California Solar Initiative

RD&D: Research, Development, Demonstration and Deployment Program

GO solar CALIFORNIA

Final Project Report:

West Village Energy Initiative Target Area One: Improved PV Production Technologies

Grantee:

University of California, Davis Energy Institute

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Preface

The goal of the California Solar Initiative (CSI) Research, Development, Demonstration, and Deployment (RD&D) Program is to foster a sustainable and self-supporting customer-sited solar market. To achieve this, the California Legislature authorized the California Public Utilities Commission (CPUC) to allocate **$50 million** of the CSI budget to an RD&D program. Strategically, the RD&D program seeks to leverage cost-sharing funds from other state, federal and private research entities, and targets activities across these four stages:

- Grid integration, storage, and metering: 50-65%
- Production technologies: 10-25%
- Business development and deployment: 10-20%
- Integration of energy efficiency, demand response, and storage with photovoltaics (PV)

There are seven key principles that guide the CSI RD&D Program:

1. **Improve the economics of solar technologies** by reducing technology costs and increasing system performance;
2. **Focus on issues that directly benefit California**, and that may not be funded by others;
3. **Fill knowledge gaps** to enable successful, wide-scale deployment of solar distributed generation technologies;
4. **Overcome significant barriers** to technology adoption;
5. **Take advantage of California's wealth of data** from past, current, and future installations to fulfill the above;
6. **Provide bridge funding** to help promising solar technologies transition from a pre-commercial state to full commercial viability; and
7. **Support efforts to address the integration of distributed solar power into the grid** in order to maximize its value to California ratepayers.

For more information about the CSI RD&D Program, please visit the program web site at www.calsolarresearch.ca.gov.

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Abstract

Target Area One of the UC Davis CSI RD&D project focuses specifically on the development, design, installation and evaluation of emerging PV technologies, in particular energy storage and solar thermal hybrid technologies which serve as the focus of the project. Technology demonstrations installed at the UC Davis West Village and Aggie Village developments include applications for multifamily, single family and commercial buildings. Results from system level analyses and testing of the demonstration prototypes in real applications yield insights into the overall technical and economic feasibility for wider scale deployment. This report includes details regarding design and implementation of the integrated energy systems. Monitoring of the installed systems continues in an effort to add longer term performance data for more comprehensive assessments of potentials for broader scale commercialization.

Key Words: sustainability, renewable energy, photovoltaic power generation, California Solar Initiative, Itron, UC Davis, West Village, West Village Energy Initiative, Zero-Net-Energy, solar thermal, hybrid solar, PVT, energy storage, second-life batteries, electric vehicle charging, smart home, demand response, peak-shaving, peak-shifting.

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Executive Summary

West Village is an on-campus neighborhood designed for student, faculty and staff at the University of California, Davis (UC Davis). The UC Davis West Village Energy Initiative includes the goal of making this the largest community in the United States to plan for achieving zero-net-energy from the electrical grid on an annual basis. The zero-net energy design is planned to be achieved through deep energy efficiency measures and traditional grid tied PV systems. This unique community also provides an outstanding opportunity for sustainable energy development because the community is a Living Laboratory for UC Davis faculty, staff and students. In this sprit, UC Davis was awarded a California Solar Initiative Research, Development & Deployment grant to develop, design, install and evaluate advanced PV technologies as part of the West Village Energy Initiative. The project research was conducted within three primary tasks, two to demonstrate integrated solar power and hybrid solar thermal systems including energy storage and another to evaluate advanced metering infrastructure for West Village. Each of the demonstration tasks was in turn comprised of two related demonstration projects. These tasks and the demonstration projects are highlighted below with full details included in the appendix.

Task 1 Demo 1 – Battery Buffered Electric Vehicle Charging Station

This energy storage demonstration focused on a commercial, workplace electric vehicle charging application. The system stores energy from local PV generation and uses the stored energy to charge electric vehicles. This demonstration attempts to optimize electric vehicle charging from the PV resource. Charging a vehicle by simply plugging into a charging station that is connected to a grid tied PV system does not necessarily use PV generation to charge the vehicle. In this context the electric vehicle may in fact be using grid energy from other sources. There are many factors that influence this including charging load, PV array and inverter size, time of day, time of year and weather. Introducing battery energy storage into the system allows an electric vehicle to nearly always be charged with PV energy. It also provides for peak load reduction (peak shaving) by reducing electrical demand on the grid and buffers, as well as stores PV generation, which is often variable. If, due to weather or other causes the PV array is unable to fully charge the battery energy storage system, the system can be charged with off peak energy from the grid, which provides for peak shifting that is also valuable in utility resource management. These applications should provide significant efficiency and cost benefits to the grid and the user while optimizing the PV energy from a large but variable renewable resource.

Workplace charging continues to be adopted by employers across California. Workplace charging installations greatly benefit electric vehicle drivers and help increase electric vehicle market growth. However, workplace electric vehicle charging loads are on-peak loads for a large part of the charging interval. As the electric vehicle market grows, California's grid will be increasingly impacted by on-peak, workplace charging. Sizing a PV system to meet daytime electric vehicle charging loads is uneconomical and has the potential to cause increased problems for grid management due to increasing peak demands on transmission and distribution infrastructure and over generation on weekend days. As California seeks to increase renewable resources and increase electric vehicle adoption, energy storage systems, such as the system installed at West Village offer advantages in overall energy system operation. The demonstration at West Village is designed to improve understanding of system performance and develop best practices for stakeholders and industry.

Results

The PV array (34 m2) for the West Village project is mounted vertically on the tower attached to the building at 1605 Tilia Street. The resultant PV energy is 7-14 kWh/day of electric energy in the summer and 14-28 kWh/day in the winter season. The PV energy should be sufficient to charge EVs that have traveled 75 and 40 miles per day in the winter and summer, respectively.

Unfortunately, due to many permitting and equipment commissioning delays, which are discussed within the body of this report, the system was only operational for part of August, before the system went down again due to inverter commissioning problems.

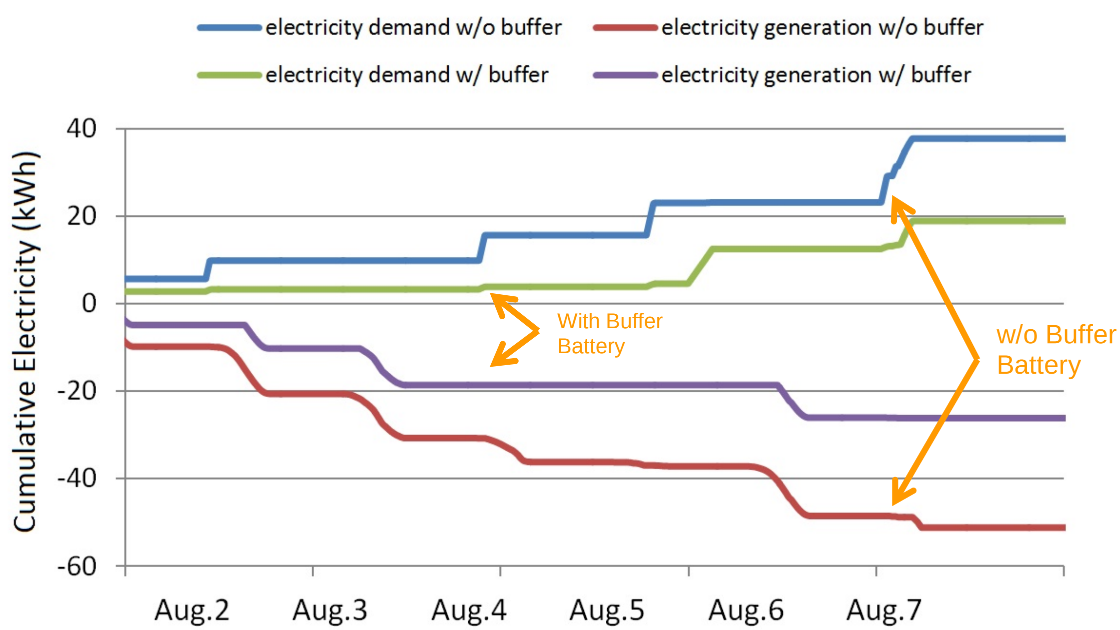


Figure 1: System Data Collected First Week of Operation

Figure 1 shows the systems effectiveness to buffer the grid from both PEV charging loads and PV generation. Due to the PV arrays vertical orientation PV production during August was not at its peak. Regardless, the graph shows the benefits to the grid for the battery system, given a modest amount of PEV charging loads and less than ideal PV generation.

Key Findings

- Permitting remains a challenge for battery storage systems, regardless of the technologies and stability.
- While many battery technologies and balance of system components exist, packaged, turnkey solutions do not. Piecing together components from many different vendors provides many challenges that our best addressed in the design stage.
- There are many strategies for battery management, control and dispatch. Currently there are not standards for distributed energy storage. Optimization of distributed energy storage should be developed by utilities and other stakeholders.

Task 1 Demo 2 – Single Family Home Energy Storage

Another energy storage demonstration evaluates the use of second-life batteries for application in single family homes. This demonstration has been deployed at an existing residential home at Aggie Village, a faculty and staff housing community located on the UC Davis campus adjacent to the downtown area of the City of Davis, CA. The batteries were retired from electric vehicles according the vehicle manufacturer's specifications. The goals of this demonstration were to optimize the grid-tied PV system in a residential context with on-site energy storage. In a residential system, the majority of PV energy is produced when the occupants are not at home and energy demands are low. PV systems do not generate through the home's evening peak period, instead beginning to supply power during the morning "partial peak" period with peak productivity around solar noon depending on PV array orientation and weather. This demonstration provides the opportunity to evaluate the grid benefits of storing PV energy so as to shift loads off peak and to better align with remaining on-peak energy use.

System Performance

Over the course of the first four months of PV array operation 967kWh energy was produced. Equivalent CO2 saving equals to 1639 lbs. The battery system starts to function from late November 2013, and over the one month it performed PV energy shifting of 63 kWh, equivalent to US$18.9 saving. It prolonged the battery second life by 11 cycles. Over all the system has saved US$145.5 over the first four months in winter time operation.

PV System (09/2013 to 12/2013)	Operation Hours (system on)	1483 Hours
	Energy Harvested	967 kWh
	CO2 Saved	1639 lbs.
Battery Pack (11/2013 to 12/2013)	Peak Usage Shifted	63 kWh
	Peak Usage Bill Saved (@0.3$/kWh)	18.9 $
	Extended Battery Life	11 Cycles
Grid Interaction (09/2013 to 12/2013)	Electricity Bill Saved (@0.15$/kWh)	145.5 $

Table 1. System operation statistics.

The system provides a renewable energy source when solar energy is available in the daytime and covers part of the load in the night using the reserved energy in the battery. Figure 2 illustrates the system functionality using usage data on November 29th, 2013. As shown in, from midnight to 10am both the PV array and battery pack were in silent mode. The house energy usage was fully supported by the grid. From 10am to 5pm, the house energy demand was fully supported by the PV array output and the excess energy of the PV was used to charge the battery. From 5 pm to 8 pm, the house energy usage peak arrived, overlapping with the utility peak pricing hour. The battery discharges to support the load demand with an efficiency of approximately 85%. When the peak pricing finished after 8pm, the battery stopped discharging. As shown in the energy consumption pie chart in the Figure 2, the house energy demand in that day consisted of 30% peak pricing usage (3.2kWh), 20% partial peak usage (2.4kWh), and 50% off peak usage (5.7kWh). Indicated by the energy source pie chart, 63% of the house energy usage was covered by the PV array production (6.8kWh). With the battery pack enabled peak shifting, the peak usage during the nighttime is covered by the stored PV energy (3kWh) in the battery.

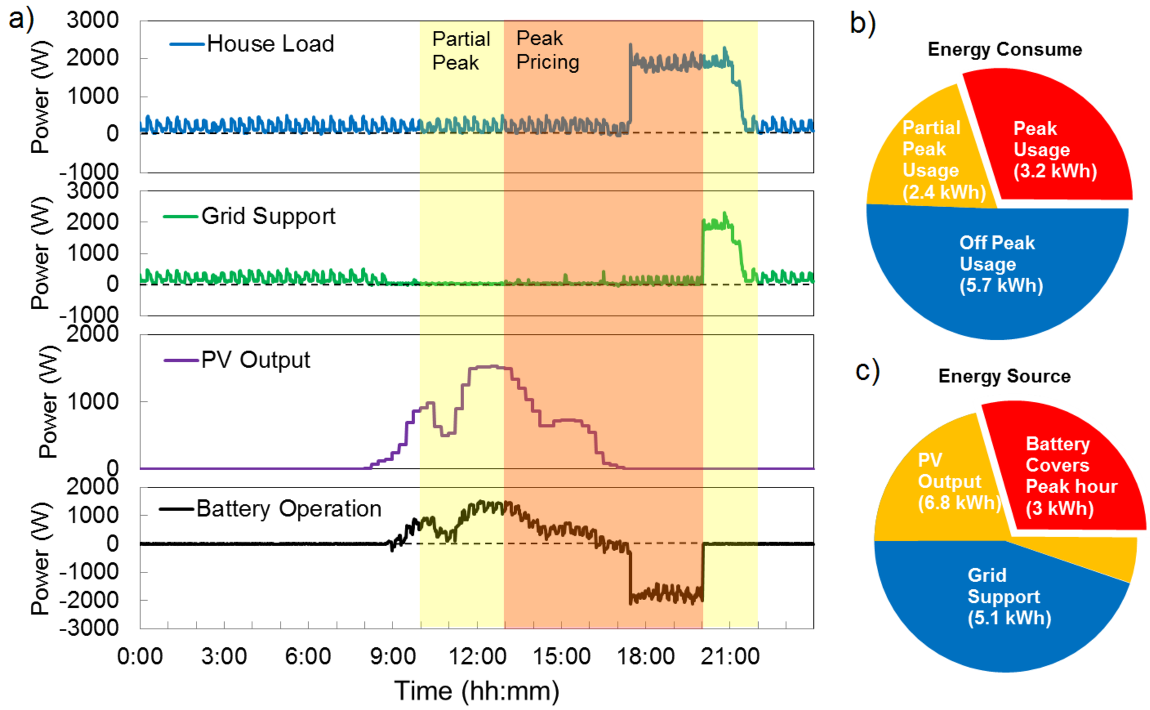


Figure 2 Sample of system operation on 11/29/2013. a) Plots of power draw and supply over an entire day. b) Pie chart of energy consumption broken down based on price of usage. c) Energy supplied as a function of the source.

On a different day of operation (November 29th, 2013), a slightly different energy management algorithm was utilized. At peak hours, instead of charging the battery, the PV output was fed back to the grid. As shown in Figure 3, from midnight to 10am, both the PV array and battery pack were in silent mode. The house energy usage was fully supported by the grid. From 10am to 5pm, the house energy demand was supported by both the PV and grid. When the PV output was higher than the house demand, excessive energy of the PV was used to charge the battery. From 5pm to 8pm, the house energy usage peak arrived, the battery discharged to support the load demand with an efficiency near 85%. At the same time, the PV supported the energy demand with the remaining sunlight. Any excessive production was sent back to the grid. When the peak pricing finished at 8pm, the battery stopped discharging. As shown in the energy consumption pie chart in Figure 3, the house energy demand in that day consisted of 17% peak pricing usage (3.2kWh), 47% partial peak usage (8.4kWh), and 35% off peak usage (6.4kWh). Indicated by the energy source pie chart, 63% the house energy usage was covered by the PV array production (7.2kWh). With the battery pack enabled peak shifting, the peak usage during nighttime was covered by the PV energy or battery stored PV energy (0.9kWh form direct PV energy, 0.9kWh from battery discharge energy). Using this energy management strategy, the PV energy was sent back to the grid to obtain more optimal economics. Meanwhile the battery usage was less. The energy system operated by this strategy can have a smaller size battery pack, but will have a larger grid dependency.

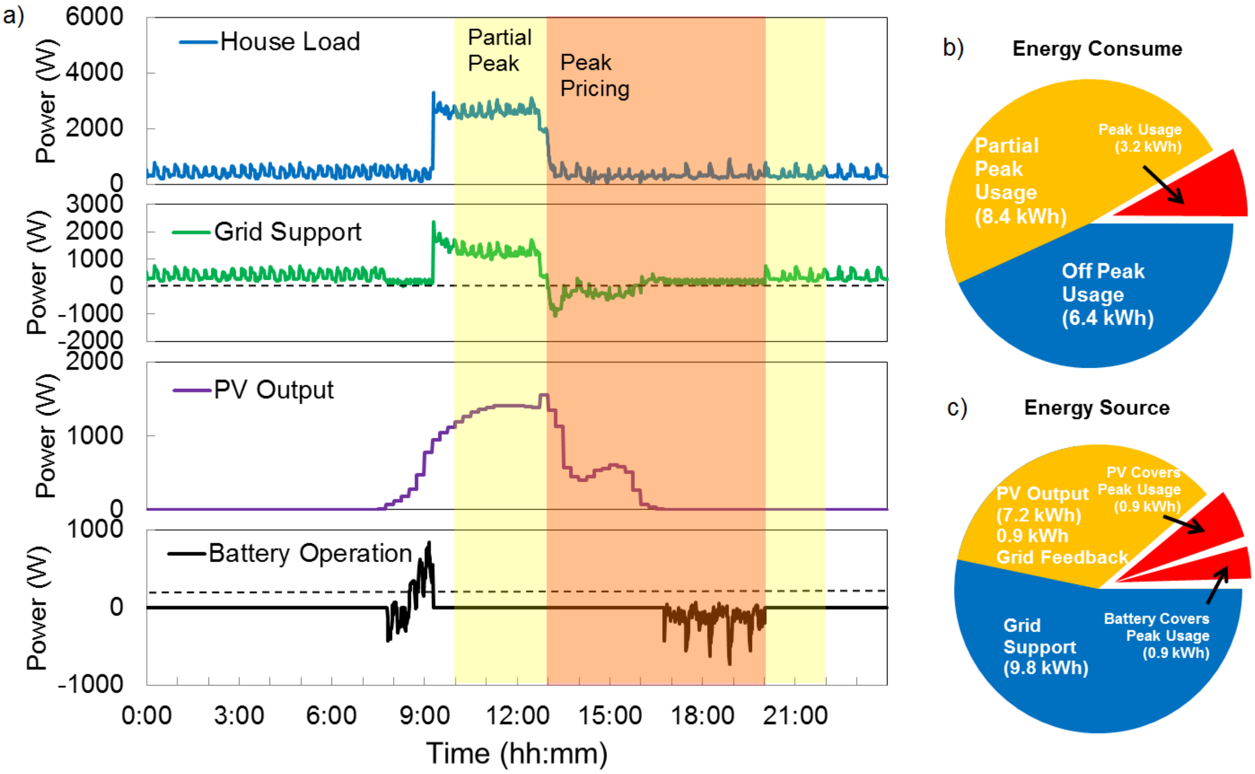


Figure 3 Sample of system operation on 12/10/2013. a) Plots of power draw and supply over an entire day. b) Pie chart of energy consumption broken down based on price of usage. c) Energy supplied as a function of the source.

The PV energy harvested significantly increased because the sun exposure also increased when approaching summer. For example, in Jan, the maximum daily energy harvested is about 7kWhr, but in May, the average daily energy harvested is about 5 kWhr. Shown in Figure 4b, PV energy harvested is higher in April through August, since it is always sunny during this time; and the PV energy harvested fluctuation in January to March is due to cloudy or rainy weather.

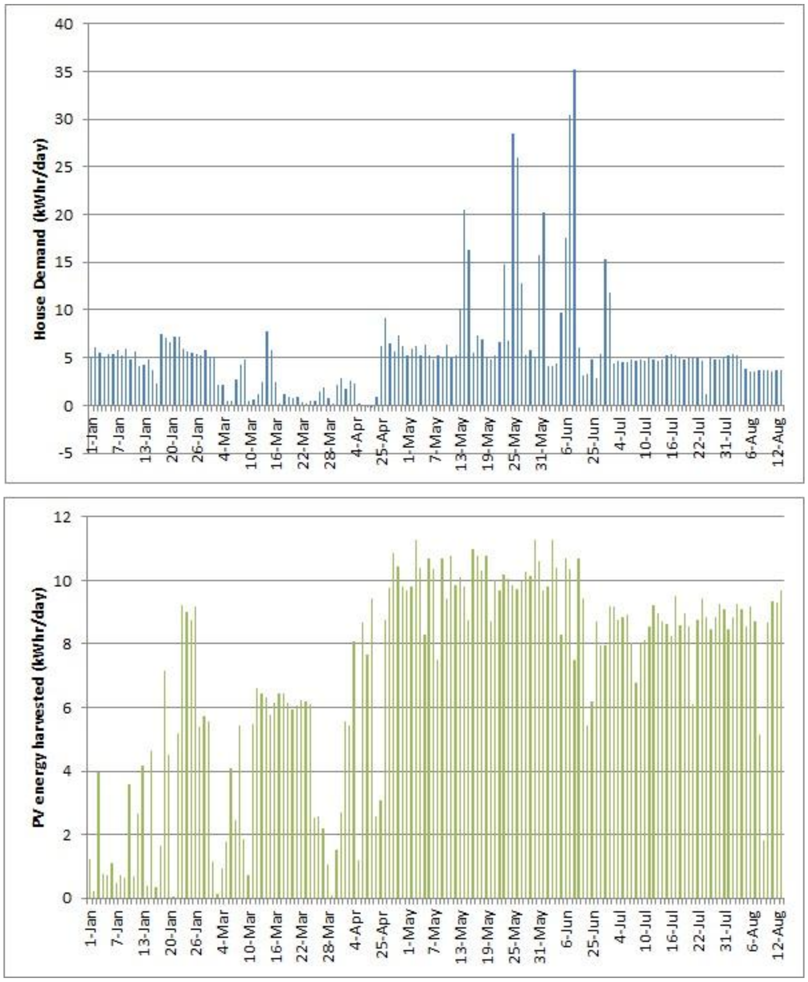


Figure 4 House demand data; b PV energy harvested, over 8 months.

Furthermore, the net energy, subtracting house demand from PV energy harvested, is calculated and shown in Figure 5. Positive value means PV energy harvested can fully support the house demand with energy surplus; negative value means house demanded power is greater than PV energy harvested hence grid power is used. Over this eight-month interval, 69.4% of the time power that PV energy harvested can fully support house demanded power.

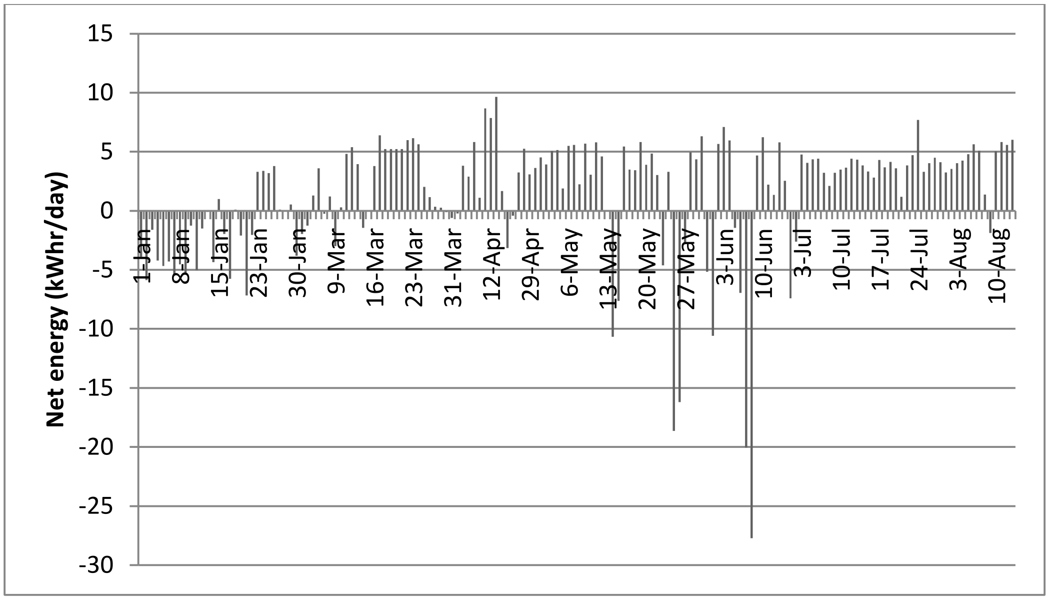


Figure 5 Net energy. Positive value means PV energy harvested is great than house demand, negative value is vice versa.

On June 8th, the net energy is -27.73 kWh, which is far greater than other days with negative energy. Therefore, the house demand data is separated into components to compare with a nominal operation day, shown in Table 2.

Power Demanded (kWhr)	**8-Jun**	**5-Jul**
A/C	23.92	0.00
Dining Room	0.84	1.47
Furnace	0.05	0.00
Garage	2.84	2.31
Garage misc.	4.38	0.12
Living Room	3.65	1.09
Master Bed	0.39	0.11
Microwave	0.15	0.07
Disposal	0.00	0.00
unknown	-0.82	-0.52
Washer	-0.19	-0.18

Table 2: Normal vs. non-normal demand data from Aggie Smart Home

Key Findings

- 2nd life battery storage was extremely affective in providing significant load shifting applications in a residential applications. From a Time-of-Use perspective this didn't necessarily optimize the value of the PV system, however it provided load shifting benefits to the utility and grid. If marketed development of residential distributed energy storage systems in California is desired, then appropriates rates and compensation mechanisms must be developed by utilities, regulators and stakeholders.

- Rather than disassembling each batter pack and testing individual cells for health, the battery and automotive industries should work to make sure battery pack's prior battery pack operational data is available to those repurposing. If a pack's health can be determined from the prior applications battery management system, this could greatly reduce the refurbishing costs significantly because many time consuming tests and disassembly would not be necessary.
- If possible, OEM's should make complete battery packs from the first life application available. Thus disassembly may not be required, depending on the packs health. Also the 2^{nd} life pack could use existing infrastructure such as cell balancing and battery management system, would offer significant cost and performance benefits.
- Power electrics should be integrated into the final product of the battery pack, rather than individual add-ons. This would streamline installation and could potentially increase roundtrip efficiencies through the use of DC-to-DC converters for battery charging directly from PV resource.

Task 2 – Integration of AMI with Solar PV and other DER Technologies

The integration of advanced metering and control technologies (AMI) with distributed energy resources (DER) offers opportunities to improve overall system performance and efficiency. For this task, GE Energy Consulting was subcontracted to develop baseline energy supply and demand estimates for West Village and to assess what means might be employed to improve user interactions toward achieving a ZNE objective. A baseline energy model was developed along with a synthetic year estimate of PV energy supply and energy demand from the different residential components of the West Village development. As full year of data from West Village operations were not yet available at time the model was developed, and an annual simulation was necessary based on actual generation and use data to that point in time.

Model results suggested that the overall electricity consumption to production (C/P; demand to DER supply) ratio for West Village with only the multi-tenant residences in place was approximately 1.25 and had not yet achieved breakeven for ZNE. Model findings were generally consistent with actual annual results when later obtained. Additional generation from an anaerobic digestion system currently in startup will complement the PV generation to boost production and help reduce the C/P, but various demand side measures could also be deployed to reduce consumption and similarly lower the C/P. Included among the latter are implementation of a master energy management system for the Village to automate real time tracking of energy performance and to communicate to residents and electronically addressable devices such as programmable communicating thermostats (PCT) the current energy status for appropriate actions to reduce demand. Three primary energy management systems were evaluated including consumption information delivery (CID), time of use (TOU) with PCT, and critical peak pricing (CCP) with PCT. All had financial paybacks of less than three years. Innovative means to modify behaviors of residents were also suggested along with centralized control of thermostats with local override capability.

Task 3 Demo – 1: Multifamily PVT Integration

This demonstration evaluated existing innovative hybrid photovoltaic/thermal (PVT) technologies and designs for solar hot water production in multifamily applications. These novel solar hybrid solutions were designed, built, and operated in a typical multifamily in a 12 unit apartment building consisting of two, three and four bedroom apartments at UC Davis West Village zero net energy community. The systems performance is monitored and compared to model simulations projecting the optimal allocation and configuration of PV, Solar thermal (ST), combined PV + solar thermal (PV + ST) or hybrid PVT systems. Overall, the results of this multifamily hybrid solar demonstration intend to provide practical insight for future development of solar hybrid systems as well as a broader body of knowledge concerning hybrid solar thermal applications for zero net energy buildings.

The PVT system installed at West Village started generating hot water at the end of 2013. The system was designed to provide hot water for two, four bedroom apartment units and electricity for one apartment unit. Thus, due to the budget constraints that influencing the design, the system was never intended to accommodate the whole buildings electrical or hot water needs. Between January 1st and end of July 2014, our PVT multifamily demo has generated 4,817 kWh energy on thermal side of the system. While the total heat energy, which includes energy produced by PVT panels, electric resistance water heater and air-to-water heat pump, is 12,780 kWh.

Figure 6 and Figure 7 shows the heat generation from PVT, air-to-water heat pump, and electric resistance water heater as well as the corresponding ratio. As we can see, in the summer season, June and July, the system generates significant less total heat than other months due to less hot water usage. This is a result of student apartment occupy rates over the summer. Except for the summer season, the ratio of heat generated by the PVT system is relatively consistent. As expected, the PVT system produces at least 20% more heat during spring and summer. The PVT heat increases from about average 670 kWh in winter to average 860 kWh in late spring. More importantly, looking at the heat generation ratio in **Error! Reference source not found.**where a rend emerges. As expected, the PVT heat generation ratio increases steadily approaching the summer months. Approximate 55% of total heat was produced by PVT system in the summer while the percentage is around 30% in the winter months.

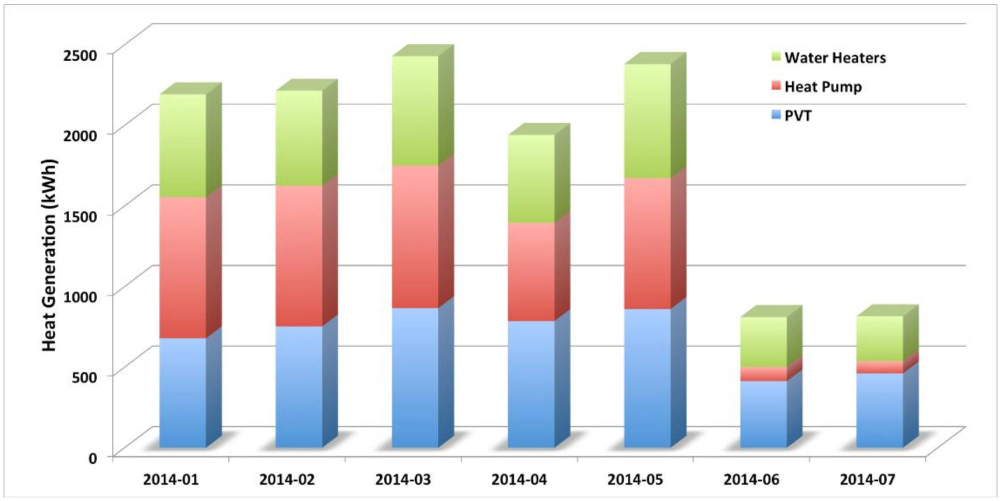


Figure 6: Heat generations from PVT, heat pump, and water heater, respectively

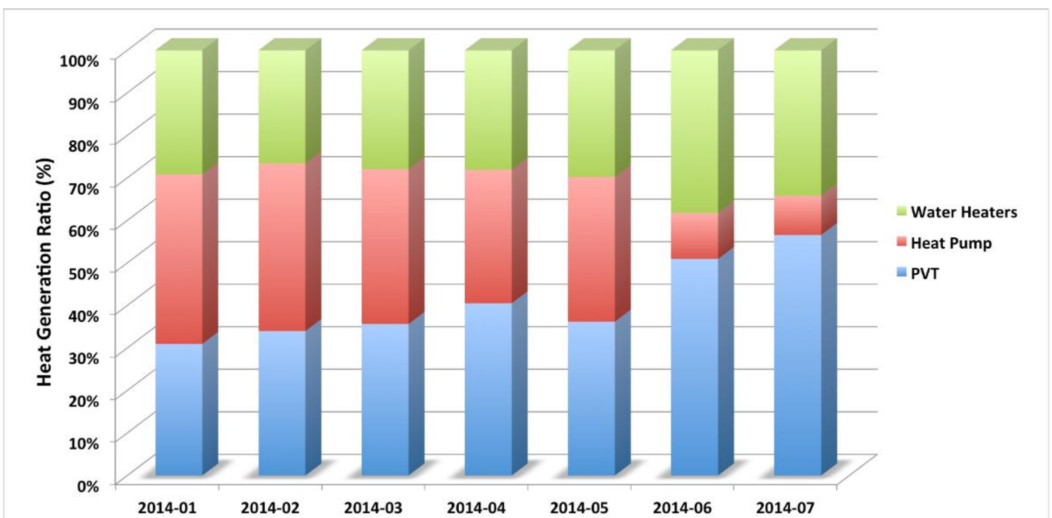


Figure 7: Heat generation ratio from PVT, heat pump, and water heater, respectively

Using total useful heat delivery to the apartment and PVT heat generation, PVT performance can be evaluated through calculating this Effective Energy Factor. Effective Energy Factors are summarized in Figure 8. All the factors are very close to one in winter, while exhibiting much higher effective energy factor when the tenants use less amount of heat during summer time. Based on the definition, when the Effective Energy Factor is close or larger than one, it means technically PVT system is sufficient enough to provide enough heat for one of the multifamily apartment for that month. Although the PVT system contributes to a central hot water system which serves all twelve units in the apartment building, it modeled and sized to produce enough hot water for two apartments on an annual basis.

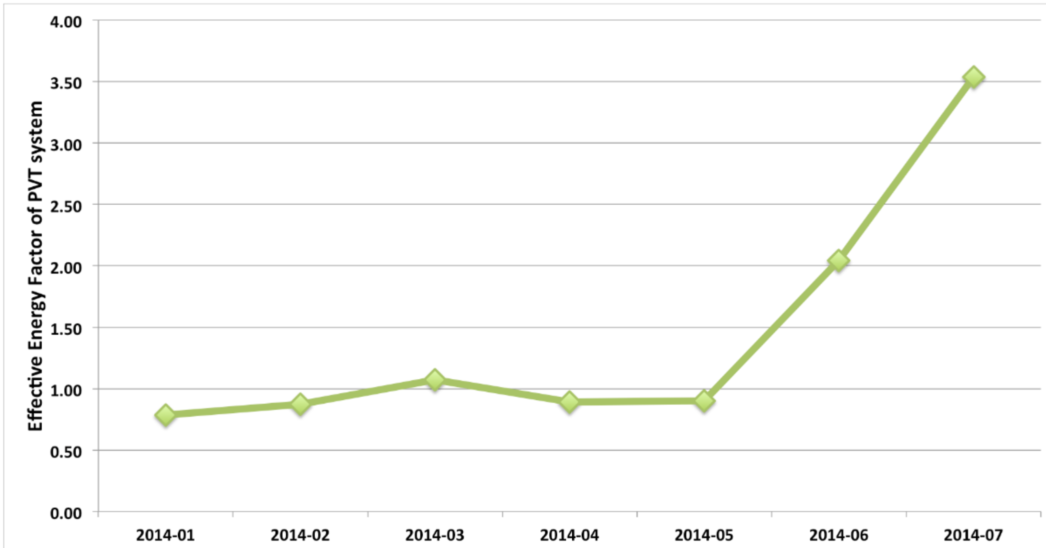


Figure 8: Effective energy factor of PVT system each month

Key Findings

- Current findings have shown a delicate relationship between thermal storage capacity, pumping volume and PVT array size. To obtain the full benefits of PVT (which include increase PV production due to cooling) thermal storage capacity and adequate pumping volume must be carefully evaluated. Currently the circulatory flow for optimal production of hot water and PV are not well understood and need further evaluation.
- Some, but not much additional training is needed to accommodate PVT systems installations. For the most part, PVT manufactures can easily provide this training.
- The PVT system, though only sized for two apartments in the 12 apartment unit building, contributed an impressive amount to the building hot water demand and thus offers a new technology pathway to achieve zero net energy in multifamily and other high density buildings.

Task 3 Demo 2: Single Family Home PVT Integration

The purpose of this subtask is to develop, design, purchase, install, test and assess the electricity and hot water production from a hybrid photovoltaic/thermal (PVT) system for a single-family home at Aggie Village. The system was modeled in a manner similar to Demo 1 in order to determine the optimal arrangement of PVT panels and compare to separate PV and solar thermal configurations. As stated above, optimization of a PVT system revolves around the delicate relationship between thermal storage capacity, pumping volume and PVT array size. To obtain the full benefits of PVT (which include increase PV production due to cooling) thermal storage capacity and adequate pumping volume must be carefully evaluated.

Following data collection extension period, a summary of the heat delivery and heat loss by month is shown in Figure 7. The total heat generated which include contributions from the natural gas heater and PVT system, vary throughout the year. In winter, the total heat generated is about 30% to 50% higher than other months, which are about 170 kWh. Those high heat generations are due to high use of natural gas heater. More specifically, more that 50% of heat comes from natural gas heater between January and March. In other words, PVT system alone is not enough to meet the hot water needs of homes occupants. In contrast, during October, April, May and June, only less than 15% of heat comes from the natural gas heater. Figure 6 shows the trend that in the fall and spring PVT system can satisfy most portion of heat needed. Surprisingly, PVT can cover over 98% of heat needed in June 2014.

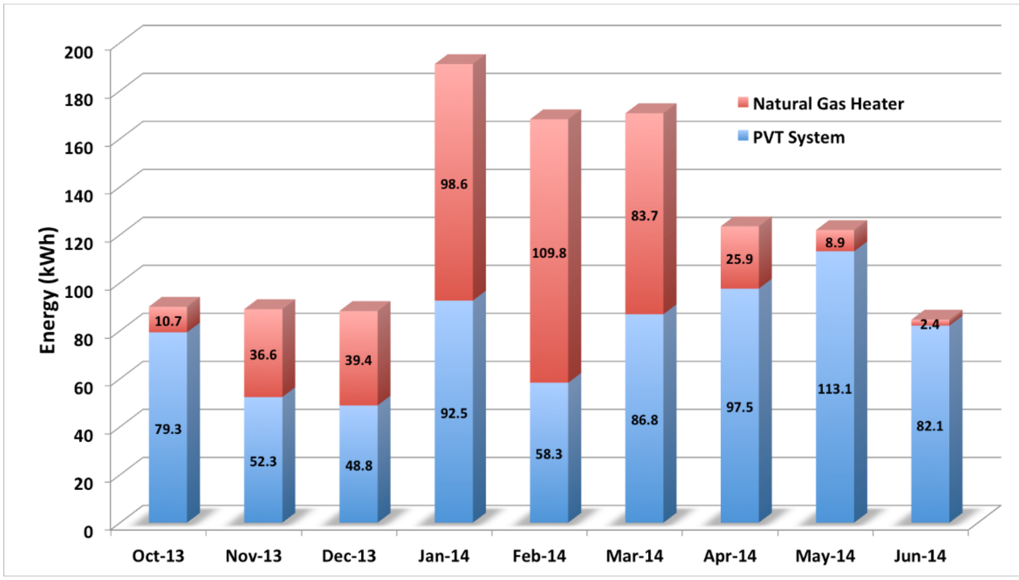


Figure 9: Heat generations from PVT and natural gas heater, respectively

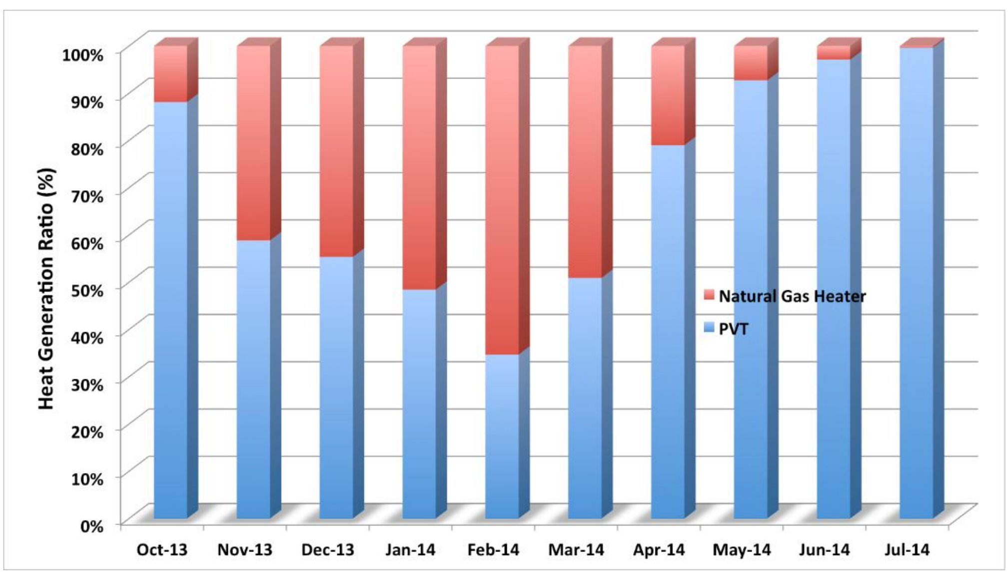


Figure 10: Heat generation ratios from PVT and natural gas heater, respectively

Effective Energy Factor of a PVT system is defined as QPVT / Qdelivered. Using total heat delivery to the house and PVT heat generation, PVT performance can be analyzed by Effective

Energy Factor, as shown in Figure 8. When Effective Energy Factor is larger than one, ideally the PVT system's total heat generation during that period is sufficient enough to provide the total needed for the house during the same period provide that there is no heat loss. As can be seen from Figure 8, the trend of Effective Energy Factor during the year is obvious. Most of wintertime, the Effective Energy Factor is below one due to relative low PVT heat generation and high hot water consumption. During June, the Effective Energy Factor reaches 2.7, which is almost two times higher than of the EEF during February.

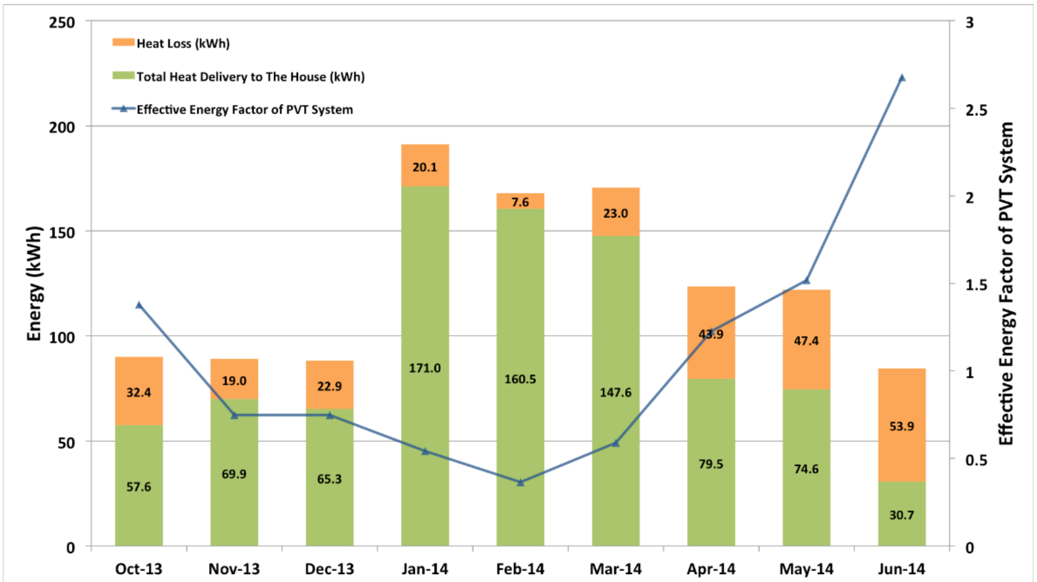


Figure 11: Monthly heat delivery, heat loss and effective energy factor of PVT system

Comparing PVT Panel Electricity Generation Performance

An interesting question is that whether there are measureable differences on electricity generations between PVT panels and conventional PV panels due to the active cooling of the PVT panels attributed to the circulating glycol. To understand our system produced these benefits the summarized monthly average electricity generations per PVT panel and PV panel were calculated in Figure 9. There were many issue with the Tigo Energy Maximizers from November to February, which required they be replaced. Thus no data is available during those months for the individual solar module performance. Quite surprisingly, the average electric generations for each PVT panel actually are few percent lower than PV panel throughout our monitoring months. One expected advantage of PVT is that PV power efficiency will increase by reducing the temperature in the cells due to the active cooling as many reports find solar cells drop 0.5% in efficiency for every degree Celsius increased above its optimum. In other words, if the PVT panels reduce the temperature from 65 C to 25 C, it will result in an approximate 20% increase in power. However, that was obviously not the case with this demonstration project. Compared with PV, PVT panel actually drops its efficiency on our system instead of increasing, which was not the expected outcome.

While further analysis is needed on this phenomenon, it is believed the decrease in PV generation efficiency is attributed to thermal storage capacity. Because this system was limited to 80 gallons in this system, the system was not able to achieve cooling for the majority of the day, as the system would quickly saturate the storage tank with heat early in the day. Thus, the afternoon hours the system either didn't need to circulate the close loop glycol through the PVT panels, or it was circulating glycol at a temperature that didn't provide cooling benefits. If increased PV generation is desired from a PVT system, care should be given to adequate storage capacity size, or applications should be selected that require hot water use during day light hours.

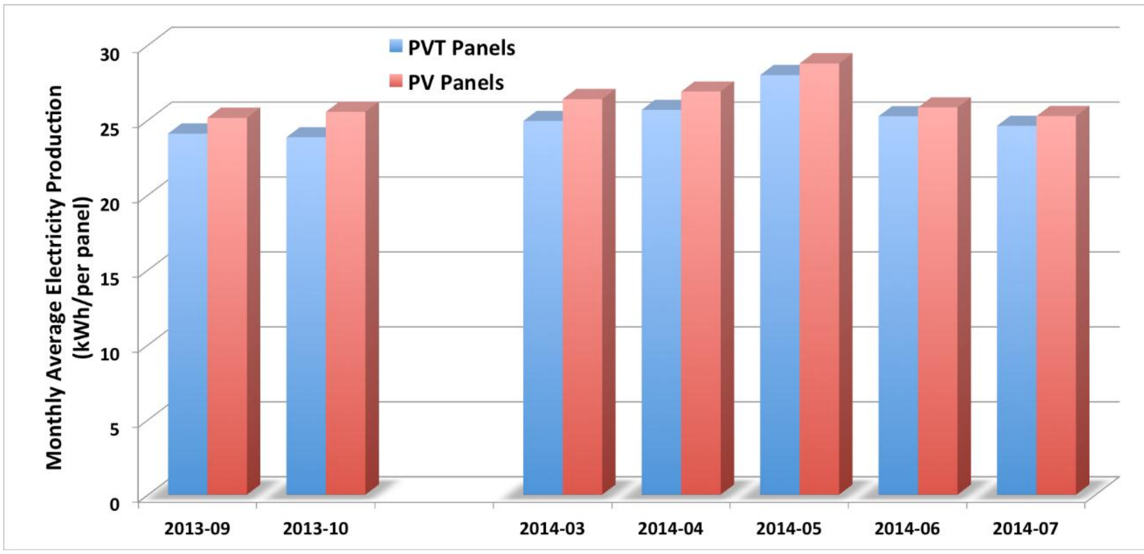


Figure 12: Average monthly electricity generations per panel from available data

Key Findings

- PVT panels demonstrated significant achievable overall efficiency increase, when combining the PV generation with thermal energy production.
- The relationship between PV generation improvements related to the active cooling as a result of circulating glycol across the thermal membrane directly beneath the PV cells is still not well understood. As a result of demonstration it is believed that these benefits are closely related to the thermal storage capacity and the pumping volume of glycol, these relationships are still not well understood.
- Currently, incentives don't exist specific to PVT technologies. While many PVT systems are eligible for both PV and solar thermal incentives, these are not ideal for a technology that is at least double the cost of PV. If California wants to develop the market for PVT technologies as well as embrace zero net energy on a wide scale, the state needs to embrace new technology incentives which are tailored specifically to PVT technologies.

Introduction

In 2011, The University of California, Davis (UC Davis), was awarded a California Solar Initiative Research, Development and Demonstration grant to support the West Village Energy Initiative (WVEI) zero net energy goals. West Village, a mixed-use community development located on the West Campus of UC Davis, was developed as a public-private partnership with multifamily housing for students, faculty and staff. The community has a village square that includes 42,500 square feet of office/retail space located in 6 mixed-use buildings around the village square. The initial phase of the project includes apartments with beds for approximately 1,980 occupants. The village square buildings and these initial apartments were completed as of August 2013. Additionally, the West Village master plan includes single family homes for faculty and staff which are to be priced at below market rate for affordability purposes.

The primary community goals for the West Village project have always been quality of place, affordability, and environmental responsiveness. However, largely due to the expertise, focus and persistence of UC Davis faculty, staff and researchers who were involved in the early stages of the project's planning, the vision quickly grew to also include zero net energy (ZNE) as one of its goals. At the time, West Village was the first and largest planned ZNE community in the United States. ZNE in this context was defined as zero-net- electrical energy from the utility grid on an annual basis. Not included in the initial planning were electric vehicle charging or any other transportation-related energy.

These energy and efficiency aspirations performed on a community scale quickly got the attention of many who were anxious to support such ambitious environmental goals. The project was striving to achieve California policy goals years ahead of schedule and doing so largely with private capital resources. In all activities and decisions made by the private developer who operates West Village, there is the need to ensure any technologies selected do not detract from the financial pro forma for the project. That is, ZNE must be achieved with no additional cost to the developer or the resident. Although the project is located on a college campus, it is a private development with the constraints of the private markets, including acceptable payback period. While these considerations constrained the project is various ways, they also gave the project a sense of relevance in examining not only the potential for success at West Village, but for replication elsewhere.

The decision to attempt ZNE included evaluation of several approaches and resulted in the decision to implement a grid-tied solar community instead of an isolated micro grid with a community energy park. This decision was largely due to the capital costs of electricity generation and distribution infrastructure without incentives available to a grid-tied community. These departures from the original vision of the West Village changed the course of the CSI RD&D project as the technology demonstrations were realigned to have direct applicability to the development project. The final structure of the CSI project therefore emphasized nearer term analysis and demonstration of system performance and reduced the effort in longer term data collection and modeling although these remain objectives for the future.

This resulted in discontinuing Tasks 4 and 5, which were developed around the original micro grid concept. Task 4-Improved Solar Forecasting, which focused on improving local solar conditions, was no longer applicable as the grid-tied systems relied on the utility and

Independent System Operator, who already have their own forecasting systems developed on regional levels. Also, with the departure of the micro-grid, Task 5-Data Collection, was no longer relevant, as UC Davis doesn't own or operate the generation and distribution equipment for West Village. Each individual demonstration had monitoring and verification build into the individual projects, thus an overarching data collection effort was not needed.

In order for the UC Davis CSI RD&D Project to have wide applicability to as many of the challenges at West Village as possible, the program was created with two different Target Areas. Target Area 1, Improved PV Production Technologies, addressed the evaluation, design, and deployment of advanced solar technology systems at West Village, while Target Area 2, Innovative Business Models, evaluated innovative business models around solar financing, evaluating barriers, identifying utility roles and developing metrics for successful adoption of new, innovative business models for solar integration and ZNE development. As mentioned above, over the course and development of the West Village project, the tasks of each target area were revised to accommodate the overall goals of the project. The final research tasks implemented under Target Area 1 of the project were:

- *Task 1: Demonstrations 1 and 2: Stationary Battery Energy Storage*
- *Task 2: Integration of AMI with PV and other DER Technologies*
- *Task 3: Demonstrations 1 and 2: Single and Multifamily Hybrid Solar Technology*

The above projects were conducted at West Village with the exception of the single family home energy storage and solar hybrid demonstrations. The single family homes at West Village and originally proposed for use with the project were not yet constructed. These projects were therefore co-located at a home in Aggie Village a faculty and staff housing community located on UC Davis property adjacent to downtown Davis, CA.

This report contains summaries from each one of these tasks. Results from the work conducted under Target Area 2 are available as a separate report. The full task reports are separately attached as appendices to this final report. These reports are interim work products as data collection began in late 2013 and will continue through summer 2014. Final reports for each demonstration will be prepared in late summer 2014 after the data sets have been expanded to include results from the winter, spring and summer months.

Project Goals and Objectives

Target Area One-Improved PV Production Technologies

Project Goals

The goal of the West Village Energy Initiative (WVEI) is to provide generation of enough on-site renewable energy to offset West Village's electric load on an annual basis at a cost to the customer that is equivalent or better than a typical PG&E annual bill in a business as usual case. The goal of the WVEI CSI RD&D Project (the Project) is to use WVEI to develop, demonstrate and deploy improved cost-effective installation of PV technologies to help build a sustainable and self-supporting industry for customer-sited solar in California.

Project Objectives

The Project was intended to enhance PV production technologies in these key areas:

1) Test and demonstrate existing energy storage technologies capable of working with smaller solar systems in residential and commercial applications.

2) Research integration of advanced metering infrastructure (AMI) with solar PV and other distributed energy resource (DER) technologies and provide recommendations to optimize existing PG&E and developer owned meters and power systems.

3) Test and demonstrate innovative hybrid solar (thermal/PV) development in multifamily and single family applications.

Results

Task 1 Demo 1 – Battery Buffered Electric Vehicle Charging Station Demonstration

Introduction

This task is concerned with the design, installation, and demonstration of a battery-buffered electric vehicle charging station in West Village. The electrical energy for this station is provided from a nearby panel of photovoltaic solar cells or from the grid. The battery buffered charging station permits the use of solar energy for charging electric vehicles to minimize the impact of vehicle charging loads on the electric utility grid. Control of electrical energy to and from the battery and to the charging station is done through a bi-directional inverter which functions either as a DC/DC or DC/AC inverter as needed. On-site the community has approximately 4 megawatts of PV generation and is also expected to be an area with high EV adoption. Hence it is an ideal site for demonstrating the battery buffered EV charging technology. This section summarizes the demonstration project. Full data and results can be found in Appendix A.

Project Objectives

Install and demonstrate a solar PV powered battery buffered electric vehicle charging station in West Village to improve design and utilization for market application and evaluate potential for load shifting, grid optimization and higher renewable energy penetration.

Project Summary

The solar powered, battery-buffered EV charging station system consists of a 5 kW solar PV panel, a 35 kWh lithium ion battery, a 10 kW demand response bi-directional inverter, and a level 2 electric vehicle charger as shown in Figure 1. The bi-directional inverter controls power flow between the different units. It has two DC ports which are connected to the PV panel and battery storage and two AC ports tied to the utility grid and the EV charger electrical panel, respectively. PV power can be used to charge the EV, be stored in the battery, and/or be exported to the grid. The green arrows in Figure 1 give the flow direction of PV power while the red arrows indicate the energy flow from the battery. The PV panels, battery storage, and the grid can then provide power for charging the EV at any time as indicated by blue arrows.

The control strategy for the system is to maximize PV energy used for EV charging and to reduce grid power demand from EV charging. There are two operating modes: grid-tied and standalone. Most of time, the charging station operates in the grid-tied mode. In this mode, the EV can be charged from PV, the battery, and/or the grid. In the case of a power outage, the system will automatically switch to standalone mode and be isolated from the grid. In this mode, the EV is only charged from PV and the battery. When grid power is restored, the system automatically transferred back to grid-tied operation.

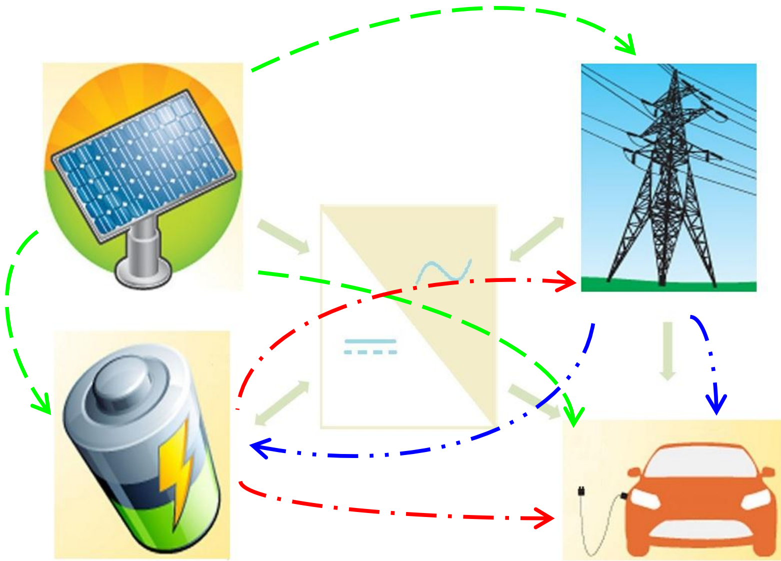


Figure 13: Solar Powered EV Charging Station Equipped with Battery Storage

In the normal grid-tied operation mode, when an EV is plugged into the charger, PV power is used to charge the EV if it is available. If more power is needed, it is drawn from the battery or/and the grid. If no electric vehicle is plugged-in, PV energy is stored in the battery until fully charged at which point excess PV power is exported to the grid. During off-peak hours, grid power can be used to charge the battery to a specified level. In the present system, energy is never fed to the grid from the battery. The battery could be used to support the grid if the customer (in this case UC Davis) chose to participate in a utility program such as Peak-Shaving or in the event of a grid emergency.

In the stand-alone mode, grid power will not be available. PV power if available will supply the EV charger, supplemented if needed by energy from the battery. If excess energy is available, the remaining PV power will be stored in the battery until fully charged. After achieving full charge on the battery in the stand-alone mode, there is no useful PV power generation (no current flow) although voltage is maintained while the panels are illuminated.

The computer controlled charging station was assembled using available components and computer software. (Figure 2). The batteries and the bi-directional AC/DC inverter are housed at 1715 Tilia Street in West Village and the vehicle chargers are in place behind the building next to parking. The battery pack consists of eleven modules of lithium iron phosphate cells in series (350V nominal voltage), stores 35 kWh of energy, and easily provides 10 kW of power to the inverter as needed when a vehicle is connected for charging. The battery pack includes battery management units (BMU) that monitor the cell voltages and temperatures and reports the results to the control computer.

Control and monitoring of the complete charging station was developed in Labview™. Operating status and measurements from both the BMS and the inverter can be viewed and recorded. The control computer gives the command for charging or discharging the battery to maximize PV energy used for EV charging and to minimize on the power drawn from the grid.

The control decision depends on the system operating modes (grid-tied or stand-alone), the availability of PV power, the state-of-charge of the battery storage, and the EV charging load. The electricity rate structure (time-of-use) is also considered to minimize energy cost when charging the batteries from the utility grid.

