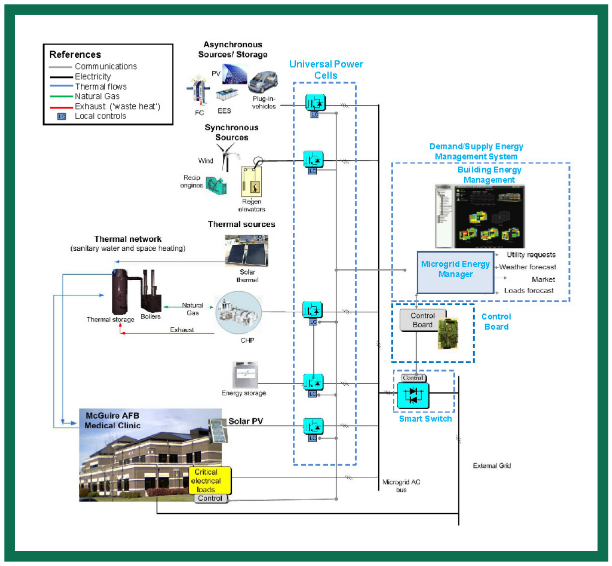
# ESTCP
# Cost and Performance Report

(EW-200939)




## Distributed Power Systems for Sustainable Energy

October 2012

ENVIRONMENTAL SECURITY
TECHNOLOGY CERTIFICATION PROGRAM

U.S. Department of Defense

# COST & PERFORMANCE REPORT
Project: EW-200939

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## ACRONYMS AND ABBREVIATIONS

| | |
|---|---|
| AC | alternating current |
| ADC | analog-to-digital |
| AFB | Air Force Base |
| ALC | Automatic Logic Corporation |
| | |
| BEMS | building energy management system |
| BMS | battery management system |
| | |
| CHP | combined heat and power |
| | |
| DC | direct current |
| DOD | U.S. Department of Defense |
| DSB | Defense Science Board |
| | |
| EES | electric energy storage |
| EMS | energy management system |
| EO | Executive Order |
| ESTCP | Environmental Security Technology Certification Program |
| | |
| FMEA | Failure Mode Effect Analysis |
| | |
| I | current |
| IEC | International Electrotechnical Commission |
| IEEE | Institute of Electrical and Electronics Engineers |
| | |
| LCC | life-cycle cost |
| | |
| MPPT | maximum power point of tracking |
| | |
| NDAA | National Defense Authorization Act |
| NEC | National Electric Code |
| NIST | National Institute of Standards and Technology |
| | |
| O&M | operation and maintenance |
| OSD | Office of the Secretary of Defense |
| OSHA | Occupational Safety and Health Administration |
| | |
| PV | photovoltaic |
| | |
| ROI | return on investment |
| | |
| SCR | silicon-controlled rectifier |
| SOC | state of charge |
| SOH | stage of health |

## ACRONYMS AND ABBREVIATIONS (continued)

| | |
|---|---|
| T | temperature |
| T&D | transmission and distribution |
| THD | total harmonic distortion |
| | |
| UCB | universal control board |
| UPC | universal power cell (or power converter) |
| U.S. | United States |
| UTC | United Technologies Corporation |
| UTRC | United Technologies Research Center |
| UWM | University of Wisconsin Madison |
| | |
| V | voltage |

# ACKNOWLEDGEMENTS

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# EXECUTIVE SUMMARY


The U.S. Department of Defense (DOD) is the largest single user of energy in the United States (U.S.) [2], representing 0.8% of the total U.S. energy consumed and 78% of the energy consumed by the Federal government. Approximately 25% of DOD energy use is consumed by its buildings and facilities. The DOD currently has 316,238 buildings across 5429 sites translating to a monetary value of > $450B [3]. The Office of the Secretary of Defense (OSD) has published an energy policy to ensure the DOD infrastructure is secure, safe, reliable and efficient [4]. The realization of this OSD energy policy, within the DOD, is being guided by (1) the Energy Policy Act of 2005, (2) Executive Order (EO) 13423, and (3) the Energy Independence and Security Act of 2007, to ensure a 30% energy reduction by 2015. The Policy Act of 2005, as well as EO 13423, has set a minimum contribution of renewable energy from DOD's installations of 5% by fiscal year (FY)2012 and no less than 7.5% beginning FY2013 [5].

Under the Distributed Power Systems for Sustainable Energy project described in this report, United Technologies Research Center (UTRC) in collaboration with the University of Wisconsin Madison (UWM), has demonstrated the key technologies that will enable scalable deployment of distributed power sources and energy storage. These key technologies have been demonstrated in such a way that the distributed power sources would appear as a single stable entity to the electrical grid. The technologies demonstrated as part of this project, when adopted, will provide the infrastructure and controls required for efficient and reliable use of renewable energy sources. These "microgrids" will provide the largest opportunity for reducing external grid utilization, reducing the environmental impact associated with the use of non-renewable sources, and is an important step toward the required security of energy supply at DOD installations. As a result of this project, UTRC has developed energy microgrids based on Li Ion batteries and solar photovoltaic (PV) systems, and has successfully validated the performance of:

1. Universal programmable converters, smart power switches and local control relying on local sensing that allowed for demonstration of:
   - Interoperability of multiple energy sources and storage, required for seamless transition between grid-parallel and grid-island operation modes, enabling critical loads to continue their normal operation during external power outages.
   - The capability to improve power quality and reduce the total harmonic distortion (THD) to levels lower than the 5% guidelines provided by Institute of Electrical and Electronics Engineers (IEEE) 1547.
   - The capability to follow power commands from a supervisory system, and to continue safe operation under the loss of communications with the supervisory system.
   - Maximum power point of tracking (MPPT) algorithms that can operate faster and more reliably than the state-of-the-art algorithm.
2. A fast power switch and smart algorithms located at the common point of coupling with the main external grid. This switch is based on utility-grade reliable technology, sensing and control algorithms. The switch communicates with the UPC Universal Power Cell

(UPC) (or Power Converter), enabling seamless connection and reconnection of the microgrid to the grid when a grid-outage or recovery condition is detected.

3. Scalable energy management system and communications infrastructure. The energy management system is based on a model predictive optimization engine that determines power flow set-points for each microgrid component. The function to be optimized, namely cost, can be chosen amongst several, including life cycle cost (LCC) minimization, energy efficiency maximization, or tracking of utility requests relative to energy usage and power export. The economic value of the optimization-based supervisory system was compared to a rule-based approach. Results and savings depend on the energy microgrid elements considered (e.g., type and size of energy systems), energy usage, weather conditions, and price of electricity and gas. For a microgrid sized to provide 20% renewable based energy (based on typical DOD installations), the proposed optimization-based supervisory system, that considers the uncertainty in loads and weather forecasts, could significantly outperform rule-based supervisory system by as much as 20%.

The system and all its components were developed at UTRC in the UTRC Energy Conversion Laboratory, where it was fully tested before being moved to McGuire Air Force Base (AFB) medical clinic for purpose of interfacing with an 80 kilowatt (kW) solar PV system. Final verification and successful demonstration of all performance objectives was achieved at McGuire AFB. This project is the foundation for the development of more ambitious and challenging goals in the energy system area, including microgrids for net-zero energy buildings, integration of advance energy storage devices such as flow battery with the grid and wind turbines, analysis of stability and subsystem interaction in microgrids systems.

# 1.0 INTRODUCTION

## 1.1 BACKGROUND

In 2008, a report was published by the Defense Science Board (DSB) task force [1] detailing the Department of Defense's (DOD) energy strategy and identifying the following key DOD energy challenge: *"Military installations are almost completely dependent on a fragile and vulnerable commercial power grid, placing critical military and Homeland Defense missions at unacceptable risk of extended outage."* The DOD is the largest single user of energy in the United States (U.S.) [2], representing 0.8% of the total U.S. energy consumed and 78% of the energy consumed by the Federal government. Approximately 25% of DOD energy use is consumed by its buildings and facilities. The DOD currently has 316,238 buildings across 5429 sites with a monetary value >$450B [3]. The Office of the Secretary of Defense (OSD) published an energy policy to ensure that the DOD infrastructure is secure, safe, reliable and efficient [4]. The realization of this OSD energy policy, within the DOD, is being guided by (1) the Energy Policy Act of 2005, (2) Executive Order (EO) 13423, and (3) the Energy Independence and Security Act of 2007, to ensure a 30% energy reduction by 2015. The Policy Act of 2005, as well as EO 13423, has set a minimum contribution of renewable energy from DOD's installations of 5% by fiscal year (FY)2012 and no less than 7.5% beginning FY2013 [5]. By providing an infrastructure for efficient and reliable use of renewable sources of energy, the largest opportunities to reduce external grid utilization and also the environmental impact associated with the use of non-renewable sources can be realized.

