Community Energy Storage Utilizing Secondary Use EV/PHEV Batteries

M. Starke[*], P. Irminger[*], B. Ollis[*], G. Andrews[*], P. Karlson[**], S. Thambiappah[**], P. Valencia[**], C. Labaza[**], S. Massin[***], K. Parn[***].

[*]Oak Ridge National Laboratory, One Bethel Valley Rd, Oak Ridge TN 37831, starkemr@ornl.gov
[**]General Motors Company, 3000 Van Dyke Ave, Warren MI 48090, pablo.valencia@gm.com
[***]ABB, 655 Century Pt, Lake Mary FL 32746, karl.parn@ee.abb.com

ABSTRACT

An important aspect to wide-scale energy storage acceptance for the utility industry is verification of the performance and life of energy storage systems. In support of this objective, a testing platform has been developed at Oak Ridge National Laboratory (ORNL) to test energy storage units in real-world applications and analyze key performance metrics. Various hardware and software systems have been interlinked to represent actual grid conditions, while maintaining a high level of safety and robust operation. Currently, ORNL is performing grid application testing on a stationary energy storage system consisting of secondary-use electric vehicle batteries provided by General Motors.

Keywords: energy storage, secondary-use batteries, electric vehicle batteries

1 INTRODUCTION

The Department of Energy (DOE) Energy Storage Program has defined a number of key barriers to widespread deployment of energy storage systems [1]. These barriers include having a cost competitive energy storage system, validation of the safety of the system, having an equitable regulatory environment, and bringing industry acceptance to energy storage. Oak Ridge National Laboratory has been involved in various levels of research on energy storage for the DOE and has been specifically tasked to support the examination of secondary-use battery storage. Secondary-use battery storage is an energy storage system developed from used electric or hybrid-electric vehicle batteries which has then been repurposed for grid applications. The hope is that this technology could bring low cost energy storage to the grid. The initial focus of the investigation into secondary-use was on the potential value proposition and applications for used batteries [2]. During this study, ORNL developed a collaboration with ABB and General Motors to look at testing a secondary-use energy storage system composed of Chevy Volt batteries [3]. The initial design to be tested is a distributed energy storage system for community energy storage applications.

2 BACKGROUND

A community energy storage (CES) system is an energy storage system that is utilized between several residential homes and the transformer connecting the homes as shown in 0

The energy storage system acts as a buffer to the distribution feeder from potential impacts of renewable resources as well as newer, larger loads such as PHEV (plug-in electric vehicle) and EVs (electric vehicles) [4]. As shown, an intentional islanding switch is also present to allow the battery system to sustain the residential homes for a short period during a system outage. These energy storage systems have been generally slated to be in the size of 25kW with 50kWh of energy storage and can supply between 2 and 5 homes depending on the aggregated load of the combined homes [4].

The driving motivation in examining this particular application is that the distributed nature of these storage systems provides an opportunity to tackle multiple applications and maximize the economic value of the system. This economic value could come from end-users or from the electric service provider depending on the owner of the system. A unique control implementation will be related to each.

When examining single cost scenarios for energy storage systems, there are very few specific grid applications where the cost to benefit ratio appear to drive the necessary motivation for investment. In a study completed in 2011, single and synergistic benefits were examined for secondary use battery applications and a number of applications where energy storage will most likely fill a role were proposed [2]. Some of the value propositions include applications such as:

- *Electric energy time shift/ Time-of-use energy cost management:* On an aggregated scale, the units can store the needed energy at night created by generation and deliver this energy during peak periods of energy consumption at homes. At each system, single unit owners could tackle their consumption and real-time prices or demand charges.