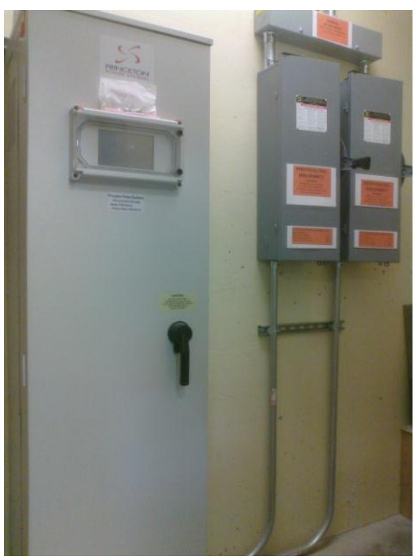
PV Array

36 V Module

(Iron Phosphate Lithium Battery)

Battery Module

Battery Rack



Bi-directional AC/DC Inverter

Vehicle Charging Station

Figure 14 Solar Powered EV Charging Station Equipped with Battery Storage

Conclusions and Recommendations

A battery-buffered vehicle charging station was installed in West Village that uses electrical energy from an on-site rooftop PV to charge electric vehicles (EVs). The charging station is also tied to the grid and the control strategy organized to minimize the impact on the grid from electric vehicle charging. The completed charging station is ready to be commissioned. Data collection and analysis will be conducted to assess energy and cost impacts.

The 44 m^2 PV array should provide about 60 kWh/day of electrical energy in the summer and 27 kWh/day in the winter season. The PV energy should be sufficient to charge EVs that have traveled 100 and 200 miles per day in the winter and summer, respectively. This should meet the current needs in West Village for EV charging and permit a meaningful demonstration of the vehicle charging station.

After this project is completed, research using the vehicle charging station will continue supported by a recent CEC Emerging Innovation Small Grant, listed as the Intelligent Energy Management for the Solar Powered EV Charging Station project. This research will include in the control of the charging station information on weather forecasts (solar intensity) and projections of the daily use patterns of the station. It is recommended that during this demonstration more PV energy than is currently available from the tower alone be made available for use at the vehicle charging station.

Recommendations:

a) Currently, the Self-Generation Incentive Program offers incentives for battery energy storage; however the system is penalized when connected to a renewable energy resource. This is because the currently language of the incentive limits the eligible watts of the energy storage system to the size of renewable resource. It appears systems which are also grid tied, remain bound to this language. Because the system at West Village can also be charged from the grid, it seems counterproductive to penalize the incentive for also connecting to a renewable resource. It is recommended that this language be reviewed in the next SGIP program update.
b) In addition to mitigating on peak loads attributed to electric vehicle charging, commercial battery storage systems are also effective at deterring capital upgrades due to insufficient power capacity. With the rapid growth of workplace charging installations, companies expanding their electric vehicle charging networks should consider battery storage before upgrading electrical capacity.
c) Fast charging is slowly being embraced as a means of workplace and public charging. With fast charging, battery storage applications will have increased benefit to the customer and grid, as managing demand charges becomes more important. As this system is monitored closely, important findings and recommendations for fast charging applications will be considered.

Public Benefit to California

This project demonstrates the use of PV energy to charge electric vehicles and the use of battery storage to maximize the fraction of the PV energy delivered to the vehicle. Technical performance and cost data to be obtained from the project within a community environment organized around ZNE are intended to yield critical information for improved design and management for extension and replication to other communities in California and for mitigating impacts on utility systems as the number of electric and hybrid-electric vehicles increases.

Task 1 Demo 2 – Single Family Home Energy Storage

Introduction

Second life batteries are those retired from their original application in either plug-in hybrid electric vehicles (PHEV) or electric vehicles (EV) and repurposed for a second application of typically lower performance due to degradation of the batteries during use. According to the US Advanced Battery Consortium (USABC) standard for EV batteries, a battery has reached the end of its useful vehicle life when it has either lost 20% of its capacity or power capability, meaning that there may still be a significant portion of use remaining in the battery for a non-vehicle application. As PHEVs and EVs gain popularity the number of used vehicle batteries will increase, posing recycling issues and making second life applications more attractive. It will be critical to explore the vast space of potential applications for second-use batteries in order to enable the effective utilization of this new resource. Further, the growth of grid tied solar-electric systems in California has caused some concerns of potential grid reliability issues. Stationary battery energy storage has been identified as a solution to accommodate a high penetration of variable PV generation, as energy storage allows for PV energy to be controlled and dispatched appropriately. This also potentially alleviates strains on expensive ancillary services that utilities must purchase to support PV systems in their service territories. Additionally, second-life battery storage applications, if successful, could greatly decrease the cost of stationary energy storage, extend the value of the electric vehicle battery pack and potentially lower the purchase cost of electric vehicles. This section summarizes the project. Full data and results can be found in Appendix B.

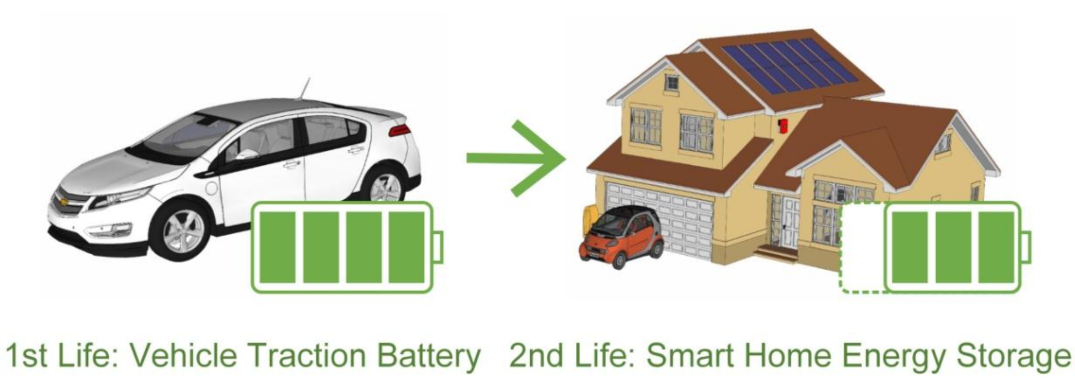


Figure 15: Second use of vehicle battery as stationary energy storage.

Project Objectives

The system was developed for a single family household and integrated the use of a grid tied PV array, battery storage, PHEV charging station and home energy management system. The following tasks were accomplished in the system development phase:

d) Integrate the battery pack into the energy system
e) Apply proper management of the battery pack, including battery safety protocols
f) Design an energy management algorithm considering a simple case encompassing grid response, PV energy harvest and building energy demand
g) Develop an information network for energy management and data acquisition. Additionally the project

Additionally, with the assistance of other project sponsors who provided match funding, the project included:

h) Supporting the energy demand of a single family household using both utility power and PV panels with the goal of minimizing peak load utility impacts
i) Study the grid interaction with battery storage
j) Life cycle analysis of second-life lithium batteries
k) Enable demand response
l) Charge a PHEV using a Level II charge station

Project Summary

Figure 16 shows a diagram of the system components. One PV string consists of 12 panels in series, each featuring 180W of rated DC power. This string provides 2.16 kW of nominal peak power output and was installed on a south facing rooftop at the project house. Each panel was connected to a DC-DC converter with maximum power point tracking (MPPT) (TiGo system®). The entire array was then connected to a DC-AC MPPT converter (SMA system®) to optimize the overall energy harvest. The TiGo MPPT converters allow for localized PV module optimization in the event of module shading. The SMA MPPT converter provides DC-AC power conversion to couple the solar power to the house AC power bus, in this case the home electrical panel. The battery pack uses the SMA Sunny Island, a bi-directional AC-DC converter to input and output energy from/to the system. The battery pack was assembled using 135 units of second-life $LiFePO_4$ based cells. The batteries have original capacity of 40 ampere-hours (Ah). After years of service as vehicle traction batteries, the second life batteries have a remaining capacity between 20-30 Ah. The battery pack has 9 cells in each parallel bank, 15 banks in series, providing 48 V nominal and 12 kWh of nominal capacity. Limited by the weakest bank in the pack, the second life battery pack has a total accessible capacity of 10 kWh, 58% of the original condition. The battery pack is controlled to absorb excess energy production from the PV during off-peak hours, and partially support the house load.

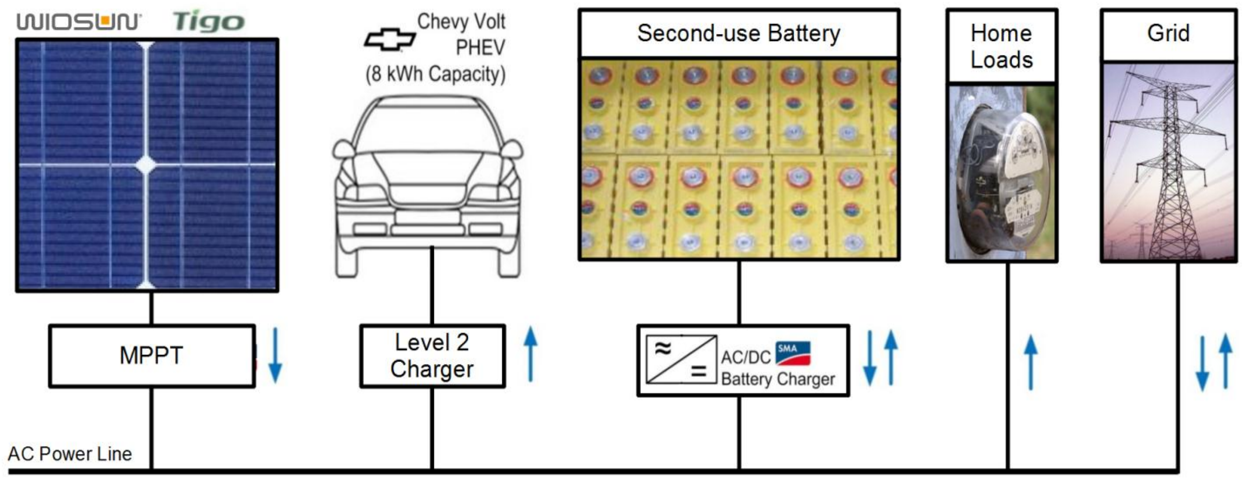


Figure 16: System diagram

An intelligent information network was installed for data collection and analysis. A WirelessGlue™ gateway serves as the information center that communicates with the battery management system (BMS), SMA®Webbox, Tigo® gateway, and ZigBee radios and records data at a local server. The system provides data logging of the battery pack, PV array, house energy consumption and grid interaction.

	Data Acquisition Service	Access
1)	Aggie Village Home Server via SSH protocol	ssh gsf@ucdavisvillage.no-ip.biz
2)	Tigo Energy via Tigo live view service	http://www.tigoenergy.com/
3)	SMA webbox server	http://ucdavisvillage.no-ip.biz:3334/
4)	Obvius smart panel server	http://ucdavisvillage.no-ip.biz
5)	Battery data server via FTP	FTP://ucdavisvillage.no-ip.biz
6)	Live data webpage	http://ucdavisvillage.no-ip.biz:9000/

Table 3: List of data logging server

The battery pack was operated as an energy buffer shifting energy from PV production peak to energy consumption peak. Battery charge and discharge control was based on three system variables: 1) battery status, 2) time varying utility price, and 3) energy demand subtracting PV production. The typical production, usage and pricing is as follows: PV production peak occurs from 9am to 6pm, with any excess production being stored in the battery pack; Energy usage peak occurs from 5pm to 9pm; and utility time varying price peaks from 2pm to 8pm. During peak usage, and peak utility price time periods, the battery tends to discharge to support the energy deficit. The system energy flow management decision table is presented in Table 4, where rows 1, 2 and 3 are input variables. Row 4 is a list of system actions.

Input 1	T	F	N	T	F	N	T	F	N	T	F	N	T	F	N	T	F	N
Input 2	T	T	T	F	F	F	T	T	T	F	F	F	T	T	T	F	F	F
Input 3	T	T	T	T	T	T	F	F	F	F	F	F	N	N	N	N	N	N
Action	F	C	F	D	S	D	F	C	C	D	S	S	F	C	C	D	S	S

Input
1:UtilityPrice T :Peak Price, N: Partial Peak, F: Off Peak
2:PVvs.Load T :PV product > Demand, F: PV product < Demand
3:BattSoC T : 90%~100%, N: Target SoC*~90%, F: 0%~Target SoC*%

*Target state of charge (SoC) is the charge level the battery pack will have at the end of the day

Action
F: GRID BACK FEED; S: GRID SUPPLY;

C: BATTERY CHARGE; D: BATTERY DISCHARGE

Table 4: Energy management decision making table

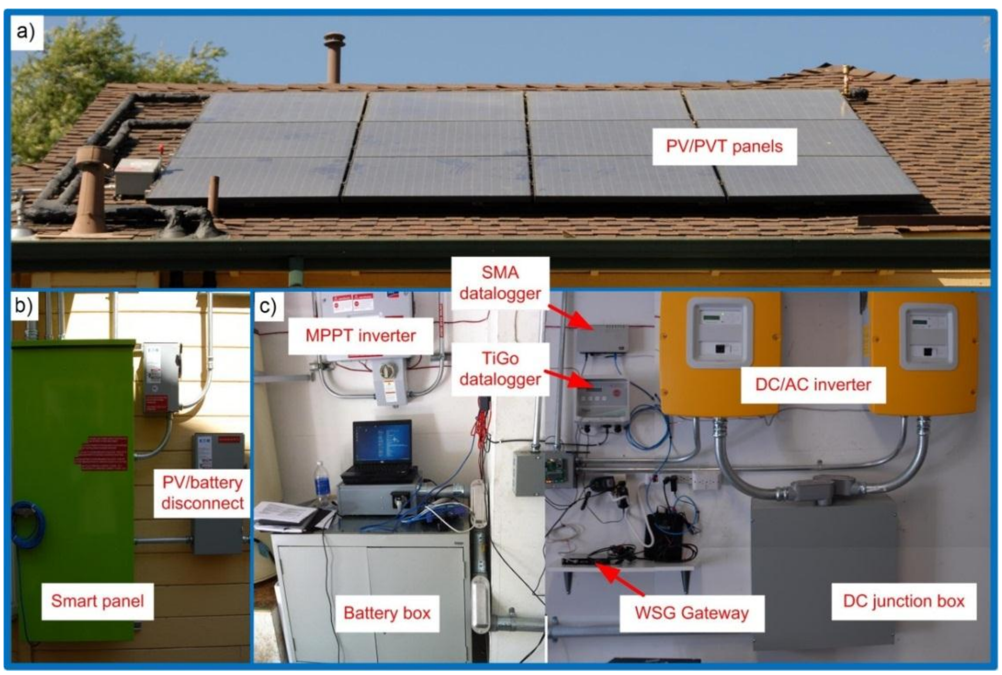


Figure 17: Photo of installed smart-grid PV battery system. a) PV array, 2.16 kW nominal production. b) Smart panel with house load measurement capability and safety disconnect to the right. c) Smart Grid-tied Photovoltaic Battery Energy System.

Key Findings

Over the course of four months of PV array operation 967 kWh of electrical energy was generated. The battery system began its operation from late November 2013, and over one month provided PV energy shifting of 63 kWh, equivalent to $18.90 savings. Placing the battery into this second application enabled the use of 11 additional cycles. Lifecycle analysis yields an equivalent CO2 saving equal to 1639 lbs. Over all the system has saved $145.50 over the first four months of the winter time operation period from energy shifting alone.

PV System (09/2013 to 12/2013)	Operating Hours (system on)	1483 Hours
	Energy Harvested	967 kWh
	CO_2 Saved	1639 lbs.
Battery Pack (11/2013 to 12/2013)	Peak Usage Shifted	63 kWh
	Peak Usage Bill Saved (@ $0.30/kWh)	$18.90
	Extended Battery Life (charge cycles)	11 Cycles
Grid Interaction (09/2013 to 12/2013)	Total electricity Bill Savings (@0.15$/kWh)	$145.50

Table 5: System operation statistics

The system directly provides solar energy when available in the daytime, and reduces a portion of the evening peak load using the stored solar energy that resides in the battery. Figure 4 illustrates the system functionality using usage data on December 1st, 2013. As shown in Figure 18a, from midnight to 10 am both the PV array and the battery pack were in silent mode, and the house energy usage was fully supported by grid. From 10 am to 5 pm, the house energy demand was fully supported by the PV array output, and extra PV energy was used to charge the battery. From 5 pm to 8 pm, the house energy usage peak occurred, overlapping with the utility peak pricing hour. The battery discharged to support the load demand at efficiencies of approximately 85%. When peak pricing ended at 8 pm, the battery stopped discharging. As shown in the energy consumption pie chart in Figure 18b, the house energy demand during that day consisted of 30% peak pricing usage (3.2 kWh), 20% at partial peak usage (2.4 kWh), and 50% at off-peak usage (5.7 kWh). Indicated by the energy source pie chart of Figure 18c, 63% of the house energy usage was covered by the PV array production (6.8 kWh)for which the battery pack enabled peak shifting capability, and the peak usage during the evening hours was covered by the battery stored PV energy (3 kWh).

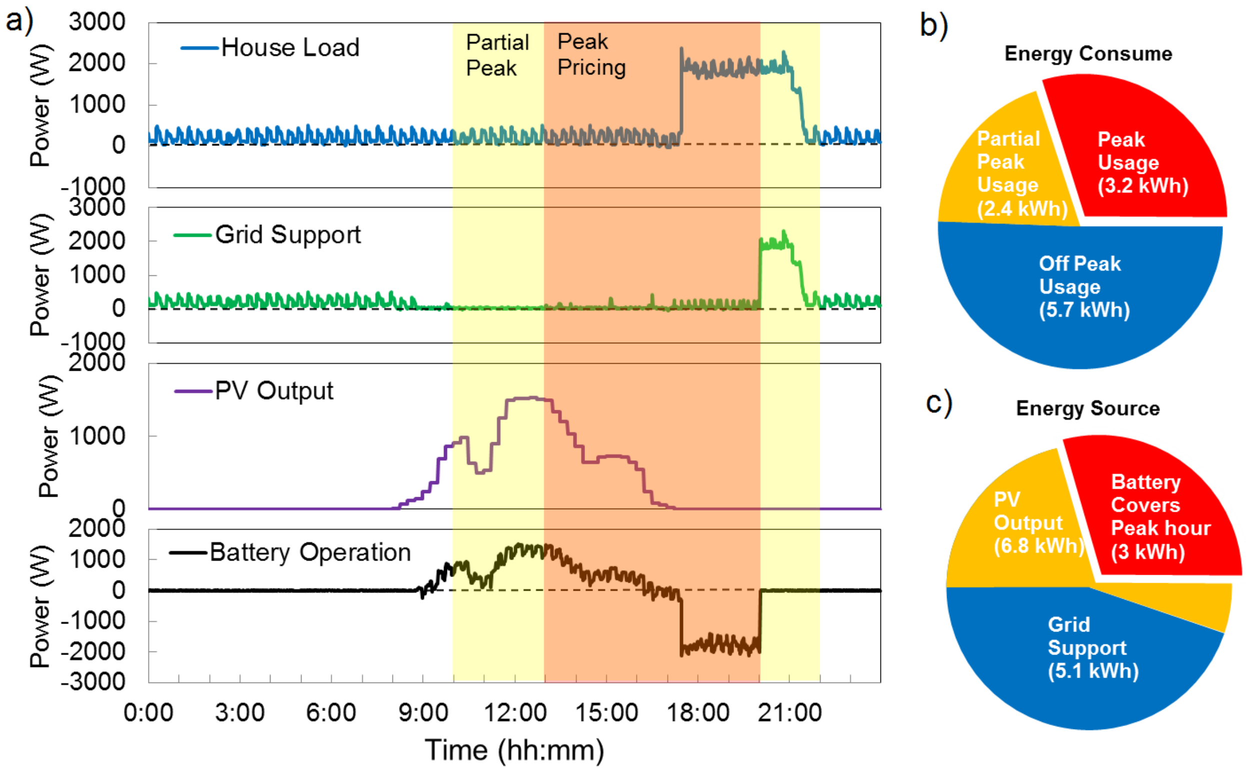


Figure 18. Sample of system operation on 12/01/2013.
a) Plots of power usages from the house, grid, PV, and battery. b) Energy consumption. c) Electricity generation. This comes from either the PV or the grid. Part of the PV is stored for later use by the house and is accounted as the battery portion in red. This is a subset of the PV.

Conclusions and Recommendations

The system development is completed at the project house, providing renewable energy to a single family, and meanwhile provides detailed data of energy system operations for research. The research team has followed the project roadmap, and fulfilled milestones. The outcome system meets the proposed functionality.

Installing the battery storage system in the home was complex undertaking. Using a second-life battery in the system added additional layer of complexity. While this particular system probably wouldn't be recreated outside of this research project, the benefits of providing solar energy storage with second life batteries in a residential environment has already shown to be significant. The system has successfully reduced peaks loads from the home, which has resulted in monthly reductions to the occupant's bill. This financial benefit will be compounded as the system operates during summer, when PV production, along with afternoon and evening cooling loads are higher. Furthermore, the project has not yet participated in any utility peak shaving or demand response programs, which will increase these benefits further.

Many of the market and policy findings as a result of this demonstration deal with the repurposing and fabrication of the second life battery pack. While this process was necessary to understand for research purposes, the labor required to perform this could quickly cause the battery pack to be the same or more as the costs as a new pack. Additionally, older cells have a lower roundtrip efficiency which causes energy losses across the system. Regardless of these facts the system's performance has illustrated the benefits of energy storage in residential contexts and the project is optimistic that repurposing battery packs could be economical if the industry embraced it. Overall the project found:

m) With grid tied systems, two phase battery inverters provide the most benefit to the grid by mitigating home loads on A and B phase, rather than just one phase as with a single phase inverter. Most residential battery inverters are only single phase, as they are used for backup on critical loads only.
n) While Authorities Having Jurisdiction, such as Fire officials, are not accustom to approving energy storage in homes, the National Electric Code does have guidelines and standards which make permitting and approval fairly straight forward, provided the system meets the code requirements. The project did not find any constraints in the code relating to small (less than 1000lbs.) lithium-ion battery storage systems.
o) If battery management system data on the batteries previous life been available, the time required to test the pack would have been significantly reduce, as information on battery health would have already been recorded.
p) Proprietary strategies for cell balancing take time to develop. However companies could choose to makes this upfront investment or license existing technology from others. One consideration is to continue using the strategy contained in the first life's battery pack, which would be the most cost effective. Regarding the latter, the pack would require no assembly at all and would only need to be integrated with the power electronics. It is also noted that residential energy storage applications are must less strenuous and demanding then the first life applications in a vehicle, potentially making second life battery cell balancing strategies less complex.
q) If a second life battery packs are going to be brought to mass market, the inverter power electronics and safety and protection hardware (disconnects, etc.) should be integrated into the pack as one unit. This will decrease overall costs including installation costs. Also, integration could increase round trip efficiencies as DC-to-DC converters could be utilizing to charge the battery direct from the PV array.

Public Benefit to California

Increased Use of Renewable Energy

California has set an ambitious goal of having 33% of its electricity generation to be provided by renewable sources. Due to the intermittency of wind and solar, energy storage will be important to help meet this target. Energy storage enables the stable use of renewables for peak shaving, which can dramatically reduce the overall pollution caused by electricity generation as this is the critical period in which "peaker" plants, which generate the highest level of emissions, are operated. Applying second life lithium ion batteries for renewable energy storage has great potential as distributed energy storage solutions at the site of renewable generation, for example when applied to residential homes as performed on this project.

Grid Stability

As mentioned above the use of renewables has a critical impact on grid stability, however, the cost of energy as well as the prediction of grid demand also have certain levels of uncertainty associated with them. Employing energy storage into the grid can enable response to changing supply and demand at rates significantly improved over current state of the art techniques. Improved demand response reduces the vulnerability of the utility grid to substantial overload.

Task 2 – Integration of AMI with Solar PV & Other DER Technologies

Introduction

Beginning in August 2012, GE Energy Consulting (GE) was engaged by UC Davis as subcontractor under Target Area 1, Task 2 to examine the integration of demand side monitoring and control as advanced metering infrastructure ("AMI") with solar PV and other distributed energy resources (DER) at UC Davis West Village. A baseline model was developed of both consumption and solar PV production for each of the existing and to-be-built building types at UC Davis West Village, as well as recommendations for future energy performance monitoring and control. This section summarizes the project. Complete data and results can be found in Appendix C.

Project Objectives

The purpose of this Task was to first establish a baseline representation of current energy performance from the available data and designs for UC Davis West Village (Subtask 1), and then to recommend a monitoring and control systems architecture that integrates the customer demand side ("AMI") with solar PV production and other DER technologies, to be able to measure and adjust performance to meet the ZNE goal on a dynamic, on-going basis (Subtask 2).

Achieving the ZNE objective has been a guiding principle in the design of the facilities at UC Davis West Village. While useful as a community-level design construct, ZNE is in fact a difficult quantity to measure on a day-to-day basis, within an evolving community, given all the variations in construction, tenancy, occupancy, and ownership, as well as the limitations in the available data.

GE sought to answer two key questions: How is energy performance tracking compared to the goal of ZNE? And, secondly, where not meeting ZNE, what options are available to track and adjust energy performance into the future?

The goal in structuring Task 2 was to provide UC Davis and the West Village Energy Initiative with the tools to answer these two questions. By laying out a framework for measurement of ZNE along with recommendations for investment in on-going energy management, the objective was to enable the facility managers and UC Davis staff at UC Davis West Village to track and adjust building performance dynamically, for example tightening energy management through automated controls and messaging to tenants, to ensure cost-effective attainment of ZNE.

Project Summary

The scope of this task consists of two main subtasks:

- Subtask 1: Understand baseline energy performance for the existing and planned new construction buildings at UC Davis West Village, which include multi-tenant housing, commercial/public space, and Faculty Staff housing, and determine baseline performance against the objective of ZNE; and

- Subtask 2: Recommend the functional specification for a monitoring and control systems architecture that integrates the customer demand side ("AMI") with solar PV production and other DER technologies, to be able to measure and adjust performance against the ZNE goal on a dynamic, on-going basis.

Subtask 1

Under Subtask 1, GE's scope included the following activities:

- Collect, validate, and analyze existing and available data for UC Davis West Village
- Develop realistic assumptions for additional parameters, as necessary
- Develop a quantitative framework representing energy generation from solar PV at UC Davis West Village and energy consumption by end use
- Characterize expected baseline performance, including the physical attributes of each technology and behavioral sensitivities for user-controlled characteristics

Developed under Subtask 1 was a baseline model of the energy performance of the UC Davis West Village Energy Initiative. The model incorporates existing and future building types, allowing an estimation of the annual net energy performance for a hypothetical "synthetic year" of baseline operation. The synthetic year was developed as a surrogate for actual annual data that were not yet available at the time of the analysis.

Subtask 2

Based on the model developed in Subtask 1, options for demand side controls ("AMI") and other alternatives to enhance the energy performance capability of UC Davis West Village were identified.

A functional specification was developed for the integration of AMI, PV, demand response, and storage technologies, consisting of:

- Recommendations for the IT and communications architecture (functional, not vendor-specific) to support the ZNE goal
- Estimated costs and benefits of incremental hardware and software
- Expected benefits of incremental control capability
- Summary of any additional design considerations, such as user friendliness, interoperability, potential electrical system, environmental, or aesthetic impacts, etc.

Key Findings

Energy Modeling: Due to the limitations of the data available at the time of the study, the model results provide an interim snapshot of the current and expected energy performance at UC Davis West Village. Several directional observations were possible. Based on the information available and the conservative nature of the modeling, it is likely that:

- The multi-tenant units are performing slightly above production of the installed PV, with some variation by unit type. The Viridian units appear to have the best performance (consumption to production ratio, or C/P, close to 1), while the Ramble and

Solstice units are not yet achieving ZNE and may require some additional tightening of performance to achieve energy balance.

- The Recreation and Leasing Center and swimming pool area (the "Club" and "Gas" accounts), as well as the mixed use (MU) spaces appear to have a greater excess of consumption over production.
- Model results confirm that the Faculty and Staff Housing do appear to be well designed for consumption to match production, with small variations by floor plan and solar size. However, the studio annex units, which are an optional addition for some home owners, may have an additional challenge meeting this goal due to a lack of roof space to support solar installation.
- Above and beyond the data limitations of this study, there remains uncertainty in the evolution of future loads, especially the EV charging and energy-intensive operations associated with the research laboratories of the Western Cooling Efficiency Center located at West Village.

UC Davis is planning to construct a Renewable Energy Anaerobic Digester facility that is expected to generate approximately 4 million kWh of electricity per year. The contribution of this renewable energy resource was not considered towards the ZNE goal in the model results outlined here.

NOTE: Subsequent to completion of this task, UC Davis and West Village Community Partners completed the *UC Davis West Village Energy Initiative Annual Report 2012-2013.* The findings of this report were generally consistent with the GE results for the subset of the ultimate development that had occurred through February 2013. This report can be found in the footnote below.[1]

AMI alternatives: Results from the assessment of AMI alternatives suggest three levels of potential investment and associated savings that could be of interest at UC Davis West Village:

- Consumption Information Delivery. These "information only" programs provide simple messaging to consumers that warn of high peak load "event days" and offer suggestions to avoid unnecessary electric use, turn back thermostats, and delay scheduled appliance usages (such as dishwasher and laundry loads) until off-peak hours. Such programs are extremely cheap to operate and have a small but noticeable impact on consumption and peak demand, typically in the low single digit percentages of peak demand reduction (2-5%).
- TOU with programmable communicating thermostat. Time-of-Use (TOU) rate schedules charge differential prices by pre-determined seasonal/time-of-day blocks – more in summer peak hours (for summer-peaking systems), less in winter and off-peak

[1] UC Davis, "*West Village Energy Initiative Annual Report 2013-2014.*" *http://sustainability.ucdavis.edu/local_resources/docs/wvei_annual_report_2012_13.pdf*

night time hours. Programs that tie installation and programming of thermostats to a TOU price incentive can result in more significant reductions in energy and peak demand, often on the order of 10%.

- CPP with programmable communicating thermostat. Critical Peak Pricing (CPP) overlays on the basic TOU structure an event-driven higher rate that can be invoked by the utility up to a certain number of times per year. PG&E's voluntary Smart Rate option is an example of a CPP. IP addressable programmable communicating thermostats (PCTs) are now available from a number of manufacturers that can receive and respond to dynamic pricing signals in order to provide higher peak savings on an event basis – often as much as 20% or more.

All units in the UC Davis West Village multi-tenant buildings come equipped with programmable thermostats, however, these are basic devices that are not communications-enabled and cannot be remotely accessed by the envisioned MEM to provide dynamic control. Due to the limitations of the user interface, most consumers find such devices difficult to program and maintain. Typically, they are set once when installed and only occasionally, if ever, reprogrammed by the tenants.

In order to achieve savings above the "Information Only" level, costs and benefits were examined for replacement and upgrading of the current thermostats with IP-addressable programmable communicating thermostats (PCT).

There are a number of technology vendors and options for PCTs that can support varying levels of control. Simple devices in the ~$100 range are available from companies such as EnergyBuddy, EnviR, and Battic.2 More sophisticated home energy management kits are also available that include such features as more intuitive full color touch screen displays and ZigbeeTM (wireless) plug adapters for on/off control of additional simple plug devices in the home. Kits of this sort run in the ~$250 range and are available from NEST, EverSense, EcoBee, and EnergyHub, among others.

Finally, there is an emerging category of "cloud based" software-as-a-service vendors, such as EcoFactor, which offer subscription-based services to remotely control and optimize thermostat settings.

For the Faculty and Staff housing at UC Davis West Village, thermostats have not yet been specified.PCT installation and PG&E Smart Rate participation for home owners (who will be customers-of-record for their own PG&E accounts) could be encouraged as part of the community covenants or HOA rules.

In investigating options for the Recreation and Leasing Center and Mixed Use Retail buildings, specific suggestions could not be provided due to limited data on end use profiles. However, a number of vendors offer advanced building energy management and control solutions that may

[2] Mention of specific tradenames does not constitute an endorsement by the University of California.

offer significant savings. These include Scientific Conservation, Inc. (SCI), 8760, and BuildingIQ.

For the pool pumping load, two of UC Berkeley's outdoor campus pools using smart pumping controls have achieved greater than 40% energy savings.

Conclusions and Recommendation

Energy modeling in association with the assessment of AMI for West Village was conducted using a simulated synthetic year. Under the model assumptions representing occupancy type, seasonality, and scaled cooling and heating requirements, the overall energy consumption to production ratio for West Village at the time of analysis was projected at 1.25 indicating for this point in the development additional means would be required to achieve ZNE for the community. Implementation of a master energy management system was recommended to automate on-going tracking of energy performance and to communicate with residents and addressable devices such as programmable communicating thermostats. All three energy management systems evaluated—Consumption Information Delivery (CID), Time of Use (TOU) with PCT, and Critical Peak Pricing (CPP) with PCT—were predicted to realize simple financial payback within three years. The payback for CID was less than one year, while for TOU the simple payback was 1.3 years. CPP with 10% peak savings was estimated to payback within 2.5 years including the cost of the home energy management system. Innovative means to encourage greater energy savings among residents may also be needed to meet the ZNE goals for West Village including both behavior modification approaches and greater centralized control of thermostats with temporary local override capability.

Public Benefits to California

Improved monitoring of energy supply and demand is critical in providing information relevant to control and use decisions in meeting ZNE objectives. Financially, the three energy management techniques investigated all offer short term benefits, and if deployed could contribute to overall energy demand reductions and improved efficiencies to reduce C/P. These effects in turn lead to lower design DER generation capacity and hence lower lifecycle impacts. The results have direct implication for replication to other communities, including retrofit applications. Innovation in both information delivery and automated central/distributed control allow for improved user interaction and decision-making in addition to more direct demand side management, and such approaches serve as future elements for evaluation within the West Village development.

Task 3 Demo 1– Multifamily PVT Integration

Introduction

This demonstration evaluated existing and innovative hybrid photovoltaic/thermal (PVT) technologies and strategies for solar hot water production. These systems are capable of working with other smaller scale solar systems in community-wide multifamily installations. These novel solutions were designed and built to be utilized for reliable and safe operation by building occupants. The system performance is monitored and compared to simulations provided by solar thermal and PV modeling software that allow for projections of optimal allocation and configuration of PV, solar thermal (ST), combined PV + solar thermal (PV + ST) or hybrid PVT systems to minimize the rooftop footprint and maximizing incentives. Overall, the results of this multifamily hybrid solar demonstration project provide practical insights for hot water systems in future developments as well as a broader body of knowledge concerning solar thermal applications for zero net energy buildings. This section summarizes the demonstration project. Full data and results are available in Appendix D.

Project Objectives

The purpose of this subtask is to develop, design, purchase, install, test and assess the electricity and hot water production from a hybrid photovoltaic/thermal (PVT) system for two apartment units at one of the West Village's Solstice apartment buildings. By modeling the system we can determine the optimal arrangement of PVT panels and compare performance to separate PV and solar thermal configurations. Data from the PVT system can be compared to the existing means of hot water production, and recommendations made for future PVT installations.

Project Summary

- Review and evaluate various commercially available or near term market PV and ST technologies.
    - Technical memorandum listing and comparing commercial and emerging PVT and ST systems, technologies and providers.
- Compare technologies that combine solar electric and thermal generation that can be considered in the next phase of WV construction.
    - Technical memorandum comparing the efficiency, footprint, and cost of PV only, PV + ST, and hybrid PVT systems using computer simulations.
- Identify a site for multifamily solar system.
- Investigate state, federal and utility incentives available for both PV and ST systems.
    - Technical memorandum explaining the available incentives and rebates and their respective amounts.
- Negotiate an ownership and operation agreement between Carmel Partners and UC Davis.
- Collaborate with manufacturer and contractor to determine systems design and specifications for the model PVT or PV + ST system.
    - Obtain cost estimate and prediction of performance.
    - Produce construction drawings.

  - PVT system model for simulating energy generation, storage requirements and energy demand, using real time forecast information.
- Determine metering, monitoring and control requirements to integrate with West Village AMI, and conduct test operation of the system.
  - Outline of a research plan, detailing the data to be acquired from monitoring.
  - Operational strategies report.
- Continue monitoring system performance and end-use consumption and compare to simulation predictions.

Key Findings

Simulations for optimizing PV, PV + ST, and PVT arrangements

Simulations were developed to predict PV, ST, PV + ST or hybrid PVT system performance. Four different software packages were compared in terms of technical and economic evaluations of PVT system performance. Preliminary estimates using Polysun solar simulation software shows that 9 solar thermal flat plate collectors (34 m^2) can deliver approximately 78% of the hot water required for one apartment building. Combined PV + ST technology would reduce the roof space required by harvesting both electricity and heat directly. Polysun was also used to model the electricity and hot water generation from different PV, PV + ST and hybrid PVT systems (Tables 7 and 8).

Technical Comparison – 3 bed home

Parameters	PV (w/ heat pump)	2 ST + PV	3 ST+PV	PVT+PV (heat pump)	PVT+PV (boiler)
Electricity Produced (≥ 6356 kWh AC)	6709	6351	6468	6272	6562
Heat Produced (≥ 3775 kWh)	3864	3731	3753	3672	4144
Electricity used for heat (kWh)	1434	376	259	870	1216
No. PV panels	23	19	19	10	12
Area (m^2)	28.61	23.64	23.64	12.44	14.93
No. ST panels	-	2	3	-	-
Area (m^2)	-	4.82	7.23	-	-
No. PVT panels	-	-	-	12	12
Area (m^2)	-	-	-	15.96	15.96
Total Area (m^2)	28.6	27.64	30.87	28.4	30.89

Table 6: Technical comparison of optimized PV, PV + ST, and PVT + PV arrangements

Financial Comparison – 3 bed home

Parameters	PV	2 ST + PV	3 ST+PV	PVT+PV (heat pump)	PVT+PV (boiler)
No. PV panels ($309/panel-Bosch 225W)	23	19	19	10	12
No. ST panels ($936/panel Bosch)	-	2	3	-	-
No. PVT panels	-	-	-	12 ($762/panel 190W-PVtherm)	12 ($724/panel – PVtherm 180W)
Electricity for heat (kWh)	1434	376	259	870	1216
Array Cost	7107 $	$7743	$8679	$12234	$12852
Operating cost per year (E6 TOU rate)	$170	$35	$24	$84	$118

Table 7: The financial evaluations of optimized PV, PV + ST, and PVT + PV arrangements

From the simulations and lower rooftop footprint, a hybrid PVT system was selected for demonstration even though PVT currently has a higher capital cost compared to separate PV and ST systems. Unlike conventional PV or ST systems, there is not a wealth of data that can be used for PVT systems. By monitoring and verifying a PVT system, the project should be able to build a database of observed performance and provide practical insights for future PVT systems design.

Summary of PVT manufacturers and selection

We also reviewed and evaluated existing PVT technologies from technical and economic points of view. Both flat-plate PVT and solar concentrator PVT are available in the market. Flat-plate PVT has lower efficiency but also lower cost and is feasible for individual houses or buildings. In comparison, most concentrated PVT has more total energy output for the same area but also requires a tracking system, which not only increases the system cost but also hinders residential and many commercial applications. PVT panels were limited in availability and panels used for the demonstration were procured from Solarzentrum North America.

PVT and monitoring system design

The design of the demonstration system included 24 PVT panels, which from in model simulations provided enough hot water for two apartment units and enough electricity for one unit. The array layout was arranged in 3 x 8 to optimize flow and cooling of the panels. The project team worked with Davis Energy Group (DEG) of Davis, California, on a design to integrate with the existing heat pump domestic hot water (DHW) system. The finalized drawing of the PVT water heater and monitoring system is shown below. The installation was completed in August, 2013. Incentives for the system were investigated and state and federal incentives are available for both PV and ST portions. Please refer to the full task report in appendix D for details.

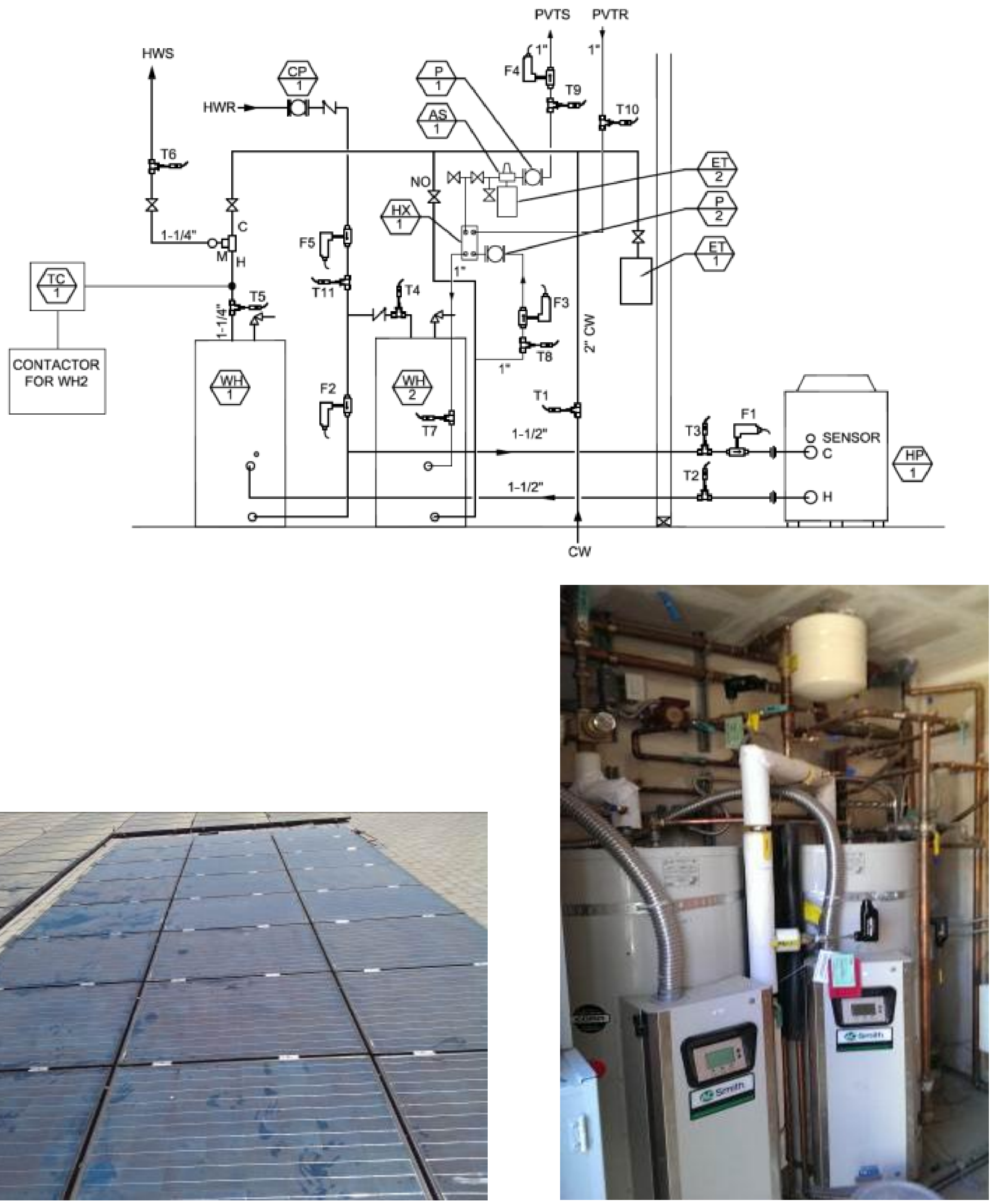


Figure 19: Design schematic and photos of the integrated PVT system installed at West Village.

Collected data and analysis

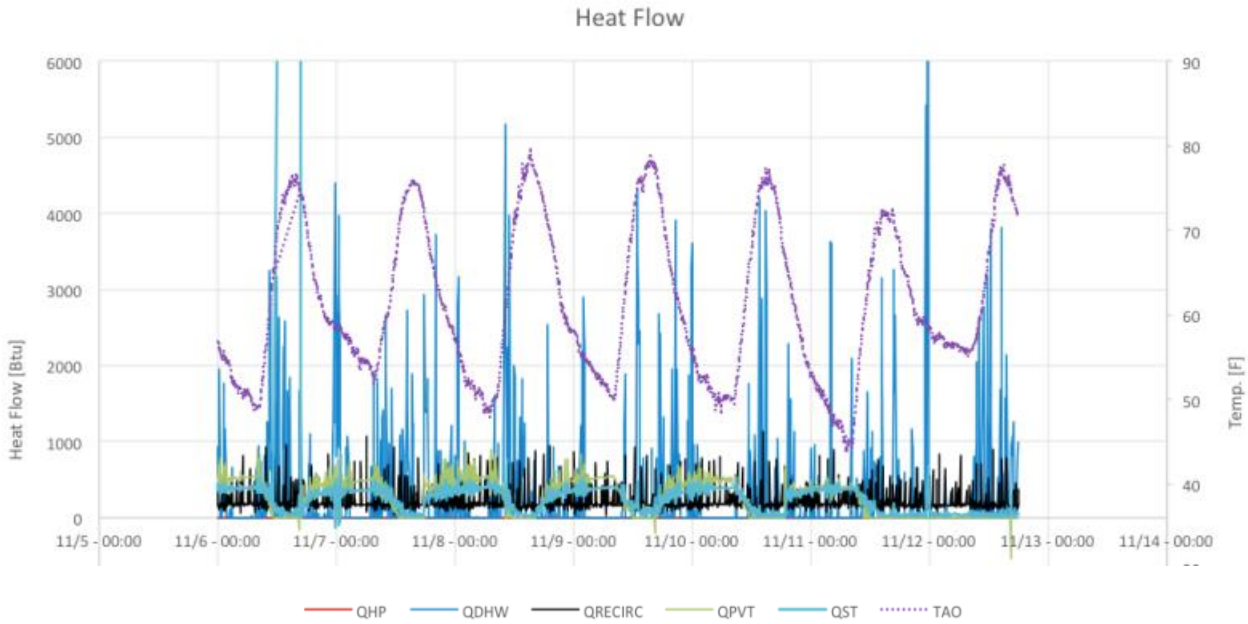


Figure 20: Monitoring data from October 2013.

Data collection began on October 1st, 2013. Based on the data from these monitoring points, heat flow was calculated for the PVT system. The calculated values are shown in Table 8. Large amounts of recirculation losses were discovered in the building hot water recirculation system, which is not a part of the hybrid PVT system. Aside from those losses, the PVT supplied 567.9 kWh of DHW for the month. Beyond the PVT loop, the heat pump only contributed approximately 10% of total heat energy. The conventional water heater provided the rest.In the future, more data will be collected in order to complete a more comprehensive analysis.

Unit: kWh	*Total Heat Delivery (kWh)*	*Recirculation Loss (kWh)*	*Useful Hot Water Delivered (kWh)*	*PVT Heat Delivery (kWh) (Percent)*	*Heat Pump Heat Delivery (kWh) (Percent)*
Oct. 1st – 31th	*994.9*	*463.5*	*531.4*	*567.9 (57%)*	*99.4 (10%)*

Table 8: Heat flow (kWh) in PVT system during October 2013

The impact of scheduling appliances and rate structure on bill savings for net-zero communities

The financial incentives of load shifting electricity under PG&E's Time-of-Use rate and Net Energy Metering pertaining to the solar net-zero energy apartment community were also evaluated as part of the project (Gaiser and Stroeve, 2013). By "smart-scheduling" the electricity [3]and domestic hot water demand of the dishwasher, clothes washer, dryer, sinks and showers

[3] Kyle Gaiser, Pieter Stroeve. "The impact of scheduling appliances and rate structure on bill savings for net-zero energy communities: Application to West Village." *Applied Energy*, 113 (2014) 1586-1995. Web published.

solely to off-peak periods, the peak demand is reduced by 18%, the partial-peak demand by 32% and the off-peak demand increased by 12%. With this shifted schedule customers accrue twice as many Renewable Energy Credits (RECs) as they would receive under a non-shifted schedule with the same Time-of-Use rate, totaling to $2,975 of "free" electricity per year for one 12 unit building. However, under current rates smart-scheduling is found to be worthwhile only during the months from May through October, when 96% of the credits are accumulated. If the rate schedule is altered to include peak-periods during the winter months, the credit savings will double again in value.

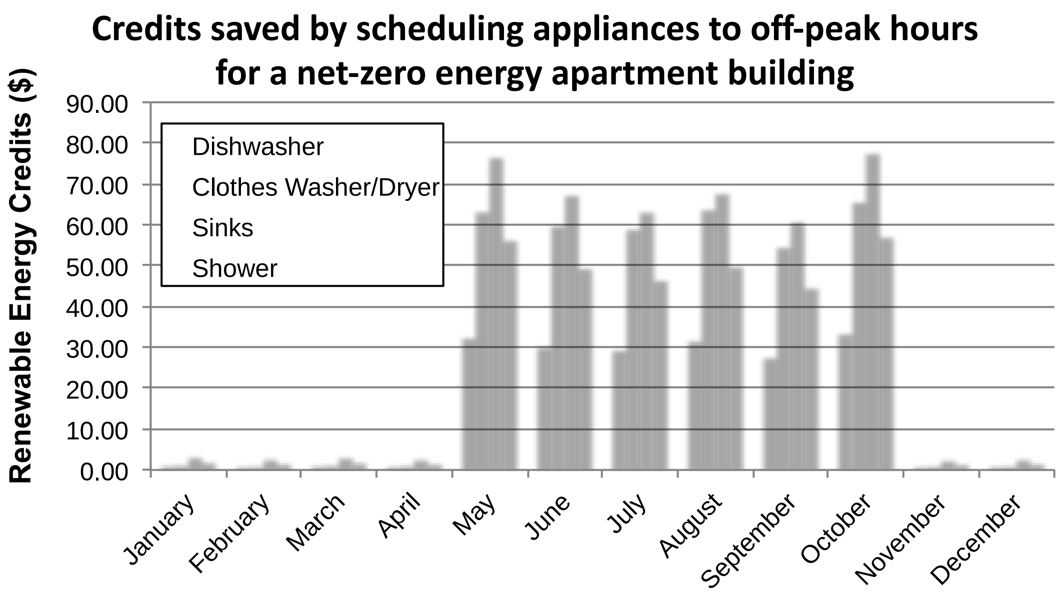


Figure 21: Appliance off-peak scheduling savings.

Conclusions and Recommendations

Conclusions

a) The review and evaluation of near term market PVT technologies from technical and economic points of view found that both flat-plate PVT and solar concentrator PVT are available in the market. Flat-plate PVT has lower efficiency but it is better adapted to the roofs of individual houses or buildings. In comparison, most concentrated solar PVT has greater total energy output for the same area but also requires tracking system, increasing system cost and hindering applications for residential usage.

b) Stand-alone PV, PV + ST, and hybrid PVT systems were simulated for comparison. Separate PV + ST perform best currently from both technical and economic points of view. However, PVT is still promising because of its relatively high efficiency and low footprint.

c) A hybrid PVT system with monitoring instrumentation was developed and installed. System performance was predicted and showed 24 PVT modules system will provide 50% of the annual electricity and 81% of the thermal demand for two West Village units. Monitoring is continuing in order to validate model simulations.

d) Large recirculation losses were discovered in the original domestic hot water system. These losses point to potential energy savings from improved inspection and monitoring of existing systems. Aside from these losses, the PVT solar thermal provided 57% of the demonstration home DHW supply in October 2013 with the potential to increase this fraction in the future.
e) PVT, as an emerging technology has manufacturers spread throughout the world with many of them were difficult to reach. Therefore, local installers and equipment wholesalers are hesitant to embrace the technology. PVT manufactures and suppliers, such as Solar Zentrum have expressed excellent customer service and support are helping to increase PVT installations, but overall, the market remains scarce and underdeveloped.
f) The team's research suggests that excess electricity credits will be generated at year-end based on the aggregate capacity of existing West Village solar electric arrays. Under current circumstances there is an over-supply of solar electricity at West Village. This means that 100% of the electricity consumed in the village is provided by the solar array. Because of the substantial contribution of the PV modules on the parking lots, some electricity is economically under-utilized, i.e., redeemed for cash at a low rate ($0.04/kWh). .
g) The amount of hot water storage influences the total percentage of the system's contribution to the buildings' hot water needs and storage capacity also effects the increased PV production inherent in combined heat and power modules. The increased PV production is a direct result of cooling the PV cells and if the system doesn't have ample thermal storage capacity, the system becomes saturated and heat can no longer be removed from the panels. Once the system is saturated with heat to the point where excess heat cannot be removed from the modules, the PVT performs no differently than standard PV modules.
h) Pumping capacity was also observed to have an important relationship to realizing the increased PV production in a combined heat and power module. What is standard pumping volume and delta T for a traditional solar thermal system will typically not be sufficient to optimize the flow needed to realize the cooling benefit of the combined heat and power module.

Recommendations

a) Future work would examine how much extra electricity is actually produced and its best use (e.g., to redeem for cash, charge EVs, or optimize solar array sizing in future phases) pending deployment of additional living space.
b) When designing and selecting the thermal storage for a PVT system, storage capacity should be carefully considered. In order to optimize the system's contribution to the buildings total hot water needs but also realize increase PV production due to cooling of the PVT modules, designers should utilize large capacity storage tanks when designing PVT systems. If California hopes to increased market saturation of PVT system, policy makers should consider incentivizing larger capacity and higher efficiency storage tanks as this equipment can presents a significant increase in cost.

c) If increased PV production as a result of cooling is desired, engineers should expect to utilize variable speed, higher volume pumps. This is another departure from what is acceptable for traditional solar thermal systems, which often use fixed speed, low volume pumps. The tradeoffs related to increasing or decreasing the delta T (as a result of pump speed and volume), to optimize the production of hot water delivery and PV performance are not yet well known. It is recommended this relationship be evaluated further through additional research.

Public Benefit to California

Hybrid PVT systems have been proposed for improving PV performance while simultaneously recovering thermal energy for building applications such as domestic hot water heating. In the past, corrosion proved a problem, and new materials, better construction and use of improved heat transfer fluids have improved modern products which recently have entered the commercial market. The hybrid PVT system installed at West Village is one of the first systems installed in California. The fully instrumented system has distinct advantages in that the solar production and the hot water energy produced can be monitored continuously to the benefit of enhanced design and performance. New control strategies for PVT can influence the pattern of energy use by the building occupants, increasing energy use efficiency and reducing cost. More detailed lifecycle analyses are needed but the PVT also appears to reduce total greenhouse gas emissions, also adding to state objectives for improved environmental performance.

Task 3 Demo 2 Single Family Home PVT Integration

Introduction

In this demonstration, PV + ST and hybrid photovoltaic/thermal (PVT) technologies and strategies for solar hot water production were evaluated with the intention of installing hybrid PVT technology, in this case in a residential single family environment. As with Task 3 Demo 1 above, simulations of system performance were made for optimizing design configuration and for comparisons among PV, solar thermal (ST), combined PV + solar thermal (PV + ST) and hybrid PVT. This section summarizes the demonstration project. The full results and performance data are available in Appendix D.

Project Objectives

The purpose of this subtask is to develop, design, purchase, install, test and assess the electricity and hot water production from a hybrid photovoltaic/thermal (PVT) system for a single-family home at Aggie Village. The system was modeled in order to determine the optimal arrangement of PVT panels and to compare with separate PV and solar thermal configurations. By collecting actual data from the PVT system, assessments can be made as to performance and energy savings in comparison to the existing means of hot water production.

Project Summary

- Review and evaluate various commercially available or near term market PV and ST technologies.
    - Technical memorandum listing and comparing commercial and emerging PVT and ST systems, technologies and providers.
- Compare technologies that combine solar electric and thermal generation that can be considered in the next phase of WV construction.
    - Technical memorandum comparing the efficiency, footprint, and cost of PV only, PV + ST, and hybrid PVT systems using computer simulations.
- Identify a site for single family solar system.
    - Select a site and negotiate an agreement with the developers or real estate managers.
- Negotiate an ownership and operation agreement between Carmel Partners and UC Davis.
- Collaborate with manufacturer and contractor to determine systems design and specifications for the model PVT or PV + ST system.
    - Obtain cost estimate and prediction of performance.
    - Construction drawings.
    - PVT system model for simulating energy generation, storage requirements and energy demand, using real time forecast information.
- Determine metering, monitoring and control requirements to integrate with West Village AMI, and conduct test operation of the system.
    - Outline of a research plan, detailing the data to be acquired from monitoring.
- Continue monitoring system performance and end-use consumption and compare to simulation predictions.

Key Findings

Reviews of PV, PV + ST, and PVT technologies and manufacturers

A combination with Task 3 Demo 1, review and evaluation of appropriate PV, combined PV + ST, and hybrid PVT technologies was conducted with industry advisors and manufacturers. Refer to Task 3 Demo 1 for more details.

Quite similar to subtask 3.1, after reviewing several manufacturers of PVT and PV + ST, a Solar Zentrum PVT system was selected. Also, a single-family house located in Davis, CA and owned by UC Davis, was selected as the demonstration site.

PVT and monitoring system design and performance prediction

Based on simulation results and advice from the manufacturer, a 4 PVT + 8 PV panels were arranged in a 4 x 3 design at the Aggie Village house. Design peak electrical capacity was 2.2 kW. The 8 standard PV panels have identical PV cells to the PVT panels which allow the comparison of electricity generation between the two. Because the PVT panels are actively cooled, it is expected they will have a higher efficiency. This demonstration was integrated with the effort under Task 1 Demo 2 at the same site. The design was permitted (410 First St. Residence Solar Upgrade Project) and approved for construction.

After the system was designed, a model based on current PVT system design, weather data and user profile was established to predict the energy output for both electricity and hot water. From the performance prediction, the estimated electrical generation was 3300 kWh/year and thermal production was 2500 kWh/year, with capacity to cover about 42% of electricity demand and 17% of domestic hot water consumption of a typical household. The system was installed on site in August 2013 (Figure 10).