United Technologies Research Center (UTRC), together with the University of Wisconsin Madison (UWM), has developed and demonstrated the technology needed to allow integration of renewable energy sources, and energy storage, with the grid. These technologies (1) enable introduction of dynamically stable, modular, and cost-effective energy microgrids that can operate seamlessly in grid-parallel and off-grid modes, and (2) allow DOD to meet their energy and renewable targets, as well as improve the security of supply to critical electrical loads by allowing these loads to seamlessly transition between islanding and grid-connected models.

## 1.2 OBJECTIVE OF THE DEMONSTRATION

The specific technical objectives of the demonstration were:

1. To develop power conversion and power electronics technologies that could (a) be universally used for plug & play interconnection of renewable and non-renewable energy sources and energy storage, and (b) could lead to large scale deployment of distributed power systems, fully integrated with building loads and the external grid at the building or district level.
2. To demonstrate the capability to integrate multiple energy sources together that could provide continuous power to critical loads while maintaining stable integration with the grid.
3. To develop an energy management system (EMS) that could provide optimal power set-points to individual sources of energy, and provide supply as well as demand response

commands, integrated with both the grid and the building energy management systems (BEMS).

4. To demonstrate the value of both energy microgrids and energy management systems by demonstrating the capability to outperform current systems. The actual energy savings of energy microgrids depends upon its type and size and utilities rates, however, could reach up to 100% in Net-Zero Installations, or even beyond 100% if the system can export power to the grid.

To accomplish these objectives, UTRC installed an energy microgrid system at the McGuire Air Force Base (AFB) medical clinic. The microgrid consisted of a universal power converter, its control board, and an energy management system. The UTRC hardware and software manage the flow of energy from the grid, the roof mounted solar photovoltaic (PV), and energy storage battery.

## 1.3 REGULATORY DRIVERS

In response to the vulnerabilities identified by the DSB Task Force on DOD Energy Strategy [6], the President, Congress and DOD leadership have mandated many energy consumption metrics at its fixed installations. The mandates relevant to the distributed power systems and energy microgrid project include, but are not limited to:

1. Installations Energy Use: Reduce by 30% by 2015 from 2003 baseline [EO 13423/ 2007 Energy Act]
2. Electricity from Renewable Sources: 25% of installation electricity by 2025 [2007 Energy Act]
3. Fossil Fuel Use in new/renovated buildings: Reduce 55% by 2010; 100% by 2030 [2007 Energy Act]
4. Hot Water in new/renovated buildings from solar power: 30% by 2015 [2007 Energy Act]
5. Renewable Electricity: use 10 year contracts to buy [FY08 National Defense Authorization Act (NDAA)]
6. Non-petroleum fuel use (ethanol, natural gas): increase by 10% annually [EO 13423/2007 Energy Act]
7. Data Collection for Energy Management
8. Create Metered Energy Benchmarking Database [2007 Energy Act]
9. Meter Electricity by October 2012 [2005 Energy Act]
10. Meter Natural Gas and Steam by October 2016 [2007 Energy Act].

# 2.0 DEMONSTRATION TECHNOLOGY: ENERGY MICROGRIDS

## 2.1 TECHNOLOGY DESCRIPTION

Under Environmental Security Technology Certification Program (ESTCP) Project EW-200939, UTRC demonstrated the key technologies required to enable scalable deployment of distributed power sources and energy storage. These technologies were demonstrated in such a way that the power sources would appear as a single entity to the electrical grid. The "energy microgrid" concept is illustrated in Figure 1, where multiple energy sources and energy storage elements can be used. These sources and storage are electrically wired together and present a single point of coupling with the grid. As a result of this project, UTRC has demonstrated its design of universal programmable converters and local controllers, with the power switch acting as a single point of coupling with the grid, and an energy management system. The Universal Power Conversion (UPC) and control board developed at UTRC has the ability to provide alternating current (AC)\AC, AC\direct current (DC), DC\DC or DC\AC conversion and be optimized, and programmable, to handle any type of devices and their interoperability and integration with the external electrical grid. These converters are controlled by the power electronics and control algorithms embedded in the Universal Control Board (UCB). The UCB comprises powerful microprocessors that enable implementation of sophisticated algorithms to provide high quality voltage and current waveforms, reduction of losses in converters, reliable operation and reconfiguration for implementing different functions and for future expansions. For the demo at McGuire AFB medical clinic, the local controls on the source side of the UPC provided maximum power point tracking (MPPT) for the solar PV system, interleaving configuration and operation of the Li-ion battery system. These controls can be easily extended to include other interfacing sources, such as fuel cells, wind turbines, or any other energy source or storage. On the grid side, the local control algorithms implemented on the UPC provide instantaneous power management, dynamic stability with the external grid, improved power quality, and seamless transition between off-grid and grid-parallel operations. The local controls provide phase angle/position and magnitude of line voltage vectors. Control of the inverter's frequency maintains the power angle and flow of the real power. To ensure appropriate loading of real and reactive power from each of the devices, the inverter recognizes load changes without communication and provides appropriate power sharing for parallel units. The control of inverters, used to supply power to an AC system in a distributed environment, is based on local information available at the inverter. Fast current and voltage control loops, and the fault management system, provide the capability to ride through sags and swells of the grid voltage without disruption of operation before the smart power switch disconnections from main grid.

The energy management system optimally schedules power flow between energy sources and storage based on operational and lifecycle metrics, customer preferences, and operational constraints associated with the microgrid components. Equipment operational constraints are included to capture limits of operation, safety, and measures to increase the lifetime of the various components. Advantages of the energy management system include: lower operational cost, increased energy efficiency, lower emission of greenhouse gases, and improved lifetime. The proposed energy management controller is flexible and expandable, and components can be easily added and removed. In addition, UTRC has demonstrated that such an approach can be made compatible with existing BEMS, such as WebCtr™, owned by Automatic Logic Corporation (ALC) (a United Technologies Corporation [UTC] owned company).

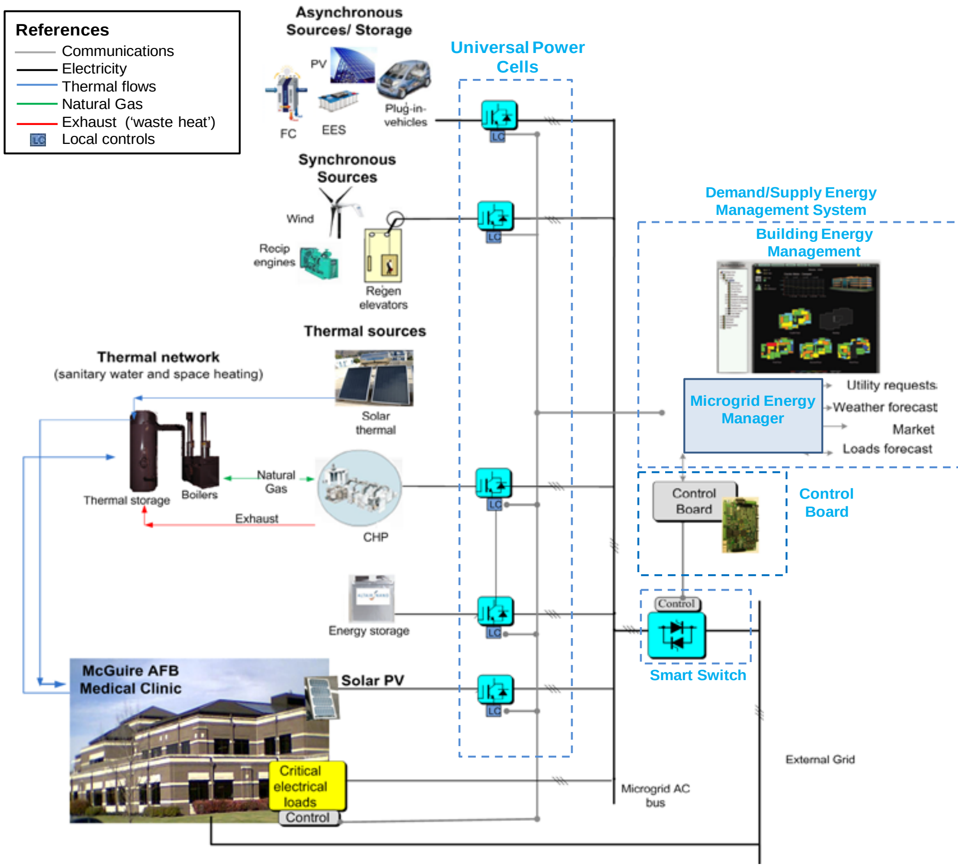


**Figure 1. UTRC energy microgrids concept.**

The proposed microgrid architecture separates communications for instantaneous power management from that of energy management, based on the different requirements on communications latencies. Instantaneous power management relies on local measurements, ensures appropriate loading of real and reactive power from each of the devices, and enables a "plug and play" modular approach for the integration of new devices into the microgrid. Instantaneous power management requires communications speed on the order of milliseconds. For energy management, the required response time for communications between microgrid components and utilities, with the supervisory system, is on the order of seconds to minutes.