- *Service reliability:* With several hours of back-up power and a disconnection/islanding switch, the CES is able to continue providing power to the homes in islanding mode during utility outage.
- *Firming and shifting renewables:* The CES is able to behave as a buffer between the utility and renewables by absorbing excess energy from the renewables, delivering energy during periods of shortage, and removing high frequency oscillations.
- *Ancillary Service applications:* The energy storage system can supply the local load on an aggregated scale with a ramping behavior that appears as ancillary services such as frequency regulation and spinning reserve.
- *T&D upgrade deferral:* Substation and other system equipment may not have to be upgraded even with the addition of PHEV and load increase due to the ability to supply energy during peak periods.
- *Voltage support:* Internal inverter that interconnects the low voltage AC to the DC bus for the batteries can be controlled to dynamically provide reactive power support and adjust power factor seen by the grid.

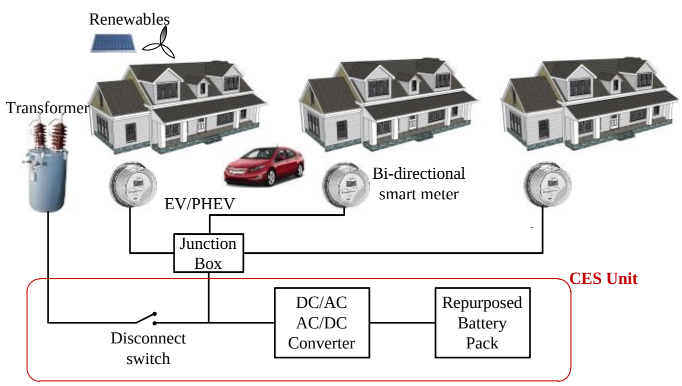


Figure 1. Community energy storage connected to three homes

ORNL, in support of DOE goals to validate and demonstrate the safety of this technology, has created a testing platform for community energy storage scale implementation. This platform has been designed to capture the interconnection requirements defined in IEEE 1547 [5], to provide a basis for an examination of various control case scenarios, and to provide ABB and GM an understanding of the impacts of these control functions on the battery system.

3 SYSTEM DESIGN

A schematic diagram of the secondary-use commmunity energy storage system is shown in Figure 2. The system has a single phase connection with the grid which is protected by an AC breaker (Zone 1). The inverter connects the grid with the battery system and controls the charging and discharging (Zone 2). The battery system connects with the inverter (Zone 3), is composed of five battery strings, and is controlled by a battery management system (BMS). The BMS measures the voltage, current and temperature from the battery systems and communicates with the inverter control to achieve a controlled charge and discharge. The system has a series of safety interlocks which prevent an unsafe access to the unit (Zone 4). The thermal management system is composed of fans and heaters in the inverter enclosure and a separate HVAC unit in the battery enclosure (Zone 5).

In addition to the filtering functionality included in the inverter, the active filter can also provide reactive power compensation. In contrast to traditional capacitor banks, the PQF's reactive compensation is continuous (stepless), fast and smooth since there are no transients at switching. Depending on the load type, the compensation can be either capacitive or inductive.

The inverter offers two types of compensation automatic and fixed. Automatic compensation requires a target power factor to set while fixed compensation is based on a pre-determined amount of kVar. The user is able to select and program which compensation is required, independently of the harmonic filtering. The only limitation is the active filter rating. In operating the inverter, the use reactive power of limits the current output capability of the filter.

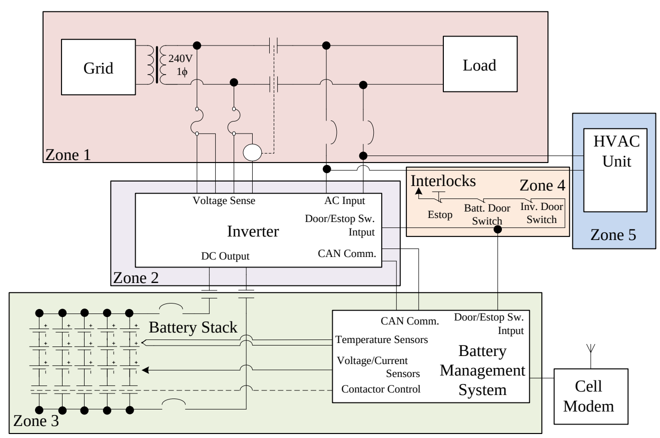


Figure 2: CES configuration.