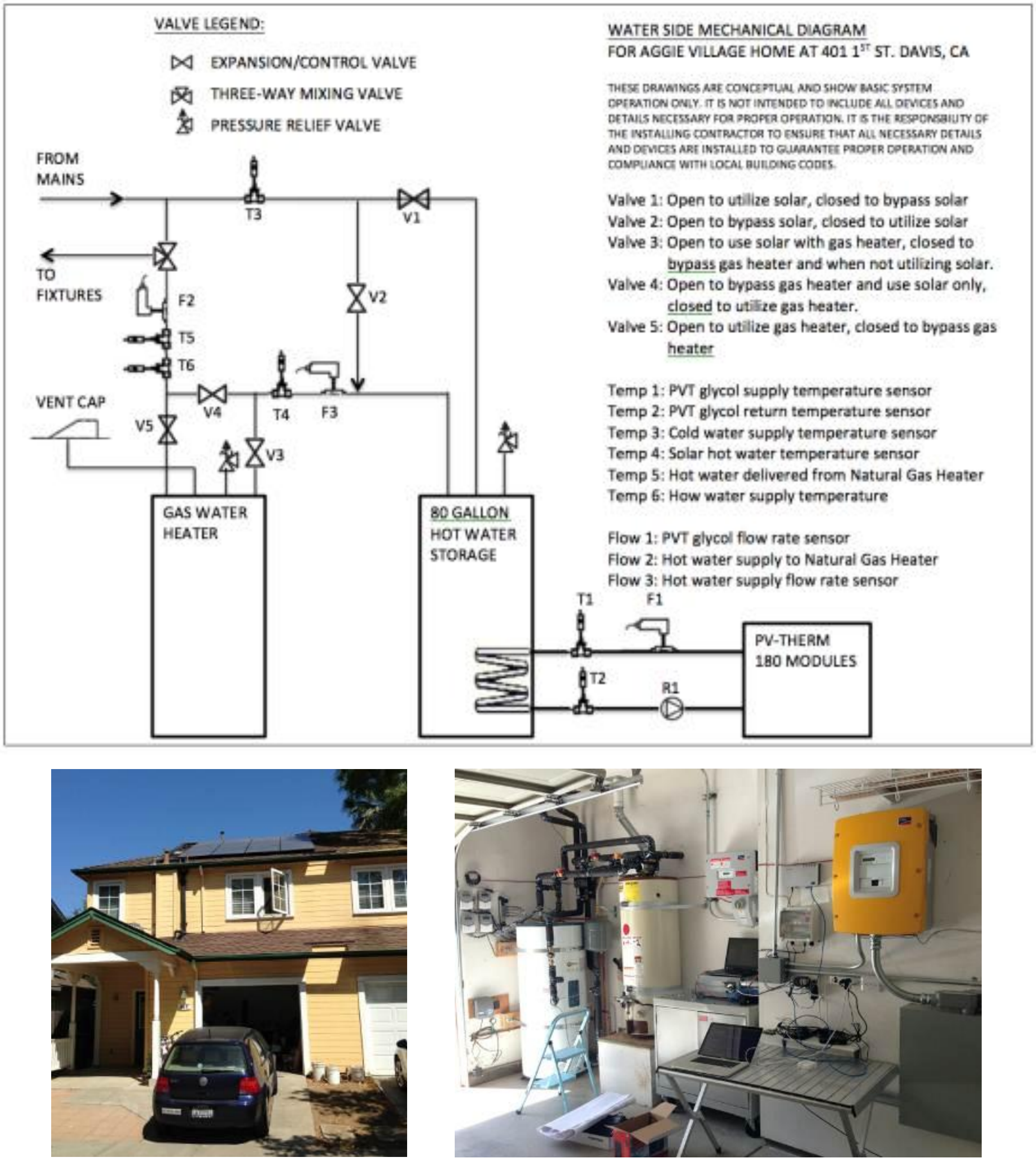


Figure 22: Instrumentation plan and photos of the PVT system installed at Aggie Village.

Collected data and analysis

a) Solar electricity generation

The PVT system started generating electricity on August 17, 2013. Due to system troubleshooting, routine operation was not established until Sep. 1, 2013. By end of December 2013, the PVT system had generated a total of 975 kWh of electricity. Visitors are able to see real-time electricity generation through the following link:
http://www.tigoenergy.com/site.php?8ac71083-e84c

One-month of solar electrical generation in September 2013 is shown below. As can be seen from Figure 11, except for day 4 and day 21 when it was rainy, the system generated approximately 8 to 12 kWh of electricity each day. Total electricity generated in September was 291.6 kWh. For comparison, we also show the electrical generation in October 2013. The electrical production in October is 290.7 kWh, which is almost the same as that in September. There is a clear trend of decreasing electrical generation associated with the change in solar radiation as winter approaches. Furthermore, we can also calculate the solar electric fraction in both months. The results show that the PVT system covered approximately 44% of electricity demand in these two months, which is consistent with the simulation result (42%). By the end of December 2013, the PVT system had generated a total of 975kWh of electricity.

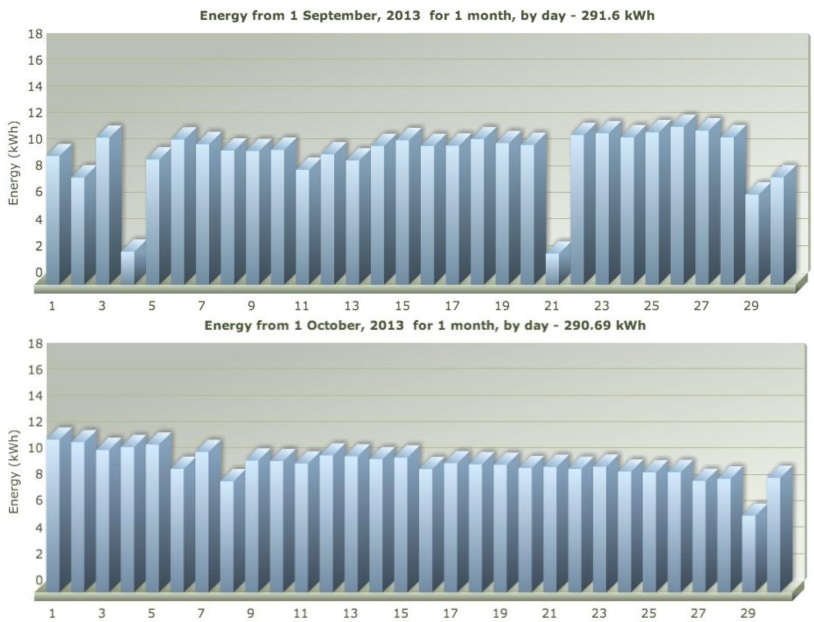


Figure 23: Electricity Generation of PVT System during September and October

b) Solar thermal production

An online system (Resol Vbus.net) was added for solar thermal data collection. Similar to the solar electric generation, visitors are able to see this real-time information through the following link: http://www.vbus.net/vbus/scheme/id/792

Flow-rate and temperature data were collected starting September 24, 2013. Figure 12 shows temperatures and flow rates during October 2013. From these monitoring points, the total domestic hot water delivered to the home, the heating contribution of the PVT array, the heat contribution of the natural gas water heater, and other system performance are determined (Table 10). The PVT fraction is much higher than the simulation results (85% versus 17%). This is largely due to the tenants in the house using much less hot water than the typical single family assumed. The system only delivered 48.8 kWh of heat as DHW in October. Regardless of that, the PVT actually performed better than expected from the simulations.

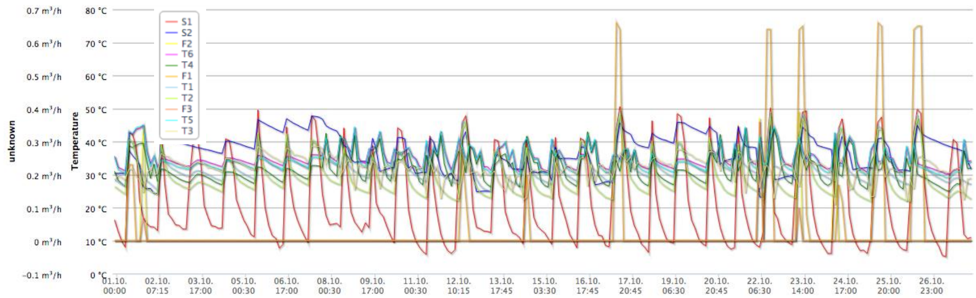


Figure 24: Temperatures and flow rates plotted versus time during October 2013

Unit: kWh	*PVT Glycol Loop (PVT heat exchanger efficiency)*	*System delivered*	*Natural Gas Heater (Fraction)*	*PVT (Fraction)*
Oct. 1st – 30th	*71.1 (58.4%)*	*48.8*	*7.3 (14.9%)*	*41.5 (85.0%)*

Table 9: Heat flow in PVT system during October 2013

Unfortunately, a problem with one of the power maximizer attachments to the PVT panels operated improperly beginning in mid-November, 2013. The defective unit is currently being replaced and monitoring will continue in the following months.

Conclusions and Recommendations

Conclusions

a) Technical and economic comparisons were made of different PV+ST and PVT systems. By simulation, separate PV + ST offers cost and performance advantages, but the PVT has a lower physical footprint for rooftop deployment. Additional monitoring data will be used in further evaluating the PVT performance.
b) Simulations show an estimated electrical generation from the installed system of 3300 kWh/year and thermal production of 2500 kWh covering about 42% of electricity demand and 17% of DHW consumption, respectively.
c) The hybrid PVT system was installed on site in August 2013. All the components and instrumentation were found to work properly.
d) Following PVT system installation in August 2013, data have been successfully collected for analysis of actual system performance. By the end of December 2013, the PVT system had generated a total of 975 kWh of electricity. The results also show that in October and November the PVT system covered approximately 44% of electricity demand, similar to model predictions (42%). The PVT thermal fraction is much higher than our previous simulation results (85% versus 17%) due to much lower DHW use by the occupants of the residence.
e) As also observed in the multifamily PVT system: the amount of hot water storage not only influences the percentage of the system's total contribution to the buildings hot water production but also effects the increased PV production inherent in combined heat and power modules. The increased PV production is a direct result of cooling the PV cells. If the system doesn't have ample thermal storage capacity to remove heat from the panels, the modules perform no differently than standard PV modules.

f) Pumping capacity was also observed to have an important relationship to realizing the increased PV production in a combined heat and power module. What is standard pumping volume and delta T for traditional solar thermal systems will probably not be sufficient to optimize the flow needed to realize the cooling benefit of the combined heat and power module.

Recommendations

a) We recommend future research to explore the financial benefits related to influencing consumer behavior or by practicing different hot water heating use and methods, such as heating at night and storing during the day, or using solar thermal and PVT collectors. Storage of hot water equates to storage of energy. Optimum water storage will need to be determined based on the cost of the storage and other factors.
b) When designing and selecting the thermal storage for a PVT system, storage capacity should be carefully considered. In order to optimize the system's contribution to the buildings total hot water needs and also realize the cooling benefits of PVT modules, designers should utilize large capacity storage tanks when designing PVT systems. If increased market saturation of PVT systems is desired, policy makers should consider incentivizing not only the panels, but larger capacity and higher efficiency storage tanks as well, as this equipment can present significant increase in cost.
c) If increased PV production as a result of cooling is desired, engineers should expect to utilize variable speed, higher volume pumps. This is another departure from what is acceptable for traditional residential solar thermal systems. The tradeoffs related to increasing or decreasing the delta T (as a result of pump speed), influences the optimization of hot water delivery and PV performance. This relationship is not yet well known and is recommended this be evaluated further through additional research.

Public Benefits to California

The hybrid PVT system installed at the house in Aggie Village is one of the first residential systems installed in California. The fully instrumented system at Aggie Village has distinct advantages in that the solar electric generation and the hot water produced can be monitored continuously, benefitting improved design and performance. As in the case of the multifamily unit, new control strategies for PVT can influence the pattern of energy use by the occupants, increasing efficiency and reducing cost. Lifecycle greenhouse gas emissions may also be reduced. Continued performance monitoring will provide additional information pertaining to the economic and environmental impacts and the potential for broader market application and replication across the state.

References

In this report, references have been included as footnotes. The individual demonstration final reports contain complete reference sections.

Appendix

Preliminary reports for the tasks are separately attached as appendices.

Appendix A – Task 1 Demo 1-Battery Buffered Electric Vehicle Charging Station Demonstration

Appendix B – Task 1 Demo 1-Single Family Home Energy Storage

Appendix C – Task 2-Integration of AMI with Solar PV & other DER Technologies

Appendix D -Task 3 Demo 1- PVT integrations, Demo 2-Single family home PVT integrations

APPENDIX A

Task 1 Demo 1 Battery Buffered Electric Vehicle Charging Station Demonstrations

Prepared for Itron

Prepared by: UC Davis Energy Institute and the
UC Davis Office of Environmental Stewardship and Sustainability

August 2014

WEST VILLAGE SOLAR PV POWERED BATTERY BUFFERED ELECTRIC VEHICLE CHARGING STATION

Researchers: Hengbing Zhao and Andrew Burke

Project Manager: Tobias Barr

August 2014

Abstract

A solar PV powered battery buffered electric vehicle charging station was designed, installed and in UC Davis West Village, the largest planed zero net energy community in the United States. The solar powered, battery buffered EV charging station system consists of a 5 kW solar PV panel, a 35 kWh Lithium-ion battery, a 10 kW demand response bi-directional inverter, and a level 2 electric vehicle charger. The battery buffered charging station permits the maximum use of solar energy for charging electric vehicles and minimizes the impact of the charging on the electric utility grid.

Acknowledgements

We would like to give our special gratitude and thanks to California Solar Initiative for their financial support, the UC Davis Energy Institute for their help in developing and managing the project and Itron for their ongoing management of support of the CSI RD&D program.

Executive Summary

Solar PV Powered Battery Buffered Electric Vehicle Charging Station

Introduction

This task is concerned with the design, installation, checkout and demonstration of a battery buffered electric vehicle charging station in West Village. The electric energy for this station is provided from a nearby panel of photovoltaic solar cells or from the grid. The battery buffered charging station will permit the maximum use of solar energy for charging electric vehicles and will minimize the impact of the charging on the electric utility grid. The control of the electric energy to and from the battery and to the charging station is done through a bi-directional inverter which can function either as a DC/DC or DC/AC inverter as needed. West Village at UC Davis is the largest planned zero net energy community in the United States. It has an on-site over 2 megawatt PV generation, and is expected to be an area with high EV adoption. Hence it is an ideal site for demonstrating the battery buffered EV charging technology.

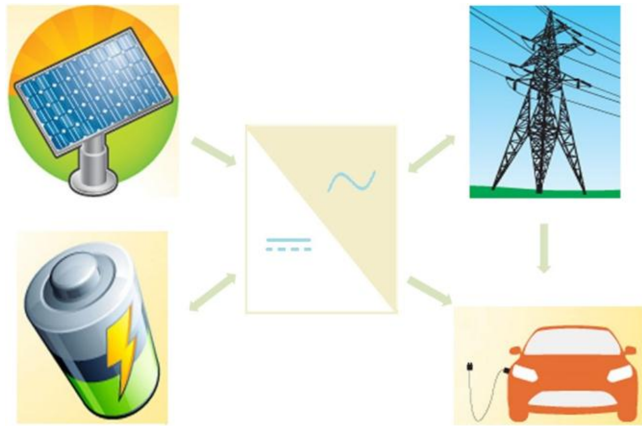
Project Objectives

Design, install, checkout and demonstrate a solar PV powered battery buffered electric vehicle charging station in West Village

Project Summary

The solar powered, battery buffered EV charging station system consists of a 5 kW solar PV panel, a 35 kWh Lithium ion battery, a 10 kW demand response bi-directional inverter, and a level 2 electric vehicle charger as shown in Figure 1. The bi-directional inverter controls power flow between the different units. It has two DC ports which are connected to the PV panel and battery storage and two AC ports tied to the utility grid and EV charger, respectively. PV power can be used to charge the EV, be stored in the battery, and/or be fed to the grid. The PV panels, battery storage, and the grid can provide power for charging the EV.

The control strategy for the system is to maximize PV energy used for EV charging and to reduce grid power demand from EV charging. There are two operating modes: grid-tied and standalone. Most of time, the charging station operates in the grid-tied mode. In the grid-tied mode, the EV can be charged from PV, the battery, and/or the grid. In the case of a power outage, the system will automatically switch to standalone mode and be isolated from the grid. In the standalone mode, the EV is charged from PV and the battery. When the grid power is restored, the system will automatically switch to grid-tied operation.



Solar Powered EV Charging Station Equipped with Battery Storage

In the grid-tied operation mode, when an EV is plugged into the charger, PV power is used to charge the EV if it is available. If more power is needed, the remaining power is provided by the battery or/and the grid. If no electric vehicle is plugged-in, PV energy is stored in the battery and if the battery is completely charged, excess PV power is fed to the grid. During off-peak hours, grid power can be used to charge the battery to a specified state-of- charge level. Energy is not fed to the grid from the battery in the present system.

In the stand-alone mode, grid power will not be available. Hence PV, if available, will power the EV charger supplemented if needed by energy from the battery.   If excess PV energy is available, the it will be stored in the battery.

Key Findings

It was found that a computer controlled battery buffered vehicle charging station using PV energy could be designed and constructed using available components and computer software. All the components are in place and connected, including the tie to the grid. The system has been commissioned and is in the early stages of demonstration.

The batteries and the bidirectional AC/DC inverter are housed in a large closet in the building at 1605 Tilia Street and the vehicle charger is in place behind the building. The control computer for the system is also in the large closet. The software for the control and monitoring of the complete system has been written and debugged. The battery pack consisting of eleven modules of lithium iron phosphate cells in series (350V nominal voltage) stores 35 kWh of energy and easily provides the 10 kW to the inverter. The battery pack includes battery management units (BMU) which monitor the cell voltages and temperatures and reports the results to the control computer.

Conclusions and Recommendations

A battery buffered vehicle charging station has been designed and build in West Village that uses electric energy from nearby PV panels to charge electric vehicles (EVs). The charging station is also tied to the grid and the control strategy for operation of the station will minimize its impact on the grid. The lithium-ion battery and bi-directional inverter which controls the energy to/from the battery and to the charging station are in place and connected into the system. The completed charging station has been commissioned and detailed data are being taken of its operation both as a means of storing PV electrical energy and charging vehicles on demand independent of the availability of PV energy or the grid.

The PV array (34 m2) for the West Village project is mounted vertically on the tower attached to the building at 1605 Tilia Street. The resultant PV energy is 7-14 kWh/day of electric energy in the summer and 14-28 kWh/day in the winter season. The PV energy should be sufficient to charge EVs that have traveled 75 and 40 miles per day in the winter and summer, respectively. This should permit a meaningful demonstration of the vehicle charging station using the present PV array and provide an opportunity for expanded vehicle charging if more PV energy is made available.

After this project is completed, research using the vehicle charging station will continue supported by a recent EISG grant, Intelligent Energy Management for the Solar Powered EV Charging Station. This research will include in the control of the charging station information on weather forecasts (solar intensity) and projections of the daily use patterns of the station. It is recommended that during this demonstration more PV energy than is currently available from the tower alone be made available for use at the vehicle charging station.

Public Benefit to California

The public benefits to California of this project are the demonstration of the use of PV energy to charge electric vehicles and the use of battery storage to maximize the fraction of the PV energy that can be used for charging and to minimize the impact of electric vehicle charging on the utility grid. Both of these benefits will become increasingly important as the number of electric vehicles in California continues to increase and the need for storage by the utilities becomes greater as the contribution of PV power generation becomes larger.

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Nomenclature

AC	Alternative Current
CANBUS	Controller Area Network Bus
BMS	Battery Management System
BMU	Battery Management Unit
DC	Direct Current
EV	Electric Vehicle
MODBUS	A Serial Communication Protocol
PCI	Peripheral Component Interconnect
PCIe	Peripheral Component Interconnect Express
PV	Photovoltaic
SOC	State of Charge
VRLA	Valve Regulated

1. Introduction

UC Davis West Village is the largest planned zero net energy community in the United States. It has an on-site 5 megawatt PV generation capacity and also is an area with high interest and expected high adoption of EVs. This makes it an ideal site for demonstrating the charging of EVs using PV generated electricity. Since when PV energy is available is not likely to match when it is needed for vehicle charging, it will be necessary to store some of the PV energy in batteries or transfer it to the grid as is done in most distributed residential PV systems. Storing the excess PV energy will make it possible to minimize the effect of EV charging on the grid and hence is encouraged by the utilities.

With rapid adoption of electric vehicles and mass installation of solar PV systems, especially in high PV and EV penetration areas, electric vehicle charging, especially fast charging poses a challenge for conventional utility grids, which lack the capacity to deliver high power and to store surplus solar electricity. One approach is to upgrade the electricity distribution networks and to employ smart grid technologies. This will require utility-wide integration of traditional IT solutions with operational energy storage technologies required to manage an increasingly complex and data-driven utility grids. It may not be economical to upgrade distribution infrastructures, including energy storage, in the early stage to handle this higher power demand and surplus solar PV energy. Another lower-cost and more reliable approach is to handle the solar PV energy and electric vehicle charging mismatch from the customers' side, which is to store the excess PV energy in a battery for later use in the vehicle charging stations. The battery storage system helps buffer the electric grid from the spike power demands of electric vehicle charging when the charging station is grid-connected.

This task is concerned with the design, installation, checkout and demonstration of a battery buffered electric vehicle charging station in West Village. The electric energy for this station is provided from a nearby panel of photovoltaic solar cells or from the grid. The battery buffered charging station will permit the maximum use of solar energy for charging electric vehicles and minimize the impact of the charging on the electric utility grid. The control of the electric energy to and from the battery and to the charging station is done through a bi-directional inverter which can function either as a DC/DC or DC/AC inverter as needed. This report discusses in detail the design of the battery buffered charging station and how it will be operated in conjunction with the utility grid. This will include consideration of various aspects of the selection of the batteries for the electrical energy storage and the characteristics of the batteries selected for this system.

2. Technical Approach

2.1 Electrical Energy Storage Technologies for Charging Stations

2.1.1 Selection Factors

There are a number of factors involved in the selection of a battery for use in a battery-buffered vehicle charge station. These factors include the following:

(a) initial cost
(b) maintenance requirements

(c) cycle life
(d) safety
(e) energy density
(f) thermal management
(g) charge/discharge efficiency

The first four factors are the most important and a large deficiency in one of these factors could preclude a battery technology from being considered for use in charge station energy storage. Energy density (Wh/kg, Wh/L) is much less important in stationary applications than for vehicle applications like in an EV. Power density (W/kg, W/L) is also much less important in the stationary applications because the power (kW) for charging is relatively low being in the range of 5-50 kW even for fast charging and the storage battery packs are relativity large (25-100 kWh). For example, charging at 6.6 kW and storage of 50 kWh results in a charge/discharge of 7.5 hours. Hence the charge/discharge times for the batteries for stationary applications are measured in hours or fraction of days.

For stationary storage, economics (initial cost and cycle life) and safety are the most important factors. In the case of economics, the most important consideration is cost of each kWh stored in $/kWh stored, which is given by

$/kWh stored = battery cost/ energy input over the life of the battery

= initial cost ($/kWh) x kWh capacity/cycle life x kWh stored

For example, consider a 100 kWh battery costing $200/kWh having a cycle life of 4000 cycles and a storage capability of 80% of its capacity.

$/kWh stored = 200 x 100 /(4000 x 80) = 0.0625 or 6.25 cents/kWh stored

In many stationary applications, the battery is charged and discharged once a day. In this example, the battery life would be slightly less than 11 years and the $/kWh stored over the life of the battery would be 6.25 cents /kWh. To greatly reduce the cost of energy storage, one needs to reduce the initial cost ($/kWh) and increase the cycle life. Fortunately there are batteries becoming available with long cycle life in excess of 10,000 cycles.

Battery safety is a critical issue for all battery applications. The main concerns for safety are the production of hydrogen during charging for aqueous electrolyte batteries, such as lead-acid and nickel metal hydride, and thermal runaway and electrolyte leakage for lithium batteries using organic electrolytes. In both cases, the primary approach to insuring safe operation of the batteries is monitoring their operation by measuring the cell voltages and temperatures and utilizing detectors for hydrogen or smoke. In addition, careful attention is given to limiting charge and discharge voltages and currents to preclude battery damage during cycling of the batteries. As noted previously, in most stationary applications like the vehicle charging station, the batteries do not experience high power conditions in either charge or discharge so they should operate at relatively low temperatures and electrical stress. Especially in the case of lithium batteries, battery management units (BMU) have been developed for all the cells and modules commercially available. The BMUs, which are linked to the battery system control computer, will stop battery operation in the event of problems with any cell and will notify key personnel, including those concerned with fire, of problems with the batteries.

2.1.2 System Design Factors

The battery pack (voltage and kWh) and cell size (Ah) will be sized by the PV energy available on a daily basis and the needs of the charging station in terms of the voltage and power required to charge the EVs. The PV energy available is proportional to the size m^2 of the PV panels and is dependent on their orientation to the sun. The electric energy required by the charging station is proportional to the number of EVs charged per day and the average energy required to charge their battery. The vehicle energy requirement follows from the energy usage Wh/mi of the EV and the miles traveled between battery charges. The maximum energy requirement for a given EV will be the size kWh of the battery pack which is between 20-30 kWh for most EVs. For example, if a charging station serviced 10 EVs which had an energy usage of 250 Wh/mi, charging efficiency of 87%, and average daily travel of 40 miles per day, the daily energy requirement of the charging station would be

$$E_{required} = 10x\ 0.250x40/0.87 = 115\ kWh/day$$

To meet the needs of the EVs charging at a station using primarily PV energy would require sufficient PV panel area to generate about 100 kWh per day. During the day when PV energy is available, it is used directly by the charging station if an EV is connected. Otherwise the PV energy is stored in the battery for later use. Most charging stations will be Level 2 with a voltage of 208-240 AC and a power requirement of about 6.6 kW AC. If it is assumed that 75% of the PV energy will be stored before it is used, the storage capacity of the buffer battery should be about 85 kWh. As will be discussed in later sections and is shown in Figure 1, a bi-directional AC/DC inverter is needed to convert AC from the PV to DC to charge the buffer

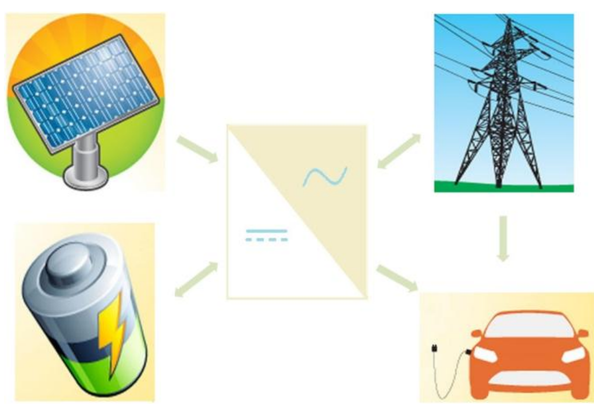

Figure 1: Block Diagram of the Battery Buffered Vehicle Charging Station

battery and back to AC to charge the vehicle battery. If the nominal voltage of the buffer battery is taken to be 400V, the cell size Ah of the battery will be

$$85000/400=212 \text{ Ah}$$

Hence the buffer battery could utilize single cells of 212 Ah or smaller cells in parallel. The maximum power to be drawn from the battery is only 6.6 kW to charge the EV so its maximum rate of discharge will be only at the 12 hour rate (C/12), which is very low. This low rate will be typical for buffer batteries. In most cases, the maximum power of the DC/AC inverter will be set by the maximum power from the PV panels if it is intended to store most of the PV energy. Otherwise a significant fraction of that energy will be transferred to the grid and only a small fraction of PV energy will be available to charge the EV. For a PV system with the panels oriented optimally, the ratio of energy generated to its peak power is about 7. Hence for the present example, the peak power of the panels is

$$P_{peak} = 115/7 = 16.4 \text{ kW}$$

The maximum power rating of the AC/DC inverter should be slightly greater than the peak power from the PV panel. For this example, a DC/AC inverter maximum power of about 20kW would be adequate.

The size of the PV panels depends on the peak power rating (W/m^2) of the panels to be installed. The panel rating of Sun Power panels is increasing and presently varies between 180 and 250 W/m2 [1]. The efficiency of the panels is between 10-20%. Assuming a peak power rating of 200 W/m^2, the size of the panels would be 16400/200 = 82 m^2. As noted above, if the panels were optimally oriented (South at the proper slope), the output of the panels would be about 115kWh in the Spring and Summer, but would be less in the Winter due primarily to a much reduced clearness factor. Estimating the panel output for vertically mounted panels as is the case for the West Village project is more difficult as there is much less experience with vertical panels than with more optimally oriented panels.

2.1.3 Characteristics of Batteries of Various Chemistries

Lead-acid and lithium batteries of various chemistries could be used in the West Village application. Recent comparisons of the performance of the various batteries are shown in Tables 1 and 2 based on testing [2, 3] done in the Battery Laboratory at UC Davis. As expected, the energy densities of the lithium batteries are higher by a factor of 3-5 than the lead-acid batteries. However, for the stationary applications, the selection of the batteries will be based primary on cost, cycle and calendar life, and safety issues and energy density is of secondary importance.

As indicated in Table 2, the cycle life of lithium batteries for deep discharge is at least several thousand cycles which is much longer than that of lead-acid which is at best several hundred cycles. However, the cost of lead-acid batteries ($100-200/kWh) is much lower than that of lithium batteries ($500-1000/kWh). There has been considerable effort to increase the cycle life of lead-acid batteries especially for applications in which the batteries spend a considerable fraction of their time at partial states of discharge. The developers of the advanced lead-acid batteries have shown particular interest in solar PV and wind applications. All the advanced lead-acid concepts have introduced carbon into the negative (anode) electrode of the battery. All these batteries are sealed and valve regulated (VRLA) and require no maintenance.

Battery	Ah	Wh/L	Resistance mOhm	V	(W/L) 95%	Density kg/L
Enerdel graphite/NiMnO2	15	276	1.4	3.8	2642	2.4
GAIA graphite/NiMnO2	40	309	.48	3.8	3008	2.4
Altairnano Lititanate/MnO2	3.8	67	1.15	2.6	2051	1.9
A123 graphite/FePhosph.	2.2	198	12	3.4	1438	2.2
Saft Ultrapower Graphite/NiCoAlO2	5	147	.8 (Saft)	3.8	6295	2.57
Panasonic Ni Metal hydride	6.5	83	1.8	1.15	370	1.8
Panasonic Lead-acid	25	65	7.8	2.0	192	2.5

Table 1: The Performance of Various Types of Batteries

Chemistry Anode/cathode	Cell voltage Max/nom.	Energy density Wh/kg	Cycle life (deep)	Thermal stability
Graphite/$NiCoMnO_2$	4.2/3.6	100-170	2000-3000	fairly stable
Graphite/ Mn spinel	4.0/3.6	100-120	1000	fairly stable
Graphite/ $NiCoAlO_2$	4.2/3.6	100-150	2000-3000	least stable
Graphite/ iron phosphate	3.65/ 3.25	90-115	>3000	stable
Lithium titanate/ Mn spinel	2.8/2.4	60-75	>5000	most stable

Table 2: Characteristics of Lithium-Ion Batteries Using Various Chemistries

Several of those development efforts are summarized in the following paragraphs.

The Ultrabattery by East Penn Manufacturing

In this design, the negative electrode, which in the standard design uses porous lead, is split into two parts. One-half of the electrode is fabricated using the porous lead and the other half is formed with porous carbon. The positive electrode consists of the same porous PbO2 used in the standard lead-acid battery. The carbon is introduced to enhance the charge acceptance of the negative electrode and to greatly reduce the tendency of the negative electrode to sulfate at intermediate states-of-charge. Tests of the Ultrabattery have indicated a long cycle life of several thousand deep discharge cycles and many thousands of shallow cycles at intermediate states-of-charge. This battery is likely to be well suited for the West Village application where much of its operation will be at intermediate states-of-charge.

The PbC battery by Axion Power International

In this design, all the negative electrodes in the lead-acid battery are replaced by porous carbon electrodes. The charge capacity (Ah) of the battery is determined by the mass of carbon in the negative electrode. The cycle life of the battery depends on the characteristics of the positive electrode because the cycle life of the carbon electrode is several hundred thousand cycles. The PbC battery has very good charge acceptance characteristics with little concern for sulfation. It is especially well suited for applications in which partial states-of-charge are experienced on a regular basis.

Lead-Carbon Battery by C&D Technologies

This battery is designed and fabricated much like the standard lead-acid battery except that a few percent by weight of carbon is added to the paste used in the negative electrode which then consists of a mixture of porous carbon and lead. The addition of the carbon is intended to enhance the charge acceptance of the negative and to reduce or eliminate sulfation at partial states-of-charge. C&D has developed this battery under contract to the US Army and is ready to commercialize it especially for standby, stationary applications like West Village.

Contact was made with the three companies listed, but it was not possible at this time to get either sample batteries to test or a commitment for batteries for use in the West Village vehicle charging station project.

2.1.4 Characteristics of the Batteries Used in the Vehicle Charging Station Project

It was decided to use lithium batteries in the vehicle charging station project for two reasons. First, space was limited in the place (large closet) in which the batteries had to be placed and second, cycle life was important as we did not want to have to replace the batteries in a couple of years. Standard deep-discharge lead-acid batteries would have been much too large to fit in the closet space and their cycle would have been less than one year assuming one cycle per day. It was decided to use lithium batteries of the iron phosphate chemistry because as shown in Table 2, they had reasonably high energy density (200-250 Wh/L) and long cycle life (2000-3000 cycles). In addition, the lithium iron phosphate chemistry is considered to be one of the most stable, safest of the lithium battery chemistries. It was decided to purchase the lithium batteries from Lithium Force (LF), located in Guangzhou, China. Dr. Burke had tested a number of cells from Lithium Force in 2011 and found them to have good performance and high quality. In addition, Dr. Burke had a good contact at Lithium Force and was able to get a good price and fast delivery of the batteries.

The battery pack for the vehicle charging station consists of 11 modules with each module containing two parallel strings of ten of the 50Ah LF cells in series. The nominal voltage of the pack is 352V (10x3.2x11) and the energy stored is 35 kWh (2x10x3.2x50x11). The charge and discharge currents for the pack will be low being about 20A if the battery is used to charge a vehicle with a 6.6kW onboard charger. This represents about C/5 rate event for the battery.

A number of the 50Ah cells were test in the Battery Lab at UC Davis. The results are summarized in Table 3. The tests confirmed that the cells had a capacity of 50Ah and 160 Wh at discharge rates appropriate for the West Village application. Note that the cut-off voltage used in the tests was 2.5V/cell which is higher than the 2.0V/cell often used to test lithium iron phosphate cells. This results in the Ah and Wh capacities being somewhat more sensitive to the rate of discharge than if a lower cut-off voltage had been used.

LF cell	Iron Phosphate			
FO 11A	Weight 1.85kg	3.65-2.5V		
Power (W)	W/kg	Time (sec)	Wh	Wh/kg
60	33	9340	156	84
109	60	4900	149	81
260	142	1900	137	75
Current (A)	Time (sec)	Ah	C Rate	
15	11950	49.8	.30	
50	3428	47.6	1.05	
100	1660	46.1	2.2	
Resistance	2 sec Pulses			
	mOhm			
Voc	50A	100A		
3.27	1.7	1.6		

Table 3: Test Data for the LF Cells Used in the West Village Charging Station

2.2 Integrated System Design

2.2.1 System Overview

The solar powered, battery buffered EV charging station system consists of a solar PV panel, a Lithium ion battery storage, a demand response bi-directional inverter, and an electric vehicle charger as shown in Figure 2. The bi-directional inverter controls power flow between the different units. It has two DC ports which are connected to the PV panel and battery storage and two AC ports tied to the utility grid and EV charger, respectively. PV power can be used to charge the EV, be stored in the battery, and/or be fed to the grid. The green arrows in Figure 2 give the flow direction of PV power. The energy stored in the battery can be used to charge an EV or fed to the grid, as shown by the red arrows. The PV panels, battery storage, and the grid can provide power for charging the EV, as indicated by the blue arrows. The system is capable of controlling the power flow according to commands from a supervisory computer.

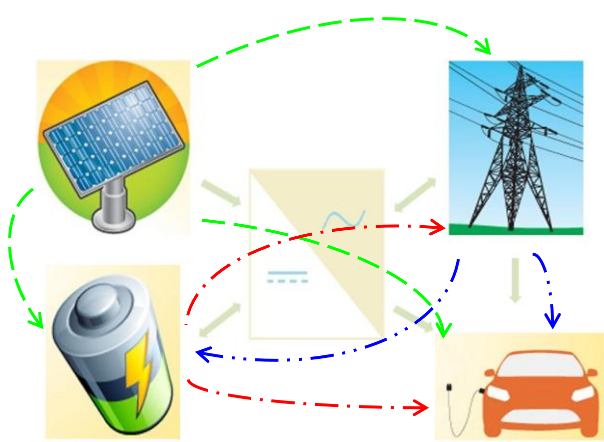

Figure 2: Solar Powered EV Charging Station Equipped with Battery Storage

2.2.2 System Design

To maximize PV energy used for EV charging and to reduce grid power demand from EV charging [4], a solar PV powered battery buffered EV charging station was developed in the present project. Considering most current electric vehicles have an on-board charger less than 10 kW and most conventional EV charging stations (level 2) are based on 240V/30A service, a 10 kW charging system is used to demonstrate the battery buffered charging station. A 5 kW SunPower PV panel on the vertical tower at West Village is nearby and available for use in vehicle charging. A GE charger with a level 2 outlet was selected for the charging station. Lithium Force provided a 35 kW lithium iron phosphate battery bank with its battery management system. A 10 kW demand response bi-directional inverter which can be connected to batteries, solar PV arrays, utility grids, and local loads was purchased from Princeton Power. At the present time, it was difficult to find a suitable high voltage, bi-directional inverter and the unit from Princeton Power was one of the few on the market. The Princeton Power unit was selected to maximize the PV output, regulate the battery charging and discharging, and to connect with electric grid. Since the PV array is positively grounded, an internal transformer option was selected to provide electric isolation between the DC side (PV and battery side) and the AC side (grid and load side) in the bi-directional inverter.

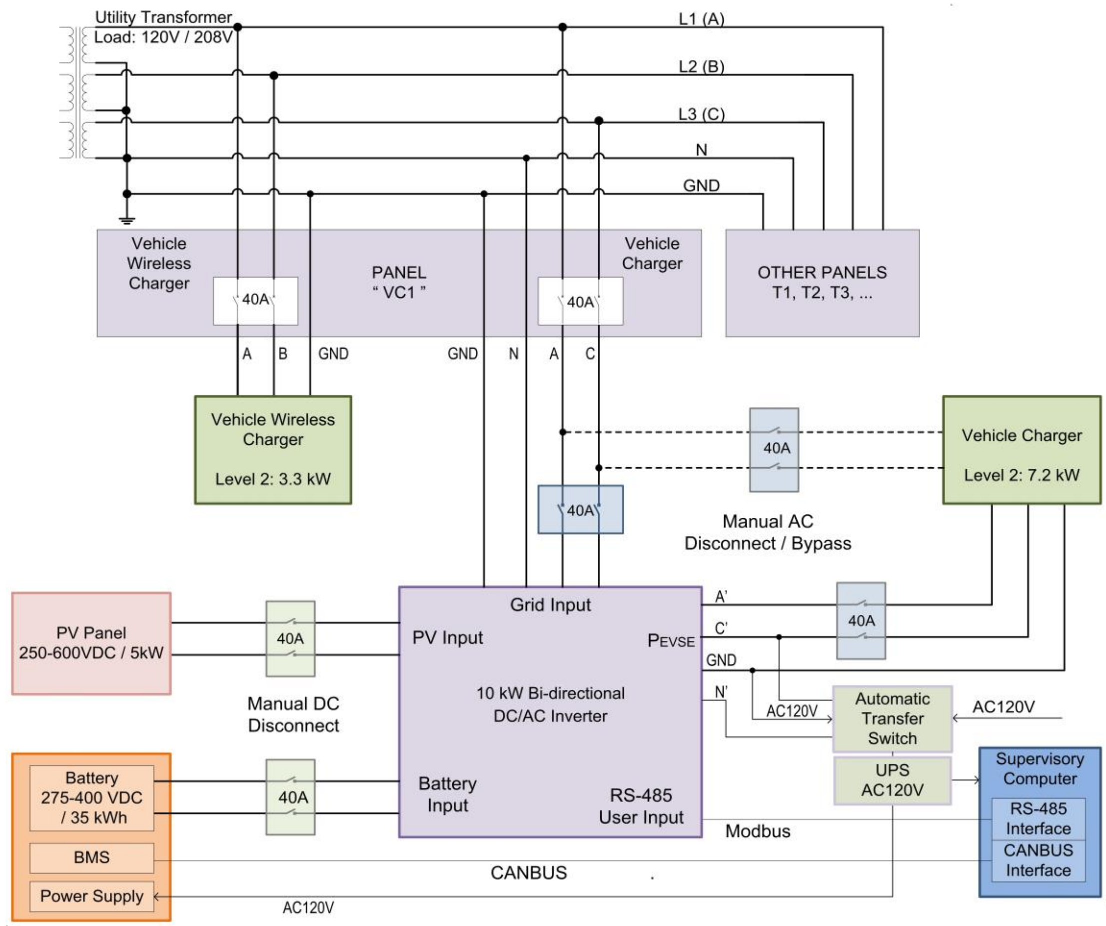

Figure 3: Block Diagram of the Solar Powered, Battery Buffered EV Charging System

A supervisory computer communicates with the battery management system and the bi-directional inverter to monitor battery status, give control commands, and record operation data for the system. A dual power supply approach was adopted to power the critical loads – the supervisory computer and the battery management system. An automatic transfer switch is used to switch from primary power supply – the utility grid to the inverter output in case of power outage. An uninterruptible power supply (UPS) is utilized to avoid power interruption during switching. An AC bypass switch directly connects the loads to the utility grid in case of the system error. Figure 3 shows the detailed block diagram of the charging station.

2.2.3 System communication

The battery management system (BMS) consists of a master BMS and six slave BMSs. Each slave BMS can monitor 20 cell voltages and 6 temperature points. The master BMS collects cell information from each slave BMS via internal CANBUS. The master BMS monitors the battery operation status, calculates the state-of-charge (SOC) and allowable maximum charging /discharging current, implements logic control, and passes all the information to the supervisory control computer via an external CANBUS. The communication board in the bi-directional inverter sends the operation status of the inverter and the measured data of each DC

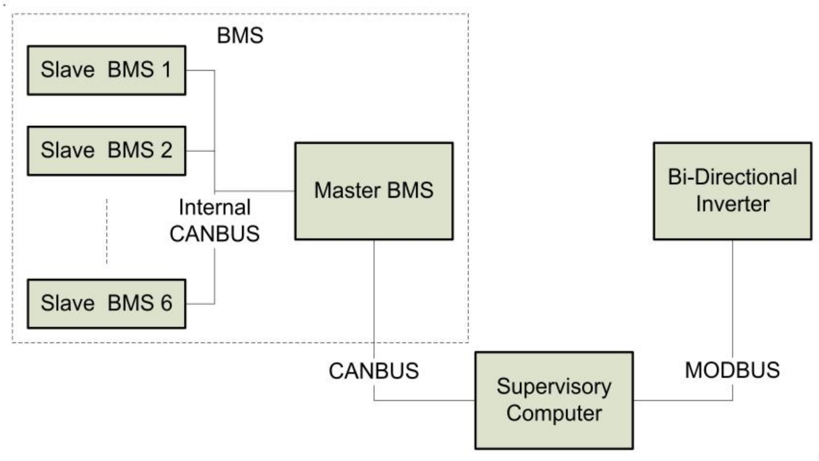

Figure 4: Block Diagram of Communication between Different Units

Master BMS	Bi-directional Inverter
Cell voltage	PV power, voltage, and current
Max. and min. cell voltage and cell position	Battery power, voltage, and current
Module Temperature	AC load side power, voltage, and current
Max. and min. temperature & sensor position	Grid side power, voltage, and current
Current	Inverter power, voltage, and current
Max. allowable charge / discharge current	PV, battery port on / off
SOC, Status of battery and BMS	System operation mode

Table 4: Overview of CANBUS and MODBUS information

and AC port, and receives operating commands from the supervisory computer via MODBUS. A PCI CANBUS high speed serial card and a PCIe RS-485 serial card are used in the supervisory computer to communicate with the BMS and the inverter, respectively. There is no direct communication between the BMS and the inverter, as shown in Figure 4. The supervisory computer will monitor and record the measurement data listed in Table 4 from the master BMS and the bi-directional inverter, and implement system-level control.

2.3 Control Strategy and Programming

2.3.1 Control Strategy

The control strategy [5, 6] for the system is to maximize PV energy used for EV charging and to reduce grid power demand for EV charging. There are two operating modes: grid-tied and standalone. Most of time, the charging station operates in the grid-tied operating mode. In the grid-tied mode, the EV can be charged from PV, the battery, and/or the grid. In the case of a power outage, the system will automatically switch to standalone mode and be isolated from the grid. In the standalone mode, the EV is charged from PV and the battery. When the grid power is restored, the system will automatically switch to grid-tied operation.

In grid-tied operating mode, when an EV is plugged into the charger, PV power is used to charge the EV if it is available. If more power is needed, the remaining power is provided by the battery or/and the utility grid. If no electric vehicle is plugged-in, PV energy is stored in the battery and if the battery is completely charged, excess PV power flows into the utility grid. During off-peak hours, grid power can be used to bring the battery state-of-charge up to a specified level if the battery charge is low. Energy is never fed to the grid from the battery in the present system due to high EV charging requirements and low PV availability.

In the stand-alone mode, grid power is not available. The system can supply reliable, clean and cost-effective power to critical loads that cannot be supplied directly from the utility grid. Hence PV if available, it will power the EV charger supplemented if needed by energy from the battery. If excess energy is available, the remaining PV power will be stored in the battery. By using the battery storage, the system is able to provide a reliable and constant power source from inherent intermittent solar PV power.

2.3.2 Control Flowchart

The power command set from the supervisory computer depends on the system operating modes (grid-tied or stand-alone), the availability of the PV power, the state-of-charge of the battery storage, the EV charging and local loads, and the status of the charging system. The electricity rate structure (on-peak or off-peak hours) is also considered to minimize energy cost during charging the energy storage from the utility grid if necessary. Figure 5 and Figure 6 show the control flowchart for the grid-tied operation and the stand-alone operation, respectively.

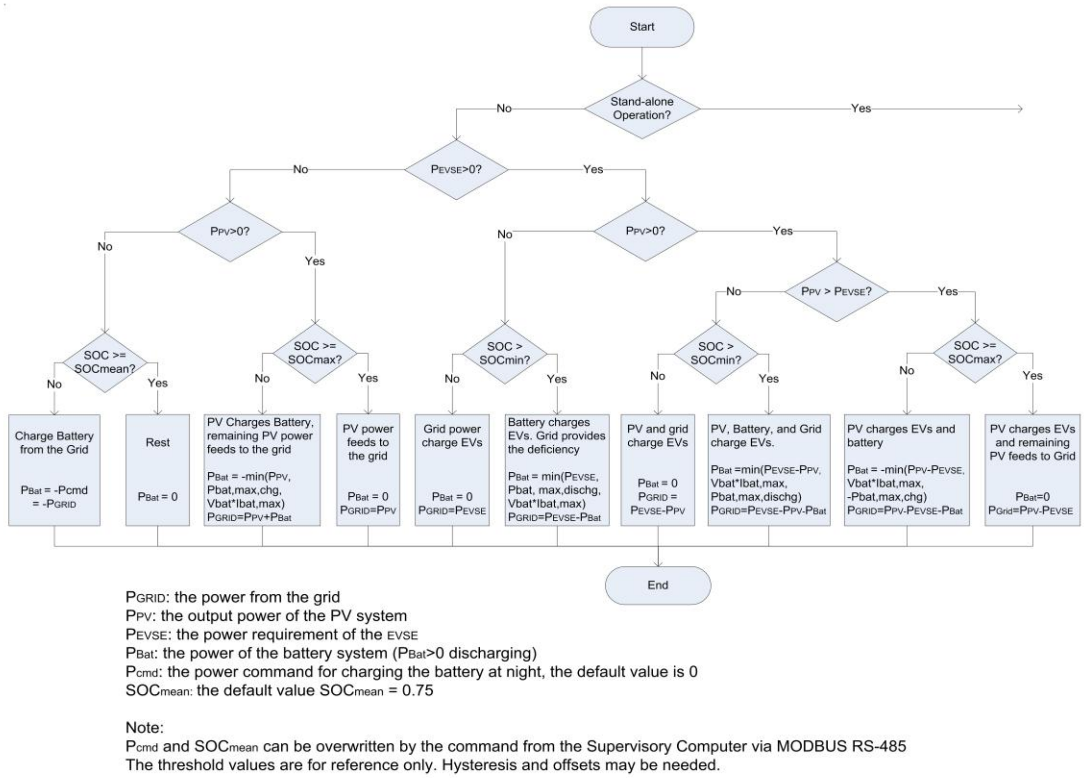

Figure 5: Control Flowchart - Grid-Connected Operation

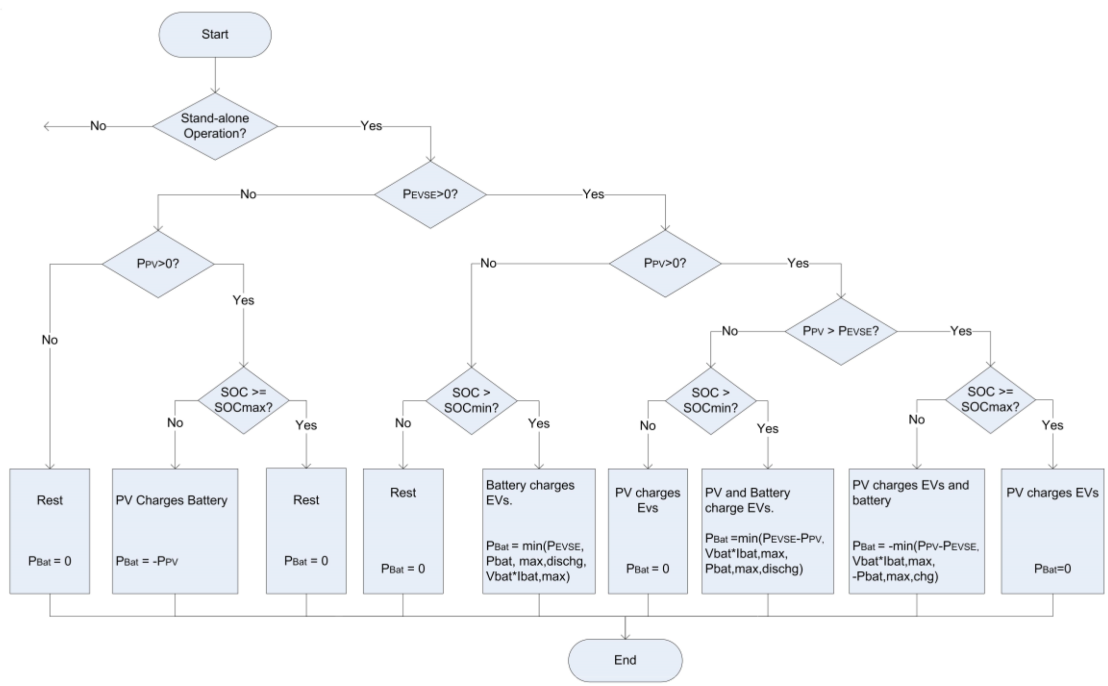

Figure 6: Control Flowchart – Standalone Operation

2.3.3 Supervisory Control

A human machine interface developed with Labview is used to control and monitor the system on the Supervisory computer. The interface consists of four different categories: main, control, protection, and communication. The main interface includes seven panels: system overview, energy storage, photovoltaic, EV charging, grid power, inverter, status & control. The user can navigate through each panel through the tabs on the top panel. Figure 7 shows the main category – system overview which gives the power input and output measurements of each unit and the battery SOC. The available information from the battery BMS and the battery measurements from the inverter are provided in the energy storage tab, as shown in Figure 8. The tabs of photovoltaic, EV charging, gird power, and inverter provide the measured power, voltage, and current of the PV arrays, utility grid, and the inverter, respectively. Status & control describes the system operation mode and the status of each port of the bi-directional inverter.

The operating status and measurement data can also be viewed in the communication interface. Changes of important setting points and testing can be conducted in the control and protection interface. Figure 9 shows the system control interface, in which the operating range of the battery SOC, the start/stop time for charging battery from the grid, the maximum power for topping up or maintaining the battery can be specified. Testing can also be conducted on the imitated operating modes to verify the control strategy.

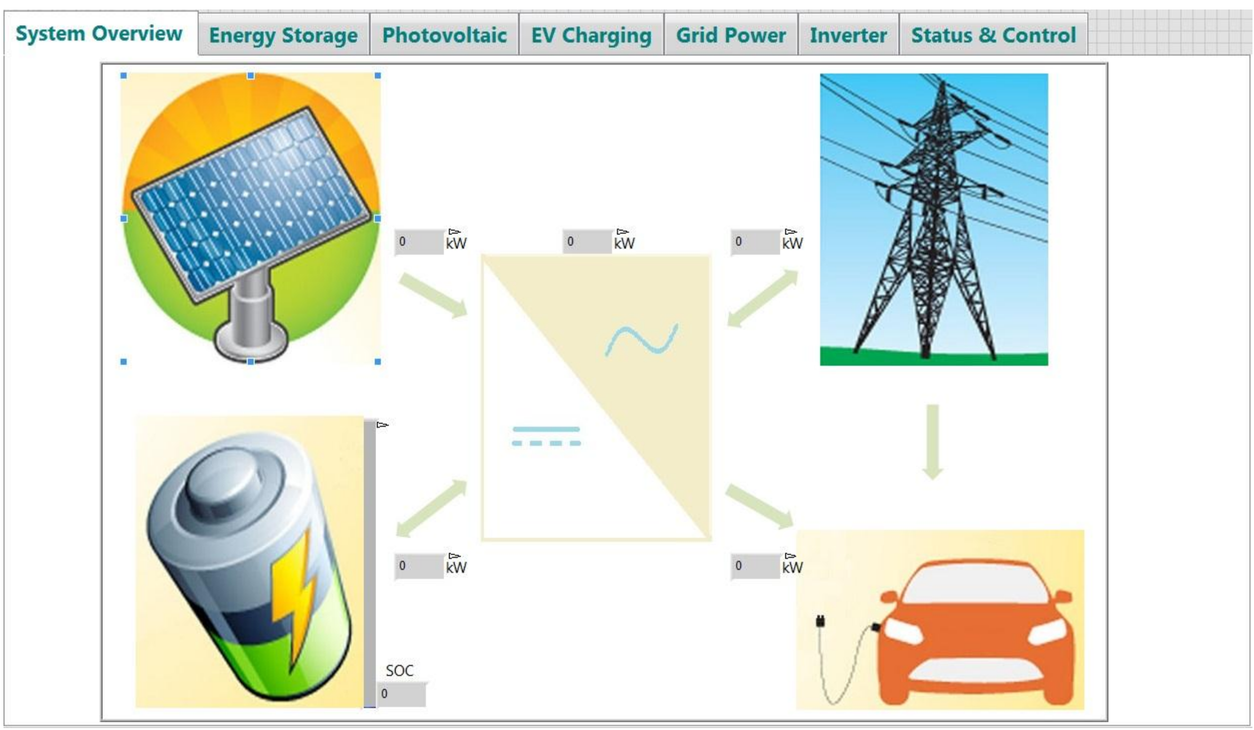

Figure 7: System Overview Screen

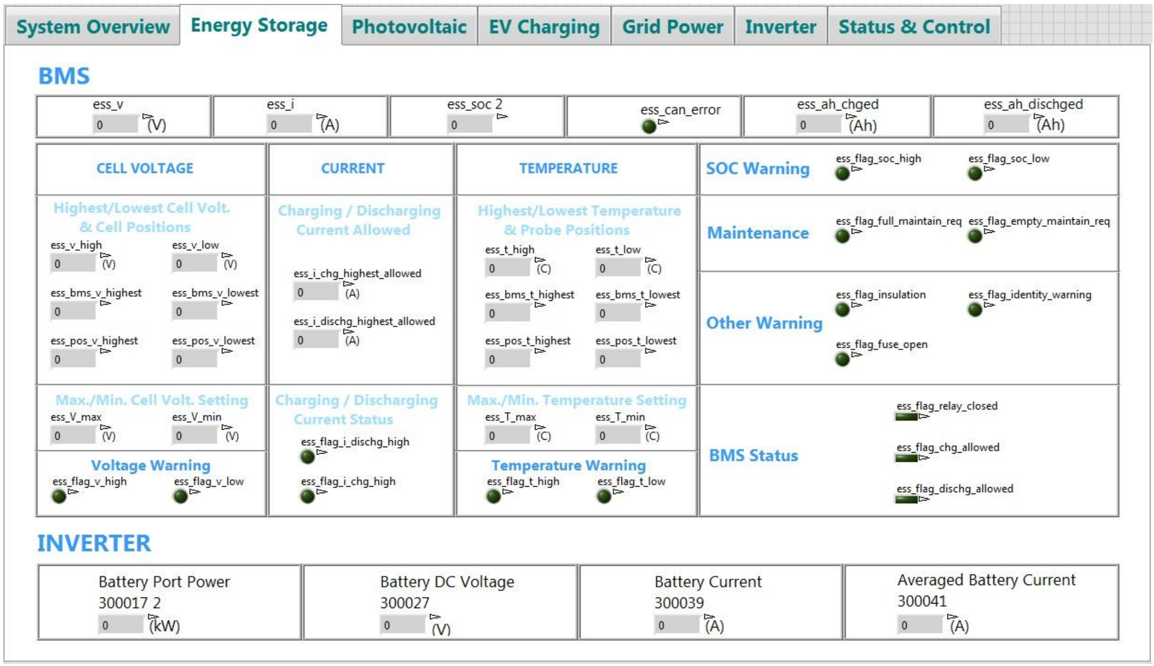

Figure 8: Energy Storage Screen

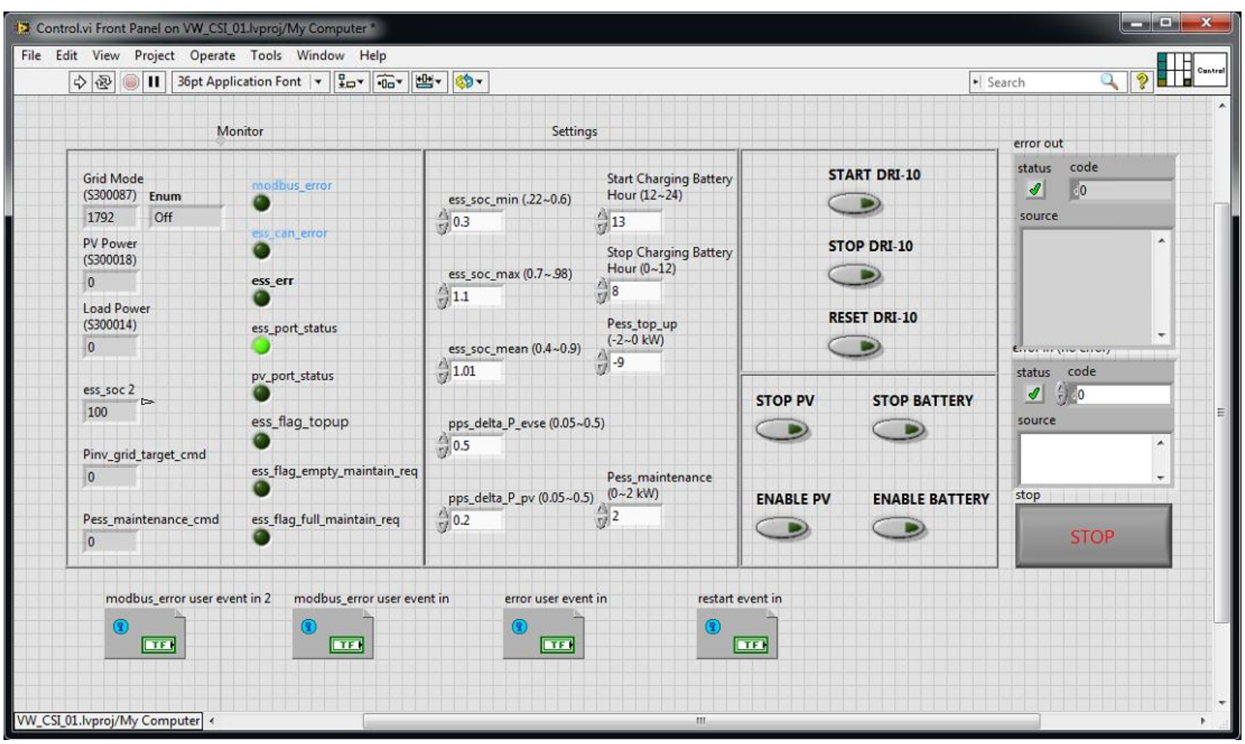

Figure 9: System Control Interface

2.4 Construction of the system

The battery storage and the bidirectional inverter are housed in a large closet in the building at 1605 Tilia Street and the vehicle charger is in place behind the building. The vertical solar PV arrays on the tower near the building are used for providing solar power. The control computer for the system is also placed in the large closet. Figure 10 shows the detailed floor arrangement for the battery storage and the inverter. The installation of the battery storage and the inverter meets all local fire , building, and seismic codes.