The static switch, which consists of three pairs of anti-parallel silicon-controlled rectifiers (SCR), enables seamless transfer of energy from the power grid or distributed generator to the loads in order to avoid service interruption upon a deficiency in power quality. The most important function of the static switch is reclosing upon restoration of normal grid conditions. A synchronization check relay is used for this purpose. It monitors instantaneous voltages across the SCRs. When the difference between the two is less than a specified percentage of the nominal voltage level, the output gives a logic signal to the SCR firing board, which then simultaneously triggers the three phase SCRs. By using a static switch, power quality problems become transparent to the vulnerable customer loads. Another key characteristic of the static switch is the speed of operation because it identifies duration of power discontinuity/interruption for the sensitive load.

## 2.2 ADVANTAGES AND LIMITATIONS OF THE TECHNOLOGY

The energy microgrid systems tested under this program enable adoption of renewable-based "smart-grids" through:

1. Security of supply: Dynamically stable, renewable-based microgrids capable of seamless transition between grid-parallel and off-grid operations.
2. Improved power quality: Robust operation of the microgrid to voltage sags and swells.
3. Utilization of renewable sources: Efficient and cost-effective integration of renewable energy sources and storage within the grid.
4. Utilization of waste heat: Waste heat utilization for dispatchable power sources, resulting in 85-90% fuel utilization versus 40-50% for central power generation.
5. Reduced energy cost: Optimized operation with energy management system, on top of local controllers. Reduced energy bill at the select customer site.
6. Energy savings and improved energy efficiency: Energy sharing algorithms between sources, such as solar or wind; energy storage elements to mitigate uncertainty and randomness in energy generation; and smooth power flow.
7. Extensibility of the technology to include supply and demand management, integration with BEMS, and energy markets with utilities request and incentives.
8. Scalability of technology to larger sites and operation of the EMS to control microgrids clusters within multiple sites.
9. Decrease in transmission and distribution losses and in transmission infrastructure requirements (e.g., by distributed power systems versus centralized generation).
10. Plug-and-play operation of the system without communications between individual sources, allowing for modular addition of other energy storage and sources to the grid.
11. Reconfigurable, universal power conversion unit able to interface with (i) DC sources, such as PV and fuel cells, (ii) AC sources, such as wind turbines and gensets, (iii) loads, and (iv) energy storage.

Limitations of the energy microgrid technology include:

- Initial cost: Energy microgrids rely on distributed generation of energy. Deploying environmentally friendly microgrids requires significant capital investment in state-of-the-art cogeneration technologies, renewable sources, energy storage, and interconnection hardware and software. It is expected, however, that economics of scale, technology breakthroughs, and natural learning curves will reduce the economic limitation of microgrid deployments.
- Readiness of new technologies. New renewable energy sources are either inefficient, require high initial investment, and/or present long payback periods. Energy storage technologies present special challenges and opportunities. Available energy storage technologies are not well-suited for large-scale energy microgrids. For example: Li-ion technologies are being tested for automotive applications, and their energy and power

capacity may not be well suited to support building or campus-scale microgrids. This is because new thermal and electrical energy storage devices, having both high-density energy and power capabilities, are required.

- Energy savings, environmental benefits, and the time during which the microgrid can serve critical loads, in the case of a power outage, vary depending on the selection of microgrid architecture. The economic and environmental benefits of energy microgrids, the power quality, and the autonomy time of the system depend on the type and size of microgrid devices and their interconnection. The optimum microgrid architecture depends on the selected performance objectives and the site-specific requirements and constraints, as well as the site location, weather, and consumption patterns. These factors change over the life of the energy microgrid.
- Tradeoffs between vulnerabilities and initial cost: There are elements of the energy microgrid that are more vulnerable to intentional and non-intentional attacks. For example, the power switch—although utility grade components with very small probabilities of failure were used, a switch failure means the microgrid will not operate. In a real environment, the vulnerable pieces of equipment should be redundant and/or located in a secure site of restricted access.
- Electrical and thermal reconfigurations for retrofit applications: Most existing buildings do not have separate electrical wiring for vulnerable and non-critical loads.[1] These separate circuits are a requirement to taking full advantage of the security-of-supply capability of energy microgrids. A building energy management system and sub-metering are also required to take full advantage of the potential benefits of smart grids and microgrids.

Limitations specific to the demo being tested by UTRC, at McGuire AFB, include:

- Reduced number of components. Only a solar PV energy source and LiIon energy storage are represented. The configuration that was demonstrated allows for (i) demonstration of power quality, (ii) seamless transition between different operating modes, and (iii) security of energy supply to critical loads. However, the economic and environmental potential of energy microgrids was demonstrated by exercising models and simulations.
- Microgrid capacity is lower than total building loads. The microgrid has a total 80 kilowatt (kW) capacity, which is, at best, ~10% of the medical building peak load. That power, however, may be enough to cover critical loads in the future (currently, critical loads are emulated by resistive load banks).
- Lack of Internet connection at DOD installations. This constraint limits EMS capability to gather real-time information about weather.
- Lack of building loads information. Demonstration with actual building loads is not required, given that the capacity of the microgrid is always a small fraction of the power

[1] In this document critical loads refer to what is technically referred to as "critical electrical loads" or those loads that must be supplied of electricity to avoid losing functionality. The distinction is made to avoid the word "critical" used for critical military missions.

that is required by the building. Moreover, the focus of this demonstration is on supply optimization. Demand and supply optimization is out of scope for this project.

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# 3.0 PERFORMANCE OBJECTIVES

Table 1 provides a summary of the objectives and metrics used to compute the success criteria for Renewable-based Distributed Power Systems.

**Table 1. Performance objectives.**

| Performance Objective | Metric | Data Requirements | Success Criteria | Results |
|---|---|---|---|---|
| **Quantitative Performance Objectives[2]** | | | | |
| 1. Security of energy supply to critical loads (availability of power to critical loads during transitions). | Seamless transition between grid parallel and islanding operation mode at the critical load. | – Smart switch status<br>– V, I at the output of the converter<br>– V, I to critical loads<br>– V, I from solar PV and from battery | Emulated critical loads operation before, after, and during an emulated power outage for a given minimum period of time allowed (at McGuire AFB demo: 15kWh/40kW *1/2~ 11.2 min.) | - Seamless transition was demonstrated between grid connected and grid islanding modes.<br>- Operating conditions ranged from limited or non-solar PV available, to full PV power. |
| 2. Stable integration of multiple energy sources and storage with the electrical grid. | – Grid synchronization<br>– Grid voltage<br>– Current harmonics<br>– Frequency deviation. | – V, I at the output of the converter<br>– V,I at loads | Power quality within ranges provided by Institute of Electrical and Electronics Engineers (IEEE) 1547. | With no load, the voltage distortion was lower than 2.5%. As the load increases distortion becomes less than 1%. |
| 3. System robustness to loss of communications (one of the enablers of plug & play capability). | Continuous reliable operation when communications between energy manager and control board fails. | – Power levels (PV, battery, at converter output, at loads)<br>– Default power set-points<br>– Power set-points from energy management system. | System continues operating at all times during communications errors between EMS and UCB. | When the loss of communication of the EMS was sensed in the local controller, the critical load was successfully powered by the UPC. |
| **Qualitative Performance Objectives[3]** | | | | |
| 1. System protection and fault management. | System shuts-down / ride through under pre-defined conditions. | V, I at output of the converter | System operates according to safety procedures design intent. | All the protections in the microgrid system were thoroughly tested and passed the tests. |
| 2. Robust integration between EMS and UCB. | Power levels set-points provided by supervisory system to converter controller. | – V, I at battery and solar PV<br>– V, I from grid<br>– Power set-points | System power levels follows set-points provided by the EMS (if safe operation is verified). | Microgrid system follows set-points established by the EMS except when the commands are out of acceptable bounds. |

[2] All quantitative results are based on field data obtained at McGuire AFB.
[3] All qualitative results are based on field data obtained at McGuire AFB, except for the “ease of use” performance metric.