The battery system consists of 5 repurposed Chevrolet Volt battery packs and a Battery Management System (BMS), which monitors and controls all of the battery system functions. The Volt battery pack in its vehicle configuration is shown in Figure 3 as pictured the cells are physically organized in three discrete 'sections' within the T-shaped pack. For the purposes more efficient packing in the CES unit, the battery sections were repackaged in the manner shown in Figure 4.

The Battery Management System (BMS) consists of a hierarchy of electronic controllers and sensors, which combined, monitor all critical battery parameters, control and enforce limits on battery operation and act as a single point interface to the inverter system. In addition, the BMS calculates key battery states (i.e. state of charge, charge/discharge power limits) and communicates these to the grid control system via the inverter.

Figure 3: Volt battery pack in vehicle configuration.

The CES system is interconnected in the ORNL distribution system and DECC (Distributed Energy, Communication, and Control) facility as shown in Figure 5. A 37.5kVA, 480V/240V split phase transformer supplies the community energy storage system with grid interconnection and a NHR programmable load bank is provided to test various discharge and charge profiles. An automatic disconnect switch has been put in series with the step-down transformer for the testing of islanding functionality. Manual disconnects have been put in place to isolate the energy storage system for safety. Photovoltaics are also integrated to demonstrate different renewable integration options with energy storage.

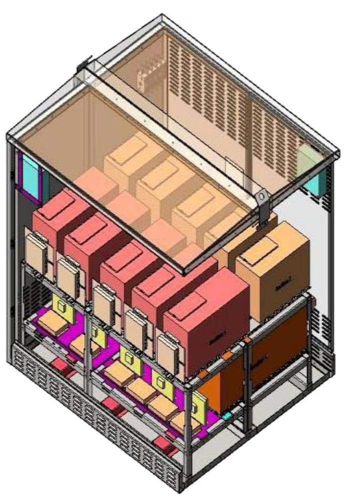


Figure 4: Integrated battery bank for energy storage system.

The system has a 37.5 kVA, 480 V/240 V split phase transformer which connects the CES system with the 480 V three phase system. There is a 36 kW three phase programmable load bank located on the same 240 V split phase circuit utilizing 2 of the legs of the load bank to test various load profiles. An automatic disconnect switch has been put in series with the step-down transformer for islanding tests while other manual disconnects have been put in place to isolate the energy storage system for safety. There have also been photovoltaics (PVs) integrated to demonstrate renewable integration options with energy storage.

The PV system consists of two arrays of panels from Hanwha which are installed on the roof of the DECC facility. One array is nearly flat, with a slight slant toward the north while a second PV array, not shown in Figure 2, is on a steep slant and faces south. The maximum rated power output of the combined arrays provided by the manufacturer of the PV array at 1,000 W/m^2 and 25°C is 13.4 kW. Each PV array system consists of an SMA inverter and two sensor modules that measure solar irradiance, ambient temperature, and module temperature. The SMA inverters are operated using maximum power point tracking control and are set to be 1547 compliant. The data collected by the sensors are used to support training of algorithms for PV output prediction [6].

The measurement system for the CES unit, load bank, grid, and PV panels consists of voltage transducers and current transducers that provide high-resolution data on the current and voltage waveforms. The system is configured as shown in Figure 3. These measurements are transmitted through BNC cables to a National Instruments CompactRio system and processed using its internal field-programmable gate array (FPGA) and LabVIEW Runtime software. The incoming analog data is processed by the software and used to calculate and store 30 different system parameters until the user requests the data. The transducers are connected on two separate phases (as the system is configured as split phase) for a total of four measurements per connection. This information is used to support calculation of the real and reactive power, as well as harmonics for the feedback controller. The CES unit also provides additional measured AC output, battery level DC currents, and DC voltages via the communication channel on the inverter.