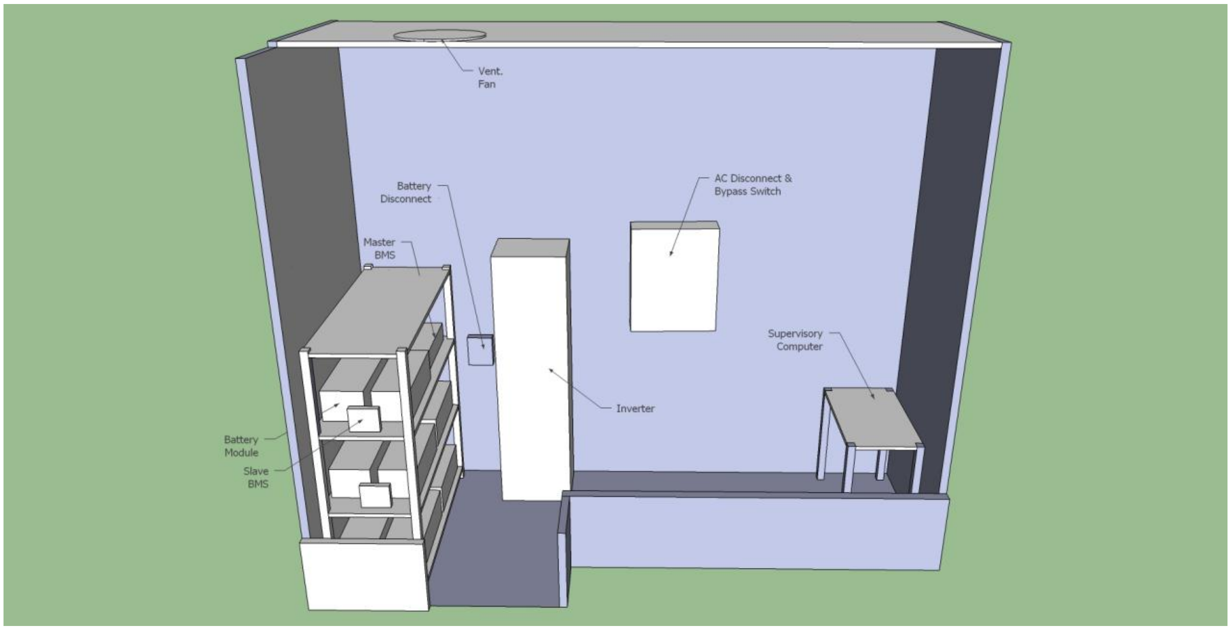

Figure 10: Closet Floor Arrangement

2.4.1 Energy Storage System

The battery pack was assembled using eleven modules in series. The modules contained 220 50-Ah lithium ion phosphate cells (Figure 11) from Lithium Force. Each module has two parallel strings of ten of the 50Ah cells in series, as shown in Figure 12. Six slave BMS were mounted on the side frame of the battery rack. Each slave BMS has 20 voltage sensors and 6 temperature sensors and monitor two battery modules. All the battery modules and a power control system box with a master BMS were mounted on a three-level heavy-duty battery rack, which was installed in the battery closet. The battery system was connected to the battery DC port of the bi-directional inverter via a DC disconnect switch and to the supervisory computer via a CANBUS network, as shown in Figure 13.

Figure 11: 50 Ah Lithium Ion Phosphate Battery Cell

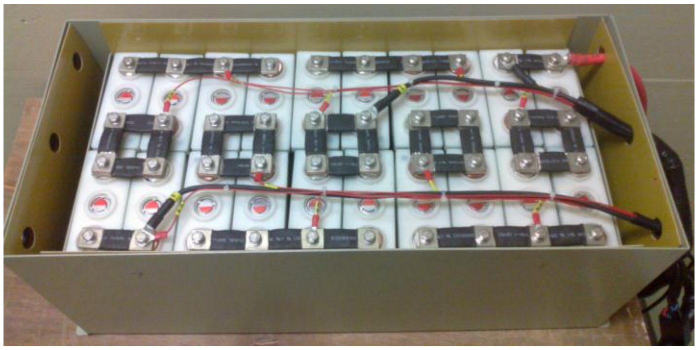

Figure 12: Assembled Battery Module with Voltage and Temperature Probes

Figure 13: Battery Bank and Battery Management System

2.4.2 Power Control System

The bi-directional inverter, housed inside a metal enclosure, consists of two DC/DC converters and a single DC/AC inverter, and has two DC ports and two AC power ports. Since the PV panel is positively grounded, an internal isolation transformer is used to provide electrical isolation between the DC side and the AC side. The two DC ports are connected to the PV and the battery, and the two AC ports are connected to the grid and the EV charger, respectively. The grid AC port works with a two-phase and a neutral line from the vehicle panel. The AC power from the utility grid is three-phase 208V/120V power format. External disconnect switches are employed on all DC and AC ports. An external bypass switch design is used for the AC grid port, which can continue to provide grid power to the EV charger during maintenance of the system. The functional block diagram of the system is shown in the System Design section. Figure 14 shows the photograph of the installed bi-directional inverter and the external AC switches.

Figure 14: Bi-directional Inverter and Disconnect & Bypass Switches

The inverter has a touch screen human machine interface (HMI) on the front door of the metal enclosure. Certain parameters can be configured via the HMI interface. A communication board was installed in the inverter to communicate with the supervisory computer via standard RS485 MODBUS. The inverter can receive the BMS information and power commands from the supervisory computer.

2.4.3 Vehicle charging Station

Figure 15: Electric Vehicle Charging Post

A GE WattStation EV charger (Figure 15) has been installed behind the building at 1605 Tilia St. in West Village. This is a Level 2 charger (40A, 208-240V) with an 8-10kW AC power capability that utilizes the SAE J1772 EV connector.   The charger has computer access, control, and monitoring capability from a desktop computer [7]. Hence the charger can be integrated into the existing system if that is needed.

3. Test Data

The battery buffered electric vehicle charging station has been successfully demonstrated in West Village. The profiles of the battery power, PV power, EV charging load, grid power, and the battery SOC between August 2 -7 are shown in Figure 16. The data indicates that there was one EV charging with 6.6 kW peak power on Aug.2, Aug.4, and Aug.5, and no EV was plugged in on Aug.3. There were two EVs with peak power of 6.6 kW and 3.3 kW, respectively, plugged in on Aug.7. The buffer battery was topped up during the off-peak hours due to low solar PV generation and low battery SOC. Figure 17 shows the PV power and the EV charging load only. Without a buffer battery, the EV charging power comes from the grid and the PV electricity is fed into the grid. Figure 18 shows the power spikes for a PV powered EV charging station without the buffer battery. Figure 19 gives the actual grid power from the battery buffered charging station. The energy exchange between the charging station and the grid were decreased. The grid power spikes were reduced by a factor of 2. The battery power and SOC are plotted in Figure 20. The power spikes from the EV charging and the PV electricity were transferred into the buffer battery.

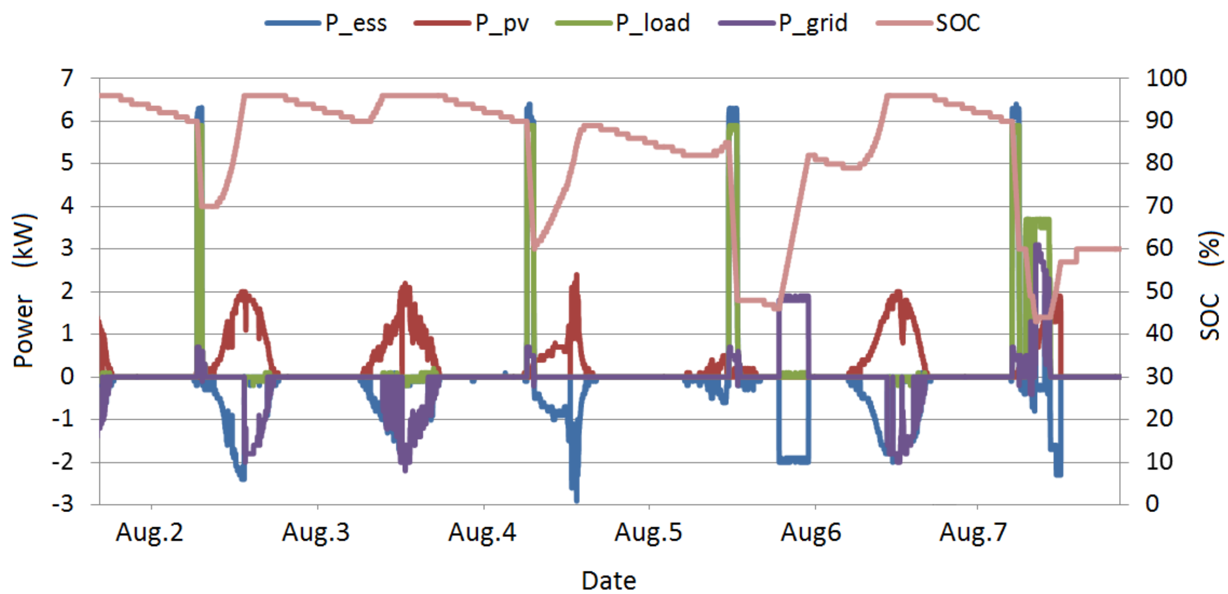

Figure 16: Profiles of battery power, PV power, EV charging load, grid power, and battery SOC

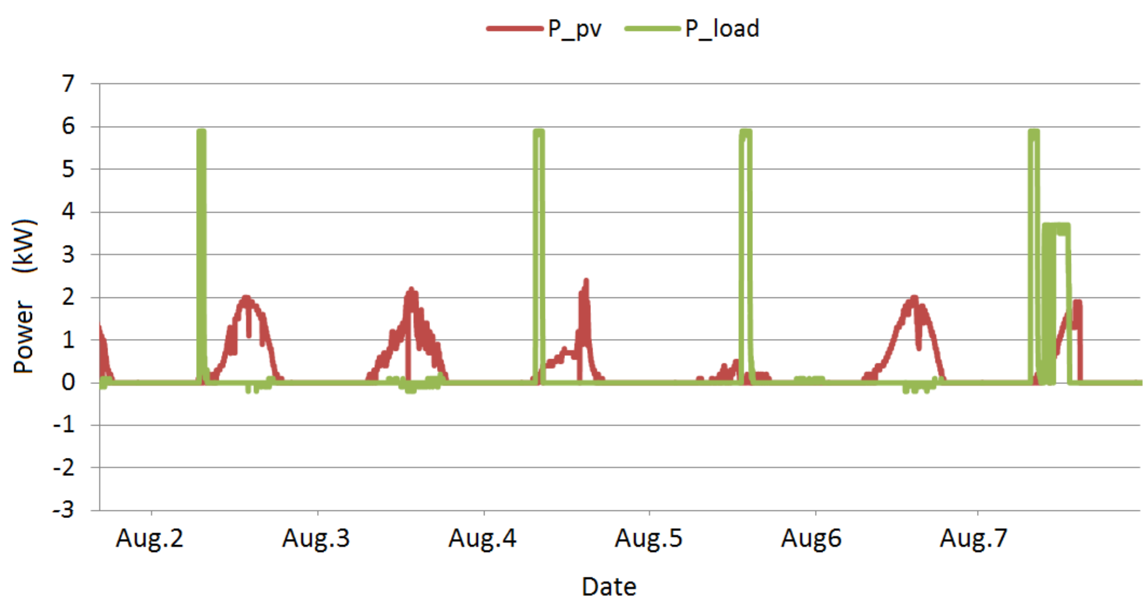

Figure 17: Profiles of PV power and EV charging load

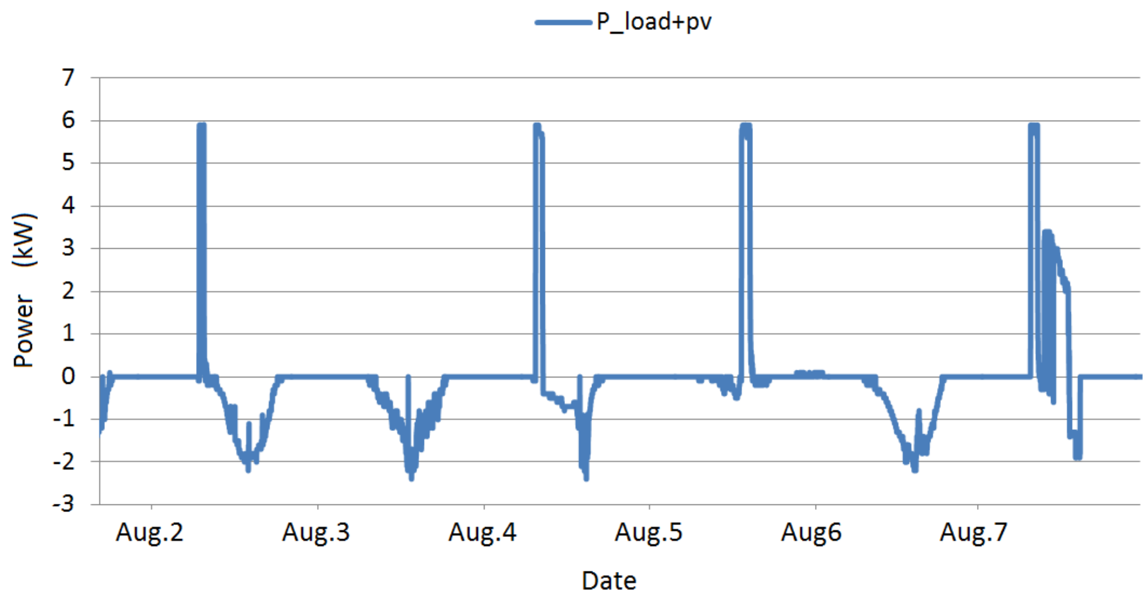

Figure 18: Grid power fluctuation caused by EV charging and solar PV electricity generation of a solar powered EV charging station without energy buffer

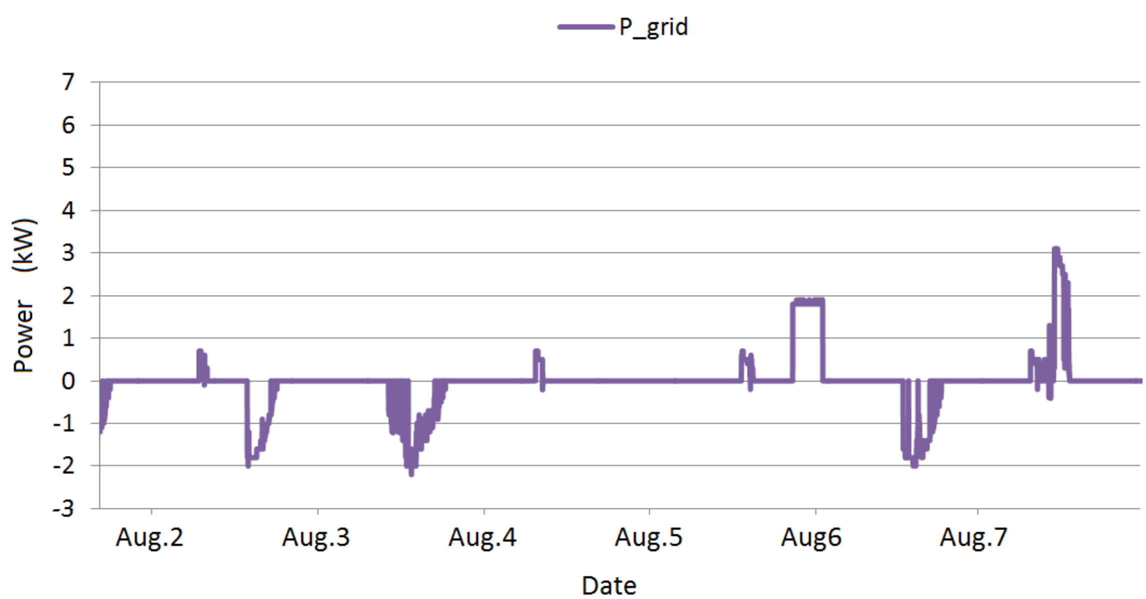

Figure 19: Reduced grid power spikes from EV charging and solar PV electricity by using a buffer battery

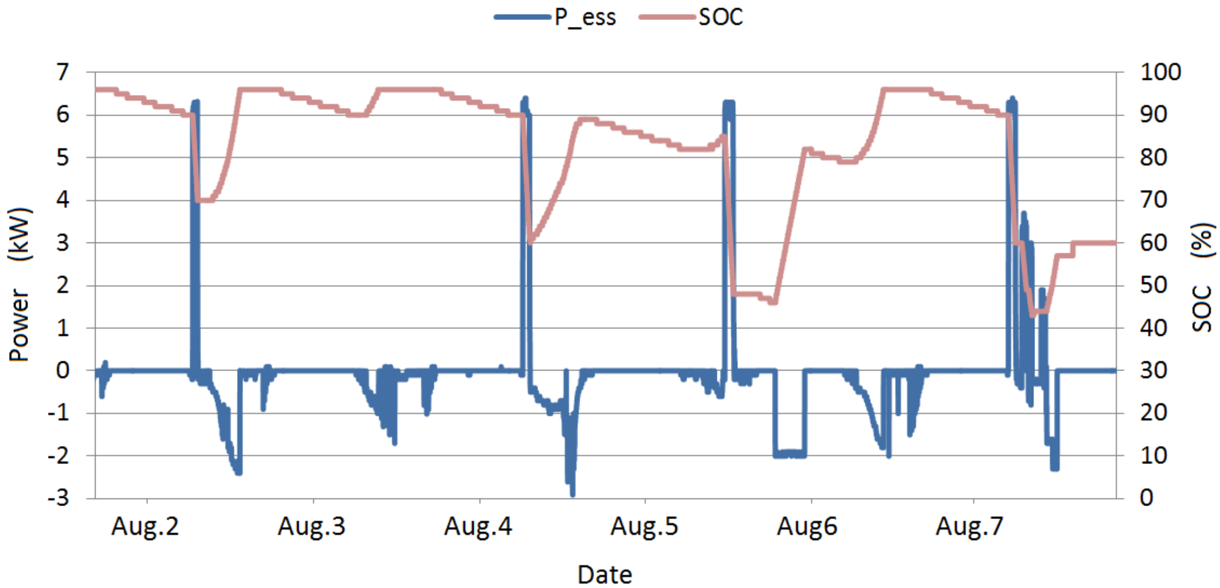

Figure 20: Profiles of battery power and SOC

4. Results and discussion

A battery buffered vehicle charging station has been designed and build in West Village that uses electric energy from a nearby PV tower to charge electric vehicles (EVs). The charging station is also tied to the grid and the control strategy for operation of the station will minimize its impact on the grid. A lithium-ion battery and bi-directional inverter which controls the energy to/from the battery and to the charging station are utilized to control energy flow to the vehicle charger. The completed charging station has been commissioned and detailed data taken of its operation both as a means of storing PV electrical energy and charging vehicles on demand independent of the availability of PV energy or the grid.

The PV array (34 m2) for the West Village project is mounted vertically on the tower attached to the building at 1605 Tilia Street. The resultant PV energy is 7-14 kWh/day of electric energy in the summer and 14-28 kWh/day in the winter season. The PV energy should be sufficient to charge EVs that have traveled 75 and 40 miles per day in the winter and summer, respectively. This should permit a meaningful demonstration of the vehicle charging station using the present PV array and provide an opportunity for expanded vehicle charging if more PV energy is made available.

Now that the present project is completed, research using the vehicle charging station will continue supported by a recent EISG grant, Intelligent Energy Management for the Solar Powered EV Charging Station. This research will include control of the charging station based on information from weather forecasts (solar intensity) and projections of daily vehicle use patterns of the station. It would be advantageous if during this extended demonstration period more PV energy than is currently available from the tower array alone would be made available for use at the vehicle charging station.

5. Public Benefits and Recommendations

The public benefits to California of this project are the demonstration of the use of PV energy to charge electric vehicles and the use of battery storage to maximize the fraction of the PV energy that can be used for charging and to minimize the impact of electric vehicle charging on the utility grid. Both of these benefits will become increasingly important as the number of electric vehicles in California continues to increase and the need for storage by the utilities becomes greater as the contribution of PV power generation becomes larger. As experience is gained with the use of the vehicle charging station in West Village, we will be in a position to recommend to other groups in California how they can best utilize PV energy for EV charging and the value of battery buffering as part of their systems.

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DRAFT

APPENDIX B

Task 1 Demo 2 Single Family Home Energy Storage

Prepared for Itron

Prepared by: UC Davis Energy Institute and the

UC Davis Office of Environmental Stewardship and Sustainability

January 2014

Single Family Home Energy Storage

Dr. Jae Wan Park, Matt Klein, Shiji Tong

January 20, 2014

Abstract

This paper presented the use of second life battery pack in a smart grid-tie photovoltaic battery energy system. The system was developed for a single family household integrating PV array, second life battery pack, grid back feeding, and plug-in hybrid electric vehicle charging station. A battery pack was assembled using retired vehicle traction battery, with 9 cells in each parallel bank, 15 banks in a series, featuring 48 V nominal voltages and 12 kWh nominal capacities. Limited by the weakest bank in the pack, the second life battery pack has accessible capacity of 10 kWh, 58% of its original condition. Battery management was applied to handle the imbalance and ensure the safety operation limits of the battery pack. Energy flow controller was established to optimize the energy harvest from PV while minimize the grid dependence. An information network was constructed to acquire data from battery, PV and appliances and major inverters using Zigbee and wireless qualified devices. The presented system achieved utilization of used vehicle traction battery for second round of application, optimization of solar energy harvest and supporting electric vehicle charging.

Acknowledgements

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Executive Summary

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Nomenclature (Table)

Name	Property
PHEV	Plug-in hybrid electric vehicle
EV	Electric vehicle
DoD	Depth of discharge
SoC	State-of-charge
PV	Photovoltaic
PVT	Photovoltaic thermal
ICE	Internal combustion engine
MPPT	Maximum power point tracking
BMS	Battery management system
SoH	State-of-health
EKF	Extended Kalman Filter
PVA	Parameter varying approach

Introduction

Second life batteries are batteries retired from their first application in plug-in hybrid electric vehicles (PHEV) or electric vehicles (EV) and repurposed for a second, typically lower performance application. The reduced performance application is generally required due to the imminent degradation that happens to batteries during their first application. According to the US Advanced Battery Consortium (USABC) standard for EV batteries, a battery cell has reached its end of life when the cell capacity has dropped below 80% of the rated capacity or the power density becomes less than 80% of the rated power density at 80% depth of discharge (DoD)[1]. For PHEVs, the impact of battery pack performance degradation is less significant, since the performance degradation of the battery pack due to aging can be compensated by the internal combustion engine (ICE). As a result, a PHEV battery may degrade more than the USABC standard specifies while still being able to provide value in an automotive application. Consequently, it is expected that battery cells with 80%, or less, of the rated capacity will be retired from PHEV/EV applications and will be available in the second life market. As PHEVs and EVs gain popularity the number of aged vehicle batteries will increase, posing recycling issues and making second life applications more attractive. Second use of lithium-ion traction battery applications is an applicable approach to extend the useful battery life. This aids in conserving resources and reducing environmental impacts, and is expected to have significant market potential as lithium-ion battery packs are beginning mass production for transportation use[2,3]. A second life battery pack, when properly sized, is able to deliver equivalent performance as a new battery pack, but at a larger volume and lower cost. Another important feature of a second life battery pack is, when cells of varying quantities of degradation are assembled together, the performance of the whole pack is governed by the weakest bank. The increased likelihood of battery bank capacity imbalance in second life battery packs has increases the risk of over voltage and/or over current within the pack, and therefore requires a well-integrated battery management system[4-9].

Battery Types	Price per kWh	Service Life	Issues?
Lithium Batteries	~600	27000+ cycles*	High price;
Lead Acid Batteries	~330	~2000 cycles**	Short life
2nd Life Lithium Batteries	~120***	~5 years****	Low power density; Cell imbalance;
Pumped Hydro	<100	>20 years	Suitable for big power rating applications;
*Test performed by Sandia National Lab on a LiFePO cell with 0.6C Utility PSOC cycle **Test performed by Sandia National Lab on AGM VRLA batteries with 1C Utility PSOC cycle. Note that carbon enhanced VRLA batteries have cycle life performance compatible to lithium battery at lower energy density ***a discount of 80% is expected for second life battery price ****Test performed in our lab on a second life LiFePO cell with 1C cycle resulting the cell degrading from original 80% capacity to 64% capacity			

Table 1: Comparisonn of candidates for stationary energy storage

As energy generation shifts from fossil fuels to alternative sources, energy storage will become an important component for grid stability and peak shifting, due to the improperly matched peak production of renewables versus grid demand [10-17]. Over the years, lithium ion battery applications have expanded from mobile electronics to automotive and aerospace. Popular candidates for battery stationary energy storage includes lithium batteries, lead acid batteries, flowing electrolyte batteries or sodium-beta high temperature batteries. The flowing electrolyte batteries and the sodium-beta high temperature batteries contain toxic or highly corrosive materials, and require advanced infrastructures to provide thermal management [3]. Several storage candidates were compared in Table 1. Lithium batteries will serve as a promising candidate for grid storage if not for its high unit price [18]. The dominant grid energy storage approach now is pumped hydro, which accounts for 99% of grid storage systems operated in the U.S. With less than US$100 per kWh unit price, long service life and 70% or higher efficiency, the pumped hydro seems to be the optimal choice when it comes to large scale energy storage. However, the advanced smart grid is also seeking energy storage solutions that are localized and more responsive to perform grid response and dynamic peak shifting. In this case, smaller scale battery systems have the advantage of handling varying loads and can be easily implemented at any location with simple infrastructure. As a result, the reduced cost of second life lithium ion batteries is appealing to stationary energy storage applications since they may be effectively implemented in small scale applications to deliver high localized fidelity for demand response.

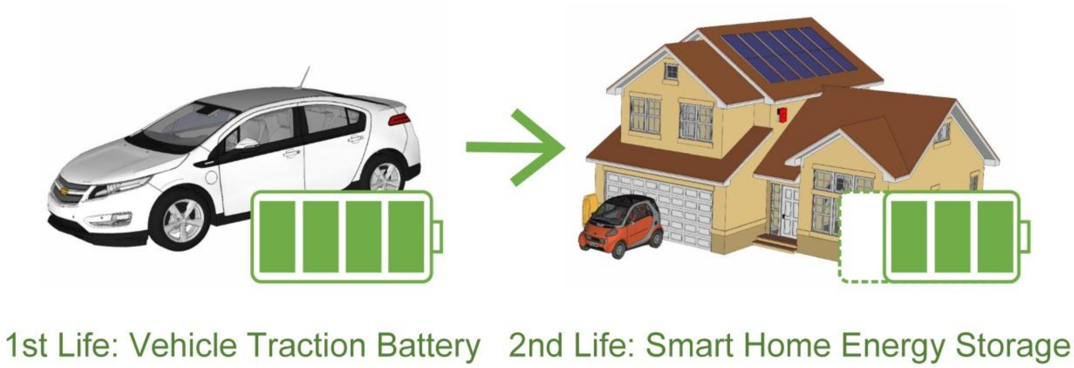

Figure 1. Second use of vehicle traction battery as stationary energy storage.

This report presents the development and preliminary use of a second life battery pack in a Smart Grid-tied Photovoltaic Battery Energy System. The system was developed for a single family household which integrates the use of a PV array, grid back feeding, battery storage and a PHEV charging station. The following tasks were accomplished in the system development phase: 1) battery pack integration into the energy system; 2) application of proper management to the battery pack; 3) design of an energy management algorithm which considers a simple case for grid response, PV energy harvest, house demand and battery safety; 4) develop an information network for energy management and data acquisition. As illustrated in the Figure 1, the project is proposed to apply a second round use of vehicle traction batteries as stationary energy storage into a PV array and vehicle charging equipped smart house.

Methods

System Design and Functional Specification

The system was designed to enable the following functions: (1) support the energy demand of a single family household using both utility power and PV panels; (2) optimize grid dependence using battery storage; (3) enable grid back feeding during peak utility cost; (4) charge a PHEV using a level II charging station.

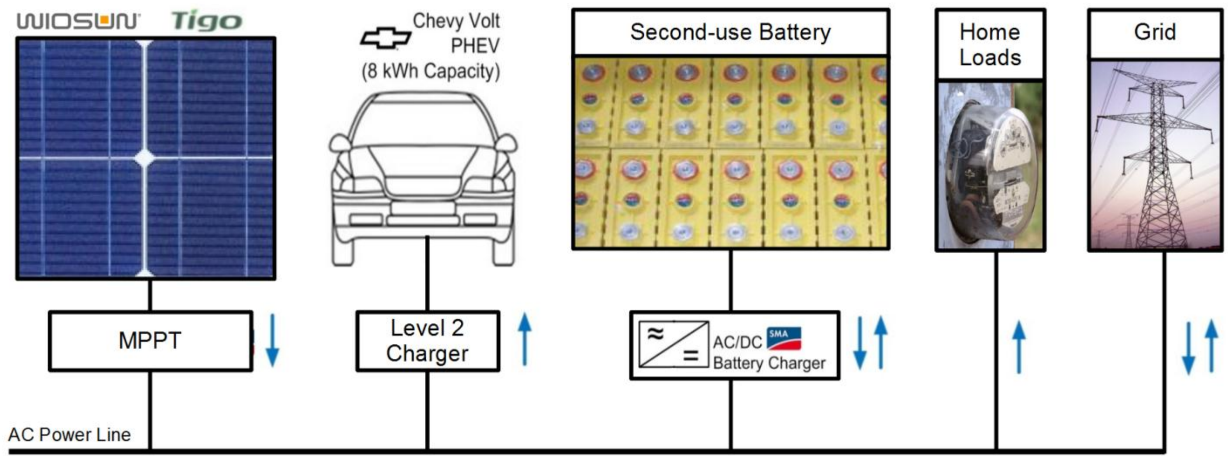

Figure 2. System diagram.

Figure 2 shows a diagram of the system components. One PV string consists of 12 panels, each featuring 180W of rated power. In series this string provides a 2.16kW nominal power output and was installed on a south facing rooftop at the project house. Each panel was connected to a DC-DC converter with maximum power point tracking (MPPT) to optimize the output of each PV module (TiGo sytem®). The entire array was then connected to a DC-AC MPPT converter (SMA system®) to convert the DC solar power into AC power for connecting to the main home power bus. The maximum power tracking provides a high solar energy harvesting efficiency considering irradiance fluctuation and partial shading. A battery pack serves as energy storage of the system and uses a bi-directional AC-DC converter to input and output energy from/to the main power bus. The battery pack was assembled using 135 units of second life $LiFePO_4$ based cells. The batteries were originally manufactured with a capacity of 40Ah, however, after years of service as vehicle traction batteries, these second life batteries have a remaining capacity between 20-30Ah. The battery pack has 9 cells in each parallel bank and 15 banks in series, which provide 48V nominal and 12kWh of nominal energy capacity. Limited by the weakest bank in the pack, the second life battery pack has a total accessible capacity of 10kWh, or 58% of the original condition. The battery pack is controlled to absorb excess energy production from the PV during off-peak hours, and partially support the house load during peak times. Additionally, the control algorithm is programmed to maintain a high level of charge in the battery to enable use as a backup power source. A vehicle charging station will be installed to provide Level II charge to a PHEV. The vehicle will be charged daily with an estimated energy requirement that may vary between 2 to 8kWh. Energy flow from the grid is monitored via a smart meter. The total rated power is 10kW for the interconnected system.

Battery Pack Design

One of the novelties of this project is that a second life battery pack has been used. We received the used battery cells from two different suppliers with different usage histories. As a result, the cells have different levels of state-of-health (SoH). In order to assemble them together to form a functioning battery pack, three design steps were taken to ensure reliable performance of the pack as shown in Figure 3. Stage 1 involved testing the cell conditions, wiring battery cells together to form a battery pack, installing electrical energy management components, and validating the functionality of the multiple redundant safety features of the battery pack; Stage 2 involved manufacturing the battery box, and assembly of the full battery pack; Stage 3 involved installing the battery pack in the house, and performing preliminary testing.

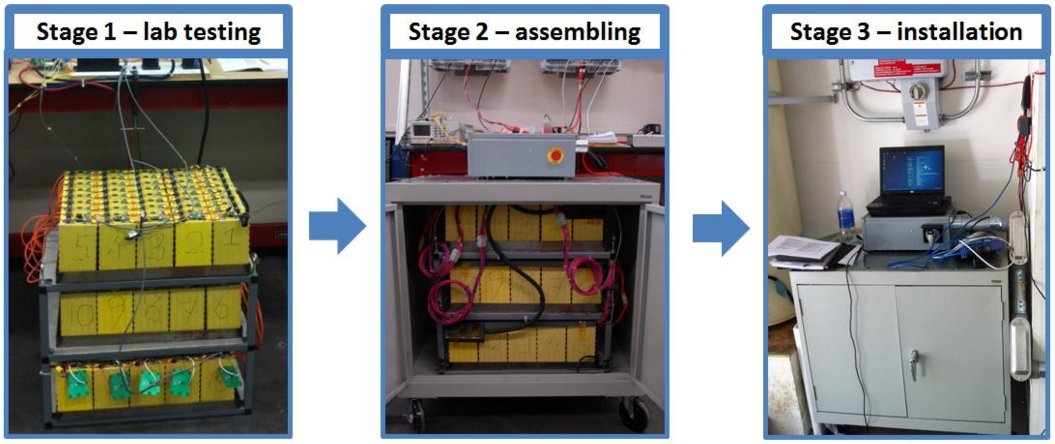

Figure 3. Process of battery pack design.

In stage 1, prior to assembling the battery pack, 15 battery banks were individually tested to quantify their capacity. As shown in Figure 4 the 15 banks possess different useable capacities, the best battery bank being #13, which has a useable capacity of 328Ah, while the worst battery bank is #14, providing 287Ah.

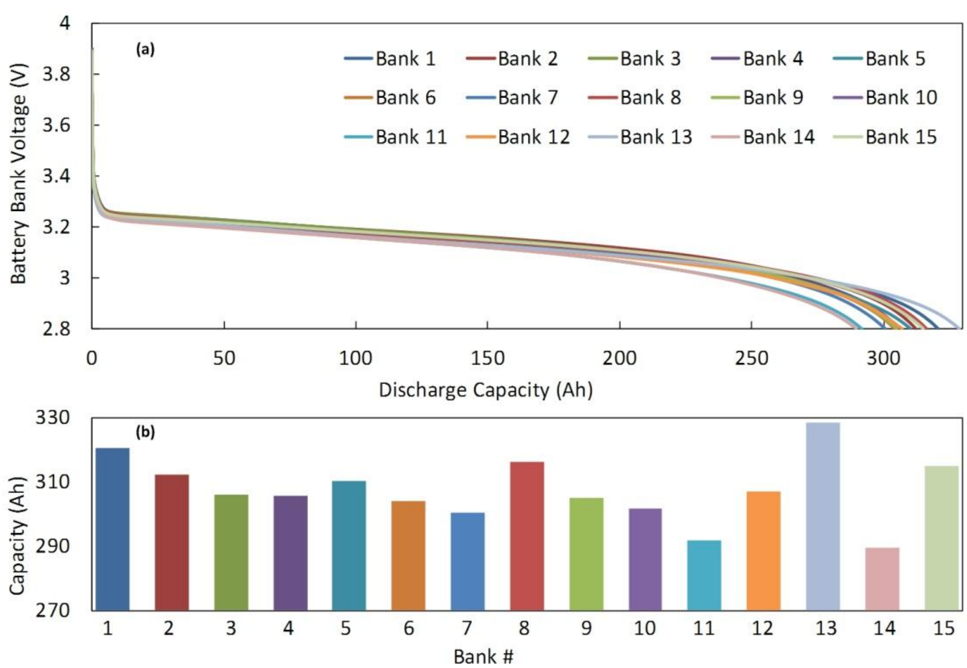

Figure 4. Fifteen battery banks with various useable capacities.

Fourteen banks were wired to form a battery pack. Each cell was wired using a copper bar on the negative terminal and a fusible link on the positive terminal. This approach will isolate an individual cell in the case of a hard short circuit. A detailed wiring illustration can be found in Figure 5(a). At the terminal of the 15 battery banks a BMS slave board was installed and each board measures the battery bank voltage as well as the slave board temperature. A current sensor was installed at the terminal of the battery pack to measure the current in and out of the battery pack. Temperature, current and voltage measurements are converted to digital signals and sent back to the BMS master via line 2 as illustrated in Figure 5(a). Safety limits were set such that if any of the banks are observed to have an abnormal measurement (temperature higher than 80°C, current higher than 150A, and voltage out of 2.8~3.65V range), the contactors (high-powered relays) will open in order to shut off the battery pack from the external source or load via line 3 as illustrated in Figure 5(a). Functions of each individual balancing board and the relay were tested at stage 1. The balancing board will turn on when the attached bank has a voltage higher than the rest of battery pack and approaches full charge. These boards may at most dissipate energy at the rate of 2A in the form of resistive heating via line 4 as illustrated in Figure 5(a). A 48 to 12V DC-DC was used to power the battery management appliances via line 8 and 9 as illustrated in Figure 5(a). This is powered directly from the battery, such that it will run even if the contactors are opened, in order to maintain fulltime control. With this architecture care must be taken to ensure that the BMS does not accidentally over-discharge the battery.

The battery pack was controlled via closed loop feedback. In Figure 5(a) the BMS master board collects essential measurements of the battery pack and sends them to BMS via line 6. The BMS estimates the battery SoC and SoH. Based on the battery SoC, PV power output, and house power load, the BMS generates a battery control signal and sends this to the inverter via line 7. The inverter then controls the battery pack current in/out of the system via line 1. The BMS was custom developed by the research team and acts as the 'brain'/high-level controller of the battery. Detailed descriptions of the battery state estimator design and energy management algorithm design are documented in the following two chapters.

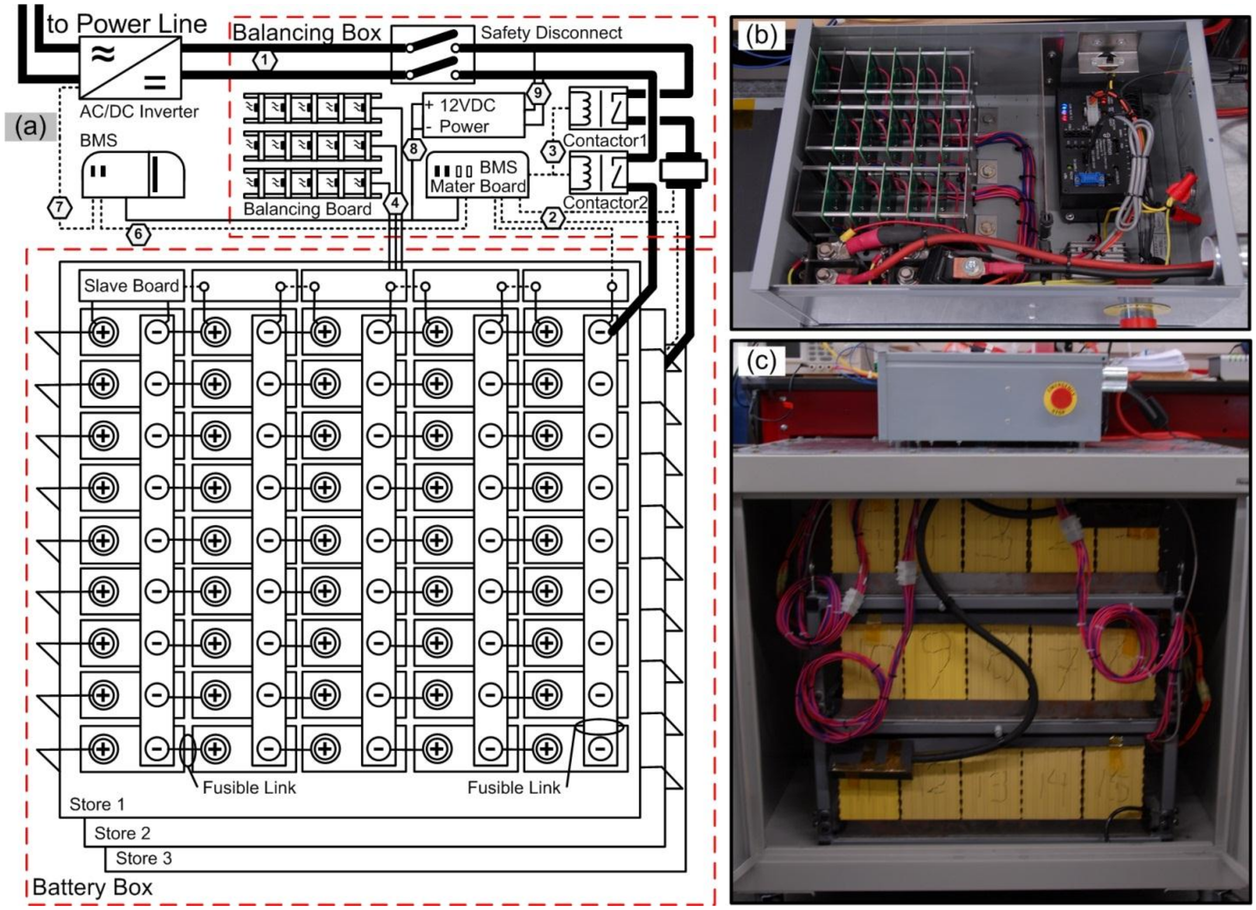

Figure 5. Assembled battery pack: (a) design diagram, (b) battery balancing box, (c) battery box.

Stage 2 is mainly the battery assembly phase. A battery box was custom designed to fulfill all design aspects and fits the battery pack in the designated space within the project house. First, a rack was manufactured to locate the battery pack in three layers. As illustrated in Figure 5(a)(c), each layer contains five battery banks and connects to the neighboring layer via fusible link wires. On top of each battery layer, a sheet of isolation plastic was applied to avoid short circuiting. ITW Formex® plastic was used as this meets UL 94-V0 flammability ratings in high-voltage applications. The rack altogether with the battery pack was installed in the battery box as a single unit via a pass-through placed at the top of the enclosure. A sheet-metal cover was then bolted on the top of the battery box with a small pass-through that allowed for the power and communication cables from the battery pack to enter the balancing box. As shown in Figure 5(b) the balancing box contains: 15 battery balancing boards, two contactors continuously rated at 150A, the BMS master board, a DC power supply, and a manual power cut-off switch. The heat sources (balancing boards and relays) are installed in the balancing box, thus isolating their heat output away from the batteries. This feature effectively prevents the battery pack from overheating while balancing. In stage 3, the fully tested and assembled battery pack was shipped to the project house. The contractors installed the battery pack with the rest of the system, some tests were performed on- site to ensure all the functionality of the system and that communication between the BMS and the rest of the system was established. Figure 6 shows the battery voltage measurements of the battery pack during a simple charge and discharge after the battery pack was installed in the house. After that, the battery pack was fully functioning in the house as the energy storage system.

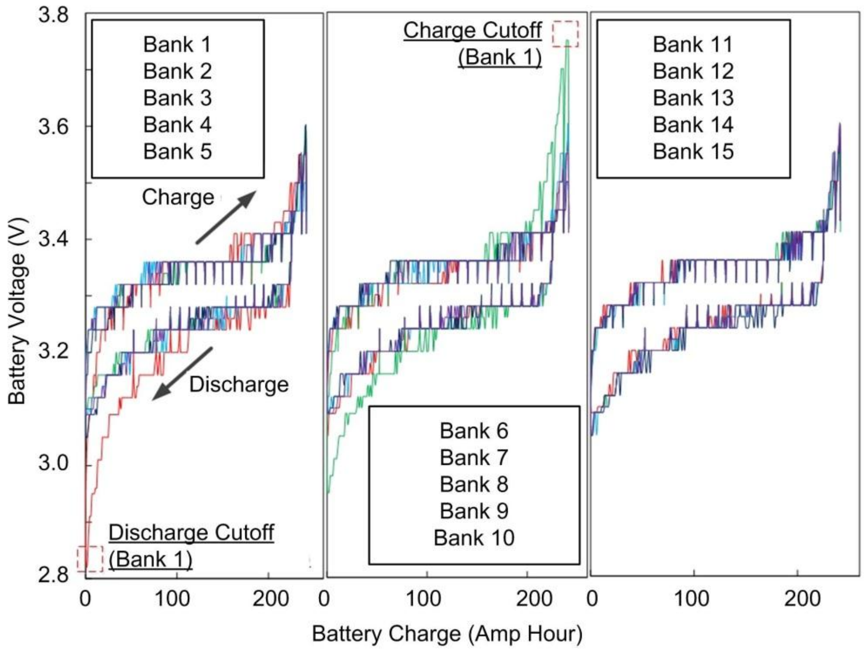

Figure 6. On-line battery voltage monitoring during battery pack charge and discharge.

We successfully delivered a second life battery pack design from scratch. It validates that used vehicle traction batteries, with proper testing and reconfiguration, can be integrated to create a functioning battery pack to be used in a stationary energy storage application.

Battery Management System (BMS) Design

Among all the reconfiguration effort to design a second life battery pack, the most important task is custom design an estimator that is able to accurately estimate both the SoC and SoH of all 15 battery banks while the system is under operation. SoC and SoH of the battery pack, which during dynamic operation may not be directly measured, are important battery state variables that are needed for battery management. For this battery pack, a multiple-time-scales worst-difference estimation approach was applied for SoC and SoH estimation.

In general, the proposed scheme identifies the worst battery bank in the pack, which has the smallest capacity, and allocates the available computing resources to provide close monitoring SoC and SoH of the worst bank. As for the rest of the banks, the scheme estimates their SoC and SoH by comparing them to the worst bank, significantly reducing computing resource demands. Figure 7 summarizes the flow chart of the scheme, which includes all the steps that are executed for a complete estimation cycle. It starts with initializing the state values, parameters and data buffers to be used in the scheme (step 1). At the beginning of the computing iteration (step 2), a fresh set of battery measurements are taken. Based on the knowledge of the battery pack, one bank will then be identified to be the worst battery bank (i.e. the lowest capacity). The SoH estimator then optimizes the battery capacity value of all 15 banks (step 3 to 7), at a frequency of Time Scale 4, using a varying parameter optimization approach.

The SoH estimator also optimizes the battery internal resistance value of the worst bank based on cached measurement data (step 8 to 10), and this is processed at Time Scale 3. An Extended Kalman filter (EKF) was then applied to estimate the SoC of the worst bank (step 11,12) at Time Scale 1. Then, another EKF was applied to estimate the SoC difference between the worst bank and the rest of the banks at Time Scale 2 (step 13, 14). A summary of the computation steps for the EKF using a state-space battery model is presented in Appendix I. This estimator executes the estimation of three of the 15 banks during a single iteration, requiring five iterations to finish the estimation of all 15 banks in the pack.

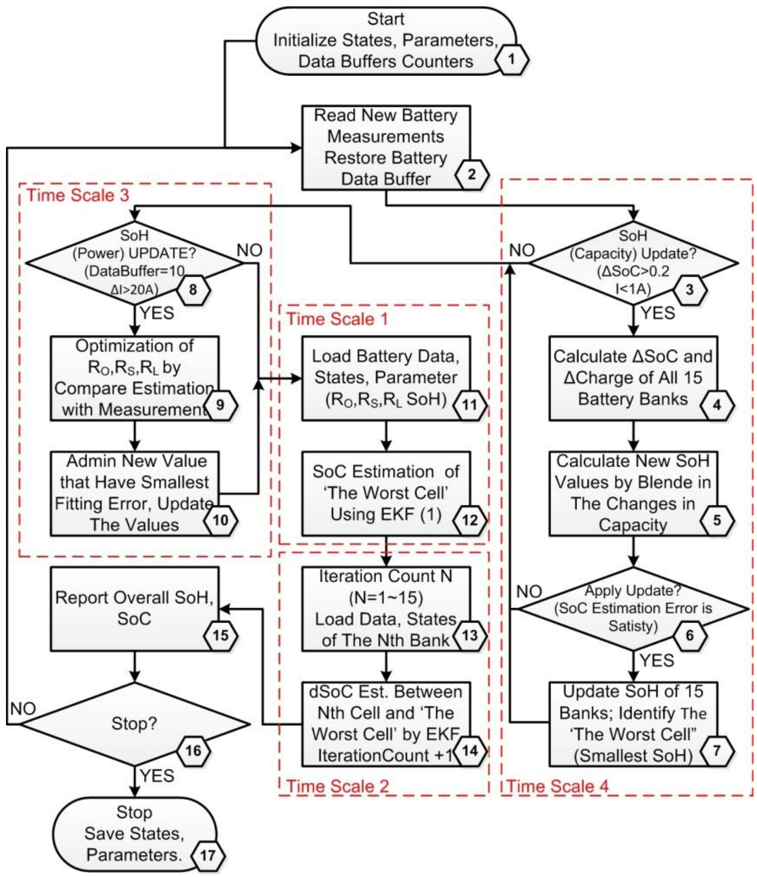

Figure 7. Flow chart of multiple time scales used for battery state estimation algorithm.

In Figure 8, four different computing time scales are compared under the same time line to illustrate how the estimation algorithms are carried out. As time is marched forward, the SoC of the worst bank is estimated in each time step (Time Scale 1). The SoCs of the rest of the banks are estimated with a larger time scale (Time Scale 2), which updates after every five iterations. The internal resistance value of the worst bank updates after every five iterations (Time Scale 3). Finally, the capacity of all 15 battery banks are updated after every 1000 iterations. Capacity degradation is a slow procedure and therefore uses the longest time steps to quantify its variation. Over all, the estimation tasks on different battery banks of different states are composed into one integrated scheme, where the computational iteration is matched to the dynamics of the each phenomenon.

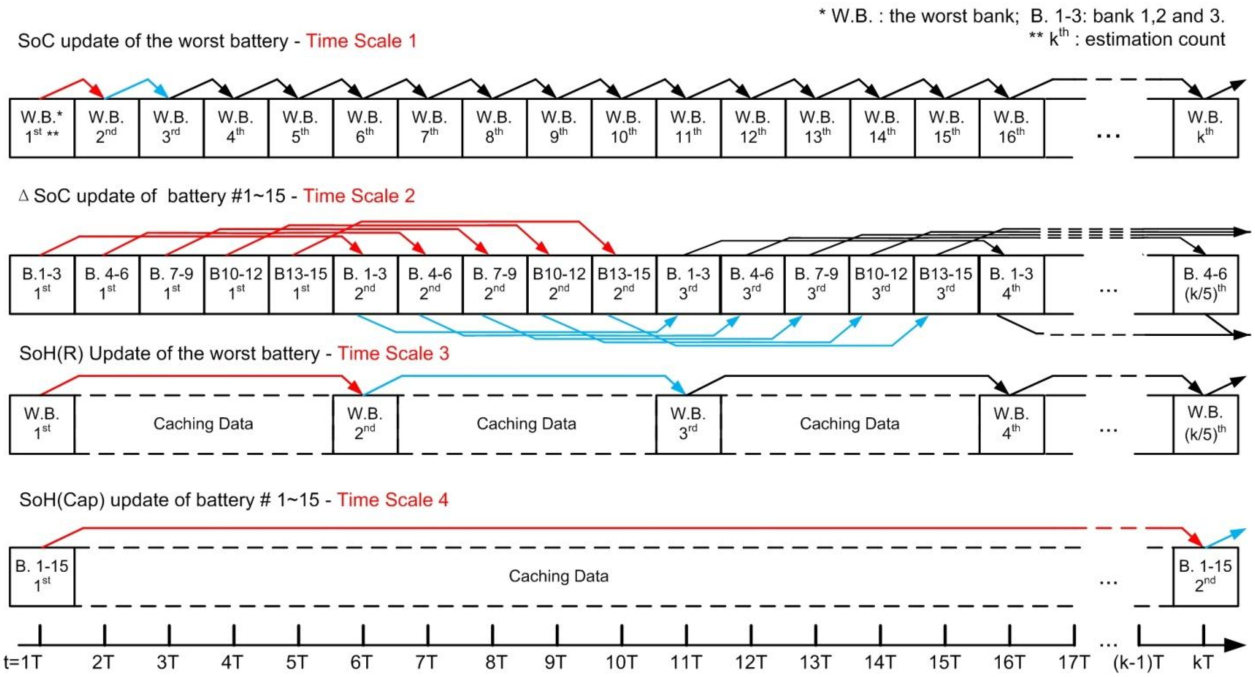

Figure 8. Diagram of multiple time scale battery state estimation algorithm.

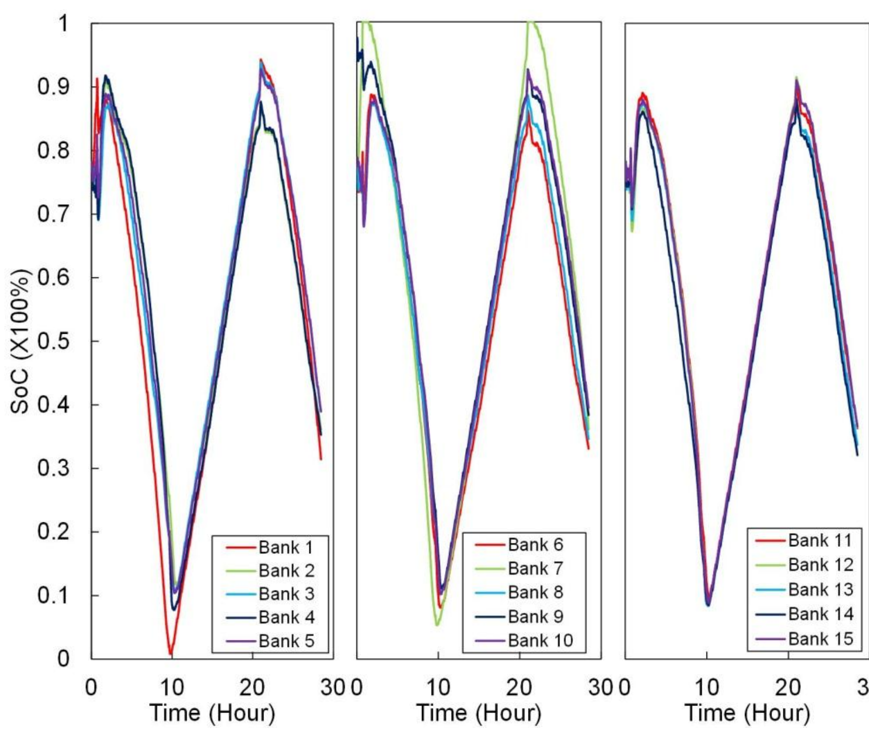

Figure 9. On-line battery SoC estimation during battery pack charge and discharge.

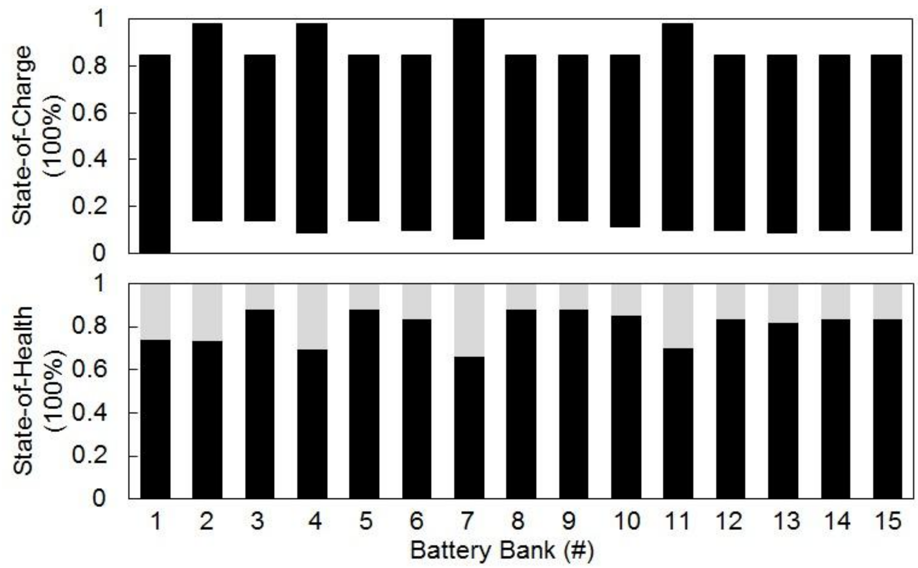

Figure 10: Identified battery pack SoC and SoH imbalance during system operation

Basic on-line estimation results are presented in Figure 9 and Figure 10. Applying the proposed battery management system, we are able to identify SoC and SoH of each individual battery bank. As shown in Figure 9, the battery estimation algorithm was able to estimate SoC of all 15 banks and successfully identify their differences during cycling. Figure 10 shows that the largest SoC difference among banks was about 10%, of which 5% will generally be compensated by the balancing circuits of the BMS and 5% was caused by SoH imbalance, which cannot been eliminated.

Energy Management Algorithm

The battery pack was operated as an energy buffer shifting energy from times of peak PV production to times of peak energy consumption. The battery charge versus discharge decision was made based on three system variables: 1) battery status, 2) time varying utility price, and 3) energy demand less the PV production. An example daily usage cycle typically has PV production occurring from 9am to 6pm, and any excess production will be stored in the battery pack. The typical energy usage peak occurs from 5pm to 9pm and typical utility time varying price peaks from 2pm to 8pm. During peak usage and peak utility price time periods, the battery tends to discharge to support the energy deficit. A detailed system energy flow management decision table is presented in Table 2, where row 1, 2 and 3 are input variables and row 4 is a list of system actions. This energy flow management approach is a mild strategy in terms of utilizing battery storage. When utility price is off peak, the energy demand will always be covered by the grid instead of battery.