**Table 1. Performance objectives (continued).**

| Performance Objective | Metric | Data Requirements | Success Criteria | Results |
|---|---|---|---|---|
| 3. Ease of use | Ease of use by facility managers. | Facility managers' survey. | The demo at McGuire AFB is supervised. | The demo at Mc Guire AFB was supervised. The system requires certification before being operated by facility managers. |
| **Quantitative Performance Objectives (proved by simulation)**[4] | | | | |
| 1. Decrease environmental Impact (directly related to increase renewable usage in the microgrid system). | $CO_2$ release avoided (in kilogram [kg] $CO_2$ / unit time) | – Loads<br>– System output power<br>– $CO_2$/kWh for the grid and the microgrid elements | – Impact larger than 30% (in $CO_2$ released) improvement compared with grid-only supply.<br>– Demonstrated through simulations in alternative DOD locations). | Result shows that compared with the grid only baseline, the $CO_2$ reduction under optimization-based control strategy are between 30-40%. |
| 2. Reduce energy consumption from external utilities. | Average energy saved (electricity and gas, in kilowatt hour [kWh]/square feet [$ft^2$] per unit time). | – Loads information<br>– System output power<br>– Weather information (e.g., solar radiation) | Impact larger than 30% (in kWh/$ft^2$) improvement compared with grid-only supply. Demonstrated through simulations in alternative DOD locations) rule-based operation. | Results were obtained based on the constraint that renewable sources should contribute to at least 30% of total energy consumption. |
| 3. System Economics | Average energy cost saved over lifetime of equipment ($/kWh) | – Loads information<br>– System output power<br>– Utility rates | Return on investment (ROI), lifetime, payback for sample microgrid architectures, estimated using National Institute of Standards and Technology (NIST) BLCC5. | Results are location dependent, an also dependent on the assumed microgrid architecture. With an optimization bases supervisory system, the annual utility savings could range from 56 to 61%. |

[4] All quantitative results are based on field data obtained by using models and simulations.

# 4.0 FACILITY/SITE SELECTION: MCGUIRE AFB MEDICAL CLINIC

## 4.1 FACILITY/SITE LOCATION AND OPERATIONS

The microgrid concept was demonstrated at McGuire AFB medical clinic using an existing 76.5 kW solar PV array as the energy source. An energy storage system was provided by UTRC and the building critical loads were represented by a load bank. The system installed at McGuire AFB medical clinic is represented in Figure 2.

The solar PV and the battery were electrically wired together. They presented a single point of coupling with the building AC bus through the smart switch. An electrical contractor provided the electrical work required to change from the existing commercial solar PV installation to the proposed microgrid demo installation. The electrical installation was achieved in such a way that the solar PV system could be easily restored to its current commercial installation once the demonstration was finalized. Mechanical work, comprising a ventilation system for the battery systems, was performed as a redundant safety system.

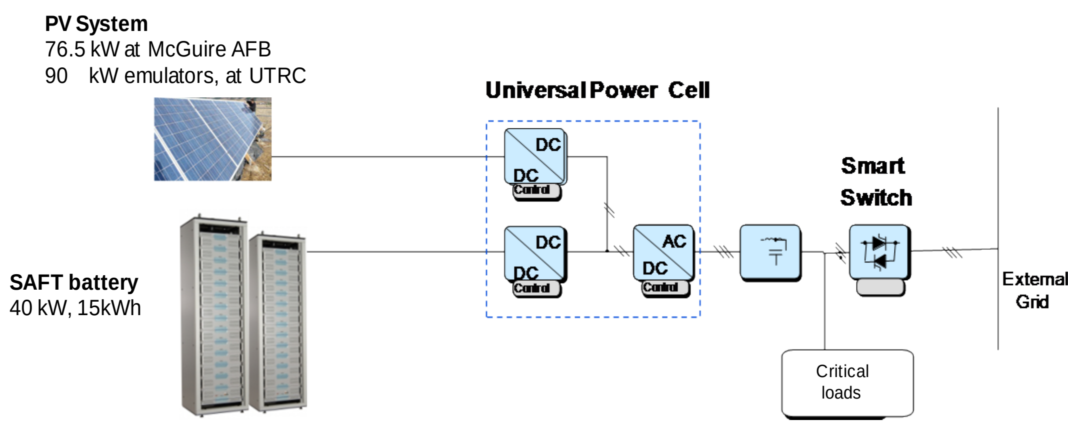


**Figure 2. Schematic diagram of the energy microgrid system and sub-system installed at McGuire AFB.**

## 4.2 FACILITY/SITE CONDITIONS

The existing solar PV system at McGuire AFB medical clinic was modified to allow operation in two modes: Operating Mode 1, which represents the already existing connection at McGuire AFB, and Operating Mode 2, representing implementation of the new ESTCP Demonstration System. Major components of the ESTCP System include the UPC, the grid tie unit with smart switch, battery, the load bank, and the EMS. The appropriate transfer switches allowed the mode of operation to be easily changed from the existing inverter setup to the ESTCP Demonstration, and back again. All approved lay-out diagrams are included in Appendix B of the Final Report.

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# 5.0 TEST DESIGN

This section provides a description of the system design and testing conducted to address the performance objectives described in Section 3.0.

## 5.1 CONCEPTUAL TEST DESIGN

The overall test consisted of two parts:

- Experimental demonstration of energy microgrids with the capability to: i) be extensible to a plug & play system capable of integrating multiple energy sources and storage with the grid; ii) enable security of supply by seamlessly providing power to emulated critical loads; and iii) work in coordination with the microgrid EMS. A formal Failure Modes Effect Analysis (FMEA) was used to support the design and instrumentation of the system, the design of the test sequence, and the implementation of safety measures.
- Simulation of optimal energy microgrid designs and operations, to provide insights into the economic and environmental value proposition of renewable based energy microgrids, demonstrated for typical DOD installations.

All metering points to measure experimental results are graphically presented in Figure 3, where all voltage (V), current (I), temperature (T) sensors and state of charge (SOC) and stage of health (SOH) estimators are shown.