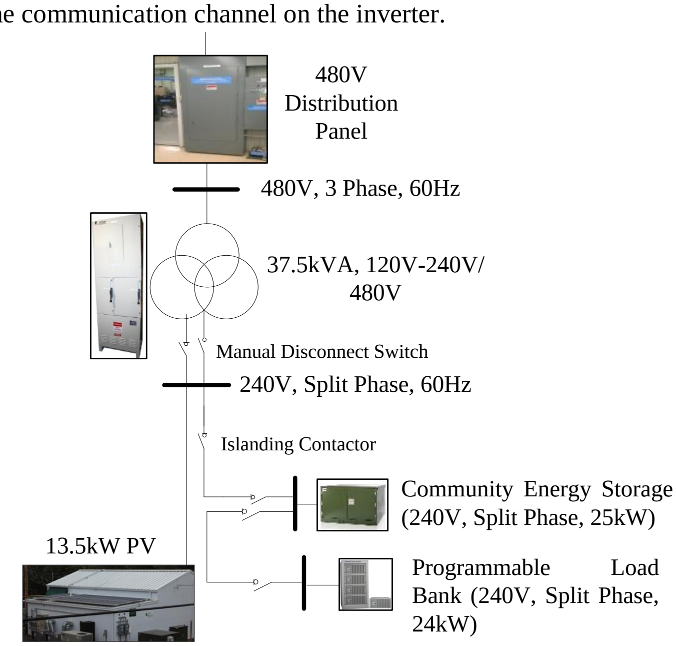


Figure 5: Grid interconnection

The CES unit and LabVIEW system are interfaced through MATLAB, which serves as the primary interface for operation and control of the unit. A MATLAB GUI developed by ORNL staff is the backbone of the grid connection and testing system. It is used to connect all of the controls, communications, data logging, and error handling. The GUI gives an operator the ability to control the inverter from inside the DECC facility, either by sending manual power commands to the unit or by activating one of the many automated control schemes.
The CompactRio is programmed with LabVIEW software for importing, formatting, and calculating the data to be sent to the main MATLAB GUI. Because the LabVIEW software resides on the CompactRio target, it is able to collect data at sampling rates independent of the speed of the computer. This provides both flexibility in data collection and increased computational speed as the main computer is free to perform control actions.

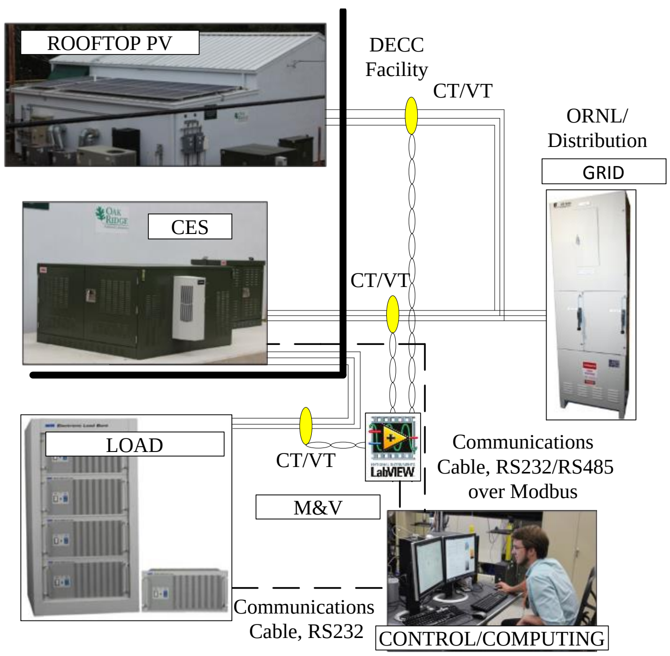


Figure 6: Communication and Hardware

Communication to the CompactRio is done through built-in MATLAB commands using User Datagram Protocol and an Ethernet cable. With the IP address of the CompactRio, MATLAB can ping the FPGA and receive all the data stored on the board. This type of communication happens quickly and allows for faster control using the transferred data.