A one day forecasting is also implemented in the algorithm. As shown in the Table 3, the battery SoC limits have a varying operation boundary condition: target SoC. This target SoC value marks the level of charge the battery pack should maintain at the end of the day. It is calculated every day at the evening when PV energy production is finished using the following equation:

$$SoC_{Target} = 60\% - 0.5 * \Delta SoC_{Batt} \qquad (1)$$

where, SoC_{Target} is the target SoC at the end of the day (23:00), and ΔSoC_{Batt} is the variation of the battery SoC during the day (from dawn to 18:00). During the utility peak time, the battery pack will discharge to support the house load, but will not exceed the target SoC level, so that it will keep a good level of charge and also leave enough capacity for receiving excess energy production from the PV on the following day.

Table 2. Energy management decision making table.

Input 1	T	F	N	T	F	N	T	F	N	~~T~~	F	N	T	F	N	T	F	N
Input 2	T	T	T	F	F	F	T	T	T	~~F~~	F	F	T	T	T	F	F	F
Input 3	T	T	T	T	T	T	F	F	F	~~F~~	F	F	N	N	N	N	N	N
Action	F	C	F	D	S	D	F	C	C	~~D~~	S	S	F	C	C	D	S	S

Input
1:UtilityPrice T :Peak Price, N: Partial Peak, F: Off Peak
2:PVvs.Load T :PV product > Demand, F: PV product < Demand
3:BattSoC T : 90%~100%, N: Target SoC*~90%, F: 0%~Target SoC*%
*Target SoC is the SoC level battery pack will maintain at the end of the day

Action
F: GRID BACK FEED; S: GRID SUPPLY;
C: BATTERY CHARGE; D: BATTERY DISCHARGE

Figure 11 and Figure 12 present three days of system operation during good solar harvesting days and bad solar harvesting days, respectively. The top plot shows PV power, house energy demand, and the time varying utility price. The bottom plot shows the battery variation in SoC and power. As Figure 11 indicates, in sunny weather from 8am to 5pm, PV production is larger than the energy demand of the house. From 9am to 10am about 2kWh of PV production was utilized to charge the battery pack when the utility price was low. From 10am to 5pm, excessive production of PV energy was sent back to the grid. From 5pm to 8pm, about 3kWh of energy was provided by the battery pack to support the house energy demand during the peak utility price. Occasionally, the battery pack needs to be charged by the utility to bring the SoC to an appropriate level by the end of the day. As Figure 12 indicates, in rainy days, the daytime PV production was too low to support energy demand of the house. The battery discharged during the daytime, and was able to provide about 3kWh of energy during the peak utility pricing time period. The battery pack was charged up using off peak electricity during the nighttime, to maintain the target SoC. Overall, the battery pack plays a roll of supporting the house energy demand when the utility price is high. The proposed management algorithm cycles the battery pack with about 2kWh throughput per day, or 20% of the present battery capacity. The results indicate that by using at least 2kWh of battery pack capacity, a single family house can avoid peak usage of electricity, which greatly contributes to the grid stability. To further study the system, the research team will optimize the system size to bring down the cost. On the other hand, some aggressive management algorithms will be investigated in which deeper cycling of the battery may be performed for grid respond and/or more peak shifting.

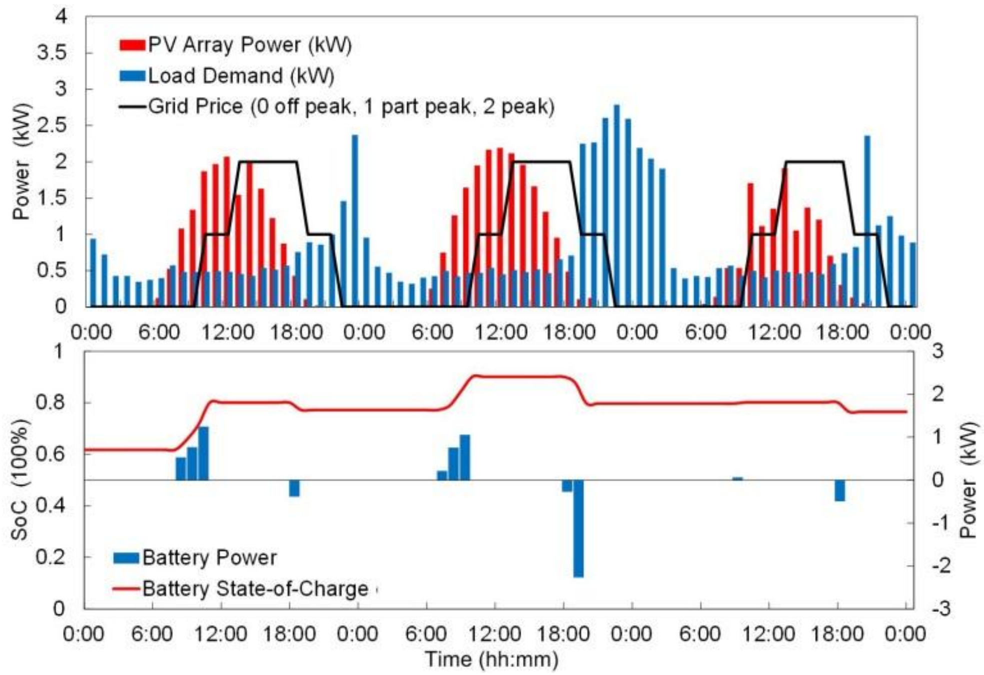

Figure 11. System operation simulation under good solar harvesting weather.

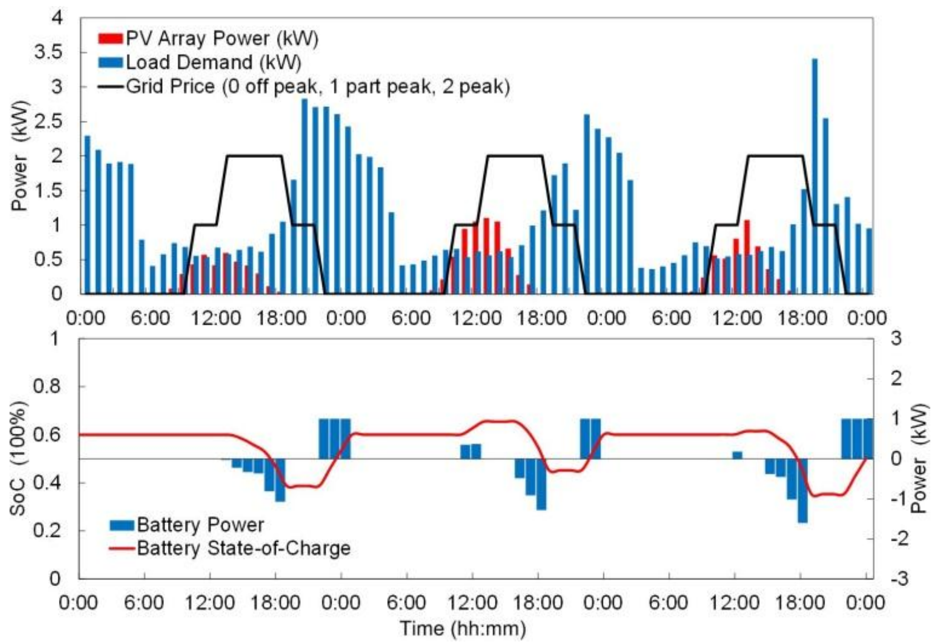

Figure 12. System operation simulation under poor solar harvesting weather.

System Design Document, Installation and Commissioning

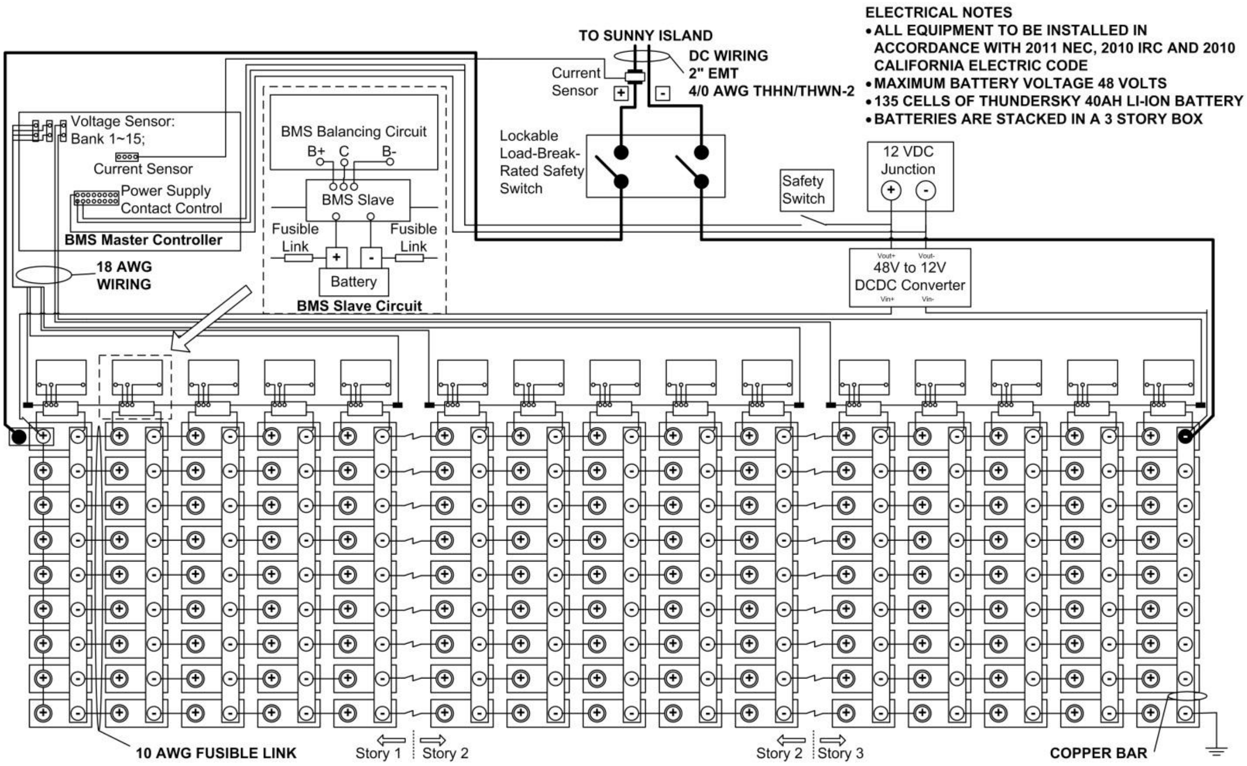

Figure 13. Design document – battery pack.

Based on the system design, the research team finalized the design documents. Figure 13 presents the finalized electrical schematic of the battery pack. Figure 14 presents the electrical schematic of the rooftop solar array with a DC junction box. Figure 15 presents the overall system electrical schematic, including one PV array, one battery pack, one vehicle charger, one Sunny Boy PV inverter, two Sunny Island battery inverters, one main electrical panel, one 240V AC panel for vehicle charger, one 48V DC panel for battery, and two 120V AC junction box for the battery inverter.

The design documents, along with the site plan, were submitted for university, city of Davis, and the fire marshal to gain permit approval. An electrical contractor was hired to collaborate with the research team to install all of the appliances into the house according to the plan. Over a period of two months all of the components were installed and tested to be functioning. A stitched photo is presented in the Figure 16, showing the primary system components after installation. PV panels were installed at rooftop. A smart meter and a smart panel were installed on the side wall of the house. The garage space is where the battery box, battery and PV inverters, junction boxes and breakers were installed.

MANUFAC.	MODULE	# OF PANEL	TOTAL WATTS	ARRAY VOC (V)	ARRAY ISC (A)	ARRAY VMP (V)	ARRAY IMP (A)
WIOSUN	PVT180P	4	720	171.36	16.64	142.80	15.12
WIOSUN	CN-A180P	8	1440	(28.56*6)	(8.32*2)	(23.80*6)	(7.56*2)

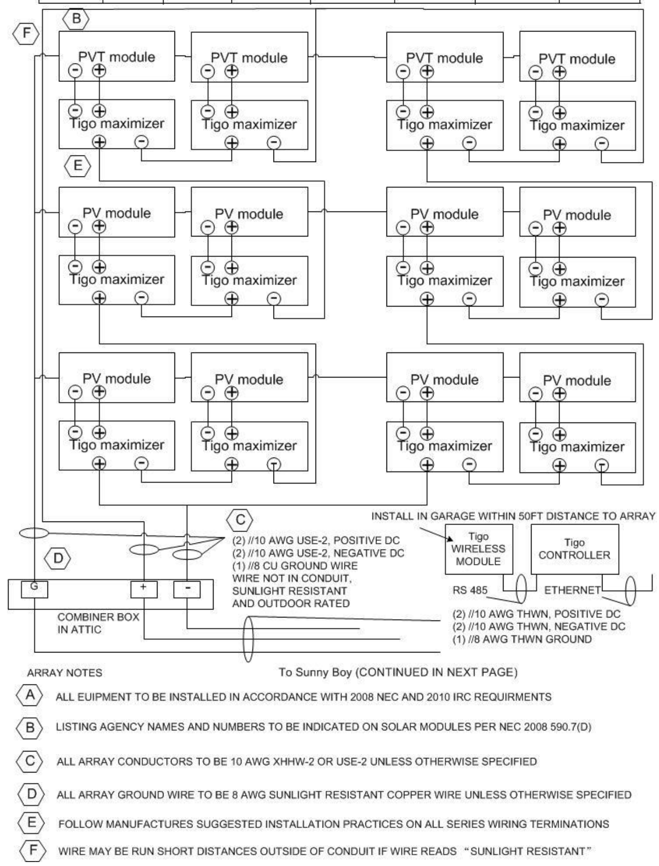

Figure 14: Design document – rooftop PV/PVT array.

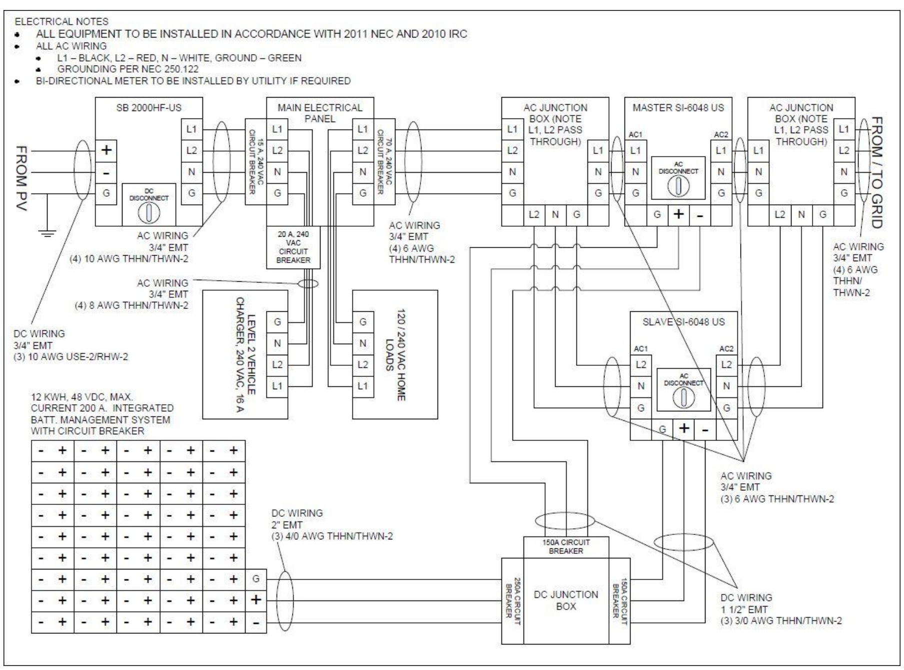

Figure 15. Design document– the overall energy system.

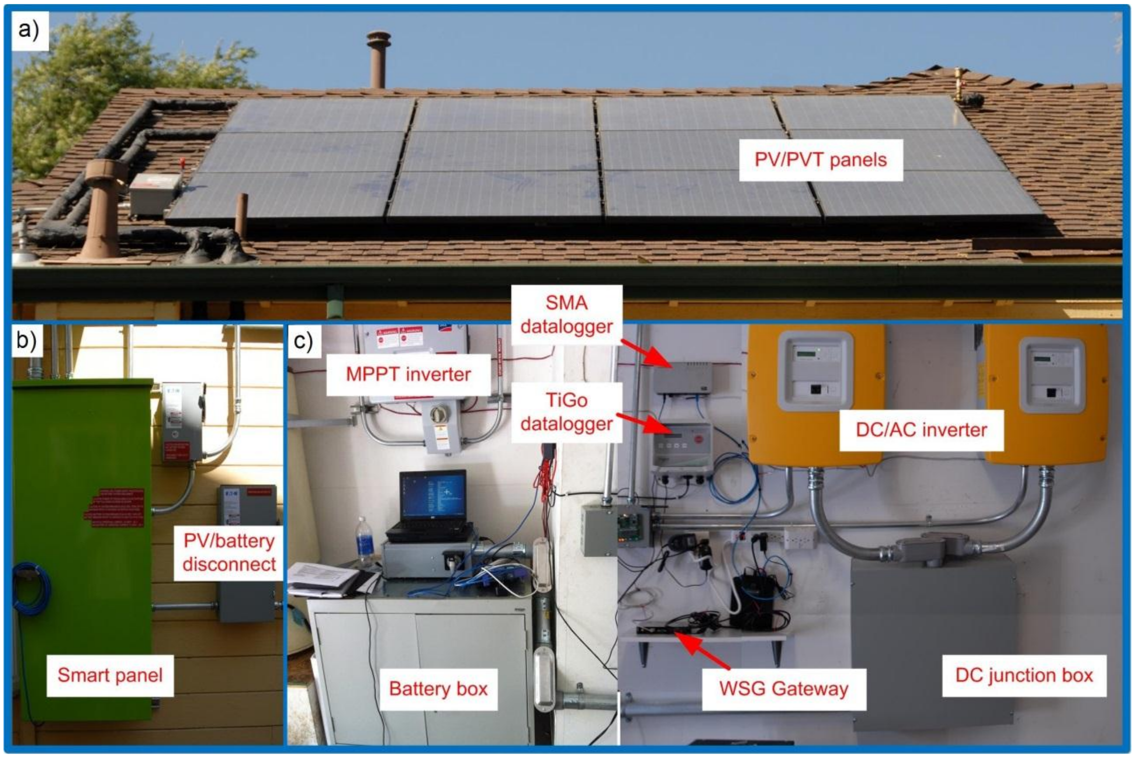

Figure 16. Photo of installed smart-grid PV battery system.

Remote Data Acquisition and Monitoring

An intelligent information network was installed for data collection and analysis. As illustrated in Figure 17, a WirelessGlue™ gateway serves as the central gateway that receives information from the battery management system (BMS), SMA®Webbox, Tigo® gateway, and ZigBee radios. The SMA®Webbox logs data of the SMA products, including the DC input from the battery pack, the AC output from the battery charger/discharger, and the AC output from the SMA MPPT PV converter. It also hosts a local HTTP server that can be continuously accessed through the central gateway (Line 4 in Figure 17). Similarly, the Tigo® gateway logs output data of each PV panel and transfers the data via wireless communication to the central gateway (Line 7). ZigBee radios connected to the central gateway via Ethernet were installed in the house. They receive data from ZigBee equipped appliances such as smart plugs, smart meter, and a ClipperCreek® vehicle charger (Line 5 and Line 6). The BMS receives voltage, current, and temperature measurements of each battery bank through Line 1, and estimates battery state-of-charge (SoC) and state-of-health (SoH) of the battery pack. Also, the BMS obtains the system operating data from the central gateway, including instant utility price, PV output, and house power demand. Based on the information, the BMS algorithm implements the design control decision, which is submitted to the central gateway (Line 2) and routed to the battery charger/discharger (Line 4) to operate the battery pack. Finally, the central gateway assembles all the data from different sources and sends the packaged system information to a server in the cloud.

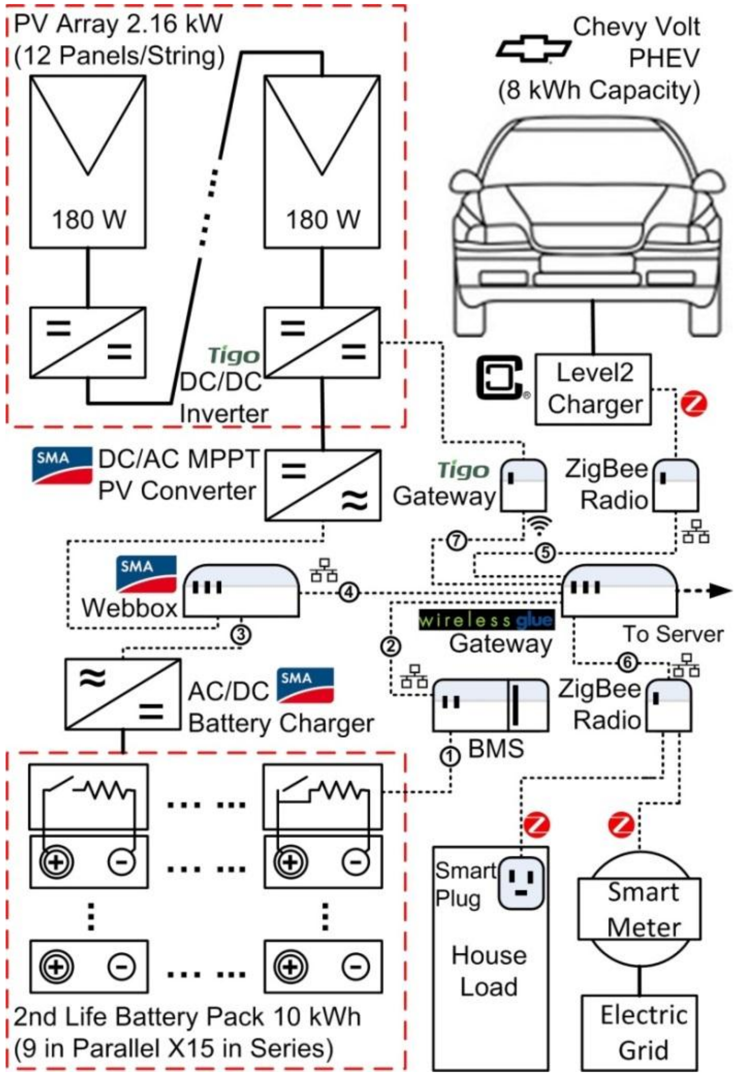

Figure 17. Diagram of system information network.

Table 3 lists the servers the research team developed for data logging. The main Aggie Village Home Server is run at the WirelessGlue gateway providing a host for the BMS and stores data on the local database. The Tigo and SMA sever logs PV energy data. The Obvius smart panel server logs grid interaction data. The battery data server logs battery operation data. Figure 18 shows a screen shot of the different data logging servers. In addition, a live data webpage was developed to monitor the PV, battery and grid operation with 24 hour data display and 7 days summation. A screen shot of the live data web page is shown in Figure 19. In addition, WirelessGlue provided the ZigBee data logger service to monitor the smart plug and ZigBee equipped appliance such as the vehicle charger. As a result, energy consumption of major appliances in the house can be individually monitored. This integrated information network allows researchers to keep good track of energy flow in the system. More importantly, it provides a convenient access for the users to check, manage and conserve their energy usage.

Table 3. List of data logging server

	Data Acquisition Service	Access
1)	Aggie Village Home Server via SSH protocol	ssh gsf@ucdavisvillage.no-ip.biz
2)	Tigo Energy via Tigo live view service	http://www.tigoenergy.com/
3)	SMA webbox server	http://ucdavisvillage.no-ip.biz:3334/
4)	Obvius smart panel server	http://ucdavisvillage.no-ip.biz
5)	Battery data server via FTP	FTP://ucdavisvillage.no-ip.biz
6)	Live data webpage	http://ucdavisvillage.no-ip.biz:9000/

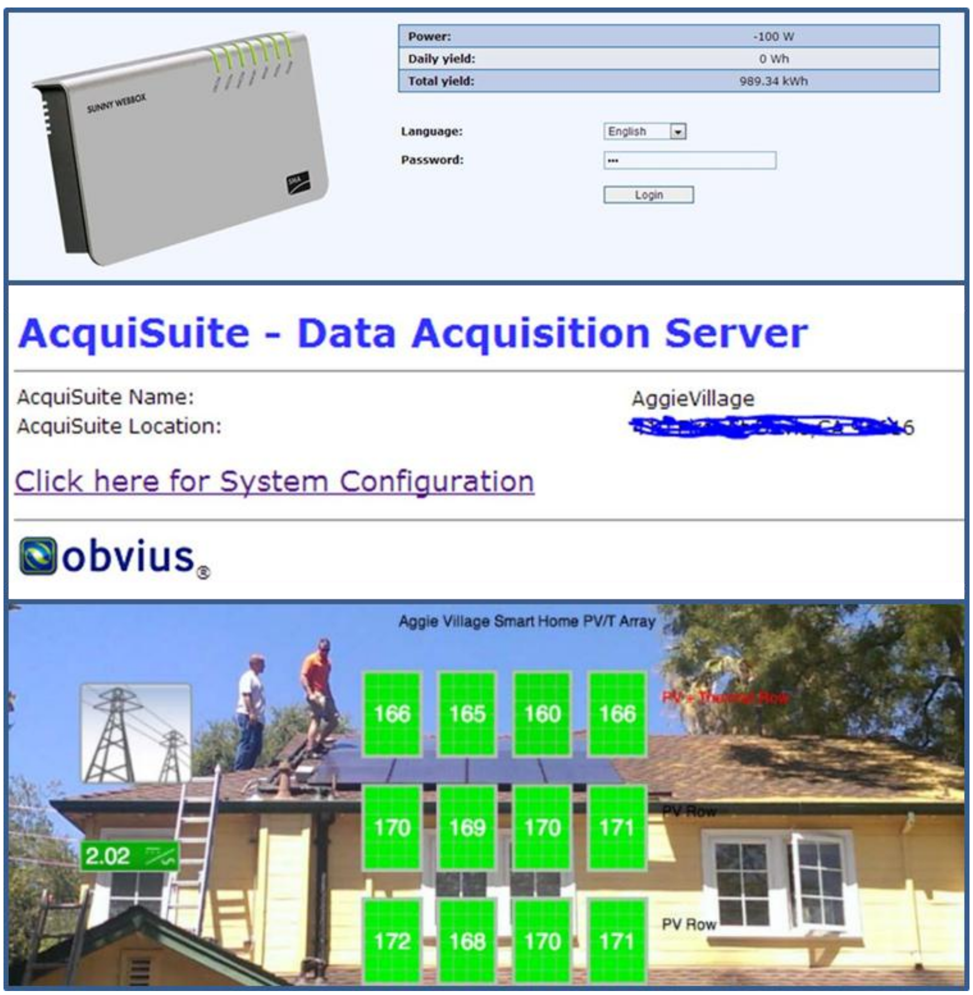

Figure 18: Screen shot of web based data server: top, SME Webbox; middle, Obvius smart panel; bottom, TiGo system

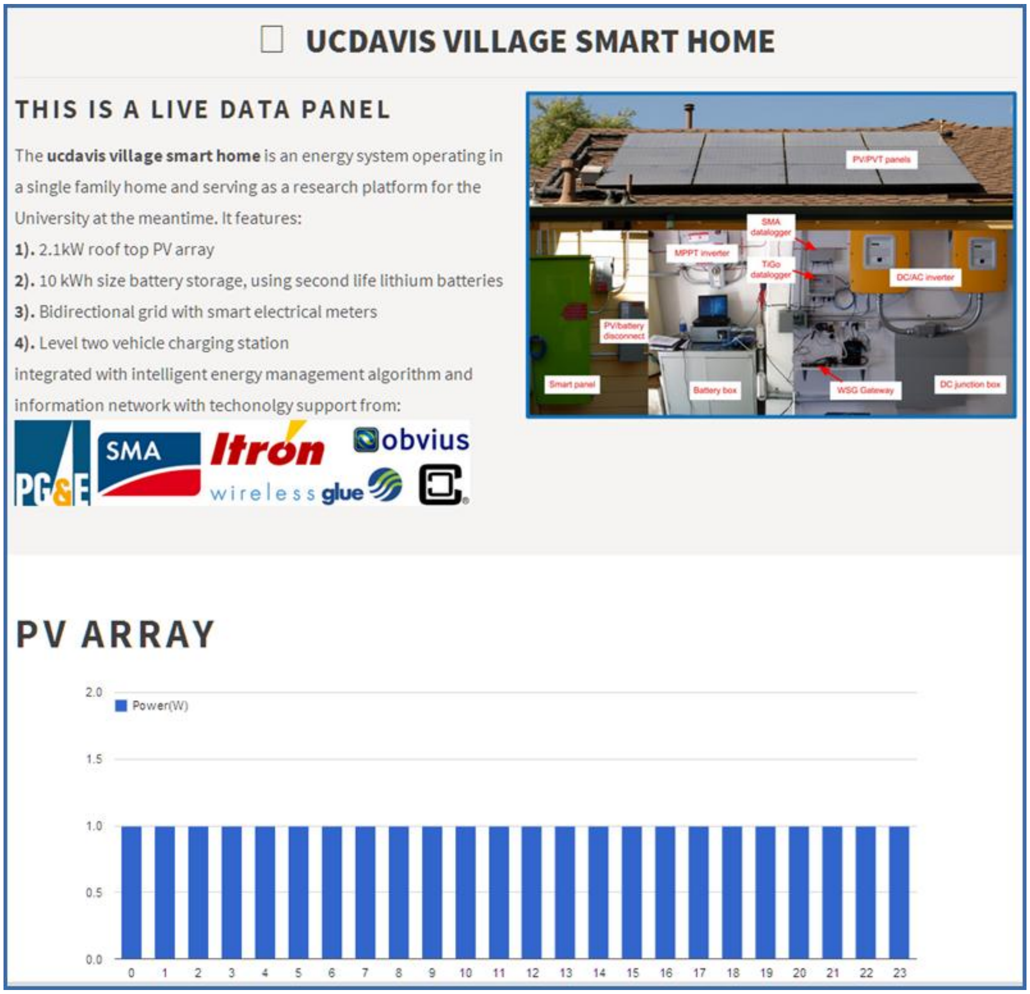

Figure 19. Screen shot of web based live data panel.

Results and Discussion

The system has been fully functioning with the data logger recording the usage history. Due to the reduced sun exposure in the winter, the PV system is outputting energy between 4 to 7kWh per day on good weather. Figure 21 shows a PV production summary from 11/19/2013 to 12/30/2013. Note that on certain days the energy output is less than 1kWh, which is due to a communication malfunction on the TiGo Solar Maximizer, resulting in zero production from one of the PV panels on occasion. This issue was resolved on January 21st 2014. Aside from that, the PV array is working properly.

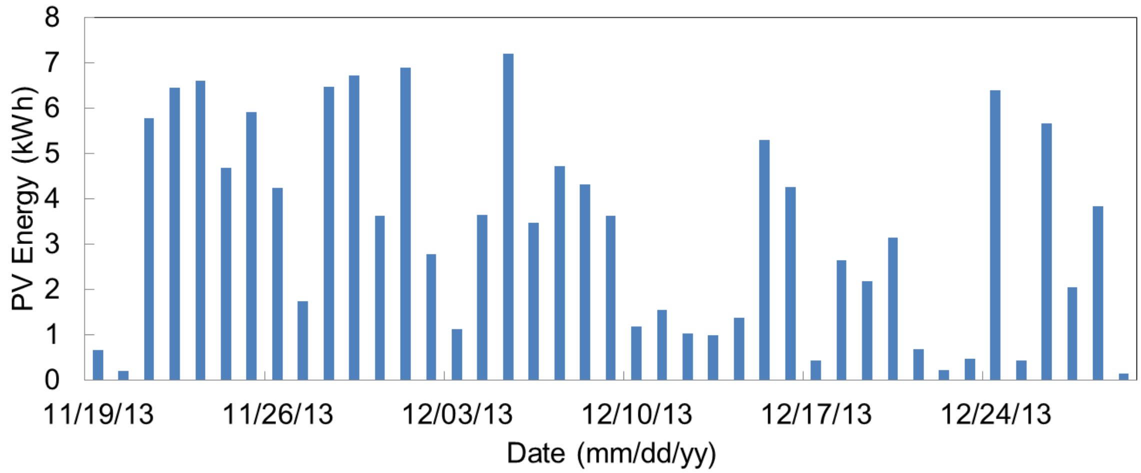

Figure 20. Daily PV Array Energy Harvesting Summary (11/19/2013 to 12/30/2013).

Over the course of the first four months of PV array operation 967kWh energy was produced. Equivalent CO2 saving equals to 1639 lbs. The battery system starts to function from late November 2013, and over the one month it performed PV energy shifting of 63 kWh, equivalent to US$18.9 saving. It prolonged the battery second life by 11 cycles. Over all the system has saved US$145.5 over the first four months in winter time operation.

Table 4. System operation statistics.

PV System (09/2013 to 12/2013)	Operation Hours (system on)	1483 Hours
	Energy Harvested	967 kWh
	CO2 Saved	1639 lbs.
Battery Pack (11/2013 to 12/2013)	Peak Usage Shifted	63 kWh
	Peak Usage Bill Saved (@0.3$/kWh)	18.9 $
	Extended Battery Life	11 Cycles
Grid Interaction (09/2013 to 12/2013)	Electricity Bill Saved (@0.15$/kWh)	145.5 $

The system provides a renewable energy source when solar energy is available in the daytime and covers part of the load in the night using the reserved energy in the battery. **Error! Reference source not found.** illustrates the system functionality using usage data on December 1st, 2013. As shown in **Error! Reference source not found.**, from midnight to 10am both the PV array and battery pack were in silent mode. The house energy usage was fully supported by the grid. From 10am to 5pm, the house energy demand was fully supported by the PV array output and the excess energy of the PV was used to charge the battery. From 5 pm to 8 pm, the house energy usage peak arrived, overlapping with the utility peak pricing hour. The battery discharges to support the load demand with an efficiency of approximately 85%. When the peak pricing finished after 8pm, the battery stopped discharging. As shown in the energy consumption pie chart in the Figure 21, the house energy demand in that day consisted of 30% peak pricing usage (3.2kWh), 20% partial peak usage (2.4kWh), and 50% off peak usage (5.7kWh). Indicated by the energy source pie chart, 63% of the house energy usage was covered by the PV array production (6.8kWh). With the battery pack enabled peak shifting, the peak usage during the nighttime is covered by the stored PV energy (3kWh) in the battery.

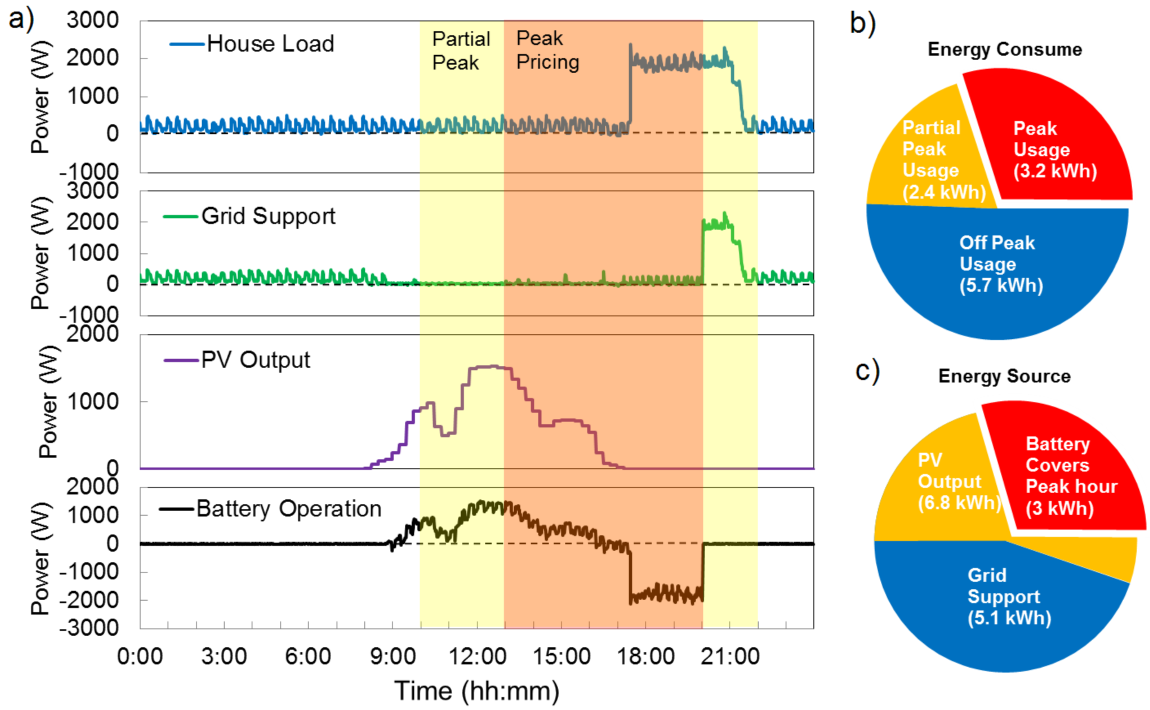

Figure 21. Sample of system operation on 11/29/2013. a) Plots of power draw and supply over an entire day. b) Pie chart of energy consumption broken down based on price of usage. c) Energy supplied as a function of the source.

On a different day of operation (November 29th, 2013), a slightly different energy management algorithm was utilized. At peak hours, instead of charging the battery, the PV output was fed back to the grid. As shown in Figure 22, from midnight to 10am, both the PV array and battery pack were in silent mode. The house energy usage was fully supported by the grid. From 10am to 5pm, the house energy demand was supported by both the PV and grid. When the PV output was higher than the house demand, excessive energy of the PV was used to charge the battery. From 5pm to 8pm, the house energy usage peak arrived, the battery discharged to support the load demand with an efficiency near 85%. At the same time, the PV supported the energy demand with the remaining sunlight. Any excessive production was sent back to the grid. When the peak pricing finished at 8pm, the battery stopped discharging. As shown in the energy consumption pie chart in Figure 22, the house energy demand in that day consisted of 17% peak pricing usage (3.2kWh), 47% partial peak usage (8.4kWh), and 35% off peak usage (6.4kWh). Indicated by the energy source pie chart, 63% the house energy usage was covered by the PV array production (7.2kWh). With the battery pack enabled peak shifting, the peak usage during nighttime was covered by the PV energy or battery stored PV energy (0.9kWh form direct PV energy, 0.9kWh from battery discharge energy). Using this energy management strategy, the PV energy was sent back to the grid to obtain more optimal economics. Meanwhile the battery usage was less. The energy system operated by this strategy can have a smaller size battery pack, but will have a larger grid dependency.

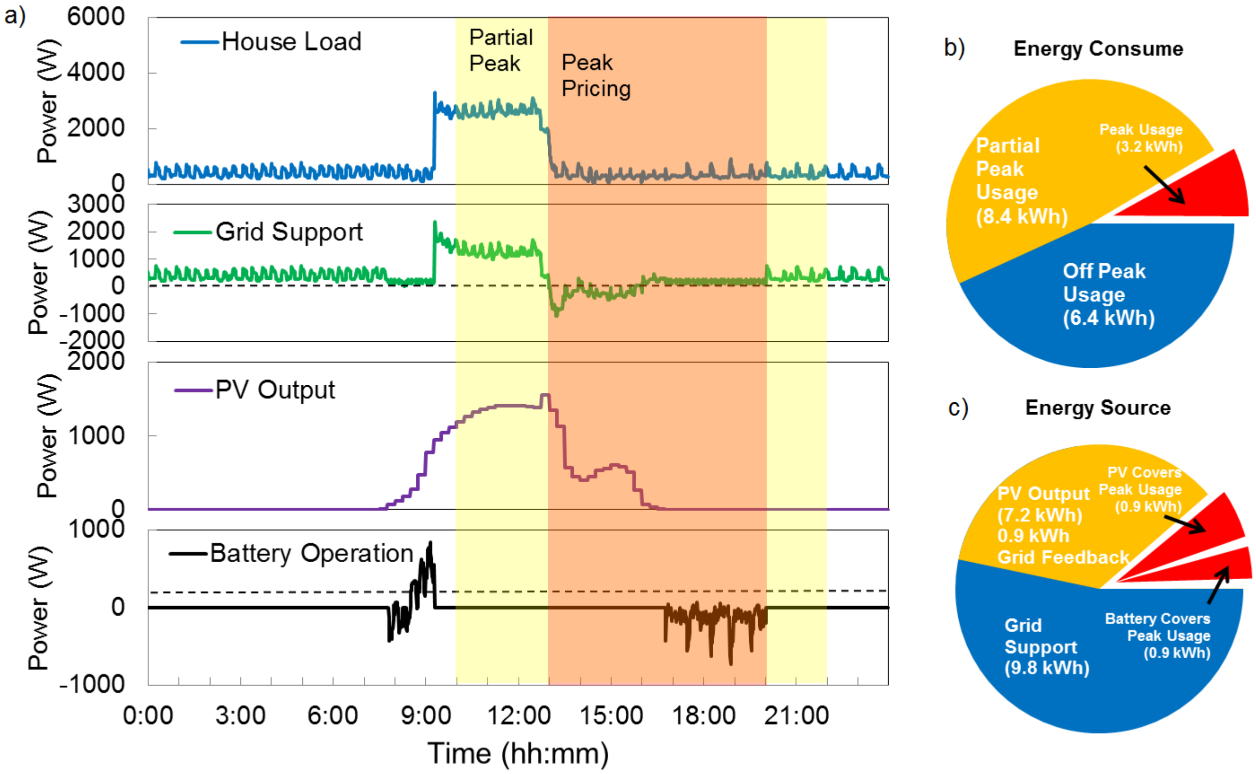

Figure 22. Sample of system operation on 12/10/2013. a) Plots of power draw and supply over an entire day. b) Pie chart of energy consumption broken down based on price of usage. c) Energy supplied as a function of the source.

Conclusions

The Research team of task 1.2 supervised by Dr. Jae Wan Park has successfully delivered a smart energy system equipped with: 1) renewable high efficiency PV/PVT array; 2) smart grid enhanced utility interaction; 3) battery storage featuring second life vehicle traction battery application for peak shifting and grid response; 4) level 2 vehicle charging station to promote PHEV ownership; and 5) comprehensive data logging service for in-depth system analysis.

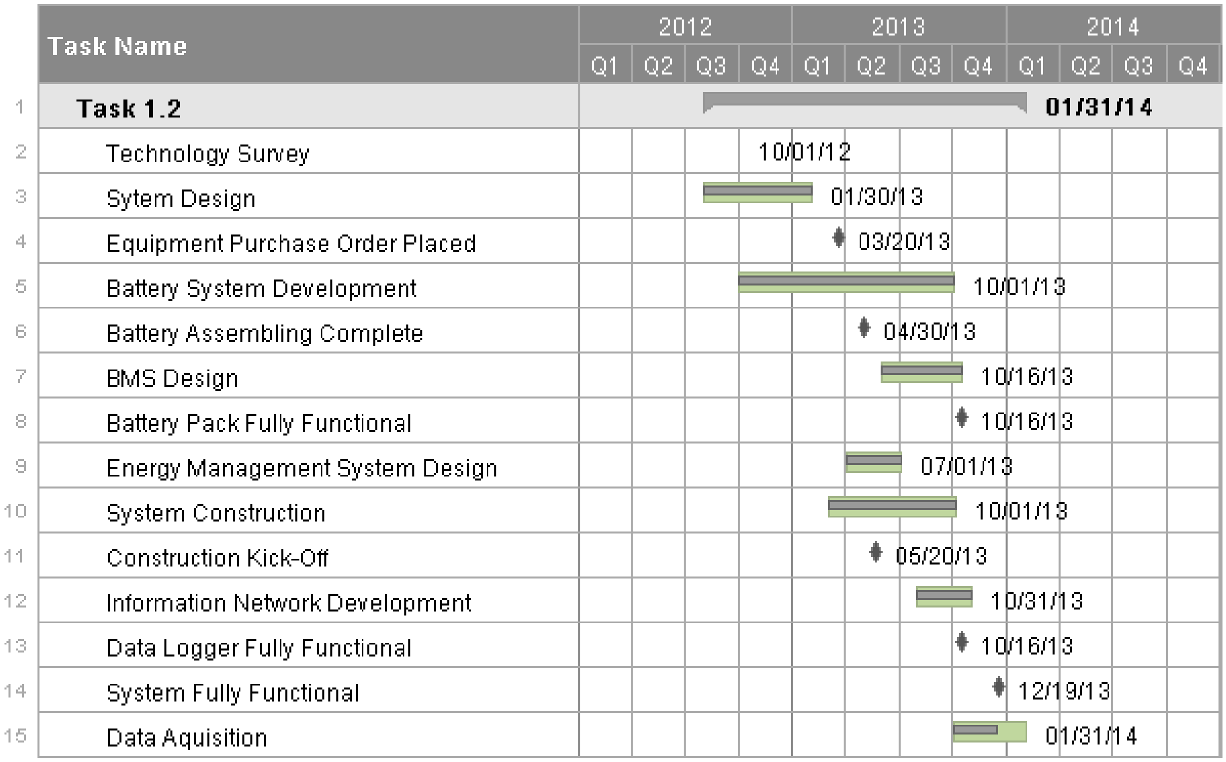

Figure 23: Summary of project roadmaps and milestones of Task 1.2

The system development has been completed at the project house, providing renewable energy to a single family, and meanwhile providing detailed data of energy system operation for research. The research team has followed the project roadmap (Figure 23), and fulfilled periodical milestones. The resulting system meets all the proposed functionality.

Recommendations

California has set an ambitious goal of having 33% of its electricity generation to be provided by renewable sources. Due to the instabilities of wind and solar energy storage will be an important component to enabling the meeting of this target. Energy storage enables the stable use of renewables for peak shaving, which can dramatically reduce the overall pollution caused by electricity generation as this is the critical period in which "peaker" plants, which generate the highest level of emissions, are operated. Finally, applying the use of second life lithium ion batteries for renewable storage have great potential when applied as distributed energy storage solutions at the site of renewable generation, for example when applied to residential homes as performed on this project.

As mentioned above the use of renewables has a critical impact on grid stability, however, the cost of energy as well as the prediction of grid demand also have certain levels of uncertainty associated with them. Employing energy storage into the grid can enable response to changing supply and demand at rates significantly improved over current state of the art techniques. With improved demand response, the possibility of Brown-outs or Black-outs may even be banished entirely, a dramatic benefit to the California public after they faced these issues first hand in the early 2000's.

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Appendix

Appendix I. Summary of EKF for battery SoC and deltaSoC estimation

The battery pack have 15 banks in serial, each requires individual estimation of its SoC. A worst-difference estimation using EKF was developed for this task. Table 5 presents the state-space model used for the worst battery bank. Table 6 presents the state-space model of the rest of the bank in comparison of the worst battery bank. Table 7 presents the computational steps used by the nonlinear extended Kalman filter

Computes each iteration Δt =5s

State and parameter variables

$$x = [SoC, U_S, U_L], \qquad P = [R_S(1 - exp(\frac{-\Delta t}{R_S C_S})), R_L(1 - exp(\frac{-\Delta t}{R_L C_L})), R_{Ohmic}]$$

Functions

$$f(x_k, u_k, \mathrm{P}_k) = Ax + \begin{bmatrix} P(1) \\ P(2) \end{bmatrix} I$$

$$g(x_k, u_k, \mathrm{P}_k) = OCV(SoC) + U_S + U_L + P(3)I$$

where

$$A_k = \begin{bmatrix} 1 & 0 & 0 \\ 0 & exp(\frac{-\Delta t}{R_S C_S}) & 0 \\ 0 & 0 & exp(\frac{-\Delta t}{R_L C_L}) \end{bmatrix}, \qquad C_k = \begin{bmatrix} \left.\frac{dOCV(SoC)}{SoC}\right|_{SoC = \hat{SoC}_k^-} & 1 & 1 \end{bmatrix}$$

$$C_k^P = \begin{bmatrix} 0 & 0 & 0 & I_k \end{bmatrix}$$

$$+\begin{bmatrix} \frac{dOCV}{dSoC} & 1 & 1 \end{bmatrix} \left\{ \begin{bmatrix} I_{k-1} & 0 & 0 & 0 \\ 0 & I_{k-1} & 0 & 0 \\ 0 & 0 & I_{k-1} & 0 \end{bmatrix} + \begin{bmatrix} 1 & 0 & 0 \\ 0 & exp(\frac{-\Delta t}{R_S C_S}) & 0 \\ 0 & 0 & exp(\frac{-\Delta t}{R_L C_L}) \end{bmatrix} \left(-L_{k-1}^x \begin{bmatrix} 0 & 0 & 0 & I_{k-1} \end{bmatrix} \right) \right\}$$

Initialize with

$$\Sigma_w = [1; 0.0001; 0.001], \Sigma_v = 10, \Sigma_r = 0, \Sigma_e = 0$$

note that parameters other than P is not time varying; $\tau_S = R_S C_S = 5$, $\tau_L = R_L C_L = 50$

Table 5: Summary of state-state model for the worst battery bank

For cell number k=1,…15, computes every 15 iteration Δt =75s

State and parameter variables

$$x = \Delta SoC, \qquad P = \frac{\Delta t}{C_{NOM} SoH}$$

Functions

$$f(x_k, u_k, P_k) = Ax + \begin{bmatrix} P & -\frac{\Delta t}{C_{NOM} SoH_{ref}} \end{bmatrix} \begin{bmatrix} I \\ I_{ref} \end{bmatrix}$$

$$g(x_k, u_k, P_k) = OCV(x + SoC_{ref}) - OCV(SoC_{ref})$$

Where

$$A_k = 1, \qquad C_k = \frac{dOCV(SoC)}{dSoC}\bigg|_{SoC = \hat{SoC}_k^-}, \qquad C_k^P = C_k(I_k)$$

Initialize with

$$\Sigma_w = 1, \Sigma_v = 10, \Sigma_r = 0, \Sigma_e = 0$$

note that parameters other than P is not time varying

Table 6: Summary of state space model for the difference between the worst banks and the rest of the banks

Nonlinear state-space model

$$x_{k+1} = f(x_k, u_k, P_k) + w_k$$

$$y_k = g(x_k, u_k, P_k) + v_k$$

Definition

$$A_{k-1} = \frac{\partial f(x_{k-1}, u_{k-1}, P_k)}{\partial x_{k-1}}\bigg|_{x_{k-1} = \hat{x}^+_{K-1}}, C_k = \frac{\partial g(x_k, u_k, P_k)}{\partial x_k}\bigg|_{x_k = \hat{x}^-_K}$$

Initialize with

$$\hat{x}^+_0 = E[x_0]$$

$$\Sigma^+_{x,0} = E[(x_0 - \hat{x}^+_{K-1})(x_0 - \hat{x}^+_{K-1})^{\mathrm{T}}]$$

Computation for $k \in \{1, \ldots, \infty\}$

State estimate time update:

$$\hat{x}^-_k = f(\hat{x}^+_{k-1}, u_k, \hat{P}^-_k)$$

$$\Sigma^-_{\hat{x},k} = A_{k-1} \Sigma^+_{\hat{x},k-1} A^T_{k-1} + \Sigma_w$$

State estimate measurement update:

$$L^x_k = \Sigma^-_{\hat{x},k} (C^x_k)^T [C^x_k \Sigma^-_{\hat{x},k} (C^x_k)^T + \Sigma_v]^{-1}$$

$$\hat{x}^+_k = \hat{x}^-_k + L^x_k [\mathrm{y}_k - \mathrm{g}(\hat{x}^-_k, u_k, \hat{P}^-_k)]$$

$$\Sigma^+_{\hat{x},k} = (I - L^x_k C^x_k) \Sigma^-_{\hat{x},k}$$

where w, v are independent, zero-mean, Gaussian noise processes of covariance Σ_w, Σ_v

Table 7: Summary of computation steps for Extended Kalman Filter.

APPENDIX C

Task 2-Integration of AMI with Solar PV & other DER Technologies

Prepared for Itron

Prepared by: UC Davis Energy Institute and the

UC Davis Office of Environmental Stewardship and Sustainability

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UC DAVIS ENERGY INSTITUTE

WESTVILLAGE UC DAVIS

GE
Energy Consulting

Final Report:

UC Davis West Village Energy Initiative: Integration of AMI with Solar PV and Other DER Technologies

Prepared for:

UC Davis under funding from the CSI RD&D Program

Prepared by:

GE Energy Consulting (Subcontract #201013696-01)

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imagination at work

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Foreword

This report was prepared by General Electric International, Inc. (GEII); acting through its Energy Consulting group (EC) based in Schenectady, NY, and submitted to UC Davis. Technical and commercial questions and any correspondence concerning this document should be referred to:

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Acronyms and Nomenclatures

AMI	Advanced Metering Infrastructure
CO2	Carbon Dioxide
CPP	Critical Peak Pricing
CSI	California Solar Initiative
DER	Distributed Energy Resources
DR	Demand Response
DSM	Demand Side Management
EEC	Energy Efficiency Center
EMS	Energy Management System
EV	Electric Vehicle
GE	General Electric International, Inc., and GE Energy Consulting
HAN	Home Area Network
HEM	Home Energy Management
IP	Internet Protocol
ITS	Institute of Transportation Studies
kW	Kilowatt
kWh	Kilowatt hours
MEM	Master Energy Manager
MW	Megawatt
MWh	Megawatt hours
NEM	Net Energy Metering
NREL	National Renewable Energy Laboratory
PCT	Programmable Communicating Thermostats
PG&E	Pacific Gas & Electric
PV	Photovoltaic
PVW	NREL PVWatts™ Calculator
SEP 2.0	Smart Energy Profile 2.0

SF	Square Foot
TOU	Time of Use
VNEM	Virtual Net Energy Metering
WCEC	Western Cooling Efficiency Center
WV	UC Davis West Village
WVCP	West Village Community Partnership
ZNE	Zero Net Energy

Executive Summary

California is a global leader in the research, development, and demonstration of new energy technologies, including solar Photovoltaic (PV), energy efficiency, energy storage, and electric vehicles (EVs). UC Davis West Village, as the first Zero Net Energy master-planned community in the U.S., represents a unique intersection of these trends and a blueprint for future development in the State. Under research funded by the California Solar Initiative (CSI) RD&D grant program, UC Davis West Village is also a "living laboratory" for proving out state-of-the-art community-level design and energy management best practices, with the aim of supporting the State's goals of sustainable, low carbon, Zero Net Energy (ZNE) performance for all new construction residential housing.[1]

Beginning in August 2012, GE Energy Consulting (GE) was engaged by UC Davis, as subcontractor under Target Area 1, Task 2 of its CSI grant, to examine the integration of demand side monitoring and control ("AMI") with solar PV and other Distributed Energy Resources (DER) at UC Davis West Village. This report presents the results of our Study, including a baseline model of both consumption and solar PV production for each of the existing and to-be-built building types at UC Davis West Village, as well as recommendations for future energy performance monitoring and control.

Our current model representation of UC Davis West Village's overall performance is as follows:

- Annual Solar PV Electricity Production: 9,271 MWh
- Annual Electricity Consumption: 12,042MWh

While outside the scope of our Study, UC Davis plans to construct a Renewable Energy Anaerobic Digester that will generate approximately 4 million kWh per year of renewable energy. A portion of this electricity will contribute to the UC Davis West Village ZNE goal.

Due to the limitations of the data available at the time of our Study and the challenges encountered in preparation of the baseline energy model, we are not able to make a definitive statement about the current state of overall energy performance at UC Davis West Village based on our model results. However, several directional observations are possible. We believe, based on the information available and the conservative nature of our modeling, that it is likely that:

- The multi-tenant units are performing slightly above Zero Net Energy, with some variation by unit type. The Viridian units appear to have the best performance (C/P

[1] http://www.energy.ca.gov/energy_action_plan/

close to 1), while the Ramble and Solstice units are farther "above ZNE" and may require some additional "tightening" of performance to achieve energy balance.

- The Rec and Lease center and swimming pool area (the "Club" and "Gas" accounts), as well as the Mixed Use commercial spaces appear to have a greater excess of consumption over production, that is, they are farther from achieving the ZNE objective.
- Our model confirms that the planned Faculty Staff housing does appear to be well designed to achieve ZNE performance, with small variations by floor plan and solar array size. However, the studio annex units, which are an optional addition for some home owners, may have difficulty achieving ZNE, due to a lack of roof space to support solar installation.
- Finally, above and beyond the data limitations in our study, there remains uncertainty in the evolution of future loads which have not been estimated adequately, notably the EV charging and energy-intensive operations associated with the Western Cooling Efficiency Center.

In Subtask 2, we developed the functional specification for future control features that could be added to UC Davis West Village to monitor and tighten energy performance over time, as may be needed to maintain the ZNE goal. Our technology recommendations focus exclusively on energy management and demand control systems. We believe these technologies represent the likeliest "low hanging fruit" of investment that can be made within the existing design to most easily modify energy performance at the lowest cost. It is our contention that energy monitoring and control is the missing piece of the puzzle at UC Davis West Village that can help translate *good design* into *good practice*, by translating the concept of ZNE into daily performance tracking and commands that can be issued to compel specific control actions.

The core recommendation is the development of a desktop Master Energy Manager (MEM) to automate the on-going tracking of performance data (ideally hourly interval production and consumption). The MEM would serve as an on-going "living" version of our baseline model and would manage communications both to residents and directly to addressable devices such as programmable communicating thermostats within UC Davis West Village.

For the multi-tenant buildings, we developed cost-benefit examples for three different levels of demand side control program: Consumption Information Only, a static Time-of-Use (TOU) rate with programmable communicating thermostats, and a Critical Peak Pricing (CPP) rate with programmable communicating thermostats. In all three cases, the investment appears to be quite economic, with simple payback periods of less than one year, 1.3 years, and 2.5 years respectively.

1 Introduction

1.1 UC Davis West Village Community

UC Davis West Village is a new construction, master-planned residential community on University-owned land immediately adjacent to the central campus in Davis, California. When complete, UC Davis West Village will provide housing for over 3000 students, faculty, and staff through a mixture of 663 multi-tenant rental apartment units and 343 Faculty Staff housing, as well as commercial and recreational space, transportation, landscaping, and other amenities. The Community was built by the West Village Community Partnership (WVCP) as the Master Developer. WVCP also serves as the property manager for the rental properties and maintains many common areas within the Community.

UC Davis and WVCP collectively have formed the West Village Energy Initiative with an explicit goal of demonstrating leading sustainable design practice through the implementation of a "Zero Net Energy" (ZNE) master plan – meaning that on net, UC Davis West Village is designed to generate enough energy from local, on-site renewable resources over the course of a year to meet the annual electricity consumption of all the residents within the community. Currently, almost every structure within UC Davis West Village is being built with rooftop solar PV and a high level of energy efficient design (in excess of California's stringent Title 24 building code). There are also future plans to add a biodigester as an additional renewable generation source.

Within the multi-tenant structures at UC Davis West Village, there are three different building types, each with a slightly different mix of 2, 3, and 4 bedroom units with different floor plans. By early 2012, the "Viridian" and "Ramble" (Phase 1) buildings were fully constructed, with occupancy increasing throughout the summer and near-full occupancy by the beginning of the fall academic year. For these two building types, a distinct solar PV array has been dedicated to each unit from the rooftop, and is connected electrically via an individual string inverter to the unit's PG&E billing meter for purposes of qualifying for PG&E's solar Net Energy Metering (NEM) tariff (see Figures 1 and 2)[2]. WVCP owns the solar PV. SunPower is the manufacturer and installer for all the existing solar PV at UC Davis West Village and provides on-going monitoring and maintenance via a multi-year services contract.