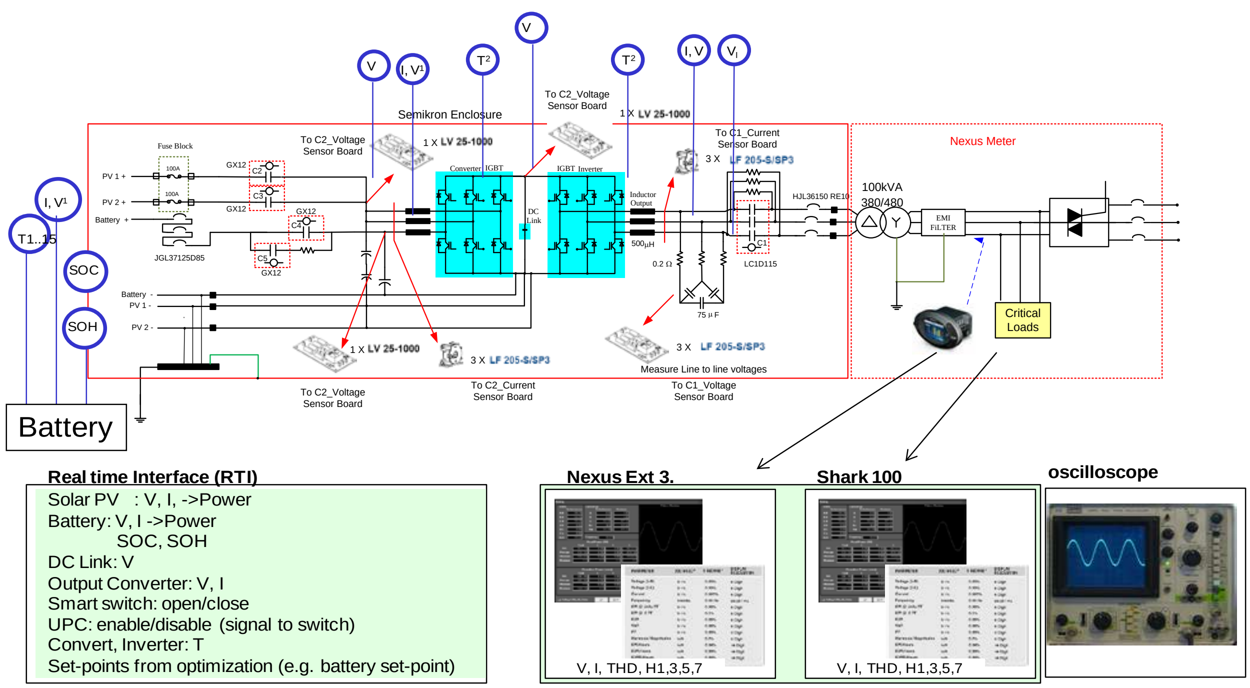


**Figure 3. Microgrid demo sensors – type and location.**

## 5.2 BASELINE CHARACTERIZATION

The IEEE 1547 Standard is the baseline standard selected for evaluating both the quantitative and qualitative microgrid performance objectives relative to the security of energy supply and power quality. The microgrid controls algorithms were designed to follow the voltage and frequency variations guidelines provided by IEEE 1547 and presented in Table 2 and Table 3, and to meet the total harmonic distortion (THD) guidelines given in Table 4.

**Table 2. IEEE 1547 voltage variations guidelines.**

| IEEE 1547 | |
|---|---|
| **Voltage Range (%)** | **Disconnection Time (s)** |
| V<50 | 0.16 |
| 50≤V<88 | 2.0 |
| 110≤V<120 | 1.0 |
| V<120 | 0.16 |

**Table 3. IEEE 1547 frequency variation guidelines.**

| IEEE 1547-2003 | |
|---|---|
| **Frequency Range (Hz)** | **Disconnection Time (s)** |
| f<59.3 or f>60.5 | 0.16 |

**Table 4. IEEE 1547 inverter current harmonics performance guidelines.**

| IEEE 1547 and International Electrotechnical Commission (IEC) 61727 | | | | | | |
|---|---|---|---|---|---|---|
| **Individual Harmonic** | **h < 11** | **11≤h<17** | **17≤h<23** | **23≤h<35** | **35≤h** | **THD %** |
| % | 4.0 | 2.0 | 1.5 | 0.6 | 0.3 | 5 |

## 5.3 DESIGN AND LAYOUT OF TECHNOLOGY COMPONENTS

Technology components deployed at McGuire AFB included UTRC universal programmable converters and local controllers, with the power switch acting as a single point of coupling with the grid, and an EMS. All these components were described in Section 2 and shown in Figure 2.

## 5.4 OPERATIONAL TESTING

System tests were performed at UTRC Energy Conversion Laboratory before moving the system to McGuire AFB. System level tests at UTRC were finalized in June 2011. The system was moved to McGuire AFB on August 4, connected to the solar PV in the medical building, and tested during August 2011. The operational tests performed at the UTRC Energy Conversion Laboratory are discussed below. These tests were repeated at McGuire AFB to the extent the weather conditions (i.e., solar radiation levels at the moment of the experiments) allowed for replication:

- Test system operation and measured performance, represented by DC link voltage, input and output current and voltage waveforms, and harmonic distortion, under grid-connected conditions, and with EMS available. Subtests included high and low solar radiation conditions[5]; and zero, low, medium and high load conditions at the resistive load bank (related to Quantitative Performance Objectives 1 and 2).
- Test software protection modes under conditions that included over-voltage, over-current, battery over and under charge, and fault ground protections (related to Qualitative Performance Objective 1).
- Simulation of different inverter reference power levels, to ensure the PV and battery properly follow sudden changes in power references, while keeping to the requirements of stability and power quality (related to Quantitative Performance Objective 3).
- Simulation of loss of communications between the UPC and the EMS, to verify safe performance under loss of communications conditions (related to Quantitative Performance Objective 3).
- Simulation of a power outage situation through a "grid disconnect switch" included in the system. Measurement of transition times, voltage, and current waveforms to demonstrate seamless transition and to compare results with guidelines provided by IEEE 1547 (related to Quantitative Performance Objective 1). *Note: Testing of power switch performance under power sag and power swell conditions were performed in a separate microgrid system at UWM lab, which possesses the capability to simulate these abnormal conditions. These power switch test results were compared to the IEEE criteria.*

## 5.5 SAMPLING PROTOCOL

Table 5 summarizes the sampling protocols and rates used in this project.

**Table 5. Sampling protocols summary table.**

| Systems to communicate | Protocol | Update time |
|---|---|---|
| UPC relevant variables (e.g., input and output I, V) communicated to UPC | Local analog sensing + analog-to-digital (ADC) | 0.1 msec (10kHz) |
| Local switch local relevant variables (I,V) communicated to power switch relay | Local analog sensing + ADC | 1 msec (1 kHz) |
| Smart switch and UPC | Binary voltage signal | 1 msec (1 kHz) |
| BMS and UPC | CAN Open | 200 msec |
| UPC and RTI | RS232, serial communications | 1 msec (1 kHz) |
| RTI and EMS | File exchange | ~ 1 min (as needed) |
| UPC and EMS | Visualization/debug tool (RTI) | ~ 1 min (as needed) |
| EMS and weather, utilities and/or electrical markets | Web services | ~ 1 min (as needed) |
| EMS and building energy management systems | Web services, BacNet RS232, or CAN (out of scope) | ~ 1 min (as needed) |

[5] Low and high solar radiation conditions (i.e >600W/m$^2$, and <200W/m$^2$ respectively) need to occur while the test was performed at McGuire AFB, NJ, and from 8 am to 6 pm. If one of these conditions does not happen, the final report will include laboratory results where any solar radiation conditions can be easily emulated.

## 5.6 SAMPLING RESULTS

A thorough description of project results is included in Section 6 of this report, whereas the tables and graphs provide the full demonstration of results accomplished during the project.

# 6.0 PERFORMANCE ASSESSMENT

Data and oscilloscope images gathered at the UTRC Conversion Laboratory and the McGuire AFB were used to assess performance objectives for this project. Energy savings were estimated from models and simulations.

## 6.1 QUANTITATIVE PERFORMACNE OBJECTIVES

Voltage and current waveforms were gathered for several scenarios, including:

- Grid synchronization (i.e., the microgrid serving the critical loads and disconnected from the grid, synchronizes, and connects to the grid)
- Sudden changes in inverters power references, that represent conditions when battery or solar PV output suddenly changes (e.g., during a cloudy day)
- Disconnection and synchronization during power outages.

The synchronization process and seamless transition between grid islanding and connected operating modes were evaluated and successfully demonstrated through data gathered at UTRC lab and at McGuire AFB, and illustrated in Figure 4, which shows how the microgrid (red line) synchronized with the grid (blue line) after reconnection.

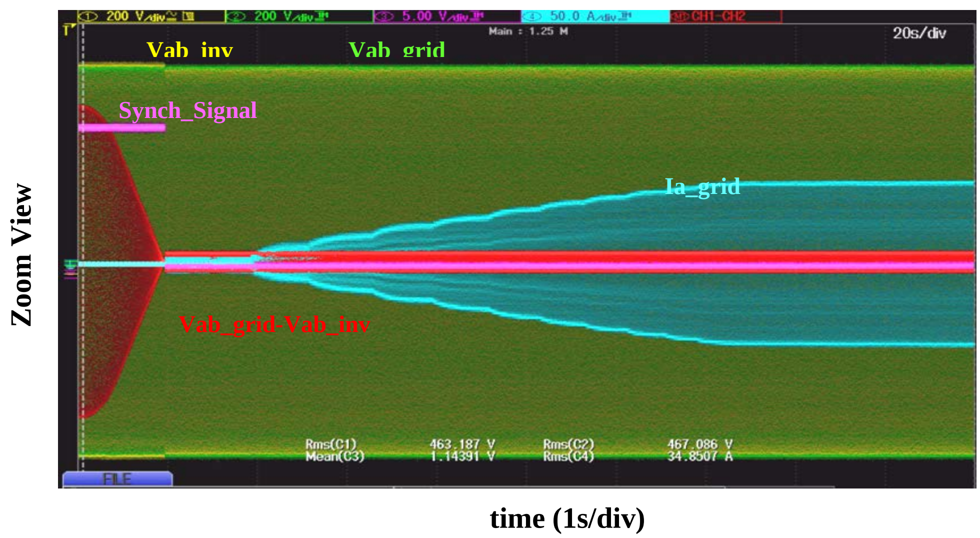


**Figure 4. Grid synchronization at McGuire AFB.**

An example of how the critical loads (Yellow) are served either from the inverter, the grid (blue line), or combination of both are depicted in Figure 5.