The ABB inverter in the CES system uses standard Modbus protocols for communication and control. The inverter communications interface is connected to a computer inside the DECC facility through a serial to RS-485 adapter located on the inverter control board. By sending commands through this communication channel, the computer can access the registers within the inverter control board and allow a user to collect all available information and control various aspects of the inverter. The communication to the inverter is performed in MATLAB. Considering MATLAB has no built-in Modbus functionality, all of the data formatting and transmitting for Modbus had to be designed based off of existing Modbus standards.

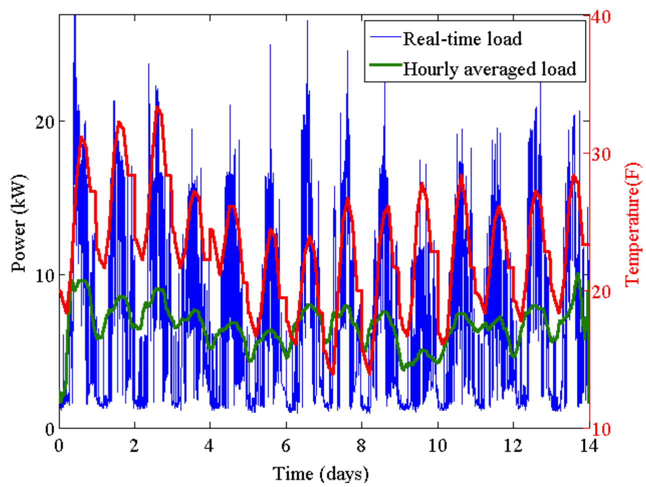
The load bank is controlled through another computer (different than the computer hosting MATLAB and interfacing the inverter and CompactRio). This is done primarily to reduce the number of applications running on the CES control computer and ensure fast operation of the controls and GUI. The two computers are connected through TCP/IP but only share access to critical files with each other for safety shutdown measures. Communication to the load bank is done through a serial cable and two software packages provided by NHR. One software package allows for manual operation of the load bank, while the other accepts comma separated values to build a load profile which runs in real time automatically. ORNL has modified the interface to automatically accept developed profiles in order to have the ability to continuously update the load profile.

Separate functions have been designed and embedded in MATLAB in order to control the community energy storage system and perform various grid applications. In order to ensure a realistic and dynamic load, the programmable load is controlled to mimic residential load consumption based on work performed in [7]-[8]. Based on the expectation of the community energy storage interconnection, only three homes are represented. An example profile of the load consumption utilized and the outside temperature for these three homes is shown in Figure 4. The overall load is highly oscillatory due to the inherent nature of loads at this level of observation. However, when an hourly average is applied to the data, the nature of the consumption is apparent.

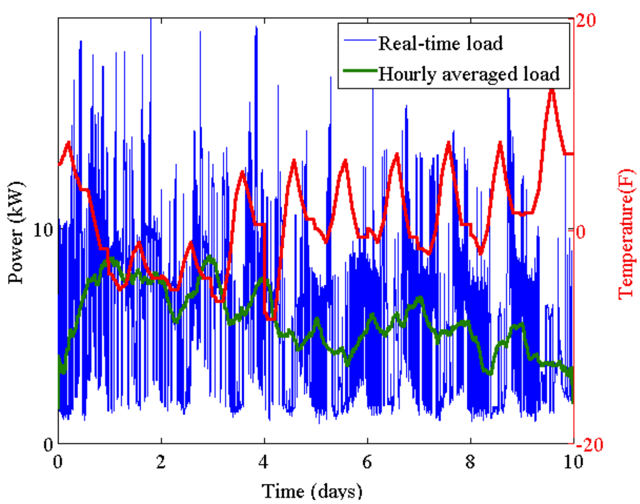
Forecasted weather and irradiance measurements for Oak Ridge are used to develop these residential profiles on a daily basis to ensure a direct relationship exists between the residential consumption, energy storage utilization, photovoltaic generation, and thermal management systems.