[2] Tenants do not directly pay their utility bill, as WVCP serves as the customer of record. WVCP pays PG&E and then assesses a monthly fee for utility costs in each tenant's rent.

Figure 1: Bank of PG&E Net Meters

Figure 2: Bank of Individual String Inverters

A third building type, the "Solstice" (previously known as the "Boulevard" apartments) was still under construction at the time of this Study. In addition, the Ramble Phase 2 building was still under construction. These newer buildings will qualify under the new Virtual Net Energy Metering rules adopted by the CPUC in late 2011[3]. Under these rules, apartment units will not require their own individual PV array and inverter. Instead, a virtual allocation of the entire solar array will be allowed, in which the benefit of the aggregate solar output will be divided between the units within the building on a percentage allocation basis.

[3] CPUC Decision 11-07-031. Further information about VNEM can be found at http://www.cpuc.ca.gov/PUC/energy/DistGen/vnm.htm.

SunPower is also the solar contractor for these facilities, except for a small demonstration solar thermal facility at the Solstice[4].

Construction of the Faculty Staff housing at UC Davis West Village has not yet begun, but is anticipated in a pending phase of development. The Faculty Staff housing will be built and sold to eligible UC Davis faculty and staff as ownership properties, with a 99-year ground lease to the land. Unlike tenants in the rental units, who pay an indirect allocation of utility costs in their rent, the home owner will be the PG&E account holder and bill-payer of record. This difference is important in that it is expected to provide more direct incentives for incorporating advanced energy management features, such as "smart", demand responsive appliances and thermostats, within the Faculty Staff housing (see discussion of Program Recommendations in Section 3.5 below).

There are four different floor plan options that will be offered to prospective residents with differences in layout and square footage. Based on the recommendation of the UC Davis team, we have assumed an equal uptake of each design in our model. In addition, up to 206 homes are permitted for an optional studio unit, which the home owner may build and either occupy or lease out as a rental unit. We have modeled these studio units as an additional housing type.

In addition to housing, there are six Mixed Use (MU) commercial spaces on the ground floor of the Viridian complex, which are designated for a combination of light retail (e.g., a grocery/convenience store) and office use. As of the beginning of this study, the MU space was not yet occupied, though several office tenants have since moved in. UC Davis has leased several of the MU spaces for campus staff, including the new offices of the Institute of Transportation Studies (ITS), the Energy Efficiency Center (EEC), the Energy Institute, and the Western Cooling Efficiency Center (WCEC)[5].

While there were no load data available yet for the occupied offices at the time of this Study, a preliminary estimate of energy usage for the MU spaces was created in July 11, 2012 by the Davis Energy Group[6], a consulting firm, and we have relied on their work to populate our model for MU consumption. In addition to portions of the rooftop, solar PV is assigned to the MU buildings from arrays on solar carports in the adjacent parking area. An EV charging

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[4] At the time of our Study, UC Davis was investigating solar products from a different manufacturer (funded through the CSI Grant, Target Area 1, Task 1) that would include passive solar hot water, as well as PV generation. We have not attempted to model these "hybrid" (electric/thermal) solar facilities in our study.

[5] Notably, the WCEC will house testing of some energy-intensive building cooling systems, such as commercial chillers, though their precise operating schedules is not known at this time.

[6] "Mixed Use Commercial Space Energy Estimate", Memo to UC Davis West Village Community Design Team, Davis Energy Group, July 11, 2012.

station will be powered by the vertical Sundial tower structure, which is a feature of the Viridian complex (see Figure 3).

Figure 3: UC Davis West Village Sundial Tower

Several months of historical solar production data were available for the MU buildings and are used in our Study.

In addition to housing and the MU space, the Ramble complex contains a Recreation and Leasing office, with meeting/study space, offices, gym facilities, a movie theater, and an outdoor heated swimming pool. While the pool is heated with natural gas, there is electric load associated with the pool pumps required to circulate water and maintain both temperature and chemical levels. The "Rec and Lease" building (also referred to as "Rec Center" or "Club House") was open and fully occupied during the time of our Study, however, due to some delays in calibration of measurement equipment, only partial data history was available for solar production.

Finally, the Community contains several types of miscellaneous common areas with both interior and exterior loads that we have attempted to capture. Each apartment building has lighted open-air hallways, breezeways, and stairways, as well as external lighted pathways and landscaped outdoor areas with irrigation sprinklers. Electric demand associated with these common areas is assigned to a set of separately metered accounts for each building, for which solar facilities are also dedicated (under NEM).

There are plans for plug-in electric vehicle (EV) charging, both for the ITS fleet and in other locations throughout the community, as consumer demand materializes. Insufficient data were available to model EV uptake and charge patterns and this future load was therefore deemed out of scope for the current Study. However, we have provided a placeholder for it in our model.

Finally, the community includes the Davis Center for Sacramento Community College, located on a corner of the UC Davis West Village plot, which is not under direct UC Davis control and has not been included in the ZNE design. We have excluded this building, along with any future out-of-plan facilities that may be located within the community footprint.

1.2 Study Objective

UC Davis is the awardee of a multi-project research grant under funding from the California Solar Initiative (CSI) RD&D program[7]. Overall, the UC Davis West Village CSI grant seeks to examine different aspects of solar usage at UC Davis West Village and demonstrate a range of technologies that will be of value to the state of California and the solar industry in general, as communities throughout the State seek to include solar generation in their strategies to achieve Zero Net Energy, sustainability, and low carbon objectives.

Beginning in August, 2012, GE Energy Consulting was engaged as the subcontractor to UC Davis for Target Area 1, Task 2 of the UC Davis West Village CSI grant, entitled “Integration of Advanced Metering Infrastructure (AMI) with Solar and other Distributed Energy Resources (DER)”. The purpose of this Task is to first establish a baseline representation of current energy performance from the available data and designs for UC Davis West Village (Subtask 1), and then to recommend a monitoring and control systems architecture that integrates the customer demand side (“AMI”)[8] with solar PV production and other DER technologies, to be able to measure and adjust performance to meet the ZNE goal on a dynamic, on-going basis (Subtask 2).

Achieving the ZNE objective has been a guiding principle in the design of the facilities at UC Davis West Village. While useful as a community-level design construct, ZNE is in fact a difficult quantity to measure on a day-to-day basis, within an evolving community, given all the variations in construction, tenancy, occupancy, and ownership, as well as the limitations in the available data.

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[7] CSI research is funded by the ratepayers of the three major California Investor Owned Utilities under the auspices of the California Public Utility Commission (CPUC). The independent administrator selected by the CPUC to oversee the CSI RD&D program is Itron, which contributed to the review of this report.

[8] We have adopted the loose definition of AMI from the grant, which we understand to include not only data from the meters themselves, but intelligent end-use devices on the customer side of the meter.

In short, GE sought to answer two key questions: How is energy performance tracking compared to the goal of ZNE? And, secondly, where we are not meeting ZNE, what levers are at our disposal to track and adjust energy performance going forward?

Our goal in structuring the Task was to provide UC Davis and the West Village Energy Initiative with the tools to answer these two questions and ensure that ZNE would live on as an operating principle beyond the design phase. By laying out a framework for measurement of ZNE along with recommendations for investment in on-going energy management, we hope to enable the facility managers and UC Davis staff at UC Davis West Village to track and adjust building performance dynamically, for example tightening energy management through automated controls and messaging to tenants, to ensure cost-effective attainment of ZNE.

1.3 Limitations of the Study

A distinct challenge of our work at this early stage in the evolution of UC Davis West Village is that no single "snapshot" of annual energy performance across the community currently exists. New buildings are coming on line and energy system start-up fine-tuning is occurring. For each of the existing, occupied housing unit types and common areas, data on both consumption and solar production were available for less than one year at the time of our study, with both gaps and inconsistencies in the available history. For the unoccupied and "to-be-built" units, no historical data are, of course, available, and we were obliged to use a mix of modeling techniques to estimate likely consumption and production patterns from the available information, together with reasonable assumptions based on our own best judgment and recommendations of the project team.

The approach we have taken is to model the energy performance of the UC Davis West Village community as it would perform during a single, hypothetical full year of "steady state" operation, in which all buildings have been constructed and are occupied over the course of the year, according to their anticipated use and normal weather and occupancy patterns. We call this representation of load a "synthetic year", as it represents an ahistorical baseline state against which to evaluate future performance.

In reality, all aspects of the community will continue to evolve and change over time, with a dynamic level of tenancy, occupancy, and usage for all the building types. For example, with the high rate of turnover of students in the rental housing, and the arrival of increasing numbers of faculty and staff in the Faculty Staff housing, it is likely that UC Davis West Village will see changes in end-use behavior each year, as each new crop of residents arrives with more and different electronic devices, appliances, and perhaps EVs. At the same time, educational outreach efforts by WVCP may be expected to help improve energy awareness and reduce consumption by continuing residents over time.

Our aim in structuring a baseline approach was to provide a single unifying framework for representing the energy performance of the UC Davis West Village community that we believe can be extended and adapted as new and better data become available. Given the limitations of the existing data and the evolving state of construction and occupancy, we caution against taking any specific numerical model result below as authoritative. Rather, we believe our results and recommendations are best viewed as directional guideposts – identifying the best opportunities for further investment in monitoring and control capability to both improve the data and drive better energy decision making for UC Davis West Village.

1.4 Project Scope

GE Energy Consulting was engaged as the subcontractor for the UC Davis West Village Energy Initiative CSI RD&D project under Target Area 1, Task 2, entitled: "Integration of AMI with Solar PV and other DER Technologies". The scope of this Task consists of two main Subtasks:

- Subtask 1: Understand baseline energy performance for the existing and planned new construction buildings at UC Davis West Village, which include multi-tenant housing, commercial/public space, and Faculty Staff housing, and determine baseline performance against the objective of ZNE; and
- Subtask 2: Recommend the functional specification for a monitoring and control systems architecture that integrates the customer demand side ("AMI") with solar PV production and other DER technologies, to be able to measure and adjust performance against the ZNE goal on a dynamic, on-going basis.

1.4.1 Subtask 1

Under Subtask 1, GE's scope included the following activities:

- Collect, validate, and analyze existing and available data for UC Davis West Village
- Develop realistic assumptions for additional parameters, as necessary
- Develop a quantitative framework representing energy generation from solar PV at UC Davis West Village and energy consumption by end use
- Characterize expected baseline performance, including the physical attributes of each technology and behavioral sensitivities for user-controlled characteristics

The key deliverable from Subtask 1 is a baseline model of the energy performance of the UC Davis West Village Energy Initiative. This model is contained in the Excel Workbook submitted with this report and is documented extensively in Section 2 below. The Model organizes UC Davis West Village according to the existing and future building types, allowing an estimation of the annual net energy performance for a hypothetical "synthetic year" of baseline operation.

1.4.2 Subtask 2

Based on the model developed in Subtask 1, GE then looked at ways to leverage demand side controls ("AMI") and other alternatives to enhance the energy performance capability of UC Davis West Village.

Under Subtask 2, GE's scope was to develop a Functional Specification for the integration of AMI, PV, demand response, and storage[9] technologies, consisting of:

- Recommendations for the IT and communications architecture (functional, not vendor-specific) to support the ZNE goal
- Estimated costs and benefits of incremental hardware and software
- Expected benefits of incremental control capability
- Summary of any additional design considerations, such as user friendliness, interoperability, potential electrical system, environmental, or aesthetic impacts, etc.

The key deliverable for this Subtask is the functional specifications with recommendations for incremental monitoring and control contained in Section 3 of this report.

[9] Energy storage technologies were originally included as part of the scope for Subtask 2. After further consultation with the UC Davis team and examination of the multiple challenges to be overcome, GE concluded that stationary battery (or other) energy storage was not currently a cost-effective resource option at West Village, due to both technical and economic constraints. In particular, as discussed below in Section 3.5.3, the nature of the annual Zero Net Energy goal provides no direct financial incentive for time-shifting of energy, for example, storing daytime-peaking PV generation to meet peak demand in the afternoon and evening hours. Technical barriers to the integration of storage are being examined elsewhere within the West Village CSI grant. GE recommends that storage options be evaluated at a later stage of the overall CSI project, when results of this pilot project become available.

2 Subtask 1

2.1 Subtask 1 Introduction

Subtask 1 is the development of a baseline model of energy performance for each building type at UC Davis West Village and seeks to answer the first of our key questions: How do we know if we are meeting ZNE? While limitations in the existing data make it impossible to determine definitively how the community is currently performing, our results permit some general inferences and provide guidance, based on the relative performance of each building type. The model we have developed can and should be adopted and further refined with the addition of new and better data as they become available in the near future.

2.2 Data Collection, Validation, and Analysis

2.2.1 Preliminary Data Analysis

We considered different data sets for review and analysis in order to determine the type of baseline model to develop. The main data challenges we encountered included the following:

- The wide mix of existing buildings with partial historical data (Ramble Phase 1, Viridian, Rec Center, MU) and to-be-built (Solstice, Ramble Phase 2, Faculty Staff Housing).
- PG&E consumption data for each existing unit were available for the last 9 months only. For different units, SunPower production data history varied from 1 to 9 last months, typically 5 months.
- Unknown occupancy patterns, future tenancy/commercial use.
- Anecdotal information that student load shapes are highly unusual, with some units experiencing very low afternoon and evening load but daily peaks that occur as late as midnight[10].
- Incomplete end-use breakdown in each unit and building.
- PG&E monthly bill history (Net metered) and SunPower hourly production and consumption data needed to be reconciled.

[10] While these observations were made from the SunPower consumption data that later proved unreliable, we were able to confirm similar behavior at other universities through conversation with utility load research experts at PG&E and other utilities.

- Limited access to hourly interval data (only one week of SunPower history downloadable at a time).
- SunPower consumption data appeared to be anomalous; software errors were later confirmed (see below).
- Unknown size and usage of future plug-in electric vehicle fleet.

We considered different data sets for review and analysis. The principal sources provided to us by WVCP included:

- UC Davis West Village Community Plan and Related Files
  - Ramble Apartments: 100% CD UC Davis West Village Student Housing Phase 1.pdf
  - Mixed-Use Buildings: MU1-MU6 University Approved (Complete).pdf
  - Solstice Apartments: 01-Gen.pdf, 08-Electrical.pdf
  - Single Family Houses: WV Single Family Floor Plans 022912.pdf
  - Lease and Recreation Center: 100% CD UC Davis West Village Square Leasing & Rec.pdf
  - UC Davis West Village Student Housing Phase 1.pdf
  - Mixed Use Commercial Space Energy Budget_Analysis_07112012.pdf
- Solar PV Inventory
  - SunPower UCD checklist Master List.xlsx
- PG&E Billing
  - Davis electrical tracking 2012 trueup v25 ~9-17 w' daily use.xls
- Hourly SunPower Data
  - Download of a several months of daily and a week of hourly SunPower Production and Consumption Data
- Davis Energy Group report (covering Mixed-Use)

The monthly PG&E data provided the “net” kWh consumption at each meter, which is the total electricity consumption minus the total solar electricity generation measured at each unit’s meter. The net kWh consumption can be positive or negative depending on the relative values of electricity production and consumption over the course of the PG&E billing cycle month[11].

SunPower, which installed and monitors the solar facilities at UC Davis West Village, provided access to monitoring data from both the inverter (solar production) and a consumption measurement derived from a Current Transformer clamp installed at the individual unit junction box[12]. The SunPower data included both monthly Solar PV electricity production and cumulative monthly electricity consumption for each unit. The hourly interval SunPower data are not stored, and can only be downloaded manually for the previous 168 hours at the time of the download.

After manual download at two different occasions, we analyzed the hourly SunPower electricity production and consumption data, and compared it to the PG&E net energy data.

We quickly observed that the hourly SunPower consumption data were inaccurate, and were correlated with solar production.[13] This anomaly was later confirmed by SunPower[14], which is working to correct an apparent software bug in its monitoring user interface. Hence, we decided to build a bottom up Monthly/Annual Model of UC Davis West Village Electricity Production and Consumption. The model builds up consumption from estimates of individual end use loads, without calibration against a total metered load for each unit. By "bottom up" we mean that the model starts with each individual unit production and consumption presentation and representation of individual end-use and then builds up and sums up the total community energy production and consumption from there as long as the relevant information is available or can be represented.

The following tables provide examples of the raw PG&E and SunPower data.[15]

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[11] PG&E calculates and delivers monthly bills based on a rolling monthly cycle of read dates that varies from account to account. GE was able to identify the read cycle calendar for the UC Davis West Village units and weight the SunPower data (which is on a calendar basis) from the previous and current month in order to approximate an equivalent to the PG&E cycle month.

[12] This CT clamp measures an instantaneous "pulse" of power flows into the unit at periodic intervals and then averages the power (instantaneous current times voltage) over the intervals in an hour to obtain an estimate of energy consumed (kWh) during the hour. This method is inherently less accurate than the utility grade metrology used by PG&E.

[13] While cooling energy usage would normally correlate well with solar production, the correlation witnessed in the data is much stronger than cooling alone would explain.

[14] Conversation with Josh Kozub, Manager, Operations & Maintenance, Residential Systems North America, SunPower Corporation

[15] In these and all subsequent tables, individual unit addresses are concealed in order to protect the privacy of residents.

			Dec - 2011		Jan - 2012		Feb - 2012		March - 2012	
address	unit #	beds	Amount Billed	Billed Usage	Amount Billed	Billed Usage	Amount Billed	Billed Usage	Amount Billed	Billed Usage
XYZ Sage	a	4	$ 16.57	166	$ 28.75	283	$ 37.89	355	$ 32.77	308
XYZ Sage	b	3	$ 31.97	324	$ 37.30	369	$ 72.53	693	$ 50.54	484
XYZ Sage	c	3	$ 30.14	304	$ 65.72	659	$ 55.11	528	$ 51.52	492
XYZ Sage	d	4	$ 10.88	108	$ 6.32	60	$ 43.86	415	$ 15.43	140
XYZ Sage	e	4	$ 44.12	442	$ 84.36	848	$ 90.23	856	$ 68.35	652
XYZ Sage	f	3	$ 12.10	121	$ 5.18	49	$ 29.92	284	$ 19.79	185
XYZ Sage	g	3	$ 23.91	241	$ 23.52	235	$ 33.86	321	$ 22.80	210
XYZ Sage	h	4	$ 17.08	171	$ (6.25)	-69	$ 22.25	207	$ 1.26	5
XYZ Sage	i	4	$ 21.61	215	$ 39.01	382	$ 56.03	534	$ 86.16	831
XYZ Sage	j	3	$ 23.66	235	$ 38.90	382	$ 33.84	317	$ 1.33	7
XYZ Sage	k	3	$ 11.20	112	$ 2.79	23	$ 29.25	276	$ 15.44	142
XYZ Sage	l	4	$ 21.08	212	$ 5.13	48	$ 30.46	289	$ 21.45	199
XYZ Sage	house a - l	#B	$ 94.44	480	$ 81.44	600	$ 202.71	960	$ 38.69	360

Table 1: Example of PG&E Data

Address	Bldg	Unit	City	Zip Code	WattNode #	Inverter #	Inverter Model #	PV Supervisor	Module Type	Count	Status
XYZ Sage Street	Building A	a	Davis	95616	64509	2001603177	SPR-4000M	TAAE01081098	SPR-425E-WHT-D	10	Completed
XYZ Sage Street	Building A	b	Davis	95616	64500	2001660433	SPR-3000M		SPR-425E-WHT-D	8	Completed
XYZ Sage Street	Building A	c	Davis	95616	64897	2001688033	SPR-3000M		SPR-425E-WHT-D	8	Completed
XYZ Sage Street	Building A	d	Davis	95616	64501	2001597624	SPR-4000M		SPR-425E-WHT-D	10	Completed
XYZ Sage Street	Building A	e	Davis	95616	64803	2001031323	SPR-5000M		SPR-225E-BLK-D	21	Completed
XYZ Sage Street	Building A	f	Davis	95616	64889	2001603362	SPR-4000M		SPR-225E-BLK-D	18	Completed
XYZ Sage Street	Building A	g	Davis	95616	64901	2001572176	SPR-4000M		SPR-225E-BLK-D	16	Completed
XYZ Sage Street	Building A	h	Davis	95616	64499	2001603333	SPR-4000M		SPR-225E-BLK-D	18	Completed
XYZ Sage Street	Building A	i	Davis	95616	64893	2001603450	SPR-4000M		SPR-225E-BLK-D	18	Completed
XYZ Sage Street	Building A	j	Davis	95616	64882	2001603175	SPR-4000M		SPR-225E-BLK-D	18	Completed
XYZ Sage Street	Building A	k	Davis	95616	64842	2001603111	SPR-4000M		SPR-225E-BLK-D	16	Completed
XYZ Sage Street	Building A	l	Davis	95616	64888	2001603245	SPR-4000M		SPR-225E-BLK-D	18	Completed
XYZ Sage Street	Building A	Common Area	Davis	95616	78881	2000960934	SPR-6000M		SPR-425E-WHT-D	15	Completed
XYZ Sage Street	Building A	Common Area	Davis	95616		2000973875	SPR-6000M		SPR-425E-WHT-D	15	Completed
XYZ Sage Street	Building A	Common Area	Davis	95616		2000973753	SPR-6000M		SPR-425E-WHT-D	15	Completed

Table 2: Example of SunPower Solar PV Inventory

2.2.2 Data Validation and Analysis: Solar Production

The following figures depict plots of daily solar PV production (from SunPower) for selected units.

The first figure includes a number of 3 bedroom units covering about 7 months of data. A clear seasonal pattern can be observed; however, there appear to be many wide swings of data. To the extent that deep sags appear to be correlated across all units for a given day, one can surmise the cause to be the daily variations in weather and cloud formation, but that does not seem to be the case in most instances.

There are a number of dips that are followed immediately by spikes in the following day's data, which we hypothesize to be the result of a communication error and a failure to report production during certain hours (which then gets added to the next day's production data). This pattern appears to explain many of the anomalous data points and could be corrected by averaging or "smoothing" the daily data.

The wide range of produced energy for different apartments shown in the same figure also indicates that different 3 bedroom apartments are connected to different panel array sizes.[16] In fact, there are about ten different ratings for the 3 bedroom apartments' panels, ranging from 3.2kW to 4.2kW. Some of the 4 bedroom apartments are connected to panels of similar ratings.

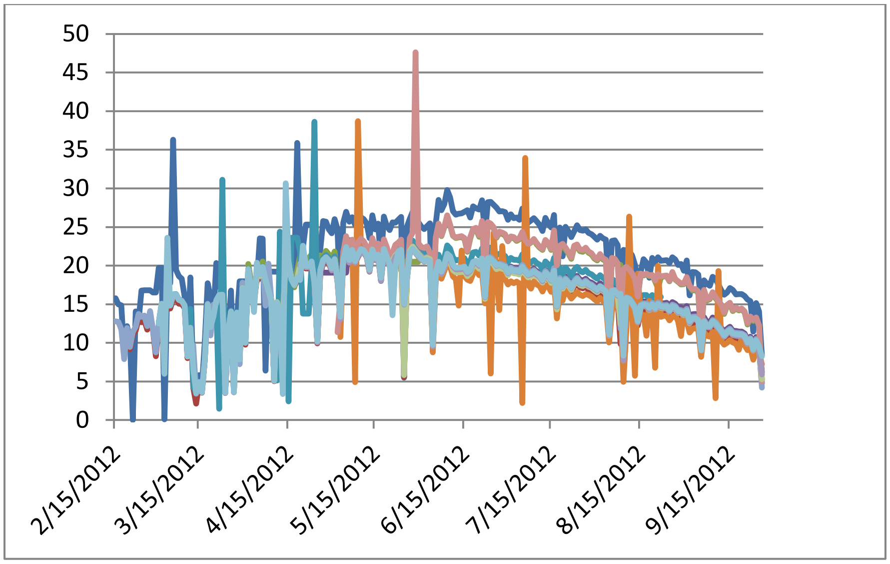

Figure 4: Daily Solar Production of Selected 3BR Ramble Units in kWh

The second figure includes three curves, each an average over sets of representative units of 2, 3, and 4 bedroom apartments, respectively. Here we observe a higher level of correlation of variations across the solar generation of different unit types ("dips" with none of the sag/spike pairs), and hence, one can assume the cause to be daily variations in solar activity and cloud formation. As might be anticipated, cloudy days appear more frequently in the spring months than in the peak summer season (which in sunny Davis may extend all the way through September and even October).

16 In addition to differences in array size, there are also some variations in PV system orientation and azimuth among the buildings in UC Davis West Village.

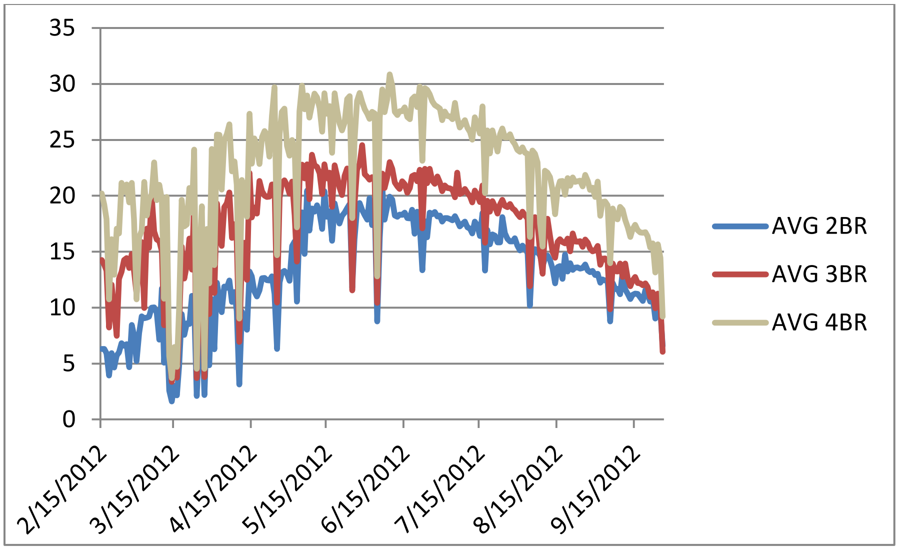

Figure 5: Average Daily Solar Production for 2, 3, and 4 BR Units in kWh

The wide variation in actual SunPower data across units and also across time led us to seek a more standard and weather normalized way to represent the average solar power during different years. As recommended to us by SunPower[17], we investigated the NREL PVWatts™ Calculator (PVW), a public domain web-based tool to generate the monthly normalized PV data. Using PVW, we are able to extrapolate production for all months of the year.

Using PVW, we determined the monthly kWh generation for a 1 kW PV panel for the Sacramento area (the closest weather station site to the Davis area available in PVW). We then calculated each individual unit's or aggregate unit's monthly solar PV production in kWh by scaling the monthly NREL PVW data (given for 1 kW PV Panel) using the individual unit's or aggregate unit's PV Panel Nameplate kW values provided in the SunPower data.

To verify the reasonableness of the PVW data, we compared the monthly PVW data with actual SunPower recorded data for a number of Phase 1 units, for the months for which actual data were available. Results are show in the following table and chart.

[17] Conversation with Josh Kozub, Manager, Operations & Maintenance, Residential Systems North America, SunPower Corporation

	PVW 3.4kW	Unit A	Unit B	Unit C	Unit D	Unit E	PVW 3.6kW	Unit F	Unit G	PVW 4.05kW	Unit H	Unit I	Unit J	Unit K
January	**150**						**158**			**178**				
February	**223**						**237**			**266**				
March	**360**		357	369		366	**381**			**429**	449		525	183
April	**478**	525	524	538		534	**506**	550		**570**	633		655	269
May	**583**	644	623	648	652	635	**617**	666	686	**695**	759	763	757	316
June	**600**	592	579	624	548	592	**635**	705	708	**714**	794	797	792	305
July	**614**	578	552	612	519	571	**650**	694	699	**731**	771	770	789	295
August	**555**	470	439		423	465	**588**	579	579	**661**	641	645	700	243
September	**439**						**465**			**523**				
October	**316**						**335**			**377**				
November	**178**						**189**			**212**				
December	**134**						**142**			**159**				
Correlation		0.5195	0.7972	0.9645	0.3992	0.8346		0.9151	0.9014		0.9627	0.8761	0.9892	0.8841

Table 3: Comparison of PVW and SunPower Data

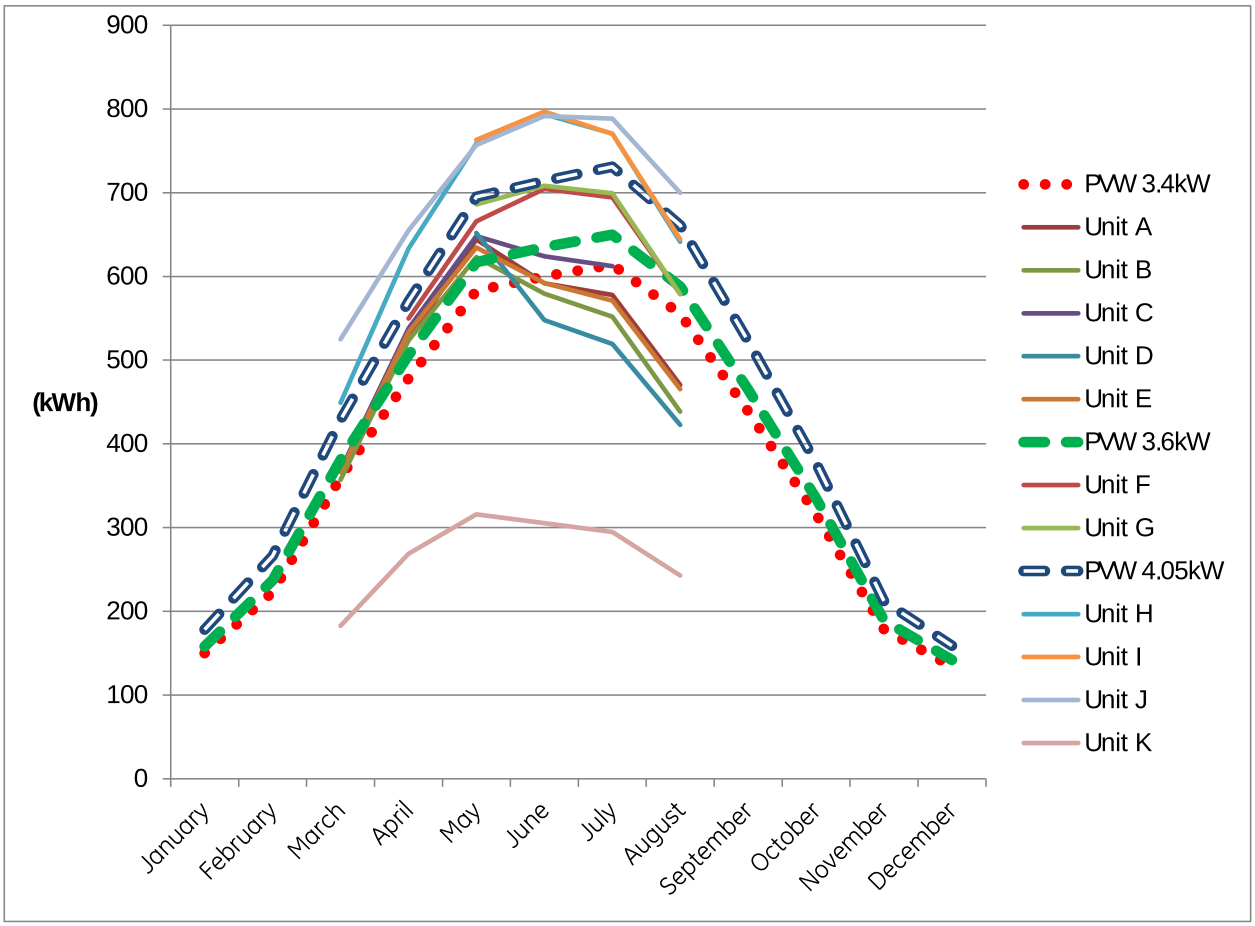

Figure 6: Comparison of PVW and SunPower Data

As can be observed, the PVW data provide a reasonably good match to the actual but incomplete monthly SunPower recorded data. The outlying SunPower data for the last unit is most likely due to incorrect assumption about the size of the solar panel, and should be ignored. Moreover, the PVW data are already "weather normalized" based on many years' of Sacramento area weather data and should therefore be a more representative and reliable predictor of solar output for our "synthetic year" baseline than the observed pattern of data for just spring-fall 2012.

In the future, as actual historical data becomes available for a longer period through on-going collection and recording of SunPower data, the PVW data can be replaced with more UC Davis West Village specific data.

The monthly PVW data for a 1 kW panel for a Sacramento location is given in the following table. For simplicity in running the PVW calculator, we assumed a South facing system orientation with 180-degree Azimuth (flat).[18]

kW	Month	Solar Radiation (kWh/m2/day)	AC Energy (kWh/Month)
1.0000	1	1.87	44
	2	2.98	66
	3	4.28	106
	4	5.92	141
	5	7.20	171
	6	7.83	176
	7	7.88	181
	8	7.08	163
	9	5.75	129
	10	3.96	93
	11	2.33	52
	12	1.73	39
	Year	4.91	1,362

Table 4: PVW Monthly Solar Electric Energy Used for Electricity Production Calculations

[18] In reviewing the detailed solar drawings, several of the buildings in UC Davis West Village appear to have a different solar orientation, however, a quick sensitivity check suggests that differences in solar production due to orientation are only on the order of 3%.

2.3 WV Electricity Production and Consumption Model

This section describes the approach we selected to construct a baseline model of UC Davis West Village electricity production and consumption based on the currently available data. Because the model was built without calibration against historical consumption data, the results are highly sensitive to specific input assumptions.

To keep the model accessible to future developers, we intentionally did not include any macros. All the operations are based on cell-based formulas that can easily be viewed. Cell to cell linkages can be viewed through "Formula Auditing" using "Trace Precedents" and "Trace Dependents". This is a stand-alone model with all the data self-contained and no links to additional files.

Areas for future improvement may include updated modeling of various components and modules of the model such as specific formulas for electricity consumption of appliances, lighting, heating, and cooling. In addition, as the UC Davis West Village community is expanded and new residential and commercial units are built, the [Model Main] worksheet can be expanded by replacing the aggregated representation of future developments with fully disaggregated representation similar to Phase 1 units.

More complexity can also be incorporated into the model in the future by "agent-based" representation of electricity usage in each unit, reflective of different behavior patterns and occupancy, with underlying stochastic/probabilistic features.

2.3.1 Model Features

The main features of the model are:

- We estimated each unit's PV electricity production
    - Based on each unit/building's kW PV capacity and the NREL PVW monthly solar electricity production projections.
- We estimated each unit's electricity consumption
    - Based on each unit's electricity consumption for appliance use, heating, cooling, and lighting, as well as miscellaneous plug loads (the model accounts for the plug loads in addition to the appliance load).
- We made assumptions for missing data.
- We modeled all existing Ramble and Viridian units individually
- We modeled all Solstice and Ramble Phase 2 units as aggregates grouped by number of bedrooms

- We modeled all Single-Family Homes as aggregates grouped by type of floor plan/area
- We modeled all Single-Family Home Studios aggregated into one group
- We included all Mixed Use Commercial, Lab Space, Café-Restaurant-Grocery shops based on modeling from the Davis Energy Group report
- We included the Recreational Center and Leasing Office (Club + Gas accounts) using projection/estimation of their energy use based on the available months of PG&E bills

2.3.2 Structure of the Model

The UC Davis West Village Monthly Electricity Production and Consumption Model (the "Model"), is an Excel spreadsheet that projects monthly electricity production and consumption for existing individual units and future aggregate units.

The main Excel Model Workbook includes the following worksheets (tabs):

- [Results Summary]: This worksheet contains tables of results by *Individual Unit Type Categories* and also by *Aggregate Unit Type Categories.*
- [Model Main]: This worksheet is the main module of the model where all the individual and aggregate units are listed and the final layers of production and consumption data are calculated. Section 2.3.3 below provides more detail on various components of this module.
- [Unit Data]: Includes unit type and area data for current and future phases.
- [Appliance Data]: Includes appliance data by building type, and lighting, heating, and cooling energy consumption assumptions.
- [HVAC Data]: Includes the main assumptions and approach to determine the annual heating and cooling electricity consumption per unit of area.
- [Pattern Data]: Includes Seasonality, Occupancy Type, and other tables used in calculation of electricity consumption.
- [Mixed Use Data]: Includes electricity consumption data of Mixed Use units based on information provided by the Davis Energy Group Report.
- [Club & Gas Data]: Contains the methodology used to project the electricity consumption of the Rec and Lease Office and swimming pool pump load.
- [PG&E Data]: Contains the PG&E Billing Statement data used to identify individual units and obtain PG&E Metered Net Energy Data.
- [SunPower Data]: Contains the unit by unit SunPower information on solar PV panel ratings.

- [PVW Data]: Includes NREL PVWatts ™ Calculator data on monthly Solar PV Power Output of 1kW Solar Panel sited in the Sacramento region.
- [PVW Analysis]: Provides a comparison of PVW data and SunPower data in order to justify using of PVW.
- [SunPower Phase 2 PV Data]: Includes the data from SunPower used to determine the Solar PV Electricity production of Phase 2 Ramble units.
- [SunPower Club & Gas Data]: Contains the daily SunPower energy production data that is used to determine the monthly Club & Gas electricity consumption for available months.
- [Compare GE PG&E]: This worksheet provides a comparison of GE model output of monthly unit electricity consumption with actual unit electricity consumption calculated based on the sum of SunPower monthly electricity production and PG&E Net Energy data.

2.3.3 Components of the [Model Main] Worksheet

The [Model Main] worksheet performs the main calculations of electricity production and consumption of the UC Davis West Village community.

2.3.3.1 Electricity Production and Consumption

- The electricity production values are calculated using PV kW ratings from the relevant architectural design specs and monthly PVW Data.
- The electricity consumption values are based on electricity consumption by (a) Appliances (including Miscellaneous Plug Loads), (b) Lighting, (c) Cooling, and (d) heating. Each of these electricity consumption components are described in later sections.

2.3.3.2 Individual versus Aggregate Units

Individual and aggregate unit identifications and unit by unit monthly and annual electricity production and electricity consumption are provided and calculated in the [Model Main] worksheet.

Residential, commercial, and recreational units are grouped into “individual” and “aggregate” units.

- Individual Units: These are units which (a) could be identified individually, and (b) for which electricity production and consumption could be calculated on a unit by unit basis. The individual unit information and data are provided in the first few hundred rows. The Individual units list includes:

  - All Phase 1 Ramble and Viridian Apartments (both electricity production and consumption)
  - Mixed Use Retail and Common Area electricity production only
  - Club and Gas components of the Club House (Recreation and Leasing Center plus outdoor pool pumping load) for electricity production only
- Aggregate Units: These are buildings that could not be disaggregated into individual units, and hence, the electricity production and consumption are calculated for the aggregate whole. The aggregate unit information and data are provided further down the table in a section after listing of all the individual units. The Aggregate Unit list includes:
  - Mixed Use Retail and Common Area electricity consumption within the Viridian and Phase 1 Ramble buildings.
  - Club and Gas components of the Club House for electricity consumption only
  - EV Fleet under "Other-Use-EV Fleet"
  - Single-Family Homes
  - Solstice and Phase 2 Ramble units

The reason for separate treatment of the Mixed Use Retail and Club House is that their electricity consumption calculation does not fit into the methodology used for calculation of electricity consumption of individual units, although their electricity production calculation does.

2.3.3.3 Description of columns in the [Model Main] Worksheet

- Columns A to H: These columns contain reference codes that identify a particular unit within the model, based on the combination of various unit related codes. These cells should not be altered, since they are referenced by other cell formulas.
- Columns I to L: These columns include data from PG&E statements that include unit building type, unit address, unit number, and unit bedroom numbers or other identification codes. All the individual "existing" (built and occupied at the time of our study) units have been included.
- Columns M to O: These columns include unit information from SunPower that are matched to PG&E unit information including unit address, unit building, and unit number.
- Columns P to AD: These columns calculate the monthly and annual PV electricity production in kWh. Column AC shows the Capacity Factor (defined as the ratio of

total energy produced to total potential energy if the PV was producing at full capacity at all hours of the day for the year).

- Columns AE and AF: These columns are, again, coded values used in later columns to search for values and should not be altered.
- Column AG: Area of the Unit/Building Component in Square Feet. The underlying formulas pull data from the [Unit Data] worksheet. Unit Area is used in the calculation of Lighting, Cooling, and Heating electricity consumption, but does not impact Appliance electricity consumption (Appliance usage is modeled as a function of the occupancy, rather than as a function of floor space within a given unit).
- Column AH: Occupancy Type, which is defined in the worksheet [Pattern Data]. Occupancy Type impacts Appliance, Lighting, Cooling, and Heating electricity consumption. Occupancy types are described later in the section on [Pattern Data] worksheet.
- Columns AI to AU: These columns calculate the monthly and annual "Appliance" electricity consumption. The underlying formulas in the cells pull data from the [Unit Data], [Appliance Date], and [Pattern Data] worksheets. Appliance electricity consumption depends on the Occupancy Type, but does not dependent on the Unit Area.
- Columns AG to BH: These columns calculate the monthly and annual "Lighting" electricity consumption. The underlying formulas in the cells pull data from the [Unit Data], [Appliance Data], and [Pattern Data] worksheets. Lighting electricity consumption depends on both the Occupancy Type and also on the Unit Area.
- Columns BI to BU: These columns calculate the monthly and annual "Cooling" electricity consumption. The underlying formulas in the cells pull data from the [Unit Data], [Appliance Data], [HVAC Data] (indirectly), and [Pattern Data] worksheets. Cooling electricity consumption depends on both the Occupancy Type and also on the Unit Area.
- Columns BV to CH: These columns calculate the monthly and annual "Heating" electricity consumption. The underlying formulas in the cells pull data from the [Unit Data], [Appliance Data], [HVAC Data] (indirectly), and [Pattern Data] worksheets. Heating electricity consumption depends on both the Occupancy Type and also on the Unit Area.
- Columns CI to CV: These columns sum up total monthly and annual electricity consumption from Appliance, Lighting, Cooling, and Heating columns.
- Column CW: This column contains the total PV Electricity Production.
- Column CV: This column contains the total Electricity Consumption.

- Column CY: This column provides the Consumption to Production ratio. A ratio of 1 would represent "Zero Net Energy" over the course of our synthetic year. A ratio less than 1 represents Production greater than Consumption – a better than ZNE performance that may be counted against usage elsewhere in the community. A ratio greater than 1 represents Consumption greater than Production or a net energy performance above ZNE for the year.
- Column CZ: This column provides the Production to Consumption ratio, which is the inverse of the value of the previous column.

The total annual electricity production and consumption values and their ratios are given in the last row under columns CW, CV, CY, and CZ.

2.3.3.4 Calculation of Electricity Production

Electricity production is based on the Solar PV panel power rating assigned or estimated for each individual or aggregate unit. The SunPower Data identifies the panel "module type" for each individual unit in Phase 1 and Phase 2, and also for other Phase 1 non-residential units such as "Retail" and "Common" and "Club" and "Gas" units identified in the [Model Main] worksheet under the "individual unit" category. The Phase 1 and Phase 2 PV name plate ratings are from SunPower. The PV data for the Solstice are from architectural design drawings. The Single Family PV data is based on scaling of Phase 2 data using area proportionality of total Single Family unit areas to total Phase 2 unit areas.

2.3.3.5 Calculation of the Electricity Consumption

Except for the Club House and the Mixed Use Retail and EV Charging, the model divides the electricity consumption into the following 4 classes:

a) Appliances (including Miscellaneous Plug Loads)

b) Lighting

c) Cooling

d) Heating

2.3.3.6 Appliances

Appliance assumptions are provided in the [Appliance Data] worksheet for Viridian and Ramble/Solstice type unites. The appliance kW ratings were taken from UC Davis West Village documents. Reference page numbers of the source are provided in [Appliance Data] worksheet.

- Dishwasher
- Disposer

- Range
- Dryer
- Kitchen Small Appliance
- Microwave
- Refrigerator
- Clothes Washer
- Miscellaneous Plug Loads (e.g. televisions, laptops, stereos, gaming consoles, etc.)

We assumed Miscellaneous Plug Loads to be 10% of the total appliance load.

We made a number of assumptions for "Minute per Cycle" and used available DOE values[19] for average "Cycles per Year" for some of the appliance types, and where no DOE values were available, we used our own assumptions to assign "Cycles per Year" for remaining appliance types. Furthermore, we assumed that the base case appliance data applies to a 4BR unit. For differently sized units, the model scales the appliance electricity usage using scaling factors from a table of Appliance Multipliers defined in the [Pattern Data] worksheet.

In the model, the Appliance kWh per Month of each unit is calculated by using the following variables in the underlying formulas in the [Model Main] cells under the monthly Appliance columns:

- Annual kWh/Year scaled based on number of days in each month – under "Seasonal" table in [Pattern Data] worksheet.
- Number of Units (1 for individual units, and greater than 1 for aggregate units)
- Occupancy Types of A, B, C, or D, as defined in "Occupancy" table in [Pattern Data] worksheet.
- Scaling by Number of Bedrooms, as defined in "Appliance Multiplier" table in [Pattern Data] worksheet.

The data tables in the [Pattern Data] are described in a later section.

2.3.3.7 Lighting

The lighting data is defined in [Appliance Data] worksheet. We have assumed a linear relationship between lighting electricity usage and area plus a fixed value (i.e., 1.22 Watts/SF

[19] "Use of Residential Smart Appliances for Peak-Load Shifting and Spinning Reserves - Cost/Benefit Analysis REPORT", Prepared for the U.S. Department of Energy under Contract DE-AC05-76RL01830 Pacific Northwest National Laboratory, Richland, Washington 99352, December 2010.

+ 125 Watts), based on the California Standards[20]. Lighting electricity usage of each unit is calculated by using the following variables in the underlying formulas in the [Model Main] cells under the monthly Appliance columns:

- Lighting equation of 1.22 Watts/SF + 125 Watts
- Area of each individual unit or aggregate units
- Monthly hours of lighting, as shown in “Seasonal” table in [Pattern Data] worksheet, based on hours in each month and the Daily hours of lighting by season, as defined in “Daily Hours” table in [Pattern Data] worksheet.
- Number of Units (1 for individual units, and greater than 1 for aggregate units)
- Occupancy Types of A, B, C, or D, as defined in “Occupancy” table in [Pattern Data] worksheet.

2.3.3.8 Cooling and Heating

Annual Cooling and Heating Electricity Usage

The cooling and heating data originate from the data defined in [HVAC Data] worksheet. The approach used was to determine an average kWh/SF-Year value for cooling and heating representative of the Sacramento cooling and heating requirements and reflective of the UC Davis West Village community building set-ups. Due to lack of detailed available data on actual cooling and heating needs in general and in UC Davis West Village community in particular, we used a public domain web-based tool (i.e., HVACOPCOST.COM) to project the cooling and heating needs (i.e., electricity consumption) of the UC Davis West Village community.

Since this was a small-scale project, which imposed limits on resources for the development of the model, the approach described below should be considered as a first order approximation for estimating the size of heating and cooling in the community. Future steps in improving the model could include a more detailed modeling of heating and cooling using ASHRAE data and standard heating/cooling degree-day or bin methods, which would require more time and effort beyond the scope of the current project.

To determine Heating and Cooling Requirements in kWh/SF-Year we used the web-based tool to determine the cooling and heating equipment size for the Sacramento region and

[20] "2013 California Building Energy Efficiency Standards, California Utilities Statewide Codes and Standards Team", March 2011.

calculate the annual cooling and heating energy usage based on given parameters, based on the following steps:

- We first used the following web link to find the Cooling and Heating Degree Days for Sacramento
  - http://www.hvacopcost.com/
- We determined that the web-based calculator was not doing a proper job of also determining the optimal cooling and heating equipment size. Changing the unit area did not change the equipment size. However, the site provides specific degree day data for the Sacramento region:
  - Cooling Degree Days for Sacramento: 1,491
  - Heating Degree Days for Sacramento: 2,361
- We then used the following web link to determine the Cooling and Heating Equipment Size for cooling and heating regions with close to or similar degree days to Sacramento.
  - http://www.hvacopcost.com/equipsize.html
  - Cooling Degree Days for Selected Region: 1,402, Cooling Equipment Size: 2.00 Tons
  - Heating Degree Days for Selected Region: 2,942, Heating Equipment Size: 36,000 Btus
- Using the Sacramento specific cooling and heating degree days, and applying degree day proportionality (which means using ratio of degree days to scale the data), we calculated the following equipment size for the Sacramento region:
  - Cooling Degree Days: 1,491, Cooling Equipment Size: 2.13 Tons
  - Heating Degree Days: 2,361, Heating Equipment Size: 29,000 Btus
- We then went back to the following web link to enter the inputs for the Sacramento region.
  - http://www.hvacopcost.com/
- The following information was entered at the site (with Sacramento selected):
  - Unit Area: 1,000 SF
  - Cooling Degree Days: 1.491
  - Cooling Equipment Size: 2 Tons
  - Electricity Price: 1 Cents per kWh (to enable getting the equivalent kWh value instead of cost)

  - Cooling System Type: A/C Variable Speed
  - SEER: 15 (Source: 100% CD UC Davis West Village Student Housing Phase 1.pdf - Page 91)
  - Heating Degree Days: 2,361
  - Heating Equipment Size: 29,000 Btus
  - Fuel Price: 29.31 Cents per Therm (to get the equivalent kWh value instead of cost, since 1 Therm is 29.31 kWh)
  - Heating System Type: Heat Pump
  - HSPF: 8 (Source: 100% CD UC Davis West Village Student Housing Phase 1.pdf - Page 91)
- The Site Calculates the Following for Efficient Equipment:
  - Cooling High Efficiency Yearly Operating Costs $22.00
  - Heating High Efficiency Yearly Operating Costs $51.00
- However, these costs were calculated for a 1000 SF House
  - At 1 Cents/kWh:
    - The Cooling Energy Requirement is: 2.2 kWh/SF-Year
  - At 29.31 Cents/Therm (and 1 Therm = 29.31 kWh):
    - The Heating Energy Requirement is: 5.1 kWh/SF-Year

Scaling Factor to Take Into Account Building External Surface Areas

The last two final cooling and heating energy requirement numbers are pulled into the [Appliance Data] worksheet from [HVAC Data] worksheet, and are then scaled to reflect the difference between the topology of the UC Davis West Village buildings in comparison with individual stand-alone units.

The reasoning is that the Heating/Cooling kWh/SF-Year calculations are for a Stand-Alone Unit with 4 external walls and 1 Roof. However, UC Davis West Village buildings are combinations of 4-unit 3-story L-Shape and I-Shape buildings with total external surface areas less than same number of external surface areas for same number of stand-alone units. Fewer external surface areas means reduced heat transfer with outside and reduced total heating and cooling load compared to the same number of stand-alone units.

The model scales the total heating and cooling requirements of UC Davis West Village units by scaling the calculated heating/cooling requirements of stand-alone units.

Based on the shape of the buildings and number of units and floors in each building we compared total number of surface areas exposed to outside for selected number of UC Davis West Village buildings based on the numbers shown on UC Davis West Village architectural map, and compared it to the total exposed surface areas of the same number of stand-alone units. The calculation is provided in the [HVAC Data] worksheet. We determined a "rough" scaling factor of 63.54%, by which we multiplied the 2.2 kWh/SF-Year Cooling Energy Requirement and the 5.1 kWh/SF-Year Heating Energy Requirement. Result for UC Davis West Village Average is:

- The Cooling Energy Requirement is: 1.40 kWh/SF-Year
- The Heating Energy Requirement is: 3.24 kWh/SF-Year

Cooling and heating electricity usage of each unit is then computed by using the calculated cooling and heating energy requirements and the following variables in the underlying formulas in the [Model Main] cells under the monthly cooling and heating columns:

- Area of each individual unit or aggregate units
- Percentage of Cooling and Heating Electricity Usage by Month, as shown in "Seasonal" table in [Pattern Data] worksheet, based on hours in each month and the Daily hours of Cooling and Heating by season, as defined in "Daily Hours" table in [Pattern Data] worksheet.
- Number of Units (1 for individual units, and greater than 1 for aggregate units)
- Occupancy Types of A, B, C, or D, as defined in "Occupancy" table in [Pattern Data] worksheet.

2.3.4 Tables in [Pattern Data] Worksheet

The [Pattern Data] worksheet includes a number of tables that are used to define the monthly usage and occupancy patterns in the model. In the following tables taken from the [Pattern Data] worksheet, the values in cells that are colored brown are based on GE assumptions.

In the "Appliance Multipliers" table below, the total appliance electricity usage is scaled by a Scaling Factor based on the number of bedrooms in the unit. The reason is that the annual appliance electricity consumption evaluated in the [Appliance Data] worksheet is assumed to apply to a 4 bedroom unit. The appliance electricity usage is expected to be lower in units with fewer bedrooms, but the relationship between appliance electricity consumption and number of bedrooms in a unit is not considered to be proportional. The assigned multipliers, shown in the following table, although being the GE team's rough assumptions, are not based on any independent study. An example is the usage of clothes washer and dryer. A clothes-washer may be used almost the same number of the times during a week in 3 bedroom versus 4 bedroom unit, but the loading per cycle may be different. However, our numbers could be conservative and overestimate appliance usage in units with fewer bedrooms.

APPLIANCE MULTIPLIERS	
Appliance Usage Multiplier by Number of Bed Rooms	
Bed Room	Multiplier
1	70%
2	80%
3	90%
4	100%

Table 5: Appliance Multipliers Based on Number of Bed Rooms

The "Daily Hours" table below is used to spread the total annual lighting, cooling, and heating load over different seasons of the year. These numbers are also GE team's rough estimates. Changing them will only re-allocate the monthly values of the total estimated annual electricity consumptions. If monthly usage is of interest, then these estimates should be revised based on further investigation.

DAILY HOURS			
	Lighting	Cooling	Heating
Spring	2.25	4	4
Summer	2.00	12	0
Autumn	2.25	4	4
Winter	2.50	0	12

Table 6: Daily Hours of Lighting, Cooling, and Heating by Season

The "Seasonal Pattern" table below draws from the preceding table to create the monthly electricity usage patterns. In case of appliance electricity consumption, the monthly differences are simply a reflection of different number of days in each month.

SEASONAL														
Season		Winter	Winter	Spring	Spring	Spring	Summer	Summer	Summer	Autumn	Autumn	Autumn	Winter	
Month		JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	Total
Month		1	2	3	4	5	6	7	8	9	10	11	12	
Days		31	28	31	30	31	30	31	31	30	31	30	31	365
Hours of	Lighting	77.5	70.0	69.8	67.5	69.8	60.0	62.0	62.0	67.5	69.8	67.5	77.5	820.8
Hours of	Cooling	0.0	0.0	124.0	120.0	124.0	360.0	372.0	372.0	120.0	124.0	120.0	0.0	1,836.0
Hours of	Heating	372.0	336.0	124.0	120.0	124.0	0.0	0.0	0.0	120.0	124.0	120.0	372.0	1,812.0
Percent	Appliance	8.5%	7.7%	8.5%	8.2%	8.5%	8.2%	8.5%	8.5%	8.2%	8.5%	8.2%	8.5%	100.0%
Hours of	Lighting	77.5	70.0	69.8	67.5	69.8	60.0	62.0	62.0	67.5	69.8	67.5	77.5	820.8
Percent	Cooling	0.0%	0.0%	6.8%	6.5%	6.8%	19.6%	20.3%	20.3%	6.5%	6.8%	6.5%	0.0%	100.0%
Percent	Heating	20.5%	18.5%	6.8%	6.6%	6.8%	0.0%	0.0%	0.0%	6.6%	6.8%	6.6%	20.5%	100.0%

Table 7: Seasonal Lighting, Cooling, and Heating

The "Occupancy Type" table below provides four occupancy alternatives:

- Type A: Full occupancy every month of the year.
- Type B: Partial occupancy during summer, e.g., some students stay in their residences to take summer courses or work in the area.
- Type C: Zero occupancy in the summer, e.g., some students leave for the summer.
- Type D: Zero Occupancy every month of the year, e.g., this pattern could apply to some unfinished building, even if the solar PV is functional and providing power to the grid.

In the current model, we have applied Type B occupancy across all units, individual or aggregate; however, in future versions of the model, different units can have different occupancy rates. Other occupancy patterns can be added to the table by inserting additional rows within the table.

OCCUPANCY TYPE														
Season		Winter	Winter	Spring	Spring	Spring	Summer	Summer	Summer	Autumn	Autumn	Autumn	Winter	
Month		JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	Total
Month		1	2	3	4	5	6	7	8	9	10	11	12	
Days		31	28	31	30	31	30	31	31	30	31	30	31	365
Full	A	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%
Partial 1	B	100.0%	100.0%	100.0%	100.0%	100.0%	60.0%	60.0%	60.0%	100.0%	100.0%	100.0%	100.0%	90.0%
Partial 2	C	100.0%	100.0%	100.0%	100.0%	100.0%	0.0%	0.0%	0.0%	100.0%	100.0%	100.0%	100.0%	75.0%
Vacant	D	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%

Table 8: Monthly Occupancy Type Patterns

2.3.5 Treatment of Club House

The solar PV electricity production of the Rec Center/Club House and its two components, i.e., Club and Gas, are based on the solar PV panel rating from SunPower data, and the monthly PVW data, which are provided within the Phase 1 rows of [Model Main] worksheet. The actual electricity consumption data covers only a few months. The [Club & Gas Data] worksheet contains the approach to project the Club House electricity consumption.

We used the actual production data from SunPower and PG&E data on net energy to construct the electricity consumption data, which cover a few months in the year (April to July of 2012 for Club, and April to June for Gas). We then extended the data to cover the whole year based on the following steps:

- JAN, FEB, MAR data based on APR Data.
- JUL Gas data based on ration of JUN Gas to Club Ratio.
- AUG Data based on JUL Data.
- SEP, OCT, NOV, DEC data based on APR Data.

The [Model Main] worksheet pulls in the constructed monthly Club and Gas electricity consumption data from the [Club & Gas Data] worksheet.

2.3.6 Treatment of Mixed Use Retail and EV Charging

The solar PV electricity production of the Mixed Use Retail units are based on the solar PV panel ratings from SunPower data, and the monthly PVW data, which are provided within the Phase 1 rows of [Model Main] worksheet. Due to lack of any actual data on Mixed Use Retail units, we relied on the Davis Energy Group Report of July 11, 2012 which provides an estimate of electricity usage in these units under a Low and a High electricity consumption scenario. We have retained the low and high estimates and also constructed an average estimate.

These estimates are contained in the [Mixed Use Data] worksheet (L109 to O117 Array). The data is pulled in by the [Model Main] worksheet for Mixed Use Retail units. We have selected the “High” electricity consumption scenario in the current model setting in the [Model Main] worksheet in the Mixed Use Retail group.