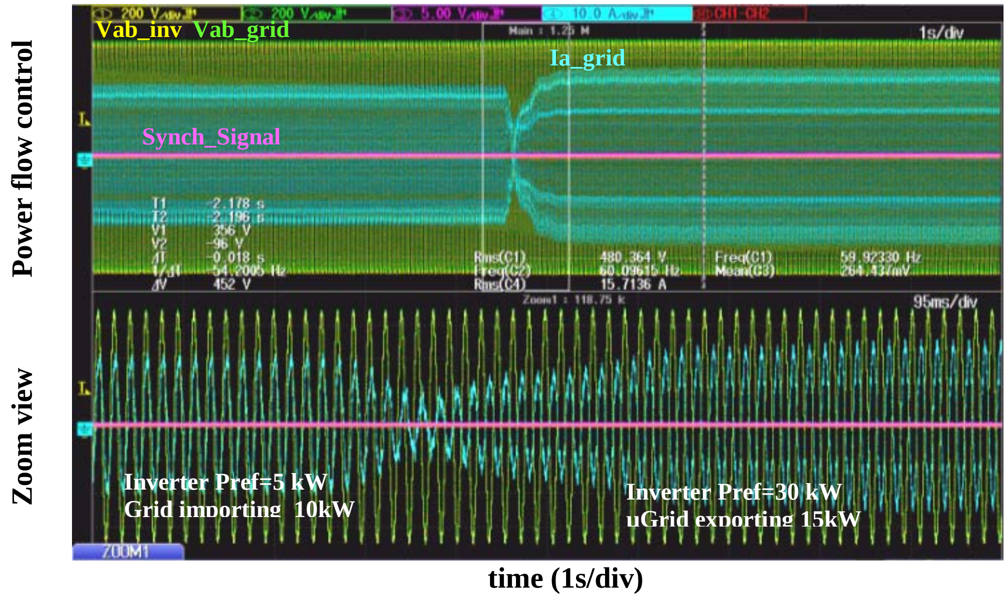


**Figure 5. Power flow control.**

In the case where there is a sudden loss of the grid connection, or commonly known as black-out, the microgrid system was able to connect and reconnect seamlessly to the grid, providing secure energy supply to critical loads as shown in Figure 6.

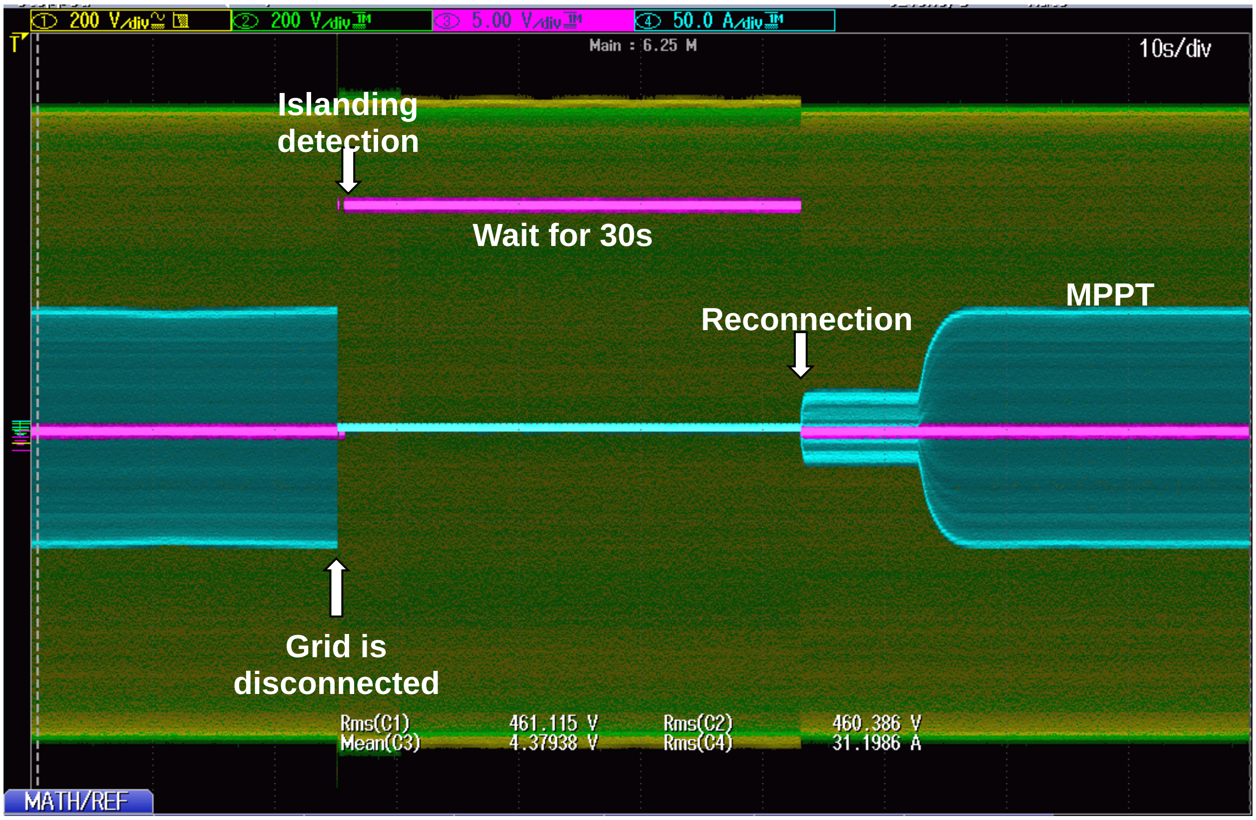


**Figure 6. Grid disconnection and reconnection tested at McGuire AFB.**

The stable integration of the energy source, energy storage, and the grid the system was assessed for the following modes and conditions:

- Grid-connected and grid island modes,
- PV array under MPPT and no-MPPT modes,
- Battery charge and discharging modes,
- Various critical load levels, emulated by changing the load bank resistive levels, and
- Transition between various modes were also be demonstrated.

The data obtained by measuring the voltage waveforms at the inverter side, enabled the team to assess the voltage quality provided to the sensitive load while the grid was disconnected. In all cases, the measured voltage harmonic distortion exceeded the electrical standard requirements listed in IEEE Standard 1547, where the maximum allowed voltage distortion is 5%.

The system also successfully passed the tests evaluating safety and performance under loss of communication condition.

## 6.2 QUANTITATIVE PERFORMANCE OBJECTIVES

To understand and assess the benefits of the use of microgrid, simulations were conducted using the historical data collected from various DOD sites in different U.S. states, including Texas, North Carolina, Colorado, Oklahoma, and New York. Detailed and realistic utility costs, including peak and off-peak energy charge and demand charge, as well as gas cost for each site, were used. Based on these data, a suitable microgrid architecture was selected for each site, specifying the type and size of the equipment. These architectures are shown in Table 6. The architectures were selected based on the cost analysis (i.e., they provided optimal net savings when comparing their installed and maintenance cost to their contribution in reducing annual operating cost).

For a given architecture, several power utilization strategies were compared, through simulation, to understand the value of the microgrid. The strategies considered in this study were:

- Strategy 1: Grid only.
- Strategy 2: Grid with renewable sources.
- Strategy 3: Grid with a microgrid that include both renewable and non-renewable sources; hourly power utilization is determined using a rule-based approach.
- Strategy 4: Grid with a microgrid that include both renewable and non-renewable sources; hourly power utilization is determined using an optimization-based approach that minimizes operation cost.

The benefits of the microgrid were determined through the comparison between Strategy 1 and Strategy 4. Furthermore, the value of optimization-based control strategy will be determined by the comparison between Strategy 3 and Strategy 4. The results are summarized in Table 7.