The full implementation of control for an end-user of a community energy storage system is shown in **Error! Reference source not found.** In the control, weather data and cloud patterns are collected and used to develop an irradiance estimate which is used to create a forecasted PV output and residential load profiles. Genetic algorithms (GAs) and other optimizers are used to determine how the system should be dispatched according to the application, and the main control uses the control discussed below to dispatch the system. A stochastic linear programming approach has been developed to assess the dispatch of the storage system according to the differing end-use residential rate structures [9]. This will help govern the most economical approach for storage utilization and provide a more concrete basis for the energy storage use.

This MATLAB control program also records data into a local historian using text files which are later processed using a separate program for data analysis. Another program, for emergency monitoring, has also been developed to monitor the different outputs from the energy storage system and to check on any related concerns of operations in the laboratory. If any flags are triggered, the energy storage system, load bank, and other accompanying equipment are shut down, and email and text messages are sent to team members. This provides the ability to safely operate the system for 24 hours a day, 7 days a week, without direct control and supervision by staff. Already several months of data have been collected and are being evaluated for reporting.



(a) Residential profile for summer



(b) Residential profile for winter

Figure 7: Temperature and aggregated load profile for residential emulation

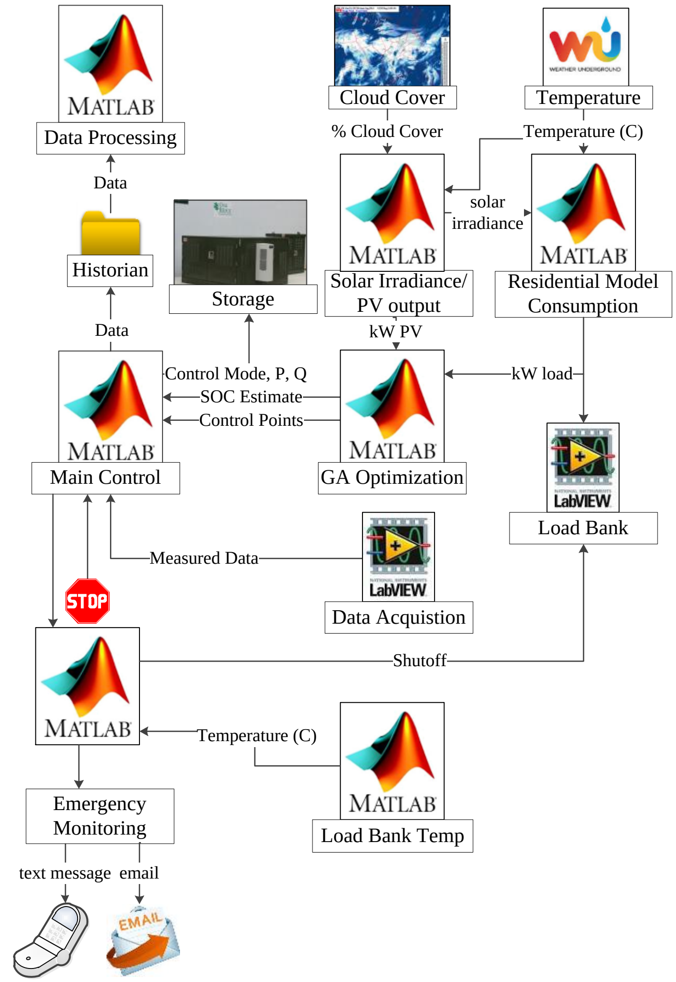


Figure 8: MATLAB and LabVIEW interface to energy storage system

4 TESTING AND RESULTS

The testing protocols discussed here consist of load flattening for T&D deferal, solar integration, and islanding. Other capabilities are also available and are being tested. The testing has been performed over a period of several months and is continuing.

Figure 8 shows an example test run demonstrating the ability of the storage system to provide T&D deferal. A three home residential load profile was created and programmed on the load bank. A genetic algorithm was utilized to optimize the flattening of the load through the use of the energy storage system. In this example, the residential peak is reduced by over 50%.