2.3.7 Treatment of Faculty Staff Housing Units

The main data for the Faculty Staff Housing Units are provided in the [Unit Data] worksheet under the “Faculty Staff Housing” heading. The Faculty Staff Housing comes in 4 types, and we are told all four types will be equally represented. We divided the expected 343 homes into 86, 86, 86, and 85 unit types of A, B, C, and D respectively.

In up to 206 homes, there will a separate studio units (in-laws, guests, or rental) built either above the garage, or on-grade.

To estimate the solar PV electricity production, we applied the Total PV kW Rating ratio to Total Area of Phase 2 Units to determine an average PV kW/SF for all of Faculty Staff housing. We then used the area by type of Faculty Staff housing to assign kW ratings for each unit type, including studios. We then applied the PVW monthly data to determine the monthly electricity production by each home type.

To project electricity consumption in the Faculty Staff Housing, we used the same approach as the one used for Phase 1 units, including the projection of appliance usage, lighting, heating, and cooling, as can be seen from the populated areas in the [Model Main] worksheet under the Faculty Staff Housing grouping.

2.3.8 Treatment of Phase 2 Ramble

The Phase 2 Ramble unit solar PV ratings are provided by SunPower for each individual Phase 2 units in [SunPower Phase 2 PV Data] worksheet.

The Phase 2 Ramble unit types, number of units, and unit areas are provided in the [Unit Data] Worksheet under the Phase 2 Ramble heading.

We used the total area by unit type to allocate PV kW ratings for each unit type in [Model Main] worksheet.

To project electricity consumption for the Phase 2 units, we used the same approach as the one used for Phase 1 units, including the projection of appliance usage, lighting, heating, and cooling, as can be seen from the populated areas in the [Model Main] worksheet under the Phase 2 grouping.

2.3.9 Treatment of Solstice

The Solstice unit types, number of units and unit areas are provided in the [Unit Data] worksheet under the Solstice heading.

The Solstice total solar PV ratings are based on the available data shown in [Unit Data] worksheet. We used the total area by unit type to allocate PV kW ratings for each unit type in [Model Main] worksheet.

To project electricity consumption for the Solstice units, we used the same approach as the one used for Phase 1 units, including the projection of appliance usage, lighting, heating, and cooling, as can be seen from the populated areas in the [Model Main] worksheet under the Solstice grouping.

2.4 Model Validation & Adjustment

We undertook a comparison of the model consumption results and actual consumption values from the available data. The actual consumption data are based on the sum of PG&E Net Metered Energy and SunPower Production values, as shown in the following table.

Consumption (kWh)	MAR	APR	MAY	JUN	JUL	AUG
Unit 2BD A	285	214	140	140	161	163
Unit 2BD B	405	322	305	325	315	359
Unit 2BD C			427	304	348	531
Unit 2BD D				420	430	732
Unit 2BD E				268	339	492
Unit 2BD F			216	222	309	260
Unit 2BD G				543	780	671
Unit 2BD H				309	147	231
Unit 2BD I			124	135	396	255
Unit 2BD J			150	291	405	427
Unit 2BD K						86
Unit 2BD L				89	27	32
Unit 3BD A	630	584	438	548	545	715
Unit 3BD B	451	454	494	559	829	627
Unit 3BD C	541	509	587	501	543	511
Unit 3BD D			837	805	839	979
Unit 3BD E		532	511	703	863	788
Unit 3BD F		462	531	641	633	608
Unit 3BD G		341	386	470	479	488
Unit 3BD H			542	607	713	743
Unit 3BD I			54	793		847
Unit 3BD J	378	311	297	293	322	
Unit 3BD K	304	364	303	395	184	390
Unit 4BD A	586	455	519	605	642	694
Unit 4BD B	479	339	277	396	408	353
Unit 4BD C	782	829	934	845	1,231	1,076
Unit 4BD D		473	486	524	388	695
Unit 4BD E			375	296	585	387
Unit 4BD F		657	561	703	619	645
Unit 4BD G	648	636	759	662	580	278
Unit 4BD H			437	407	468	404
Unit 4BD I	583	562	724	741	729	714
Unit 4BD J	702	503	428	453	463	424

Table 9: Actual Historical Consumption Data (PG&E Net Energy + SunPower Production)

In the following tables, we compared the model data (labeled "GE") with actual data (labeled "PG&E").

2BR Units	GE (kWh)	PG&E (kWh)
Unit 2BD A	2,994	1,104
Unit 2BD B	2,994	2,030
Unit 2BD C	2,354	1,610
Unit 2BD D	1,979	1,581
Unit 2BD E	1,979	1,099
Unit 2BD F	2,381	1,007
Unit 2BD G	2,002	1,994
Unit 2BD H	2,002	688
Unit 2BD I	2,354	910
Unit 2BD J	2,354	1,273
Unit 2BD K	652	86
Unit 2BD L	1,908	147
Total	**25,951**	**13,529**

3BR Units	GE (kWh)	PG&E (kWh)
Unit 3BD A	3,546	3,461
Unit 3BD B	3,546	3,413
Unit 3BD C	3,546	3,192
Unit 3BD D	2,695	3,460
Unit 3BD E	3,127	3,397
Unit 3BD F	3,127	2,875
Unit 3BD G	3,127	2,164
Unit 3BD H	2,695	2,605
Unit 3BD I	1,981	1,695
Unit 3BD J	2,800	1,601
Unit 3BD K	3,546	1,941
Total	**33,738**	**29,803**

4BR Units	GE (kWh)	PG&E (kWh)
Unit 4BD A	4,195	3,501
Unit 4BD B	4,195	2,253
Unit 4BD C	4,195	5,697
Unit 4BD D	3,700	2,566
Unit 4BD E	3,190	1,643
Unit 4BD F	3,700	3,185
Unit 4BD G	4,195	3,564
Unit 4BD H	3,190	1,715
Unit 4BD I	4,195	4,052
Unit 4BD J	4,195	2,973
Total	**38,949**	**31,149**

Table 10: Comparison of GE Model Consumption Results with Actual Historical Consumption Data

We can make the following observations:

- Actual historical data show a very wide variation, likely due to the evolution in tenancy, occupancy, etc., during the study period, as well as the wide range of student living and consumption patterns.
- GE model data comes close to actual historical data for a few units.
- GE model projections are on the "conservative" side, i.e., they are projecting higher energy consumption compared to actual historical values.
- Units that demonstrate extreme variation from our model may reflect specific occupancy patterns or the presence of end use loads that differ significantly from our model assumptions.

There are various ways to improve the model further. Options are:

- Keep as is (be conservative).
- Scale monthly data patterns to come close to actual historical total values.
- To show variability, add stochastic/probabilistic multipliers for each unit based on the statistical variation seen in PG&E data.
- Refine occupancy model to match aggregate data.

2.5 Model Summary Results

Under our simplifying assumptions, covering the following:

- Occupancy Type
- Seasonality Pattern
- Scaling of Energy Use by Bedroom Numbers

- 10% Miscellaneous Plug Load
- Lighting: 1.2 W/SF + 125 W
- Scaled Cooling Energy Requirement: 1.40 kWh/SF-Year
- Scaled Heating Energy Requirement: 3.24 kWh/SF-Year

Our current model representation of UC Davis West Village's overall performance is as follows:

- Annual Solar PV Electricity Production: 9,271 MWh
- Annual Electricity Consumption: 12,042MWh
- Consumption to Production Ratio: 125%

These results are "demonstrative" based on our preliminary underlying assumptions, and we expect them to be very sensitive to changes in the main drivers such as appliance, lighting, cooling, and heating, assumptions. Other assumptions that can have potentially significant impacts are Appliance Multiplier and Occupancy Pattern assumptions.

Results have been summarized in the following tables.

Individual Unit Type	Area (SF)	Production (kWh)	Consumption (kWh)	C/P	P/A (kWh/SF)	C/A (kWh/SF)
Phase-1-Ramble-2	16,797	64,716	140,117	217%	3.85	8.34
Phase-1-Ramble-3	89,762	375,636	723,122	193%	4.18	8.06
Phase-1-Ramble-4	136,488	565,053	1,059,303	187%	4.14	7.76
Phase-1-Ramble-Common	N/A	454,642	0	0%	N/A	N/A
Phase-1-Viridian-1	44,442	212,486	348,219	164%	4.78	7.84
Phase-1-Viridian-2	71,802	257,025	520,455	202%	3.58	7.25
Phase-1-Viridian-3	4,113	13,814	29,232	212%	3.36	7.11
Phase-1-Viridian-Common	N/A	305,885	0	0%	N/A	N/A
Phase-2-Ramble-2	39,192	242,094	323,111	133%	6.18	8.24
Phase-2-Ramble-3	62,143	383,865	495,766	129%	6.18	7.98
Phase-2-Ramble-4	136,488	843,105	1,050,431	125%	6.18	7.70
Phase-3-Solstice-2	38,588	219,351	294,892	134%	5.68	7.64
Phase-3-Solstice-3	42,575	242,020	312,354	129%	5.68	7.34
Phase-3-Solstice-4	114,290	649,681	812,920	125%	5.68	7.11
Faculty-Staff-Housing-1	83,018	512,813	835,913	163%	6.18	10.07
Faculty-Staff-Housing-4	591,613	3,654,473	4,037,596	110%	6.18	6.82
Recreation-Viridian-Club	16,901	168,424	422,087	251%	9.97	24.97
Recreation-Viridian-Gas	N/A	41,647	61,198	147%	N/A	N/A
Mixed-Use-Retail	44,028	401,427	563,870	140%	9.12	12.81
Other-Use-EV Fleet	N/A	0	11,280	N/A	N/A	N/A
Total	**1,532,239**	**9,608,156**	**12,041,867**	**125%**	**6.27**	**7.86**

Table 11: Summary Results by Individual Unit Category

Aggregate Unit Type	Area (SF)	Production (kWh)	Consumption (kWh)	C/P	P/A (kWh/SF)	C/A (kWh/SF)
Phase-1-Ramble	243,047	1,460,047	1,922,542	132%	6.01	7.91
Phase-1-Viridian	120,357	789,210	897,906	114%	6.56	7.46
Phase-2-Ramble	237,823	1,469,063	1,869,308	127%	6.18	7.86
Phase-3-Solstice	195,452	1,111,052	1,420,166	128%	5.68	7.27
Faculty Staff Housing	674,631	4,167,286	4,873,509	117%	6.18	7.22
Recreation	16,901	210,070	483,285	230%	12.43	28.60
Mixed-Use	44,028	401,427	563,870	140%	9.12	12.81
EV Fleet	N/A	0	11,280	N/A	N/A	N/A
Total	**1,532,239**	**9,608,156**	**12,041,867**	**125%**	**6.27**	**7.86**

Table 12: Summary Results by Aggregate Unit Category

In the table of summary results by aggregate unit category it can be observed that on a per unit area basis, the projected PV generation per area (P/A) shows significant variation across unit types. Variations in the Production/Area values by unit type point at the potential for additional PV installations.

It should also be noted that the zero values are not literally so, and in the above tables indicate unavailable information.

2.6 Conclusions of Subtask 1

Due to the limitations of the data available at the time of our Study and the challenges encountered in preparation of the baseline energy model,our model results provide only an interim snapshot of the current and expected energy performance at UC Davis West Village. However, several directional observations are possible. We believe, based on the information available and the conservative nature of our modeling, that it is likely that:

- The multi-tenant units are performing slightly above production of the installed PV, with some variation by unit type. The Viridian units appear to have the best performance (C/P close to 1), while the Ramble and Solstice units are farther “above ZNE” and may require some additional “tightening” of performance to achieve energy balance.
- The Rec and Lease center and swimming pool area (the “Club” and “Gas” accounts), as well as the MU spaces appear to have a greater excess of consumption over production.
- Our model confirms that the Faculty Staff Housing does appear to be well designed for consumption to match production, with small variations by floor plan and solar size. However, the studio annex units, which are an optional addition for some home owners, may have an additional challenge meeting this goal, due to a lack of roof space to support solar installation.

- Finally, above and beyond the data limitations in our study, there remains uncertainty in the evolution of future loads which have not been estimated adequately, notably the EV charging and energy-intensive operations associated with the Western Cooling Efficiency Center.

UC Davis is planning to construct a Renewable Energy Anaerobic Digester that is expected to produce approximately 4 million kWh of electricity per year. The contribution of this renewable energy resource has not been considered towards the ZNE goal in our model.

Subtask 2 presented in Section 3 below outlines a comprehensive program for on-going tracking of energy performance and develops recommendations for achieving ZNE where current performance may not be meeting the objective.

3 Subtask 2

3.1 Subtask 2 Introduction

Based on the analysis and baseline model created in Subtask 1, Subtask 2 seeks to answer the second key question of our study:

- Where the ZNE goal is not being achieved, what levers are available to adjust energy performance within UC Davis West Village?

The following sections present the functional specification and recommendations for implementation of a monitoring and control systems architecture for UC Davis West Village, including a cost-benefit framework for improving energy management, and recommendations for both specific technology options and other program design elements.

In section 3.2, we present a functional specification for the overall system architecture that will allow on-going energy performance management at UC Davis West Village. We envision a centralized "Master Energy Manager" – a performance tracking system, running on ordinary desktop software and updated daily with data from currently available or soon to be available sources, along with associated communications to the residents (and their intelligent end-use devices) to effectuate demand controls when necessary to adjust performance. This system would ideally be updated and operated by on-site personnel within UC Davis West Village (i.e. either UC Davis staff or a WVCP Partners' facility manager already responsible for building operations).

In Section 3.3, we evaluate a range of commercially available technology options and present recommendations for each building unit type, based on the directional results of Subtask 1 presented in Section 2.6 above.

Section 3.4 presents a cost-benefit example, showing the economics of alternative technology options for energy management and control, using assumptions of DR impacts developed from the available literature on utility pilot programs.

Finally, Section 3.5 offers recommendations with regard to non-technical program design features. This includes a discussion of the regulatory barriers to implementation of price-based incentives for demand management in the multi-tenant units ("the Rule 18 issue"). We also provide some comments on non-technical aspects of program design, such as the user-friendliness and usability of different energy management solutions within the specific context of UC Davis West Village.

3.2 Functional Specification

During development of the UC Davis West Village Energy Initiative, UC Davis and WVCP agreed upon broad parameters for achieving the Zero Net Energy master plan. It was agreed that UC Davis West Village properties would be made attractive, efficient, livable, and affordable – no more expensive than comparable properties elsewhere in the community. This meant that many potential design alternatives that could achieve higher energy performance at some increase in cost were rejected.

In assessing opportunities for improving energy performance from baseline, we have attempted to adhere to the Partnership's objectives, and to specify a design for energy monitoring and control that will allow on-going energy performance tracking and, where needed, performance improvement, at the least possible incremental cost. For example, investments in upgrading capital equipment – such as changes to building envelope, or the addition of smart appliances, or more efficient HVAC systems – were ruled out on the basis of cost.

For purposes of this study, we have concentrated exclusively on energy management and control systems. We believe these technologies represent the likeliest "low hanging fruit" of investment that can be made within the existing design to most easily modify energy performance at the lowest cost. It is our contention that energy monitoring and control is the missing piece of the puzzle at UC Davis West Village that can help translate *good design* into *good practice*, by translating the concept of Zero Net Energy into daily performance tracking and commands that can be issued to compel specific control actions, when needed. As shown by the cost-benefit examples in Section 3.4 below, the investment case for this level of incremental control is likely to be quite compelling.

3.2.1 Master Energy Manager System

The core of our proposed architecture is what we are calling a Master Energy Manager (MEM), a centralized energy performance monitoring and control system that would provide the following functionality:

- Continuous tracking of production and consumption of all existing (built and occupied) properties within UC Davis West Village, through automated daily download from available sources of interval data (SunPower and PG&E);
- Periodically updated modeling of future/under construction properties, including both planned generation and loads, to reflect any new information and changes in anticipated design/occupancy/tenancy and end use;
- Calculation of net energy performance in a simple desktop model, building on the baseline spreadsheet model developed in Subtask 1; and

- Broadcast messaging capability to issue event signals to participating residents and/or intelligent devices, such as IP-addressable programmable/communicating thermostats capable of directly receiving and responding to such signals with appropriate, pre-programmed control action.

3.2.2 Performance tracking

The first and most important feature of a centralized MEM will be to provide a consistent mechanism for tracking energy performance, through daily automated download of interval data for both production and consumption of electric energy in all UC Davis West Village Units.

3.2.2.1 SunPower interval production data

As noted in Section 2 above, the SunPower user interface provides download access for an authenticated user to view kWh production data from the solar inverter installed on each unit. Data are available on a rolling one week basis, but are neither validated nor archived by SunPower. The MEM should include a script to automate download and archiving of the SunPower interval data for each unit, ideally on a daily basis, in order to populate the production side of the desktop model.

3.2.2.2 Interval consumption data

At the time of this study, two options were available for providing future, on-going access to interval consumption data for the existing units at UC Davis West Village. First, SunPower provides non-revenue grade monitoring of consumption at each unit via a Current Transformer clamp at the unit junction box. Access to this data is made available on a one week rolling basis, similar to the interval production data.

Unfortunately, as discussed in Section 2.2.3 above, during the course of the baseline modeling effort in Subtask 1, the GE team uncovered anomalies in this data that made it unusable. GE brought these issues to the attention of SunPower and SunPower confirmed an error in its user interface that was corrupting reporting of the consumption data. SunPower reports that this problem is now fixed, however, historical data have not been archived. Assuming the data can be validated going forward, we believe that the SunPower consumption data could be utilized to support the MEM desktop model.

Independently, another possibility is automating upload of interval consumption data directly from the PG&E smart meters at UC Davis West Village via the “Green Button” program. Green Button is a national initiative, sponsored by the federal government (under the White House Office of Science and Technology Policy) with voluntary participation by many U.S. utilities, including all three of the California Investor Owned Utilities. The Green Button interface provides a standardized web-based format for export of meter data history to customers and their authorized representatives, allowing wider use of the data in third party energy management software applications.

For interval metered customers, such as all PG&E Smart Meter customers, Green Button should provide interval data within 24-36 hours of usage. These data have been through basic validation checks within PG&E's Meter Data Management System and are therefore likely to be more consistent with the final "revenue grade" data used to generate the monthly PG&E bill[21]. If WVCP is able to secure access to the Green Button data for UC Davis West Village accounts, this would represent – in our opinion -- the best, most reliable source of interval consumption input to the MEM.

3.2.3 MEM Desktop Model

The objective of the MEM is to continuously gather in one place all the data necessary to track performance against the ZNE goal. Based on the availability of interval production and consumption data, a simple desktop model should be able to track performance for the UC Davis West Village community on a continuous basis. This model can be structured based on the baseline energy model developed in Subtask 1 to represent each unit type – with actual data for existing units and simulated performance of to-be-built units – in order to provide a comprehensive view of energy performance. Such a model can readily be set up to detect and predict trends, such as expected deviations from desired levels of energy performance.

In section 3.3 below, we lay out recommendations for different levels of demand side technology that could be used to "tighten" energy performance. In order to implement these recommendations, the MEM desktop model would need to be used in conjunction with a broadcast messaging interface to provide event communications to participating residents via a "blast" text or email option. The following section describes the architecture that would enable the necessary device-level communications.

Below we also consider the implementation of a demand response program that would follow the behavior of PG&E's "Smart Rate" (a voluntary Critical Peak Pricing rate option). In order to effectuate control under this type of program, the MEM desktop model would need to subscribe to automated event information from PG&E (available over the web to participating Smart Rate subscribers) and broadcast event signals to participating residents and intelligent devices within the UC Davis West Village network. In ideal form, the MEM would issue communications to a network of smart thermostats and other intelligent devices present within UC Davis West Village using a standardized DR protocol such as

[21] Additional validation checks are conducted by the utility billing system in calculating the final bill and may result in occasional discrepancies with the Green Button data.

OpenADR or SEP 2.0, over any mix of wireless or powerline communications, in order to effectuate control action.

3.2.4 Communications architecture

As discussed in Section 3.3 below, there are a variety of IP addressable programmable communicating thermostats and other HEM devices on the market with different functionality availability at different price points. These devices all have in common the ability to receive and act on event information and communications related to utility demand response rates, such as PG&E's TOU and Smart Rate options.

Within the UC Davis West Village community, we envision that the MEM desktop model would issue control signal commands and communicate directly with a network of smart devices, such as smart thermostats in the multi-tenant buildings.

Many utility smart grid and demand response pilot programs have experienced difficulty with poor interoperability of equipment from different manufacturers – for example, metering communications that did not work well with in-premise devices. It is GE's understanding that recent advances in the standards landscape, such as the adoption of SEP 2.0 interoperability testing protocols have eliminated much of this risk. SEP 2.0 allows equipment using different physical-layer media – for example, Zigbee™ and HomePlug™ equipment -- to send and receive DR price and event communications with standardized data and message formats.

3.3 Technology Recommendations

There is a considerable literature of reported results from utility demand response pilots. Based on review of this literature and, in particular, recent studies comparing results for different technology and program types[22], we believe that there are three levels of potential investment and associated savings that should be of interest at UC Davis West Village:

- **Consumption Information Delivery**. These "information only" programs provide simple messaging to consumers that warn of high peak load "event days" and offer suggestions to avoid unnecessary electric use, turn back thermostats, and delay scheduled appliance usages (such as dishwasher and laundry loads) until off-peak hours. Such programs are extremely cheap to operate and have a small but

[22] "Rethinking Prices - The changing architecture of demand response in America", By Ahmad Faruqui, Ryan Hledik, and Sanem Sergici, Public Utilities Fortnightly, January 2010. [Permission pending]

noticeable impact on consumption and peak demand, typically in the low single digit percentages of peak demand reduction (2-5%).

- **TOU with programmable communicating thermostat**. Time-of-Use (TOU) rate schedules charge differential prices by pre-determined seasonal/time-of-day blocks – more in summer peak hours (for summer-peaking systems), less in winter and off-peak night time hours. Programs that tie installation and programming of thermostats to a TOU price incentive can result in more significant reductions in energy and peak demand, often on the order of 10%.
- **CPP with programmable communicating thermostat**. Critical Peak Pricing (CPP) overlays on the basic TOU structure an event-driven higher rate that can be invoked by the utility up to a certain number of times per year. PG&E's voluntary Smart Rate option is an example of a CPP. IP addressable programmable communicating thermostats (PCTs) are now available from a number of manufacturers that can receive and respond to dynamic pricing signals in order to provide higher peak savings on an event basis – often as much as 20% or more.

All units in the UC Davis West Village multi-tenant buildings come equipped with programmable thermostats, however, these are basic devices that are not communications-enabled and cannot be remotely accessed by the envisioned MEM to provide dynamic control. Due to the limitations of the user interface, most consumers find such devices difficult to program and maintain. Typically, they are set once when installed and only occasionally, if ever, reprogrammed by the tenants.

In order to achieve savings above the "Information Only" level, we examine the cost-benefit argument for replacement and upgrade of the current thermostat with an IP-addressable PCT in Section 3.4 below.

There are a number of technology vendors and options for PCTs that can support varying levels of control. Simple devices in the ~$100 range are available from companies such as EnergyBuddy, EnviR, and Battic. Higher end home energy management kits are also available that include such features as more intuitive full color touch screen displays and Zigbee™ (wireless) plug adapters for on/off control of additional simple plug devices in the home. Kits of this sort run in the ~$250 range and are available from NEST, EverSense, EcoBee, and EnergyHub, among others.

Finally, there is an emerging category of "cloud based" software-as-a-service vendors, such as EcoFactor, which offer subscription-based services to remotely control and optimize thermostat settings. Pricing was not available for EcoFactor.

For the Faculty Staff housing at UC Davis West Village, no thermostats have yet been installed (or specified to our knowledge), and there does not appear to be any restriction that would prevent the community from requiring or encouraging PCT installation and PG&E

Smart Rate participation for home owners (who will be customers-of-record for their own PG&E accounts) as part of the community covenants or HOA rules.

In investigating options for the Rec and Lease Center and Mixed Use Retail buildings, we were not able to provide specific suggestions. However, a number of vendors offer advanced building energy management and control solutions that may offer significant savings. These include Scientific Conservation, Inc. (SCI), 8760, and BuildingIQ.

Finally, for the pool pumping load, we identified a recent report of over 40% energy savings at two of UC Berkeley's outdoor campus pools using smart pumping controls[23]. Although GE is not familiar with the vendors in this space, this appears to be a direction well worth investigating further, as it could significantly contribute to better overall energy balance.

3.4 Cost-Benefit Examples

In this section we analyze the dollar value of several possible technology upgrades. Using the data from the baseline model developed in Subtask 1, we present a cost-benefit analysis per unit. In particular, the analysis is shown for Ramble Phase 1 apartments for which the data set is most complete. We assume impacts of technology based on results from the available literature on utility pilot programs.

We consider three scenarios that differ in technology and the type of energy management program applied:

- Consumption Information Delivery (CID): The information about consumed energy is communicated to residents, but there are no control actions.
- Time-Of-Use program (TOU): Consumed energy is controlled through a fixed schedule known to residents.
- Critical Peak Pricing program (CPP): Consumed energy is controlled through a dynamic schedule.

We present details of each program in sections 3.4.1., 3.4.2, and 3.4.3 respectively.

All of the individual apartments in the UC Davis West Village community are expected to be on the E-6 Rate Schedule, which is PG&E's Residential Time-of-Use Schedule. According to this schedule the consumed energy is billed based on the time of day. In particular, there are different rates for "on-peak", "partial-peak" and "off-peak" periods. In addition, these periods are different during summer and winter seasons. Following table defines the TOU periods for PG&E's E-6 schedule.

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[23] http://recsports.berkeley.edu/new-energy-saving-pool-pumps/

Summer (May-October)		
Peak:	1:00 pm to 7:00 pm	Monday through Friday
Partial-Peak:	10:00 am to 1:00 pm	Monday through Friday
	7:00 pm to 9:00 pm	Monday through Friday
	5:00 pm to 8:00 pm	Saturday and Sunday
Off-Peak:	All Other Hours	Including Holidays
Winter (November-April)		
Partial Peak:	5:00 pm to 8:00 pm	Monday through Friday
Off-Peak:	All Other Hours	Including Holidays

Table 13: E-6 Time-of-Use Periods

As explained in section 2.2, the hourly consumption data from SunPower turned out to be unreliable and was not used in the scope of this project. In order to perform the analysis of benefits, we needed a different way to estimate residential hourly usage.

PG&E maintains class average load profiles based on a representative sample of customers in each rate class that are updated "dynamically". These samples have been maintained continuously since 2000, when Dynamic Load Profiling was created to support the needs for retail settlement in the deregulated market. The data continue to be published and updated daily and historical data are posted to the web at:

http://www.pge.com/nots/rates/006f1c4_class_load_prof.shtml.

We used the historical data for PG&E's E-1 (residential general service) rate to compute percentages of total energy consumed in each of the five TOU periods as shown in Table 16. The numbers are reasonably similar across the years, so in our analysis below we used the average values. For each of the three cases we combined this data with the baseline model consumption and production data to determine the appropriate PG&E rates and compute the difference in energy bill before and after the energy management program is applied.

Year	Summer Peak	Summer Partial-Peak	Summer Off-Peak	Winter Partial-Peak	Winter Off-Peak
2000	22.0913	22.1952	55.7135	12.5457	87.4543
2001	21.7761	21.7727	56.4512	12.4583	87.5417
2002	21.6373	21.837	56.5257	12.3042	87.6958
2003	22.0491	21.9547	55.9963	12.2033	87.7967
2004	21.8544	21.7492	56.3964	12.3614	87.6386
2005	21.4899	21.7639	56.7461	12.0596	87.9404
2006	22.0804	21.9523	55.9673	11.8976	88.1024
2007	22.0739	21.7571	56.1691	11.7809	88.2191
2008	22.2361	21.8649	55.899	11.8403	88.1597
2009	22.0543	21.8407	56.105	11.8044	88.1956
2010	21.3257	21.7668	56.9075	11.8563	88.1437
2011	21.9846	21.6607	56.3547	11.4129	88.5871
2012	22.2407	21.8403	55.919	11.2113	88.7887
Average	**21.9188**	**21.844**	**56.2371**	**11.9918**	**88.0082**

Table 14: Averaged percentages of energy consumed in different TOU periods

3.4.1 Consumption Information Delivery

In this program the information on energy usage and event conditions is periodically sent to residents, but there is no automatic control of end-use devices. Participating residents are assumed to manually control thermostats and other appliances in response to information.

Studies [Fischer 2008], [Faruqui 2009] and [ACEEE 2010][24] have argued that programs based only on energy consumption feedback can result in savings ranging from 2-6 percent. Note that the communicated information is not broken into individual TOU periods. Thus, in our analysis we assumed that the energy reduction is proportional in each of the TOU periods. With this assumption and considering the appropriate PG&E rates, the average benefit per year per unit can be computed for each apartment complex of the community. Figure 7 shows how the benefit depends on the percentage of energy saved for the Ramble Phase 1

[24] Fischer C. 2008. "Feedback on Household Electricity Consumption: A Tool for Saving Energy?" Energy Efficiency 1(1):79-104. DOI: 10.1007/s12053-008-9009-7. Available at

www.springerlink.com/index/276m42024x61wh1h.pdf.

American Council for an Energy Efficient Economy (ACEEE). 2010. Advanced Metering Initiatives and Residential Feedback Programs: A Meta-Review for Household Electricity-Saving Opportunities. Available at http://www.aceee.org/research-report/e105

Faruqui A, S Sergici, and A Sharif. 2009. "The Impact of Informational Feedback on Energy

Consumption – A Survey of the Experimental Evidence." Energy.

complex. For instance, for the energy reduction of 2% we get $27.57 value savings per year per unit.

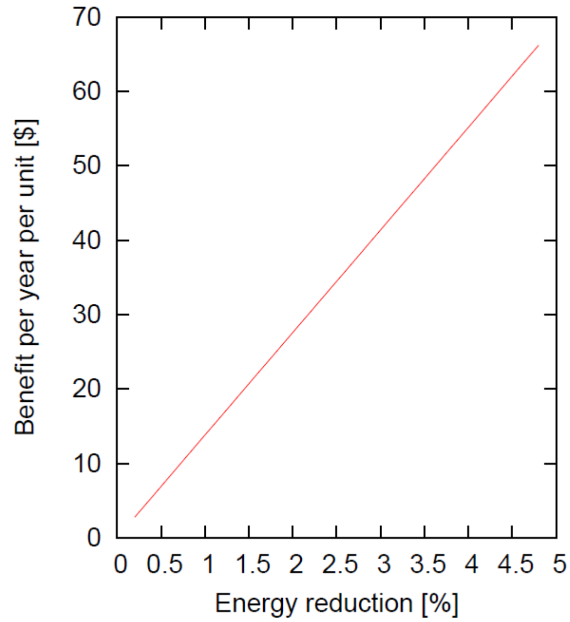

Figure 7: Benefit of the CID program per year per unit [$]

In simplest scenarios, this program can be implemented with almost no additional investment in technology. The MEM described in Section 3.2 above would send daily consumption information and event messages through email or text messages.

A more sophisticated option would be providing the residents with devices that measure consumption of individual appliances. For example, smart plugs, such as *Kill-A-Watt* cost around $20. More sophisticated solutions measure and display total consumption of a unit, based on multiple smart end-point devices, typically sold as a kit. A typical Home Energy Management system consists of a power meter, a Wi-Fi transmitter and a display. Examples of this technology that cost around $100 include *EnergyBuddy, EnviR and Battic.*

3.4.2 Time-Of-Use Program

In this program, in addition to feedback on usage, the HVAC system is controlled through programmable communicating thermostats (PCT). This is performed by a centralized command from the MEM. However, residents are allowed to override the command at any time. The control takes into account TOU periods trying to shift usage to a lower cost period. Thus, the benefit comes both from energy savings and reduction of loads in the peak period. Previous pilot studies of this type have shown that around 5% of energy reductions [Ontario

2007][25] together with about 10% of peak load reduction [Edison 2008] can be achieved with such a program.

By manipulating the distribution of energy consumed in different TOU periods with the assumed values of energy and peak load reduction percentages one can estimate average dollar value of benefits for this program. Figure 8 shows this for an average Ramble Phase 1 apartment for a range of energy and peak load reductions. For instance, with the expected 5% energy and 10% peak load reductions the estimated benefit would be $76.54 per year per unit.

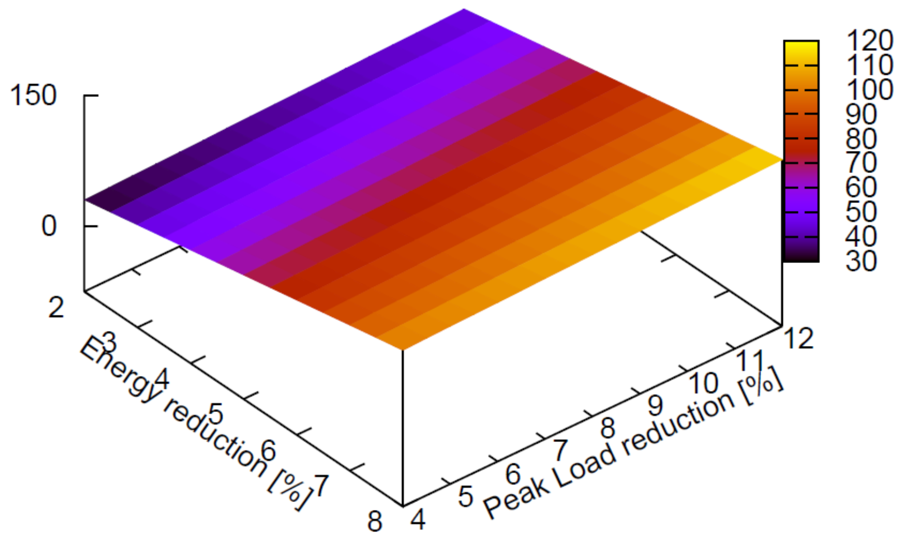

Figure 8: Benefit of the TOU program per year per unit [$]

Programmable communicating thermostats (PCT) and other smart appliances can communicate wirelessly through the Internet or via a home automation technology. The costs of wirelessly controlled light and fan controllers are in the $50-100 range (e.g. *Insteon*). The simplest PCTs start at around $100. More advanced thermostats, which can be adjusted via Internet-capable smart phones to allow residents to remotely adjust the temperature settings in their units, cost above $200 (e.g. *NEST, EverSense*).

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[25] Ontario Energy Board Smart Price Pilot, 2007, available at:

http://www.oeb.gov.on.ca/documents/cases/EB-2004-0205/smartpricepilot/OSPP%20Final%20Report%20-%20Final070726.pdf

Edison Electric Institute 2008 Study, available at:

http://www.smartgridinformation.info/pdf/2399_doc_1.pdf

3.4.3 Critical Peak Pricing Program

In the CPP program, the time-of-use rates are in effect most of the time, except for certain peak consumption days, when prices are considerably higher. For instance, in PG&E's SmartRate Plan, from 2 p.m. to 7 p.m. on so called SmartDays, there is surcharge of $0.6 per consumed kWh on electricity. No more than 15 SmartDays with this critical peak rate are called each summer season. Due to such a high surcharge residents shift considerably more energy usage out of this critical peak period. In this program the Property Manager Office would again control PCT's and potentially other appliances, but this time on a more dynamic schedule. The residents would still have an option to override these settings.

Various pilot projects have shown that CPP programs can yield substantial critical peak load reductions. For instance, according to the review in [Edison 2008] all cited CPP studies reported critical peak load reductions above 10%, most often around 20%. Figure 9 shows average benefits of an apartment in Ramble Phase 1 complex for a range of critical peak and peak load reductions with the assumed value of 8% for the total energy reductions. For instance, with the expected 20% critical peak and 10% peak load reductions the estimated benefit would be $101.7 per year per unit.

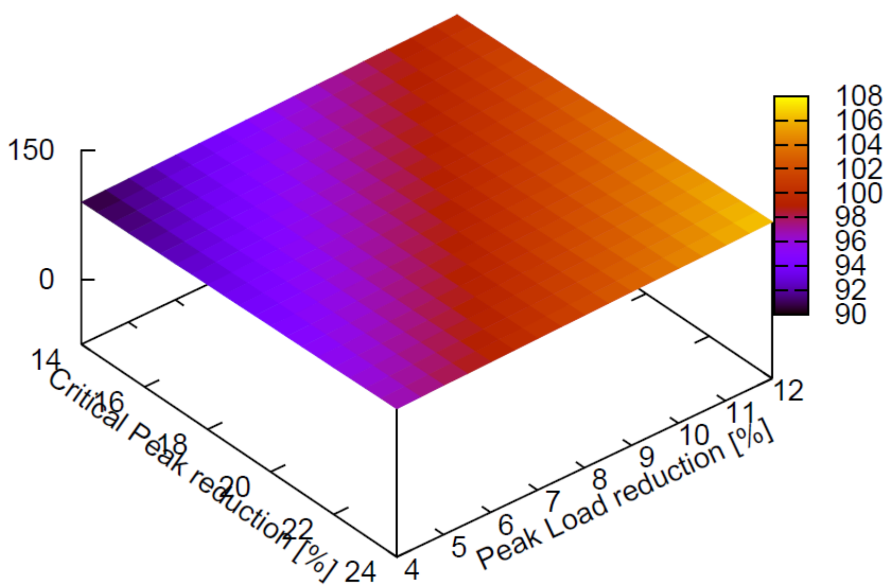

Figure 9: Benefit of the CPP program per year per unit [$] (for energy reduction of 8%)

The technology solutions used for this program would be similar to those listed for the TOU program at the end of section 3.4.2 with the exception that software for dynamic control would be more sophisticated. Moreover, providers such as *Ecofactor* have recently started to partner with utilities to offer subscription based services that collect usage and temperature data and control thermostat settings much more frequently and using big-data analytics.

3.5 Program Recommendations

3.5.1 Rule 18

PG&E Electric Rule 18[26] governs "Supply to Separate Premises and Submetering of Electric Energy" and specifies conditions for electric service in multi-tenant buildings. The original intent of Rule 18 was to prevent a landlord or property manager from intervening in the metering relationship between PG&E and its customer, by, for example, altering the meter read or charging a premium above PG&E rates for service to the ultimate customer. Rule 18 also prevents such fraud as charging one customer for another's usage or serving a non-residential customer under a residential rate.

WVCP has been informed by PG&E that under Rule 18, it may not pass along TOU or dynamic pricing schedules to the tenants at UC Davis West Village. We do not find this restriction anywhere in the clear language of Rule 18 covering Residential Service[27], but understand that interpretation of the tariff rules can be an art.

Our understanding of the situation in the multi-tenant buildings is that they are individually metered (not master-metered) residential accounts for which WVCP is designated as the billing agent and pays the bills directly to PG&E. Costs of utility service are then passed along to the tenants through fees included in their rent. Since the tenant does not directly pay the utility bill, they do not see any incentive to conserve or to move usage to cheaper, off-peak periods. WVCP has established a system of penalties if a tenant exceeds a certain maximum threshold of kWh in a month.

One option, if allowed without violating Rule 18, would be to establish a similar system of price penalties if a tenant does not follow a prescribed peak demand reduction – for

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[26] http://www.pge.com/tariffs/tm2/pdf/ELEC_RULES_18.pdf

[27] The following provision for master-metered Non-Residential Service, under 18.C.2.b, may be related:

> "2) Where a master-meter customer installs, owns, and maintains electric submeters on its existing building's distribution system for *cost allocation of dynamic pricing and/or conservation incentive purposes* the cost of electricity allocated to the commercial building tenants will be billed at the same rate as the master meter billed by PG&E under the CPUC approved rate schedule servicing the master meter." [italics added]

example, by ignoring an event signal or overriding the settings on a programmable thermostat.

In the event Rule 18 does indeed prevent direct price-based incentives and penalties, there may be alternative options for motivating demand responsive behavior in the multi-tenant buildings:

- Option 1: Non-price incentives. By using prize awards for participation, such as T-shirts or "Aggie bucks", the WV Partnership could stimulate social competition among tenants to encourage greater program participation.
- Option 2: Centralized (rather than distributed) control of devices. Under this option, the MEM would need to be able to directly communicate with and control thermostats and other HEM devices within UC Davis West Village. Individual tenants could still retain override capability to temporarily reset their unit thermostats to provide higher comfort, but the device could be programmed to automatically restore to its default settings after a certain period of time or whenever new instructions are issued from the MEM (similar systems are found in many hotels). In principle, this should not violate Rule 18 authority, since the tenant would be ceding control of its end-use equipment, which, though perhaps somewhat invasive, is not a utility asset and therefore non-CPUC jurisdictional.

Time and scope did not permit us to investigate these options further.

3.5.2 Other Program Considerations

Students are not typical residential electric consumers and any on-going program of energy management and control in UC Davis West Village should be sensitive to the unique demographics of the student population in the multi-tenant units, if it is to be successful.

Students vary significantly from the general adult population in terms of:

- Lifestyle pattern and daily schedule
- Use of major appliances (less laundry and cooking; more computers and gaming consoles)
- Low disposable income
- High acceptance of new technology

One recent technology that may prove well-suited to student lifestyles is the Allure Energy EverSense thermostat and GPS based smart phone app announced at the 2013 Consumer

Electronics Show[28]. This system links to a PCT to provide location-based awareness, such that if a consumer goes more than a certain distance (e.g. three miles) from home, the app automatically puts the thermostat into energy savings mode. Since Davis students lead less predictable schedules than most consumers (while rarely leaving home without their smart phones), this feature would seem a good fit.

3.5.3 Policy Recommendations

According to the CPUC, "The goal of the California Solar Initiative (CSI) Research, Development, and Deployment (RD&D) plan is to help build a sustainable and self-supporting industry for customer-sited solar in California." In the course of GE's work on Task 2, we uncovered several flaws or gaps in the current policy and regulatory design that affect the ability of West Village to fully realize and implement the vision for zero net energy communities as a viable keystone of California's solar growth. The following observations and recommendations are therefore directed at the policy audience as funders of the CSI RD&D program, and go beyond the specific opportunities for UC Davis or the West Village Energy Partnership.

- **Defining ZNE on an annual energy basis as a performance metric does not incent the most economically efficient combination of distributed energy resources.** A key difference between electricity and other energy commodities is the highly time-sensitive value of electric energy on the grid, which can vary by an order of magnitude or more over the course of a single day. West Village, as a ZNE community, may or may not maximize the benefits it provides to the larger California electric grid, depending on the timing of energy exports and imports needed to maintain net energy balance over the course of the year. To the extent that West Village residents and businesses produce net energy (generation greater than consumption) at times that align with high value peak hours and consume net energy (consumption greater than generation) primarily during off-peak hours and seasons of the year, West Village should be rewarded for this value. Conversely, if West Village is achieving ZNE by producing net energy off-peak and consuming net energy on peak, it should be penalized. The current annual calculation does not differentiate between peak and off-peak resources, and therefore, as a design criterion, does not incent investment in the societally efficient mix of resources.

  As an example, solar PV, while generally coincident with air conditioning loads that drive system peaks in California will nevertheless tend to contribute more energy during the mid-day period on hot summer days (when the sun angle is optimal for PV

[28] http://www.greentechmedia.com/articles/read/allures-eversense-says-its-one-better-than-a-learning-thermostat

generation) and too little energy during evening shoulder hours, which correspond better with the consumption peak. If the desired goal of ZNE is to minimize the net impact of new load on the grid, the current emphasis on PV may not be helpful. Especially in a residential setting, and with a student population that incurs peak demand well into the nighttime hours, it is likely that the annual ZNE goal is not the most accurate measure of system costs and benefits. GE believes that a modified metric that takes better account of the time value of electricity (driven by the capacity costs of serving peak demand) would provide a more accurate overall basis for evaluating energy performance at West Village, as well as a stronger incentive for alternative DER investment. These alternatives might include not only more advanced demand controls, but potentially economic investments in battery energy storage, smart EV charging systems, and other renewable generation alternatives that are not currently in scope at West Village.

Fundamentally, zero is just a number. Whether zero net energy is the "right" number from a policy perspective – that is, whether the goal of net energy balance over the course of a year results in the mix of resources that best meets the underlying policy objectives (such as stabilization of greenhouse gas emissions and efficient capital investment) at lowest cost, depends on the cost of balancing supply and demand with local distributed resources and controls, as compared to the cost of alternatives on the larger grid, such as utility scale renewables, combined with flexible conventional generation and/or storage. Without the right success metric in place, it will be difficult to evaluate the merits of projects like West Village in the future and to optimize the efficient use of scarce capital to meet California's ambitious clean energy policy agenda.

- **Multi-family tenants in West Village should be entitled to the same range of demand response tariff options as other residential customers.** During the course of the project, GE was unable to definitively resolve the issue of interpretation of Tariff Rule 18 with regard to the availability of PG&E's demand response rate options for the multi-family units at West Village. As individually metered PG&E customers, the West Village multi-family units should be entitled to participate in the same rate options as other PG&E residential ratepayers and we believe the CPUC would be accommodative of any tariff language waivers or modifications needed to support this objective. We recommend UC Davis and the WVEP continue to work with PG&E and, if necessary, seek regulatory relief to allow DR tariff participation by tenants in the multi-family units.

- **Net Energy Metering customers with smart meters should have separate access to their consumption and production data.** The current AMI architecture being deployed by PG&E (and to the best of our knowledge, the other California IOUs) provides net energy metered customers with only a net energy kWh read for each metered interval, not separate consumption and production values. This limitation inhibits efforts to measure and achieve local objectives for energy management (such as ZNE) through automated, dynamic control of demand (or eventually storage technologies). While we were able to synthesize a substitute historical data set for benchmarking purposes using the SunPower production data, this data will not be available for all NEM customers, nor can it be easily compared and reconciled with PG&E billing data (due to differences in the read cycle, for example). Finally, data from local pulse metering of consumption may not be of the same quality or revenue-level accuracy as utility metering, which is subject to numerous CPUC regulations and industry standards (i.e., the ANSI c12 series). While cognizant of the costs of changes in the existing deployments, GE recommends that California policy makers consider evolving the requirements for AMI data collection to better accommodate the needs of NEM customers to make informed energy choices, with transparency to both the production and consumption side of the ledger.

4 Summary of Recommendations

In Subtask 1, GE developed a baseline model of energy performance at UC Davis West Village, based on the best available information. Given the limitations and challenges inherent in this effort, we were unable to make a definitive assessment of current energy performance, but believe our results support several directional observations. We believe, based on the information available and the conservative nature of our modeling, that it is likely that:

- The multi-tenant units are performing slightly above production of installed PV, with some variation by unit type. The Viridian units appear to have the best performance (C/P close to 1), while the Ramble and Solstice units are farther "above ZNE" and may require some additional "tightening" of performance to achieve energy balance.
- The Rec and Lease center and swimming pool area (the "Club" and "Gas" accounts), as well as the MU spaces appear to have a greater excess of consumption over PV production.
- Our model confirms that the Faculty Staff housing do appear to be well designed for consumption to match production, with small variations by floor plan and solar size. However, the studio annex units, which are an optional addition for some home owners, may have an additional challenge from PV production alone, due to a lack of roof space to support solar installation.
- Finally, above and beyond the data limitations in our study, there remains uncertainty in the evolution of future loads which have not been estimated adequately, notably the EV charging and energy-intensive operations associated with the Western Cooling Efficiency Center.

In Subtask 2, we recommended functional specifications and a set of monitoring and control options to address tightening the energy performance at UC Davis West Village. The core recommendation is the development of a desktop Master Energy Manager to automate the on-going tracking of performance data (ideally hourly interval production and consumption). The MEM would serve as an on-going "living" version of our baseline model and would manage communications both to residents and directly to addressable devices such as programmable communicating thermostats within UC Davis West Village.

We examined three different levels of potential energy management and control at different levels of technology and cost:

- Consumption Information Delivery
- TOU with PCT
- CPP with PCT

As our cost-benefit examples show, there are attractive simple paybacks of less than three years available with each level of technology. For example, a CID program involving a single $20 plug monitor and achieving energy savings of 2% would pay for itself in less than a year. A TOU program with 5% energy and 10% peak savings saves approximately $75 a year at a cost of $100, for a simple payback of 1.3 years. A CPP program with 8% energy and 10% peak savings, plus an additional 20% critical peak savings, would result in roughly $100 in benefits per year, recovering the initial cost of a $250 advanced HEM system in 2.5 years.

We sketch out two options with regard to addressing program design obstacles, in particular, the apparent constraints of Rule 18 that prevent sharing of dynamic pricing incentives with residents in the multi-tenant units. These are:

- Non-price incentives, such as prize awards; and
- Direct centralized control of thermostats with temporary local override capability.

GE provides several recommendations for improving the policy and regulatory framework for Zero Net Energy communities in California, based on our experience at West Village. We suggest that the ZNE metric – currently a design criteria but proposed as a future building code requirement for new construction in the state -- be modified or elaborated to contain a notion of the varying time value of electric energy. ZNE may be achieved over the course of a year in different ways, some of which will be more beneficial than others. In point of fact, zero is just a number, and the appropriate goal for any given community or building should be to contribute to the overall system sustainability and least-cost energy balance to meet future needs, which will likely depend on a mix both distributed energy resources and cost-effective centralized/utility scale renewable resources.

We also recommend that the CPUC clarify the tariff rules with regard to DR participation by individually metered multi-family units, such as those at West Village. To the extent current rules do not allow all ratepayers on a given rate the same access to the full menu of DR rate options for which they are eligible, waiver or modification to the tariffs should be sought. Finally, we recommend that policy makers consider the needs of Net Energy Metered customers for separate production and consumption data in any future evolution of the AMI data requirements of the California IOUs. Separate production and consumption data are necessary inputs to the cost-effective integration and optimization of demand against local generation resources that is the heart of the ZNE community concept.

APPENDIX D

Data Collection Results

Task 3 Hybrid Solar Photovoltaic/Thermal Innovative Development: Data Collection Results

Subtask 3.1 Hybrid Solar Photovoltaic/Thermal System for West Village Apartment Building

Introduction

The purpose of this subtask is to develop, design, purchase, install, test and assess the electricity and hot water generation from a hybrid photovoltaic/thermal (PVT) system installed at one the Solstice apartment building located at the West Village community at UC Davis. Previously, modeling the system determined the optimal arrangement of the PVT panels and compares it to a PV and Solar Thermal configurations. By collecting actual data from the PVT system, the project will assess the systems real world performance, evaluate the electrical energy savings, compare to the existing means of hot water generation, and make recommendations for future PVT installations.

Data Collection Results and Discussion

As mentioned earlier, 24 PVT panels (3x8 layout) were installed at West Village multifamily apartment. Data are collected in 5-minute average intervals. Items being logged include flow rate, temperature, and power consumption for the two water heaters, heat pump, and PVT system. For the data analysis, the simplified energy flows in PVT system are shown in Figure 1. Please also refer to as-built water heater and instrumentation diagram for symbol information.

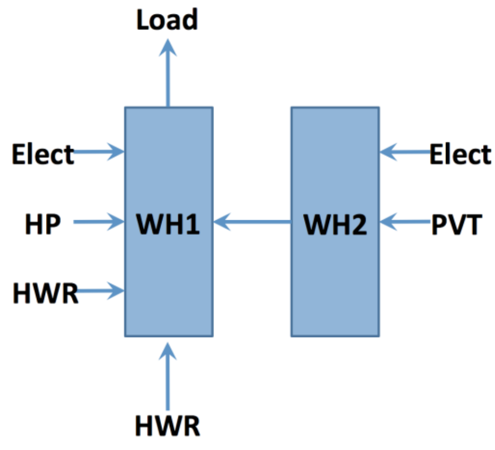


Figure 1 Simplified energy flows in PVT system

The energy balance equation can be written as:

Hot Water Use + Recirculation Loss + Tank & Pipe Loss = Heat Pump Energy + Resistance Heat + PVT

Because the hot water recirculation-return line is returning heat (though with some heat losses in between) back to WH1 tank (HWR), total heat delivery can't be measured directly by using the cold water flow and the difference between the hot & cold water temperatures. However, the information we want can still be obtained using the following functions:

- Useful Hot Water Delivered: Qd = (F2-F5) x (T5-T1)
- Recirculation Loss: Qr = F5 x (T6-T11)
- Total Heat Delivery: Qu = Qd+Qr
- PVT Energy Delivered to WH1: Qw1 = (F2-F5) x (T4-T1)
- PVT Energy Delivered to WH2 from Heat Exchanger: Qw2 = F3 x (T7-T8)
- PVT Energy Delivered to Heat Exchanger from Panels: Qpx = F4 x (T10-T9)
- Heat Pump Energy Delivered to WH1: Qhp = F1 x (T2-T3)
- Electrical energy input can be measured using CT's and power monitors
- Tank & pipe loss can only be estimated from the energy balance and/or heat loss calculations.

The PVT system started generating hot water at the end of 2013. Between January 1st and end of July 2014, our PVT multifamily demo has generated 4,817 kWh energy on thermal side. While the total heat energy, which includes energy produced by PVT panels, electric resistance water heater and air-to-water heat pump, is 12,780 kWh. Useful hot water delivered to apartments was calculated as 4,707 kWh, which points to huge heat losses in the system. Detailed results and discussion are provided below.

Figure **2** and Figure **3** shows the heat generations from PVT, air-to-water heat pump, and electric resistance water heater, respectively as well as the corresponding ratio. As we can see, in the summer season, June and July, system generates significant less total heat than other months due to less hot water usage, due to student apartment residence not occupying the apartments. This is also shown in Figure **5**. The reduction in hot water demand reduces all three parts heat generations as well. Except summer season, the ratio of heat generated by the PVT system is relatively consistent. As expected, the PVT system produces at least 20% more heat during spring and summer. The PVT heat increases from about average 670 kWh in winter to average 860 kWh in late spring. More importantly, looking at the heat generation ratio in Figure **3**where a trend emerges. As expected, the PVT heat generation ratio increases steadily approaching the summer months. Approximate 55% of total heat was produced by PVT system in the summer while the percentage is around 30% in the winter months.

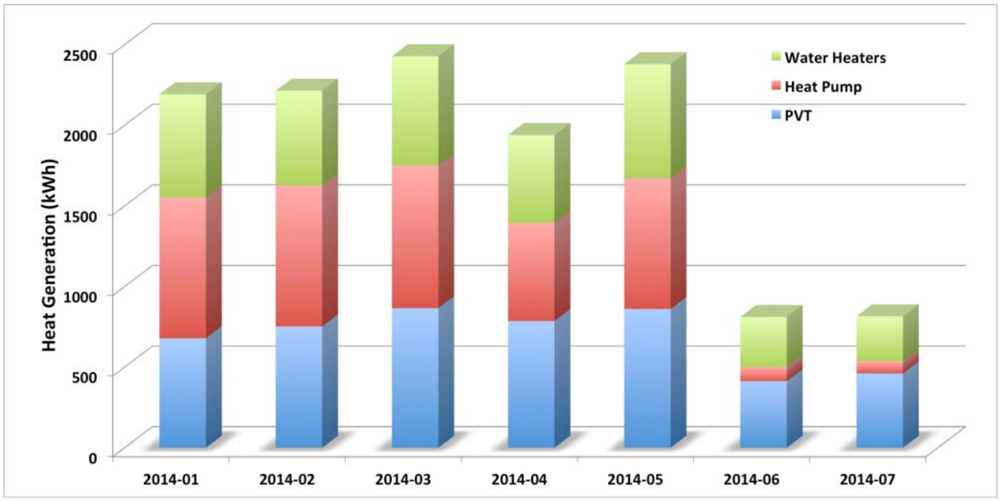


Figure 2 Heat generations from PVT, heat pump, and water heater, respectively

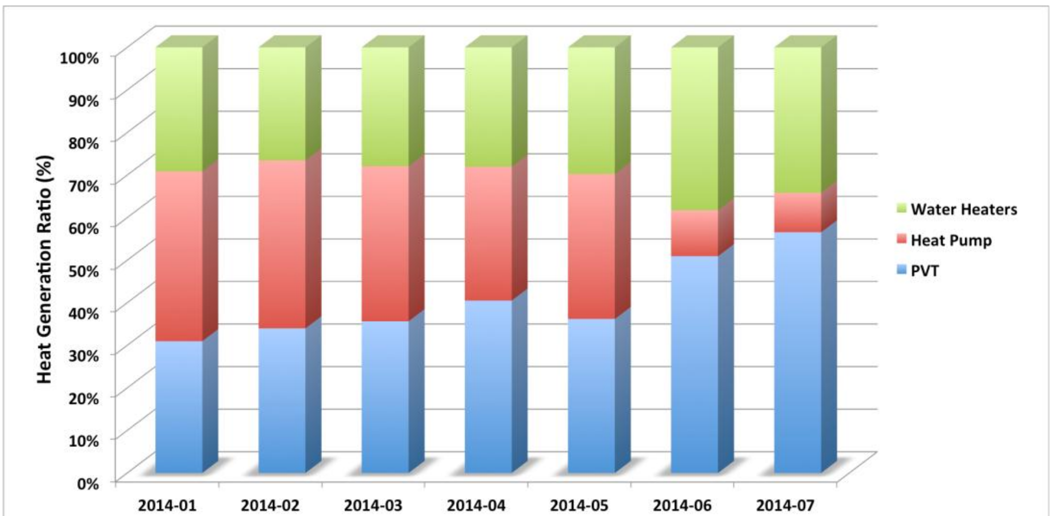


Figure 3 Heat generations ratio from PVT, heat pump, and water heater, respectively

Effective Energy Factor of PVT system was also expressed as Q_{px} divided by Q_u. Using total useful heat delivery to the apartment and PVT heat generation, PVT performance can be easily evaluated through calculating this Effective Energy Factor. Effective Energy Factors are summarized in Figure **4**. All the factors are very close to one in winter, while exhibiting much higher effective energy factor when the tenants use less mount of heat during summer time. Based on the definition, when the Effective Energy Factor is close or larger than one, it means technically PVT system is sufficient enough to provide enough heat for one of the multifamily apartment for that month. Although the PVT system contributes to a central hot water system, which serves all twelve units in the apartment building, modeled and sized to produce enough hot water for two apartments on an annual basis. Heat losses are addressed in Figure **5**.