**Table 6. Microgrid architecture for selected sites.**

| | NC | CO | OK | NY | TX |
|---|---|---|---|---|---|
| **Grid** | Yes, unlimited | Yes, unlimited | Yes, unlimited | Yes, unlimited | Yes, unlimited |
| **Solar PV (kW)** | 35 MW | 0 | 0 | 0 | 20 MW |
| **Wind turbines (kW)** | 65 MW | 70 MW | 65 MW | 55 MW | 50 MW |
| **Combined heat and power (CHP) (microturbines+ absChiller)** | 5 MW microturbines | 17.5 MW microturbines | 35 MW microturbines | 27.5 MW microturbines | 12.5 MW microturbines |
| **Diesel generators** | 4 MW | 2 MW | 8 MW | 12 MW | 2 MW |
| **Batteries, Li-ion (kWh capacity)** | 1 MWh | 1 MWh | 1 MWh | 1 MWh | 1 MWh |

MW – megawatt
MWh – megawatt hour

**Table 7. Annual cost savings of microgrid.**

| | NC | CO | OK | NY | TX |
|---|---|---|---|---|---|
| **Scenario 2 (Grid & Renewable)** | 17% | 13% | 19% | 16% | 21% |
| **Scenario 3 (Grid & Microgrid, Rule-based)** | 41% | 49% | 58% | 51% | 54% |
| **Scenario 4 (Grid & Microgrid, Optimization-based)** | 60% | 56% | 64% | 61% | 61% |

# 7.0 COST ASSESSMENT

## 7.1 COST MODEL

The optimal microgrid architecture varies, depending on many factors, including: requirements, location, available budget, stages of operation, mode of operation, building targets, energy usage and environmental conditions, etc. The cost and savings will then depend on the selected microgrid architecture and the utility rates. A summary of the estimated cost of energy microgrids for each major component and on how to interpret the cost and the available sources of information is presented in Table 8. The total cost of a microgrid, as previously mentioned, is very dependent on (i) the topology selected for microgrids, and (ii) the economies of scale for its different components. In general, the initial cost of a microgrid is represented by the summation of the first four rows in Table 8 (Installed cost of equipment+ Software cost + Site preparation + Electrical and Civil work). While the software cost may be negligible, the installed cost of equipment may vary widely from $400/kW (installed price of CHP with subsidies) to $8000/kW (e.g., install price of solar PV without subsidies). The cost of the electrical and civil work also varies widely depending on each site and the type of work required. The annual operation and maintenance (O&M) cost, is calculated based on the maintenance cost of equipment, the replacement cost of the multiple pieces of equipment within the microgrid system, and the utility costs.

The reader of this report must consider that the cost of future microgrids is not a direct extrapolation of the cost of the ESTCP project because: 1) the ESTCP project was a research project, where the highest quality elements were purchased for the converters, auxiliaries and protection switches, transformers and switches; 2) the system was overdesigned, to ensure all protection and safeties required for the experimental test cases that stretched the limits of performance; 3) given the constructed microgrid was small in scale and was one-of-a-kind rather than a product, there was no purchasing deal with manufacturers or technology providers with negotiated discounts; 4) there were not subsidies, and, as a result, economies of scale apply; and 5) it is expected that the cost of all the equipment considered will decrease as the economies of scale and continuous learning processes are reached.

**Table 8. Cost model for energy microgrids.**

| Cost Element | Data Tracked During the Demonstration | Estimated cost |
|---|---|---|
| **Equipment installed costs** | Estimates are based on best information available in open literature for current and projected cost of energy sources and storage components. | ***Energy Conversion devices***, $300/kW<br>***Sample installed cost energy sources***<br>Solar PV, average $8000/kW<br>Wind Turbines, average $2000/kW.<br>CHP equipment $800-1200/kW<br>Diesel generators $400-800/kW<br>***Sample energy storage***<br>Projected ~$1000-1500 /kWh (actually paid $3600/kWh).<br>***Power switch and auxiliaries*** ~$5000 (for 100kW and above) |

### Table 8. Cost model for energy microgrids (continued).

| Cost Element | Data Tracked During the Demonstration | Estimated cost |
|---|---|---|
| **Software costs (and computer)** | Cost of software estimates are based on prices that UTRC paid for all programming and optimization software that may be required in DOD installations to provide optimal microgrid energy management. | Computers and visualization monitors: ~$1000/computer; $300/ monitor |
| **Site preparation** | The demonstration did not incur site preparation cost beyond electrical wiring and battery vent piping. In other situations where a microgrid and all its components need to be installed, site preparation could be a considerable cost. For example, the site preparation required for wind turbines, which is usually included in their installed cost. | The siting, civil construction, and electrical wiring cost depends on the selection of type and size of equipment, the existing infrastructure for microgrid location, and the special distribution or location of the individual pieces of equipment and the critical loads or other loads to be supplied. |
| **Electrical wiring cost** | Electrical wiring cost is estimated based on the price UTRC paid for electrical wiring at McGuire AFB. These costs could be reduced for commercial large applications rather than scientific demonstrations. | Electrical wiring and electrical diagrams cost was ~$50K for this one-time migrogrid demo, with an installed microgrid a ~ 0.5 miles or wires.<br>However, this cost varies depending on the transmission and distribution (T&D) lines that need to be set-up in the base, and the selected microgrid architecture, and special distribution. For example, if transmission lines are required, their estimate cost is $1M/mile. |
| **Civil work cost (e.g., structures, piping, etc.)** | Civil work cost is estimated based on the price UTRC paid for it at McGuire AFB. This cost could be considerably reduced for commercial large applications rather than scientific demos. | In the demo case, this cost is combined with the electrical wiring, except for a battery vent cost.<br>As in the electrical wiring and siting costs cases, the siting and electrical wiring cost depends on the selection of type and size of equipment, the existing infrastructure for microgrid location and the special distribution or location of the individual pieces of equipment and the critical loads or other loads to be supplied. |
| **Maintenance cost** | The maintenance cost of each microgrid is estimated based on the maintenance schedule and cost of each equipment comprising the microgrid, including transmission and distribution lines and software.<br>Stochastic events (e.g., the cost of a stochastic power outage) are not considered. | Each of the components of a microgrid has a lifetime between 10-20 years.<br>Minimum maintenances cost of each piece of equipment can be included:<br>***Energy Conversion devices*** ~$ 0<br>***Sample O&M cost energy sources***<br>**Solar PV**, average $7/kW/year for chrystalline and $21/kW/year for thin film<br>**Wind Turbines**, average $421/kW/year [18]<br>**CHP equipment** $21/kW/every 4 years<br>**Diesel generators**, $100 /kW/year<br>***Sample energy storage***<br>~$1000-1500/kWh (actually paid $3600/kWh).<br>Potential future flow batteries $1000 /kWh<br>***Power switch and auxiliaries (1 or 2 per microgrid)***<br>NA |

**Table 8. Cost model for energy microgrids (continued).**

| Cost Element | Data Tracked During the Demonstration | Estimated cost |
|---|---|---|
| **Replacement cost (Lifetime related)** | The replacement cost of the system over a given period of time "N years," is estimated based on the lifetime of individual equipment and the number of replacements over the N years. | The initial cost if re-incurred at the replacement times, estimated as:<br><br>Power conversion ~ 10 years<br>Power switch: ~ 20 years<br>All energy source components ~ 20 -25 years. |
| **Operational (fuel) cost** | The fuel cost of the system is estimated based on the fuel usage for each equipment, when the usage is optimized. The fuel cost depends on the inflation rate and the location of the microgrid. | Microgrids could be purely "renewable" base energy systems.<br>If equipment, such as CHP or diesel generator, are added. |
| **Facilities managers training cost** | Estimate of training costs for facility personnel on usage of the equipment and operational adjustments to both energy microgrid equipment and EMS. | The system should be automatically operating. The operator should receive the training to be able to visualize and interpret results only. For example, the cost of one day of training would be about $1000/person in labor hours. Additional training materials are not required. |

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# 8.0 IMPLEMENTATION ISSUES

This section provides a description of challenges, lessons learned, and information to be considered in future developments and implementation of this technology, and also in other projects that specifically relate to demonstrations and installations on DOD bases. The topics for discussion include:

- New regulatory and standards
- Required access to Internet or external communication networks at DOD sites
- Approval process and access to information at DOD Sites
- Economics
- Technical

Each of these topics is discussed below in the following subsections.

