization ("RTO") that coordinates the movement of wholesale electricity in all or parts of Delaware, Illinois, Indiana, Kentucky, Maryland, Michigan, New Jersey, North Carolina, Ohio, Pennsylvania, Tennessee, Virginia, West Virginia, and the District of Columbia. PJM is the largest electric consumption deregulated market within the United States.

New York Independent Service Operator ("NYISO") is the independent service operator for New York.

The Independent Service Operator for New England ("ISONE") is the regional transmission organization that coordinates the movement of wholesale electricity in all or parts of Maine, New Hampshire, Vermont, Massachusetts, Connecticut, and Rhode Island. ISONE has similar rules to PJM and is interconnected to Canada.

Midwest Independent Service Operator ("MISO") is a North American regional transmission organization that provides services to 15 states and the Manitoba territory in Canada. MISO is the largest ISO when measured in square miles or distance of transmission lines.

Deregulated Western Interconnections

California Independent Service Operator ("CAISO") is the independent service operator for California that regulates transmission and the wholesale energy market.

Electric Reliability Council of Texas ("ERCOT")

The Electric Reliability Council of Texas ("ERCOT") manages 85 percent of Texas' electric load. As the independent system operator ("ISO") for the region, ERCOT schedules power on an electric grid that connects 40,500 miles of transmission lines and more than 550-generation units. ERCOT also performs financial settlement for the competitive wholesale bulk-power market and administers retail switching for over 7 million premises in competitive choice areas. ERCOT's members, similar to other ISOs and RTOs, include consumers, cooperatives, generators, power marketers, retail electric providers, investor-owned electric utilities (transmission and distribution providers), and municipal-owned electric utilities. ERCOT is unique because its electricity grid is not synchronously connected outside of the state.

Demand-Response

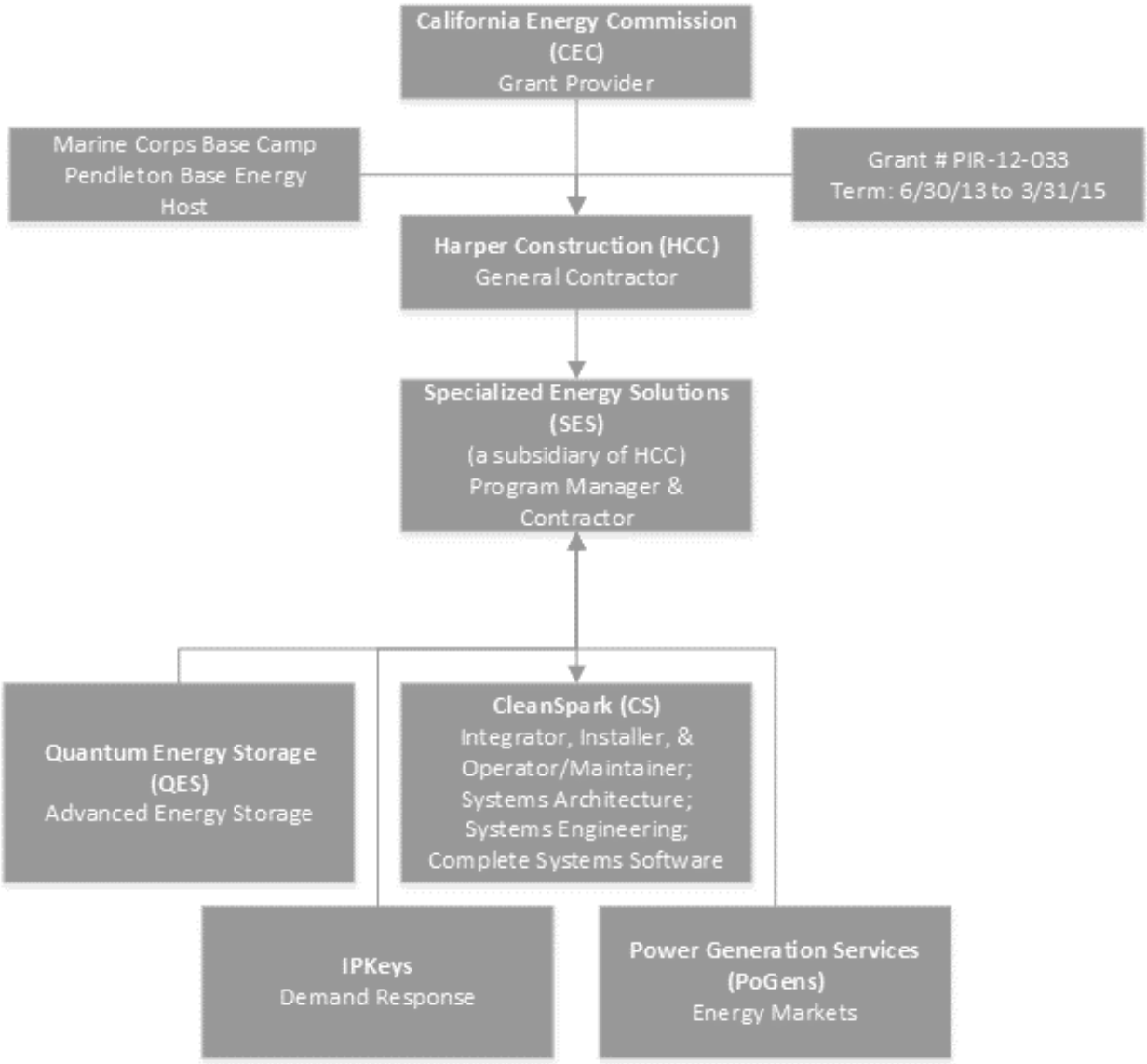
Demand-response is a program in which consumers reduce their consumption of electric energy from the network when instructed in exchange for compensation. The ISO and utilities operates three types of demand-response programs: those activated by price, those activated for reliability, and those that reduce peak consumption.