Figure 9 shows an example of solar integration. A PV forecast was created so that the energy storage system could enforce this forecast even as the solar output of the PV on the rooftop of the DECC facility produced intermittent output due to cloud cover. The intermittency is a

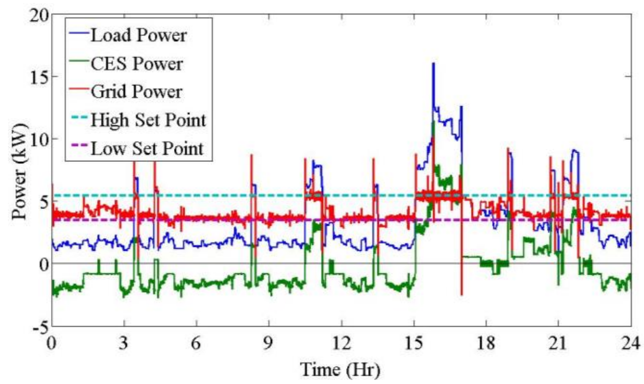


Figure 9: Load flattening example

distribution system challenge. Upstream transformers, as an example, may be forced to perform a significant number of increased tap changes to ensure system voltage is maintained. This could cause higher O&M costs while still not completely stabilizing the line voltage.

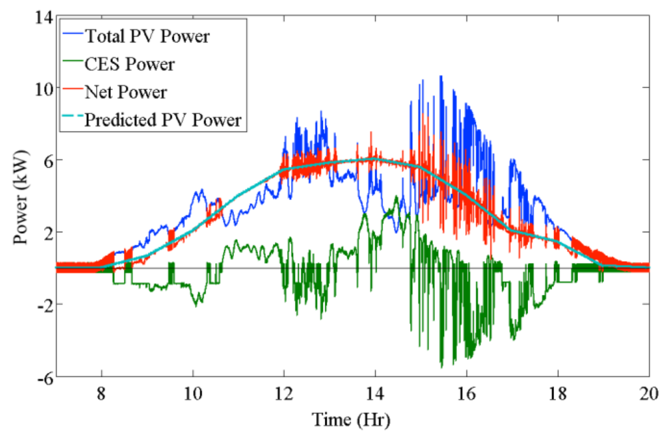


Figure 10: PV integration example

Figure 10 shows the use of the storage to go 'off-grid' and reconnect to the grid. A residential load profile is used to demonstrate that the CES is able to follow the needed load power.

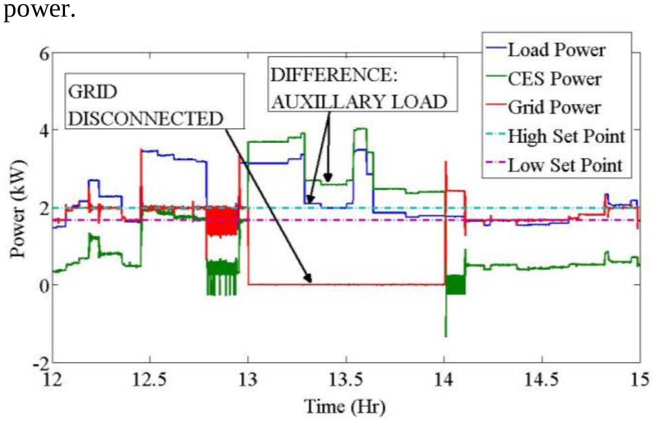


Figure 11: Energy storage entering and reconnecting to distribution from island mode

5 CONCLUSION

In this paper, the ability of secondary use storage systems to perform the same functions as a new battery system at a potentially lower cost has been demonstrated. The algorithms needed to perform different energy storage functions have been demonstrated with measured results shown.

Future work will focus on developing multi-objective functions that will lead increased value propositions for energy storage systems.

6 ACKNOWLEDGEMENTS

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