## 8.1 REGULATIONS AND STANDARDS REQUIRED TO IMPLEMENT THE TECHNOLOGY

Regulations found in the National Electric Code (NEC) and Occupational Safety and Health Administration (OSHA) 70E can be applied to two key areas of the system: (1) application of PV solar systems, and (2) application of high voltage/energy batteries. Regulations from NEC and other international authorities, like IEC, are moving towards a unified code for dealing with PV installations, however, these codes are still evolving. Grounding requirements in the U.S. are not consistent with European standards. Residential versus commercial requirements also seem to be evolving. This presents an uncertainty for equipment providers which may inhibit growth and innovation.

Defining and implementing adequate safety provisions, including venting issues, for new batteries and microgrid installations requires new regulations and standards. Currently, this presents a challenge to system integrators seeking to provide safe, cost effective solutions.

## 8.2 REQUIRED ACCESS TO INTERNET OR EXTERNAL COMMUNICATION NETWORKS AT DOD SITES

Advanced energy systems, including energy microgrids, require communications between several sub-systems and with weather channels. Although the latter could be partially resolved with local weather stations, there are still prediction components that should be made to correlate with the weather channels. In DOD installations, it is not possible to achieve the level of communications required to take full advantage of advanced EMS (for microgrids and for building controls) given that a special approval process lasting over one year, which could exceed the period of performance of the ESTCP projects, is needed. This is a barrier that would need to be pre-approved for ESTCP projects, to fully demonstrate the project potential, requiring communications with the external world or with other systems.  The key lesson learned from this is that, for future projects, one should start the approval process at an earlier stage, at least one year before the communications needs to be implemented, and work with ESTCP and the person responsible at the installation site to obtain the required permits.

## 8.3 APPROVAL PROCESS AND ACCESS TO INFORMATION AT DOD SITES

Specific to this ESTCP project, the requirement to demonstrate in DOD installations proved somewhat challenging. First, the performance of DOD energy managers was related to high-impact energy savings on the entire base. In our experience, there was little natural incentive for the base to provide support to an ESTCP project of the nature presented in this report. More direct communication between ESTCP managers and energy managers may help resolve this issue.

## 8.4 ECONOMIC CHALLENGES AND LESSON LEARNED

Except for the high electric energy storage (EES) devices, all elements of the energy microgrids were available as off-the-shelf equipment. The difficulty in developing energy microgrids is in the integration of components and control technologies, not in the components themselves. Renewable-based energy microgrids with EES, however, are expensive. As a result, it is a challenge to demonstrate a good payback with the present installed prices of these technologies. Some other components, for example wind turbines, are becoming more competitive in certain areas of the country, with high electricity prices and high wind availability. EES can make renewable sources more competitive by dealing with intermittencies. EES is adequate for high energy/high power applications. At the grid level, however, they are not commercially available yet, and the industry is rapidly evolving towards providing technical and economically sound solutions. The lesson learned in this area is that if the equipment is not subsidized and/or already installed, energy storage capable of providing power to critical loads for long periods of time is economically infeasible. New energy storage solutions with long lifetimes and performance for large energy and power applications are needed.

## 8.5 TECHNICAL CHALLENGES AND LESSONS LEARNED

The communication channel between the battery controller, the BMS, and the microgrid system local controller, UCB is quite susceptible to the switching noise generated by the power converters (UPC). In this case, CAN communication system is used for the information exchange between the battery and the UCB. It was observed that, at a higher power level, the communication was getting disrupted due to the noised created by the power converter switches.

Another technical lesson learned was that the objective of seamless transitions from multiple operating modes was possible only when using real time data from the inverter terminals, and power flow data. When trying an alternative method, based on State machine, implementation proved cumbersome and difficult to apply. Batteries, in general, need standardization in terms of power electronics, communication protocols, and data available to the user. Today’s batteries require custom development in all of these areas that make the system more expensive and less reliable.

Another major lesson learned was that demonstration of the concept itself, a power electronics conversion system capable to work grid connected, grid independent, and transition seamlessly, was a challenging problem where the team had to develop a control algorithm capable of operating in multiple modes, without changing control structure or human intervention.

## 8.6 SUPERVISORY CONTROL

Communication with other modules required: (1) a way to either retrieve data from a local weather station or internet access for national weather forecast website, and (2) a way to retrieve data from building management system for load data. For demand management, this needs to be a two-way communication. In addition, communication with local controller needs careful design and additional testing.

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## 9.0 REFERENCES


1. Office of the Under Secretary of Defense For Acquisition, Technology, and Logistics, Report of the Defense Science Board Task Force on DoD Energy Strategy, *"More Fight – Less Fuel,"* Feb 2008.

2. Department of Defense Facilities and Vehicles. Energy Use, Strategies and Goals, August 6, 2008. http://www.govenergy.com/2007/pdfs/procurement/Hancock_Procurement_track_S3.pdf

3. DoD Base Structure Report. Fiscal year 2008 baseline (Summary of DoDs Real Property Inventory).

4. DoD Facilities and Vehicles Energy Use, Strategies and Goals – Program Overview, GovEnergy 2008, August 6, 2008.

5. Army Key Energy Initiatives. http://army-energy.hqda.pentagon.mil/renewable/renewable.asp

6. "The U.S. Department of Defense: Valuing Energy Security," Journal of Energy Security, June 2009. http://www.ensec.org/index.php?option=com_content&view=article&id=196:the-us-department-of-defense-valuing-energy-security&catid=96:content&Itemid=345

7. U.S. Patent US7116010B2/US20060208574A1, Control of distributed energy resources.

8. U.S. Patent US20070129110A1, Interface switch for distribute energy resources.

9. Patent 7116010 Issued on October 3, 2006, Control of small distributed energy resources.

10. Kameswaran, S., S. Krishnamurthy, S.M. Oggianu, L. Arnedo, and V. Blasko. *"Optimization Formulations for Supervisory Control and Coordination of Microgrids"*. To be published in OPTIMAL CONTROL APPLICATIONS AND METHODS Optim. Control Appl. Meth. 2010; 00:1–28 Published online in Wiley InterScience (www.interscience.wiley.com). DOI: 10.1002/oca.

11. Arnedo, L., S. Dwari, and V. Blasko. *"Hybrid Solar Inverter Based on a Standard Power Electronic Cell for Microgrids Applications"*, to be presented in Energy Conversion Congress and Exposition (CCE 2011), Nov. 17-22, 2011, Phoenix. Arizona.

12. Dwari, S., L. Arnedo, and S.M. Oggianu. *"High Performance Maximum Power Point Tracking Techniques for Photovoltaic Energy Conversion Systems,"* APEC - The Applied Power Electronics Conference and Exposition 2012.

13. Yiqing Lin "Economics Study on Microgrids and Optimization-based Energy Management System."

14. ENERGY STAR Portfolio Manager: Methodology for Greenhouse Gas Inventory and Tracking Calculations, http://www.energystar.gov.

15. Morgantown, W. Emission rates for new dg technologies. The Regulatory Assistance Project, May 2001. http://www.raponline.org/ProjDocs/DREmsRul/Collfile/DGEmissionsMay2001.pdf.

16. http://www.dieselserviceandsupply.com/Diesel_Fuel_Consumption.aspx.

17. Ryan, W. “Cogeneration for Confectioners,” The Manufacturing Confectioner, December 2004, Page 101-107.

18. Ryan Wiser, Lawrence, Mark Bolinger, 2009 Wind Technologies Market Report. “2008 Market Report,” http://www.nrel.gov/docs/fy10osti/48666.pdf NREL/TP-6A2-48853. September 2010.

19. Study of Economics and Performance of Solar Photovoltaic at the Former St. Marks Refinery in St. Marks, Florida. Lars Lisell and Gail Mosey. Technical Report NREL/TP-6A2-48853. September 2010. http://www.nrel.gov/docs/fy10osti/48853.pdf.

20. Energy Data. http://www.eia.doe.gov/state/.

21. Energy Price Indices and Discount Factors for Life-Cycle Cost Analysis – 2010, http://www1.eere.energy.gov/femp/pdfs/ashb10.pdf.

# APPENDIX A

# POINTS OF CONTACT

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|---|---|---|---|
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| Harry Carson | Electrical Engineer<br>PMH Associates Inc. | Phone: 856-273-0554<br>Fax: 856-273-7701<br>E-mail: hcarson@pmh-associates.com | Electrical engineer (provided stamped drawings) |
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