Products, type of equipment, system, service, practice, or strategy that verifiably reduces end-use demand for electricity from the power system are all critical components of Demand-response ("DR"). Active demand resources reduce load in response to a request from the ISO for system reliability reasons or in response to a price signal. Passive demand resources are principally designed to save electric energy use, which is in place at all times without requiring direction from the ISO. Passive demand resources include energy-efficiency measures, such as the use of energy-efficient appliances and lighting, advanced cooling and heating technologies, electronic devices to cycle air conditioners on and off, and equipment to shift load to off-peak hours of demand. Some of the specific types of demand-response products are:

Demand Response Type	Characteristics
Residential and Commercial Voluntary	Voluntary load reduction programs for customers to reduce load during high price periods
Direct Load Control Switches (DLC)	Load control devices for HVAC, water heaters, heat pumps, etc., switches for on/off control
"Fast response" Adjustable DLC (FA-DLC)	Adjustable load control devices for HVAC, water heaters, refrigeration, lighting, microgrids, provides capabilities for scheduling, extended timeframes, move up/down
Dynamically controlled DLC (DC-DLC)	Dynamically controlled load devices at customer sites through utility systems. Examples are water pumping stations and water storage facilities or microgrids
Load Transfer DR (LT-DR)	Ability for customers to transfer load from utility feed on onsite generation, storage, or microgrid
Peak Shifting DR (PS-DR)	Ability to shift the load from on to off peak. Means to do this are through work scheduling, pre-cooling, or microgrids

Microgrids are unique in that they are one of the only demand-response products that can provide all types of DR. As described in this report, microgrids can provide capacity to fast acting frequency response. Finally in the extreme case microgrids can completely disconnect from the grid and can independently operate. When looking at the different types of demand-response capabilities and how they generally translate into energy markets, microgrids can span nearly all market types:

Grid Service Type	Response Speed	Minimum Response Duration	Description	Demand Response
Capacity	Minutes	Few hours	Used to meet demand plus reserve margin requirements.	DLC, FA-DLC, DC-DLC, LT-DR, PS-DR
Ancillary Services Contingency Reserve	<15 minutes	Minutes to Hours	Reserves used to replace sudden loss of power, or major system changes.	FA-DLC, DC-DLC, LT-DR
Ancillary Services Regulation or Reserve	Seconds	Minutes to Hours	Used to maintain system frequency.	FA-DLC, DC-DLC, LT-DR
Ancillary Services Non-Spinning Reserve	10-30 Minutes	Minutes to Hours	Used to augment/restore regulation and reserves. Slower response than Reg or reserve.	DLC, FA-DLC, DC-DLC, LT-DR
Ancillary Services Inertial Response	Seconds	Seconds	Local response to mitigate transient stability issues (e.g. solar or wind)	LT-DR
Black Start	Seconds	Time to restore system	Standby generation or storage units which can keep power on local areas.	LT-DR
Energy Price Response (peak reduction)	Minutes	Minutes	Ability to increase generation or reduce load during high price peak demand events.	DLC, FA-DLC, DC-DLC, LT-DR, PS-DR
Energy Price Response (turn down)	Minutes	Minutes	Ability to decrease generation or increase load during high price valley demand events.	FA-DLC, DC-DLC, LT-DR, PS-DR

The value of microgrids is inherent not only to the owner, but also to the energy market it interconnects. The monetary value can greatly vary based on grid service type and real time pricing. One of the keys to microgrid success is the ability to take advantage of energy market revenue in addition to KW/KWH savings to the customer. In general, this could increase the returns to the customer by 2-10x.

APPENDIX D:
Organization Chart