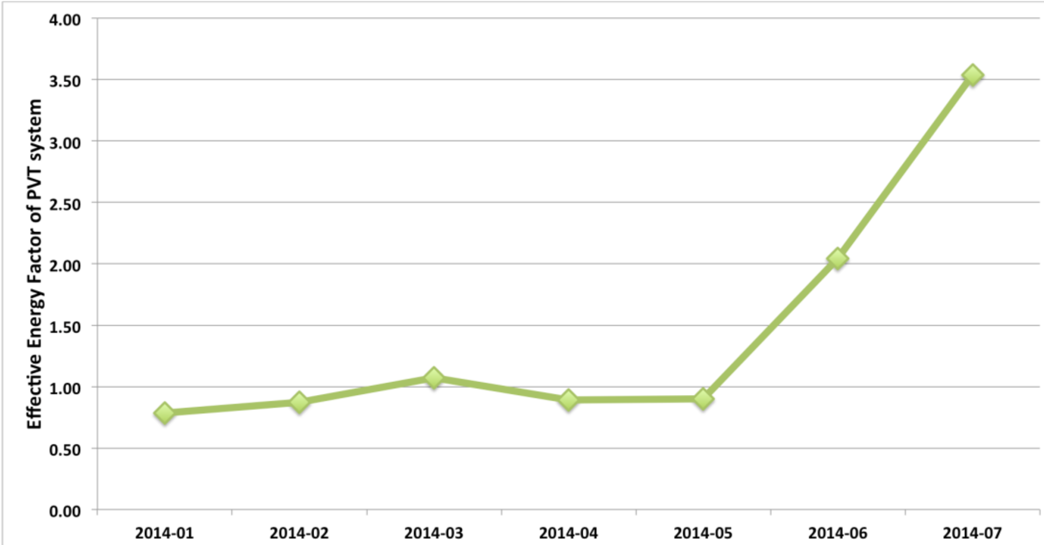


Figure 4 Effective energy factor of PVT system each month

In Figure **5**, shows heat recirculation loss and useful hot water delivered to the apartment. As mentioned earlier, the tenants use significant less heat during summer time, as shown in blue bars, because many students do not occupy the apartments at that time. In contrast, the hot water usage is very similar prior to summer season, at about 1,000 kWh per month. Furthermore, heat recirculation losses are quite close to each other throughout the months that that were monitored. Because of the hot water recirculation (which is designed to save water from being wasted) a small amount of hot draw is consistent 24 hours a day. Therefore, the recirculation loss in this system is the main heat loss source. The calculated recirculation loss ratio for each month is shown in Figure **5**. We can see that at least 26% of heat is lost due to recirculation and in summer case this loss ratio reaches up to about 42%. In short, average 34% heat will loss due to recirculation in a typical month.

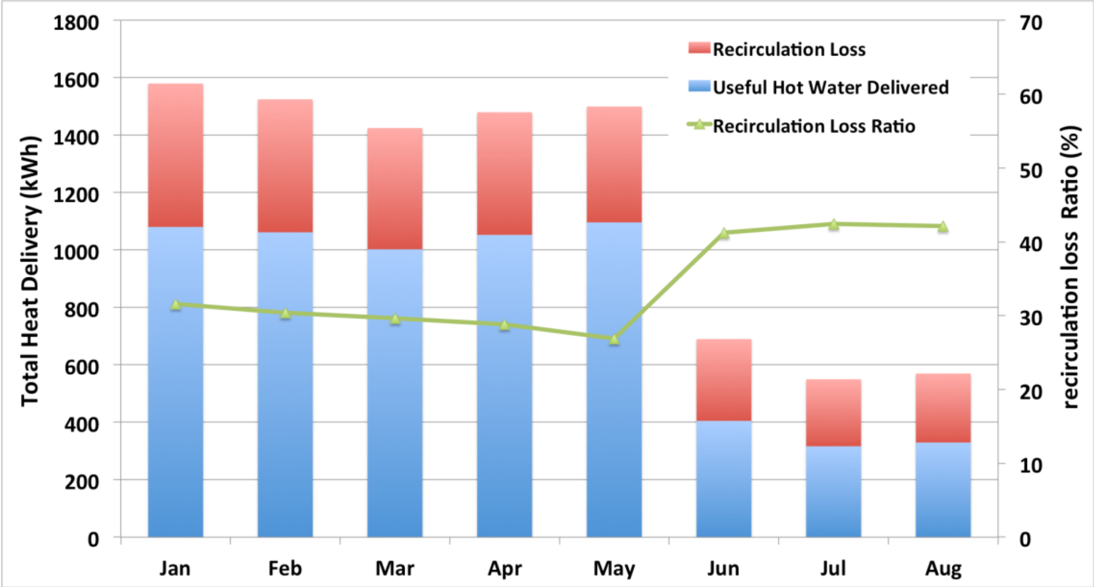


Figure 5 Monthly recirculation loss and useful hot water delivered in multifamily apartment

Finally the efficiency of PVT heat exchanger is examined as part of this demonstration. The results of PVT energy delivered to water tank from heat exchanger Qw2 and PVT energy delivered to heat exchanger from panels Qpx are shown in Figure 6. During summer season when tenants use less heat, the PVT panels generate less heat correspondingly even there is more solar radiation. From Figure 6, we can also see that PVT heat exchanger efficiency varies from about 50% in winter to about 90% in the summer.

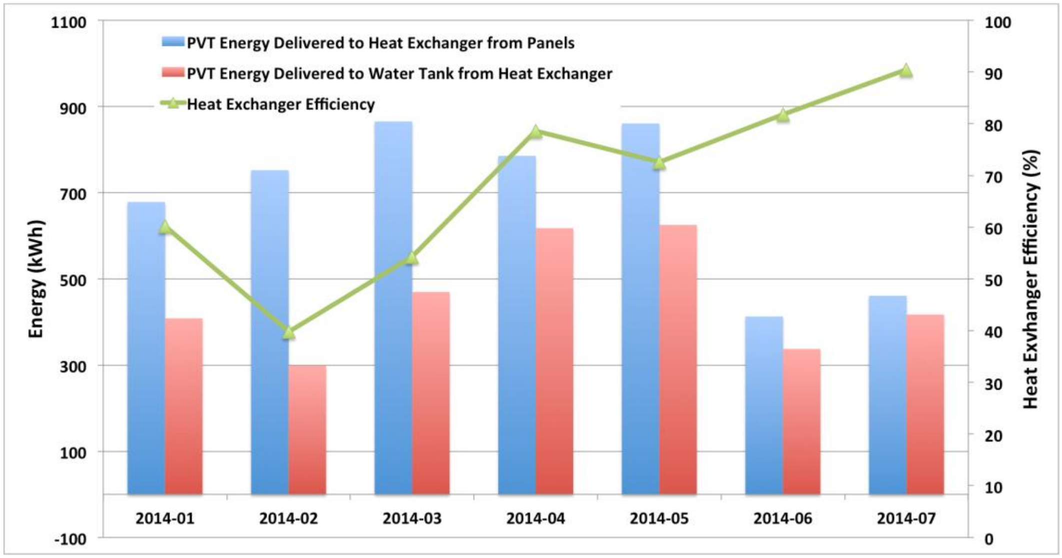


Figure 6 Heat exchanger efficiency results

Conclusions

a) PVT system and instrumentations has been installed at the end of 2013. Data have been successfully collected and an analysis was performed.
b) Between January 1st and end of July 2014, our PVT multifamily demo has generated 4,817 kWh energy on thermal side. The total heat energy, which includes energy produced by PVT panel, water heater and heat pump, is 12,780 kWh. In the meantime, useful hot water delivered to apartments is only 4,707 kWh, which means there is huge heat loss in the system.
c) The PVT heat generation increases from average 670 kWh in winter to 860 kWh in late spring. In addition, as time goes from winter to summer, the PVT heat generation ratio increases steadily.
d) Effective Energy Factors of PVT system are very close to one in winter, while exhibiting way higher effective energy factor when the tenants use less mount of heat during summer time
e) Large recirculation losses were discovered in the system. Average 34% heat is lost due to recirculation in a typical month in this demo.
f) PVT heat exchanger efficiency varies from about 50% in winter to about 90% in the summer.

Subtask 3.2 Hybrid Solar Photovoltaic/Thermal System for Single Family Home

Introduction

The purpose of subtask 3.2 is to develop, design, purchase, install, test and assess the electricity and hot water generation from a hybrid photovoltaic/thermal (PVT) system for a single-family home. The system will be modeled in order to determine the optimal arrangement of PVT panels and compare it to PV and Solar Thermal configurations. By collecting actual data from the PVT system, we will be able to assess its performance, evaluate the electrical energy savings, compare it to the existing means of hot water generation, and make recommendations for future PVT installations.

Data Collection Results and Discussion

Solar Electricity Generations

The PVT system started generating electricity on August 17, 2013. Due to system troubleshooting, the system was not settled into routine operation until Sep. 1, 2013. By end of July 2014, the PVT system has generated a total of 2,890 kWh of electricity, approximately equivalent to 1,515.92 kg of CO2 saving based on lifecycle impact factors according to Tigo as shown in Figure 7. The peak power of system is 2.16 kW.

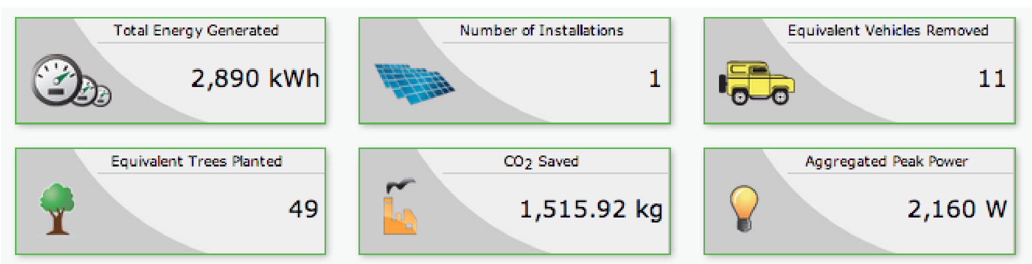


Figure 8 Electricity generation summary till July 2014 (from Tigo Energy)(

Visitors are also able to see real-time electricity generation through the following link:

http://www.tigoenergy.com/site.php?aggievillagepvt

Figure 9 Real-time Electricity Generation of PVT System

Figure 8 shows the real-time information on electricity generation. For example, at 12:37 pm on May 30th, the PVT system was generating a total of 2.04 kW electricity. The solar electrical performance of each PVT and PV panel can also be seen from this figure. The individual module level monitoring is provided by the Tigo maximizers, which monitor voltage and current at each panel. Typically energy generation is across all twelve panels depending on conditions. An example is shown in Figure 8.

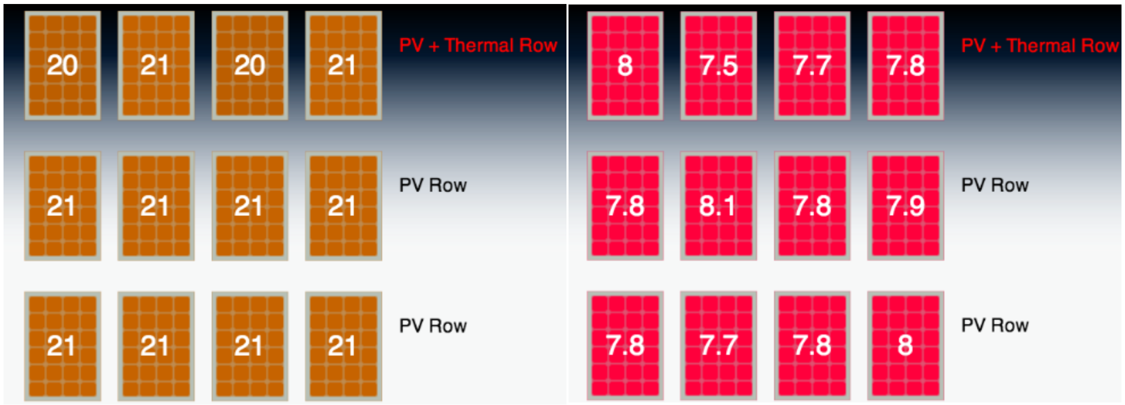


Figure 10 Real-time voltages (left) and currents (right) of Aggie Village Smart Home PVT panels

Monthly solar electricity generations are summarized in Figure 10. Unfortunately, the Tigo maximizer attached to PVT panels failed from middle Nov. 2013 to Feb. 2014. Therefore, the electricity generations in those months are significant less than normal, which we can also see from Figure 10. Those months of PV data have been excluded. The system averages 305 kWh of electricity generation per month.

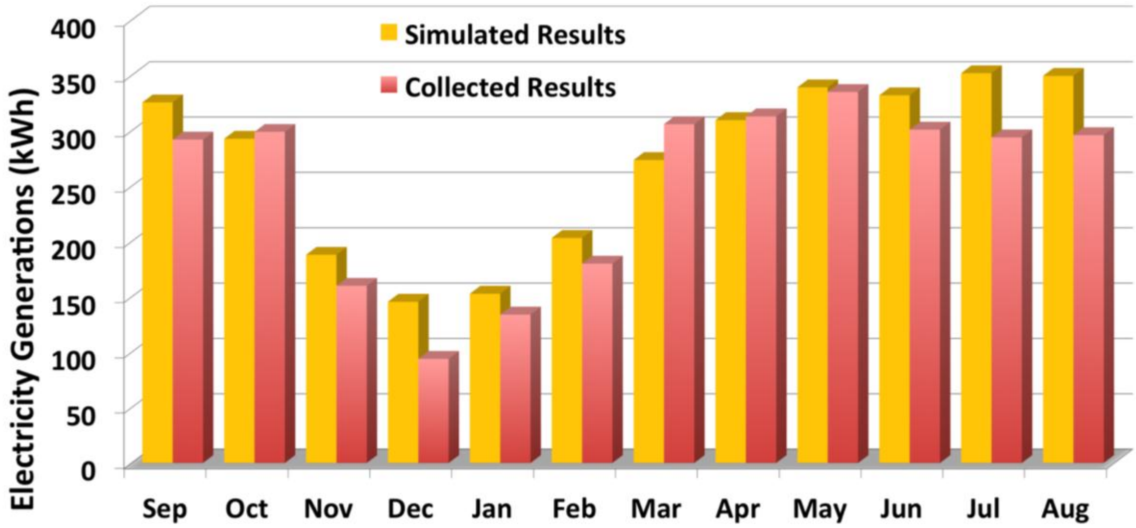
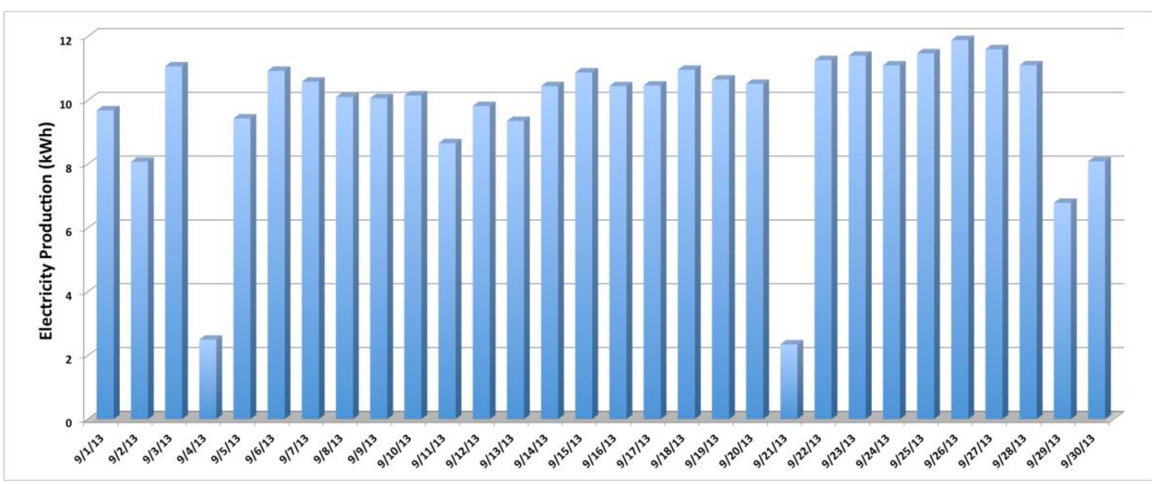


Figure 11 Monthly solar electricity generations from Sep. 2013 to Jul. 2014

Selective one-month daily solar electricity generation data are presented above. As shown during September 2013, except for day 4 and day 21 when rainy weather occurred, the system can generate approximate 8 to 12 kWh of electricity each day. Total electricity generation was 291.6 kWh during September. In contrast, electricity generation in October is 299.5 kWh. These data show the clear trend of electrical generation decrease as the month of October goes on, as expected in the northern hemisphere. The supplementary section includes electricity generations for each month.



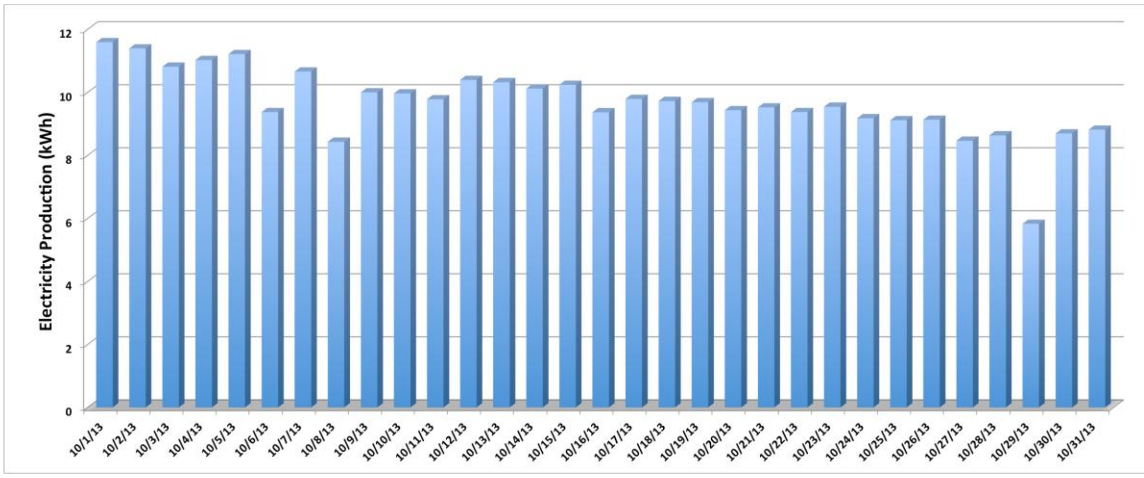


Figure 12: Electricity Generation of PVT System during Sep. 2013 (above) and Oct. 2013 (bottom)

In order to fully understand the PVT performance in a day, we can also investigate the electricity generation hourly. Figure 12 shows the hourly electricity generations in a typical sunny day. Although PVT panels can continuously generate electricity between 5am to 8pm, about 89% electricity is generated between 10am to 5pm. As expected, the system reaches max performance around 1pm.

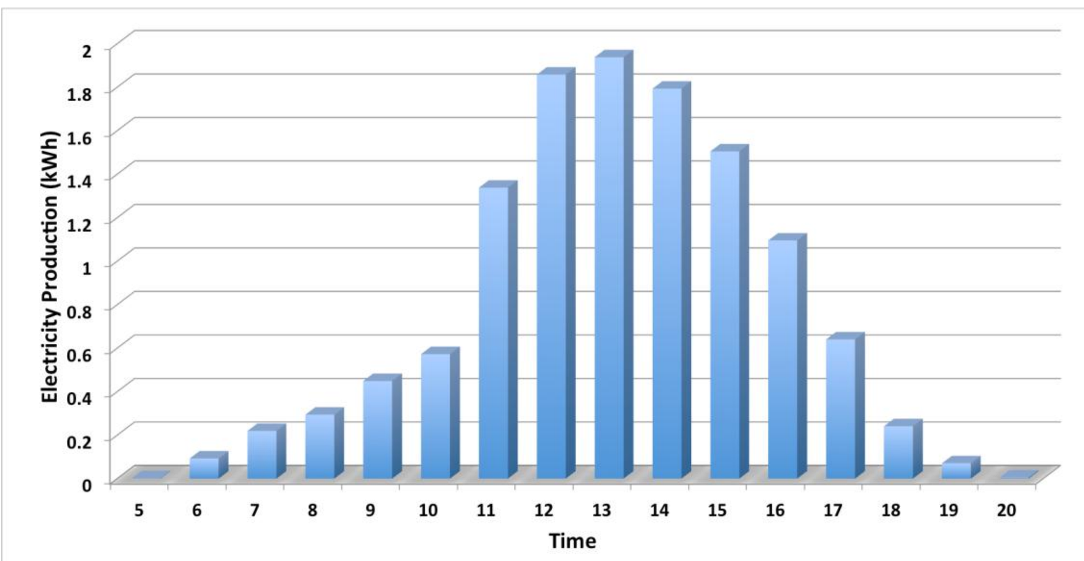


Figure 13 Hourly electricity generations in a typical sunny day (May 30th, 2014)

Solar Thermal Generations

Successful in configuration of the Resol data modules and Vbus.net also took place during August 2013 for solar thermal data collection. The Resol data collection system collects the flow rates and temperature sensors from the thermal system and it contribution to the home hot water generation. The log interval was set to 5 min averages in order to avoid exceeding the storage capacity of the data logger. Similar to the solar electricity generation, it can also show the real-time results on all flow rates and temperature sensors that have been installed, as shown in Figure 13. As can be seen in Figure 13 the PVT loop pump is working at about 0.21 m3/h (210 L/h or close to 1 gpm). The temperature of the PVT panels on the roof is around 42.9°C while the temperature in the hot water storage tank is 38.5°C. Since the tenants were not using hot water, the flow-rate sensors F2 and F3 show zero.

Visitors are also able to see this real-time information through the following link:

http://www.vbus.net/vbus/scheme/id/792

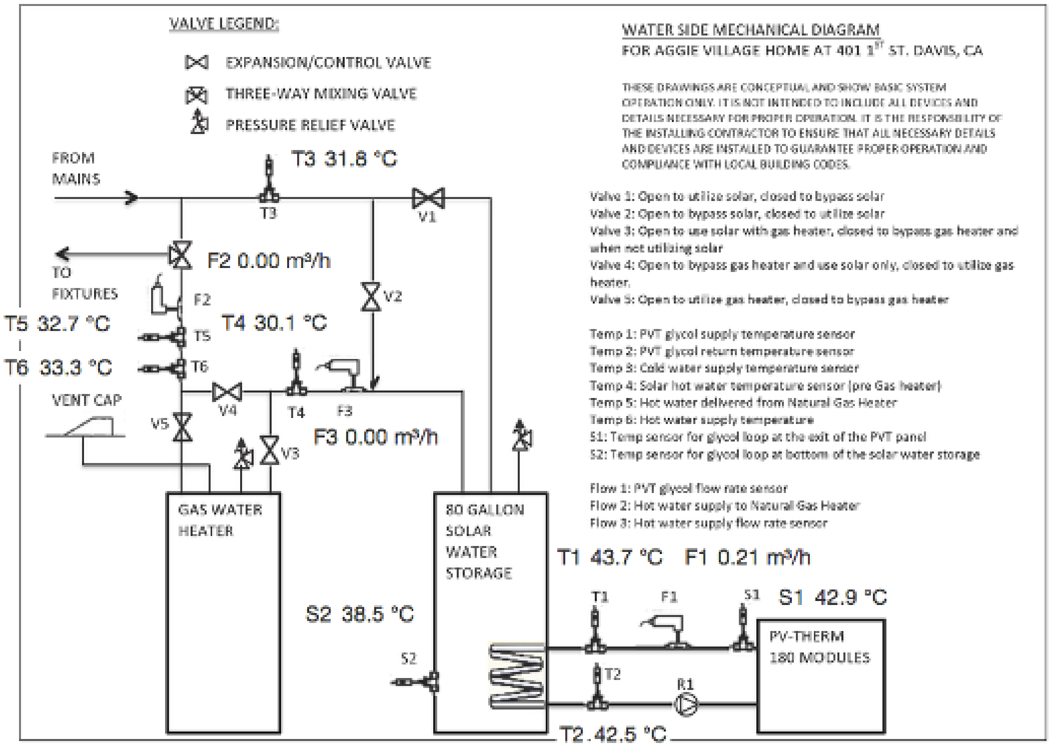


Figure 14 RESOL real-time information on flow-rate and temperature sensors super imposed on the construction drawing

The following calculations are considered for our analysis in the Aggie Village smart home. Please refer to sensors in the **Figure 13**.

For domestic hot water delivered to the home:

$$\text{Eqn. 1: } Q_{delivered} = F2 * (T5 - T3)$$

The heating contribution of the PVT array is calculated as follows:

$$\text{Eqn. 2: } Q_{PVT} = F1 * (T1 – T2)$$

The heating contribution of the natural gas heater is calculated as follows:

$$\text{Eqn. 3: } Q_{NGH} = F2 * (T6 – T4)$$

Equations 1-3 can be calculated automatically by using WMZ modules 1, 2 and 3 respectively. The lost heat in storage is the difference between the heat generated and heat delivered:

$$\text{Eqn. 4: } Q_{loss} = Q_{NGH} + Q_{PVT} – Q_{delivered}$$

Therefore, the effective energy factors of the system are:

$$\text{Eqn. 5: Effective energy factor of PVT system} = Q_{PVT} / Q_{delivered}$$

Based on the analysis above, the total domestic hot water delivered to the house, heat contribution of the PVT array, heat contribution of natural gas heater, etc. can be calculated. The monthly heat generations calculated using these methodologies are summarized in Figure 14 and Figure 15. Also, a summary of the heat delivery and heat loss by month is shown in Figure 16. As we can see from Figure 14, total heat generated which include contributions from the natural gas heater and PVT system, vary throughout the year. In winter, the total heat generated is about 30% to 50% higher than other months, which are about 170 kWh. Those high heat generations are due to high use of natural gas heater. More specifically, more that 50% of heat comes from natural gas heater between January and March. In other words, PVT system alone is not enough to meet the hot water needs of homes occupants. In contrast, during October, April, May and June, only less than 15% of heat comes from the natural gas heater. From Figure 15, shows the trend that in the fall and spring PVT system can satisfy most portion of heat needed. Surprisingly, PVT can cover over 98% of heat needed in June 2014.

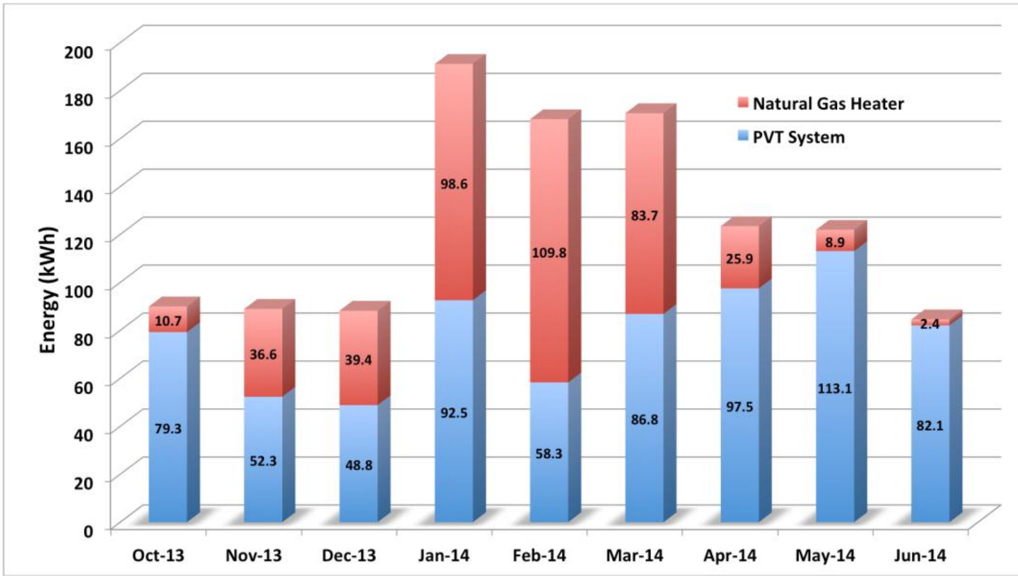


Figure 15 Heat generations from PVT and natural gas heater, respectively

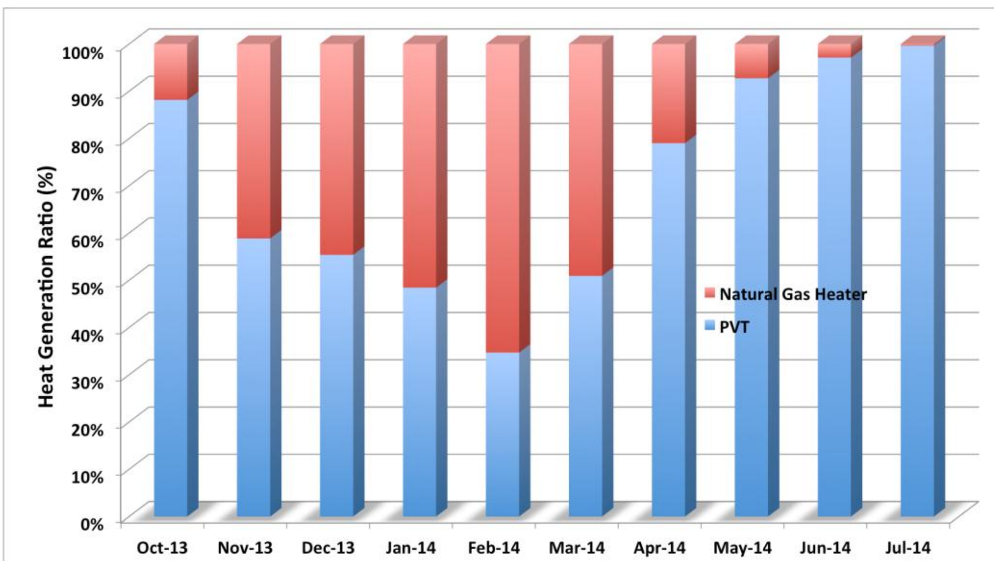
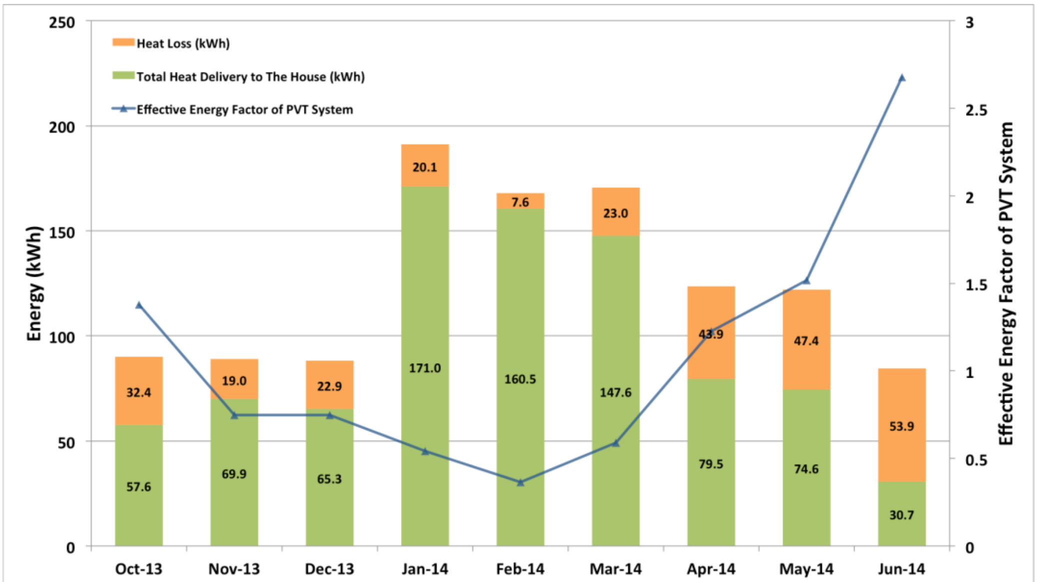


Figure 16 Heat generation ratios from PVT and natural gas heater, respectively

As mentioned in the multifamily PVT analysis section, Effective Energy Factor of a PVT system is defined as QPVT / Qdelivered. Since we are able to get total heat delivery to the house and PVT heat generation, we can easily evaluate PVT performance by analyzing Effective Energy Factor, as shown in Figure 16. When Effective Energy Factor is larger than one, ideally the PVT system's total heat generation during that period is sufficient enough to provide the total needed for the house during the same period provide that there is no heat loss. As can be seen from Figure 16, the trend of Effective Energy Factor during the year is very obvious. Most of wintertime, the Effective Energy Factor is below one due to relative low PVT heat generations and high hot water consumption. During June, the Effective Energy Factor reaches 2.7, which is almost two times higher than of the EEF during February.



1 17 Monthly heat delivery, heat loss and effective energy factor of PVT system

Comparisons between PVT and PV Performances

a) Differences on electricity generations

An interesting question is that whether there are measureable differences on electricity generations between PVT panels and conventional PV panels due to the active cooling of the PVT panels attributed to the circulating glycol. In order to answer this question, we summarize average monthly electricity generations per PVT panel and PV panel, respectively, shown in Figure 17. The PVT/PV factor is defined as: the electricity generated by PVT divided by that by PV. PVT/PV factor as function of time is also presented in Figure 18. As mentioned earlier, there was an issue with the Tigo Energy Maximizers from November to February, which required they be replaced. Thus no data are available during those months. As can be seen in Figure 17, each panel, both PVT and PV, can generate approximately 25 kWh electricity every month, and is very stable during the monitoring period. Quite surprisingly, the average electric generations for each PVT panel actually are few percent lower than PV panel throughout our monitoring months. One expected remarkable advantage of PVT is that PV power efficiency will increase by reducing the temperature in the cells due to the active cooling. Furthermore, lots of reports show that solar cells drop 0.5% in efficiency for every degree Celsius increased above its optimum. In other words, if the PVT panels reduce the temperature from 65 C to 25 C, it will result in an approximate 20% increase in power. However, that was obviously not the case in our project. Compared with PV, PVT panel actually drops its efficiency on our system instead of increasing, which was not the expected outcome. Further analysis of this is below.

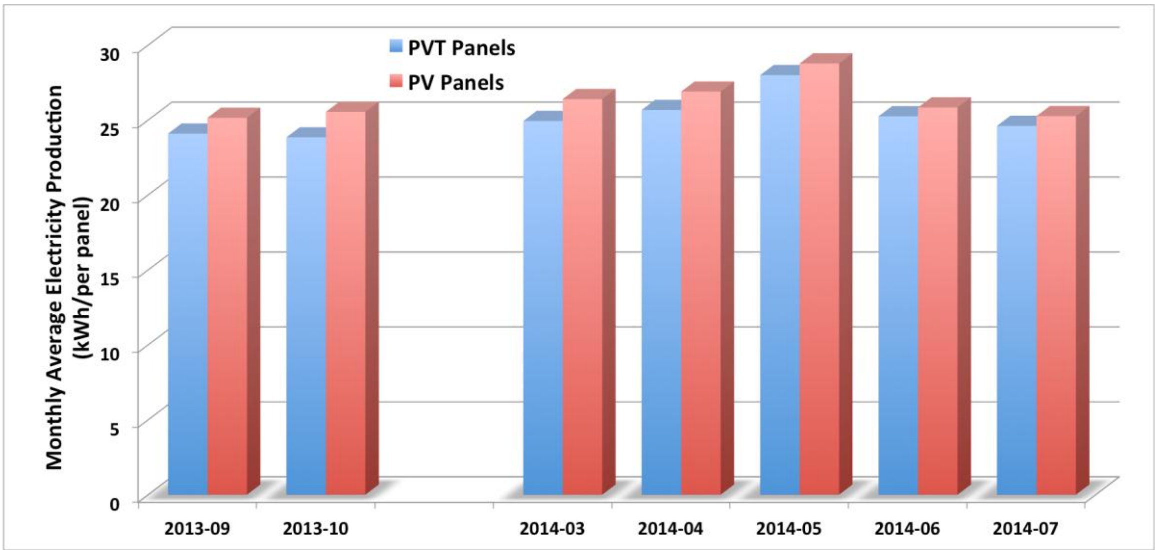


Figure 19 Average monthly electricity generations per panel

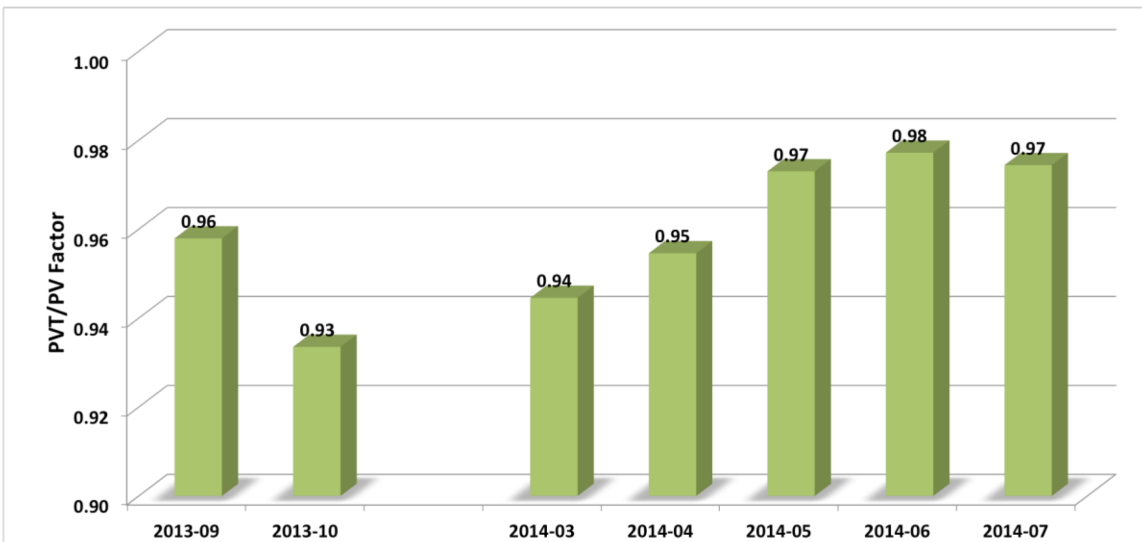


Figure 20 PVT/PV factor as function of time

In order to understand what causes this difference, hourly electricity generations were evaluated. Figure 19 shows the aggregated average hourly electricity generation from each panel type during a typical sunny day, shown in May 3th, 2014. This shows that electricity generations from PVT and PV panels are very close to each other even at hourly intervals. However, some differences do emerge. In a typical sunny day in May, PVT generations is slightly lower than PV before 10am, while between 10am and 2pm they are very close to each other. Surprisingly, the PVT generations exceed PV panel after 2pm in electrical side. Similar to the monthly plot, hourly PVT/PV factor is also summarize (green dots) in Figure 20. As we can see from this plot, PVT/PV factor increases from average 0.8 early in the morning to 1 around 10:30am. Then the factor remains at one untill 2pm. After 2pm, there is a notceable increase in the PVT/PV factor which then drops to orignal value. Some explaination of the increased PVT/PV factor beginning at by relating other monitoring parameters in the themal system. Figure 23, shows the changes of PVT panel temperature (red) and PVT glycol Loop flowrate (blue) on hourly basis. Although there doesn't appear to be any obvious correlation between PVT/PV factor and PVT panel temperature.

However, we do notice that if the PVT panel temperature underneath exceed certain temperature which is due to better azimuth conditions, the PVT panels start to perform better. That is extact the time the glycol loop pump begins to circulate fluid through the system and is show, in the blue curve. Also plotted is the PVT system hourly heat generation during day in Figure 21. At 10am, PVT starts to generate hot water and then keeps running till 5pm.

However, the PVT electricity generation is still lower than convertional PV panel. We attribute this to the different PV efficiency between PVT panels and PV panels, althrough the manufacturer claims they are the same. In other words, based on their performaces in our demo, the performace of PVT panels are approximate 20% lower than that of PV panels on electrical generation side. Then when the glycol loop temperture reaches setup temperture during day time, PVT panels start to generate hot water which draw amount of heat from PV panels above at the same time. As a result, PVT performs 20% better which is consistent with results reported. Finally, when the temperature drops PVT performance reduces to its original value.

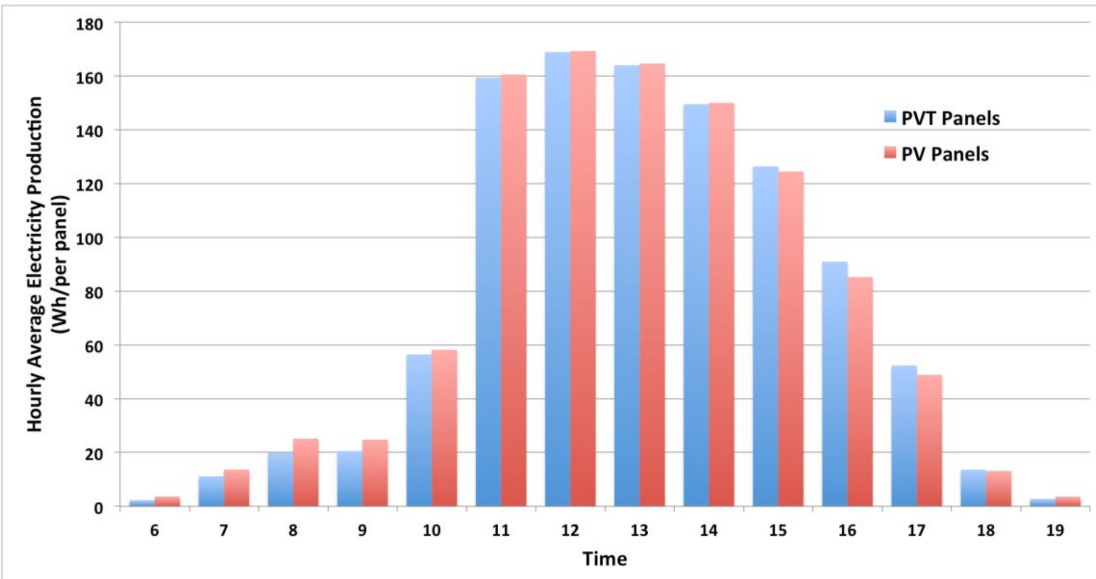


Figure 22 Average hourly electricity generation each panel in a typical sunny day (May 3th, 2014)

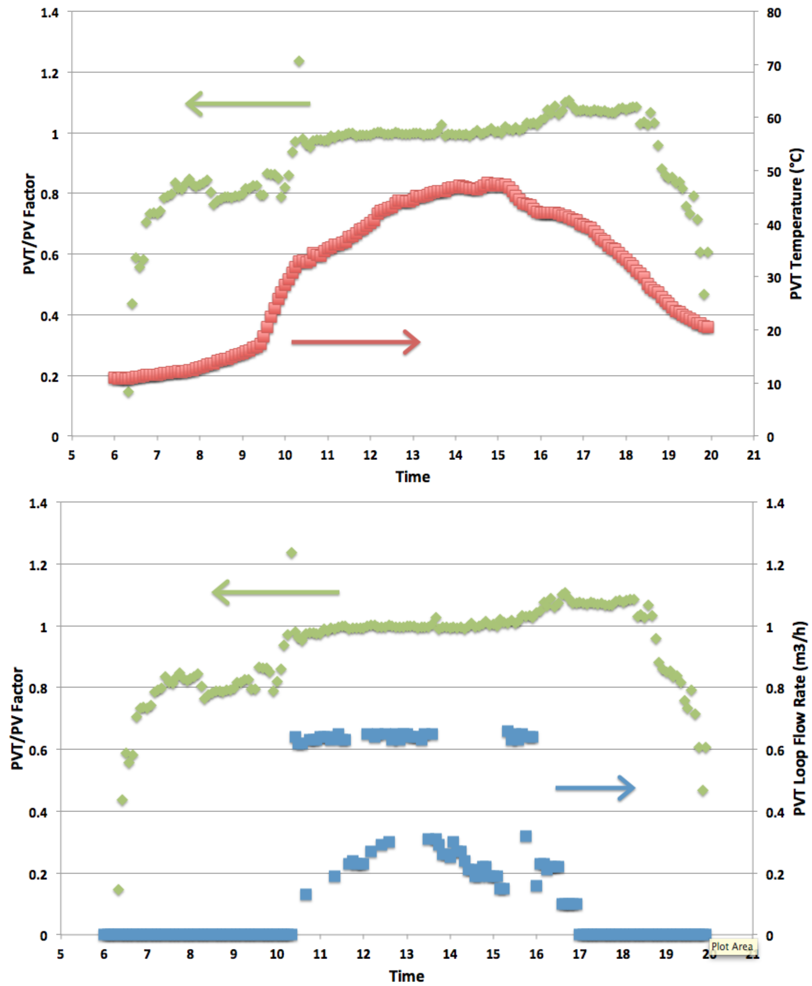


Figure 23 The change of PVT/PV factor, PVT panel temperature (top) and PVT glycol Loop flowrate (bottom) in a typical sunny day (May 3th, 2014)

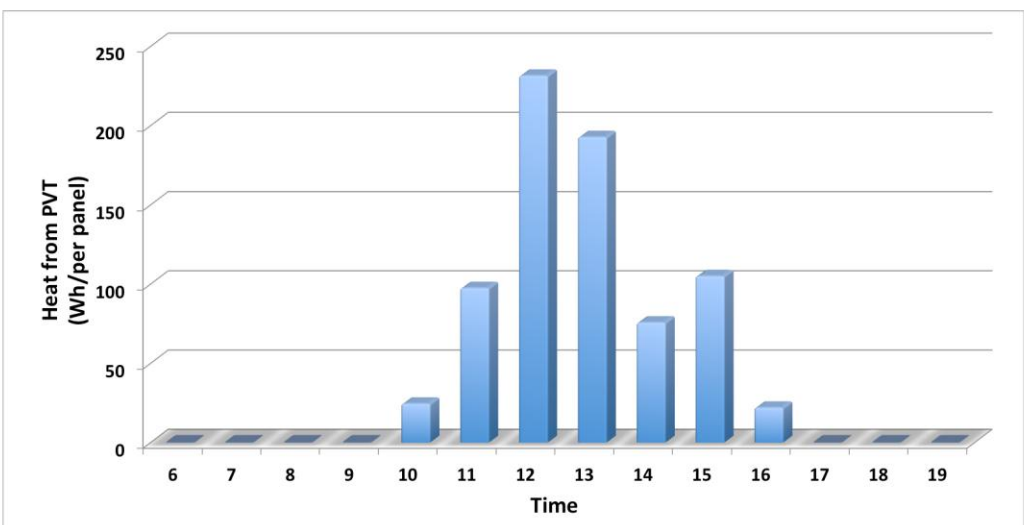


Figure 24 PVT system heat generation in a typical sunny day (May 3th, 2014)

b) Total panel performances comparison

Another goal of the project was to compare the conventional PV and PVT panels to determine whether PVT behaves more favorably overall. It was understood that the combined heat and power of the PVT panel would provide higher overall efficiencies but it was not understood how much more efficiency the PVT panels would provide. Therefore, a summary of both electricity and heat generation illustrating total PVT panel performance is found if Figure 22. Overhead efficiency of PVT panels (green line) is also shown. During our monitoring months, it appears that PVT panel produces at least 70% more energy that a conventional PV panel. In May, it almost provided two times more energy than a PV panel, which reaches 56 kWh for each PVT panels.

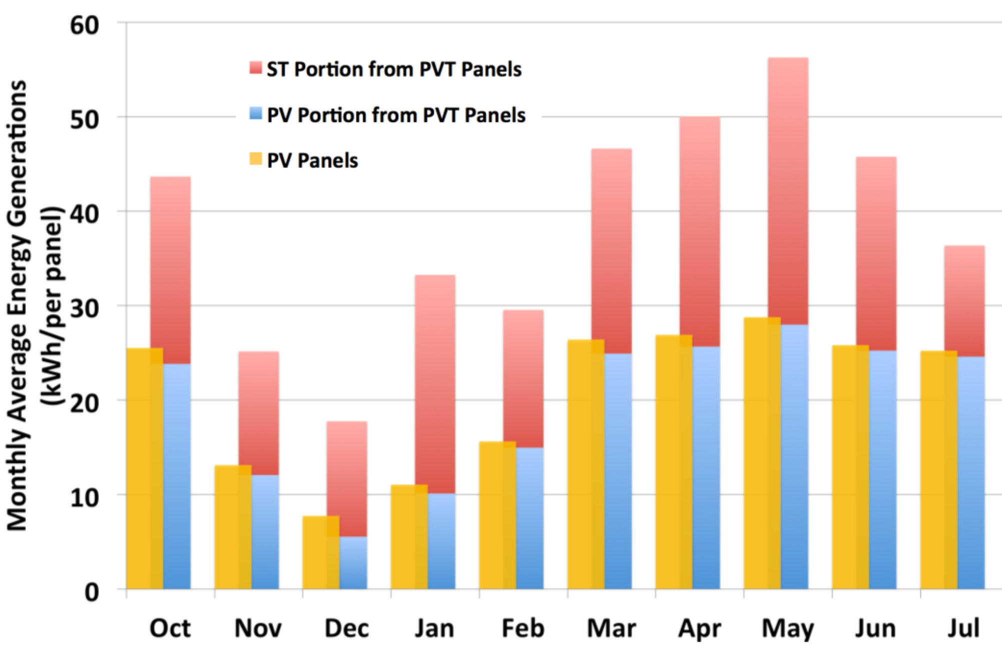


Figure 25 Total panel performances comparison

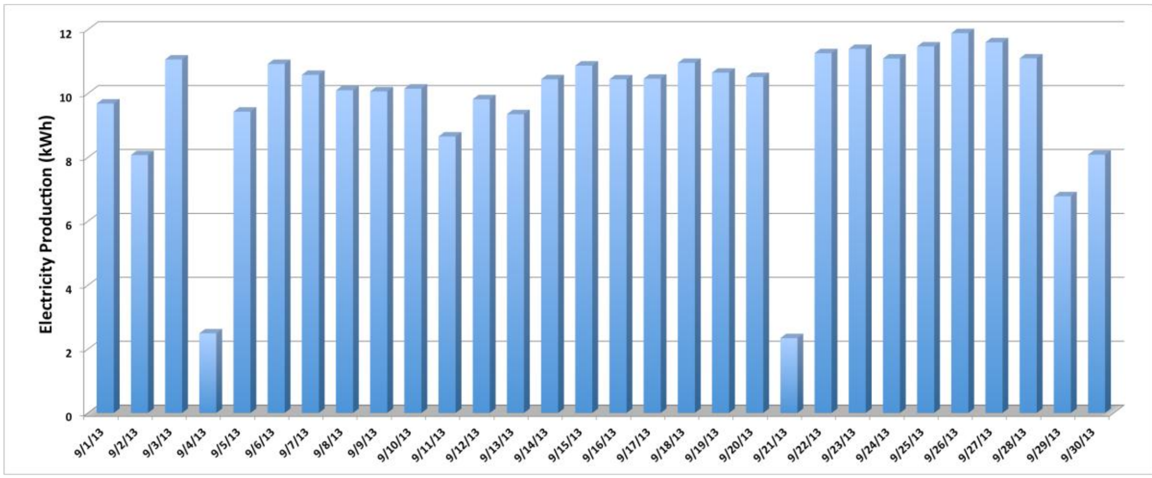
Conclusions

a) Data have been successfully collected and analysis was performed. By the end of July 2014, the PVT system generated a total of 2,890 kWh of electricity, approximately equivalent to 1,515.92 kg of CO2 saving based on lifecycle impact factors. The peak power of system was 2.16 kW.
b) An online user interface was built. Real-time collected data can be seen through the following links: http://www.tigoenergy.com/site.php?aggievillagepvt and http://www.vbus.net/vbus/scheme/id/792
c) Monthly and daily electricity generations of PVT system were summarized. An average 305 kWh electricity was generated every month.
d) In winter, the total heat generations are about 30% to 50% higher than other months, which are about 170 kWh. In contrast, during October, April, May and June, less than 15% heat comes from natural gas heater. The PVT is able to cover over 98% of heat needs in June 2014.

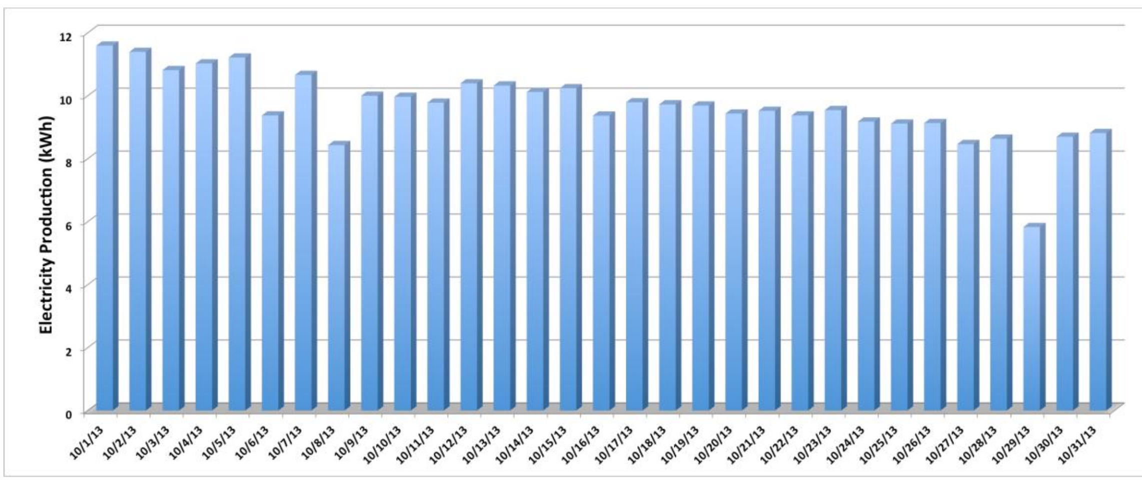
e) Most of the wintertime, the Effective Energy Factor is below one due to the relative low PVT heat generations and high heat consumptions. However, the Effective Energy Factor reaches 2.7 in June, which is almost two times higher than that of February.
f) We also compared the PVT panel and PV panel performances throughout our monitoring months. Surprisingly, the average electric generation for each PVT panel is a few percent lower than a PV panel throughout our monitoring months.
g) We sum up both electricity and heat generation parts to get the total PVT panel performance. During our monitoring months, it appears that the PVT panel produces at least 70% more energy than the conventional PV panel. In May, it almost provides two times more energy than a PV panel, which reaches 56 kWh for each PVT panel.

Supplementary

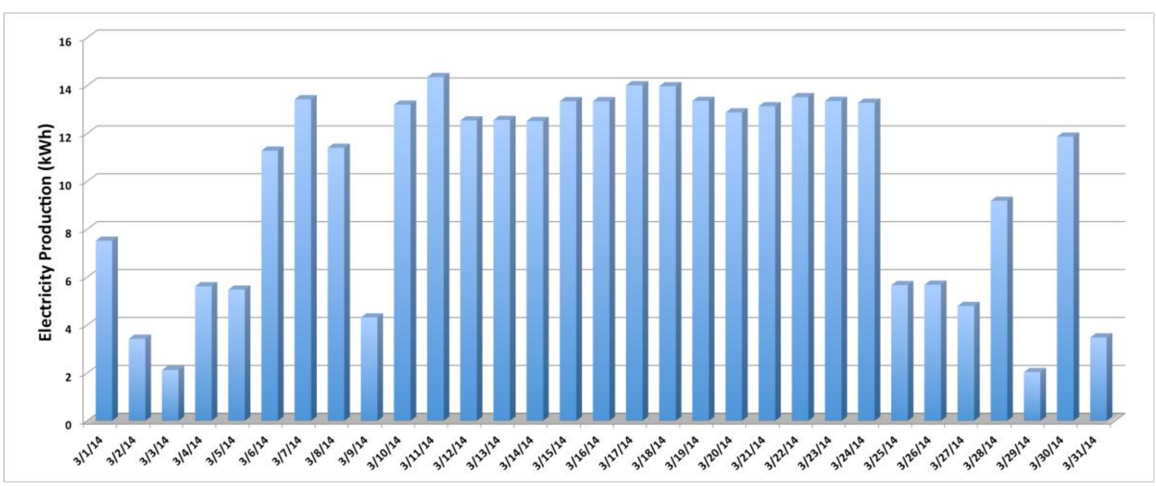
a) Electricity generations for each month



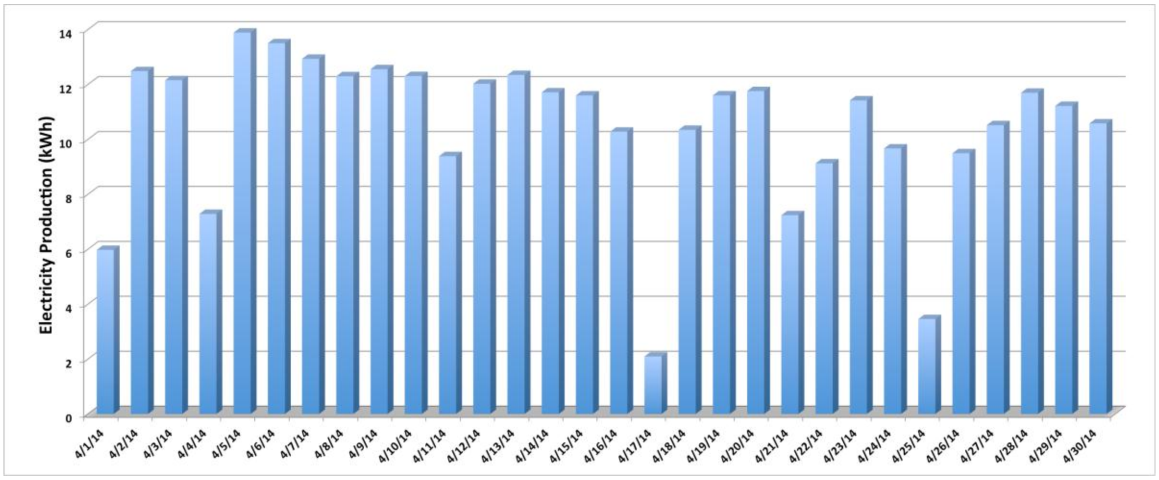
Electricity Generation of PVT System during Sep. 2013



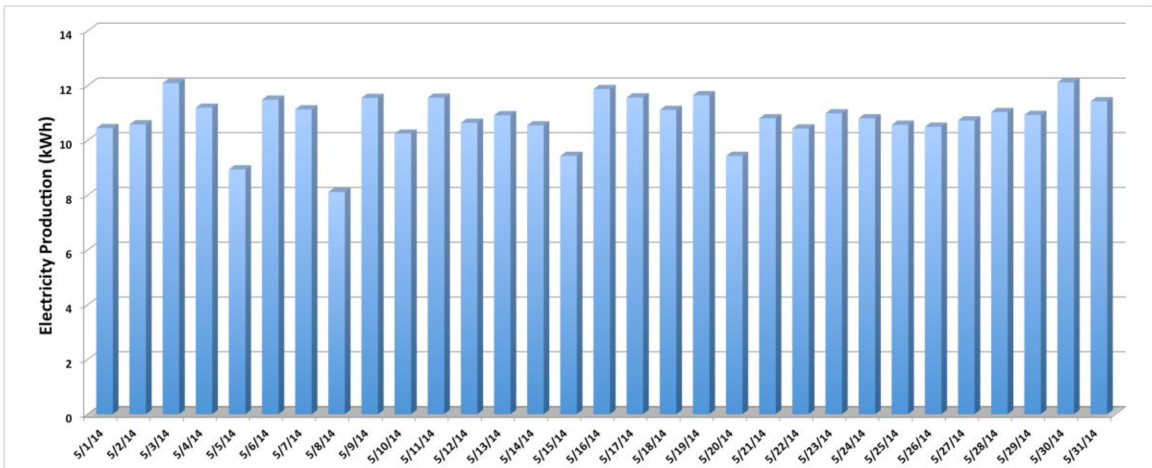
Electricity Generation of PVT System during Oct. 2013



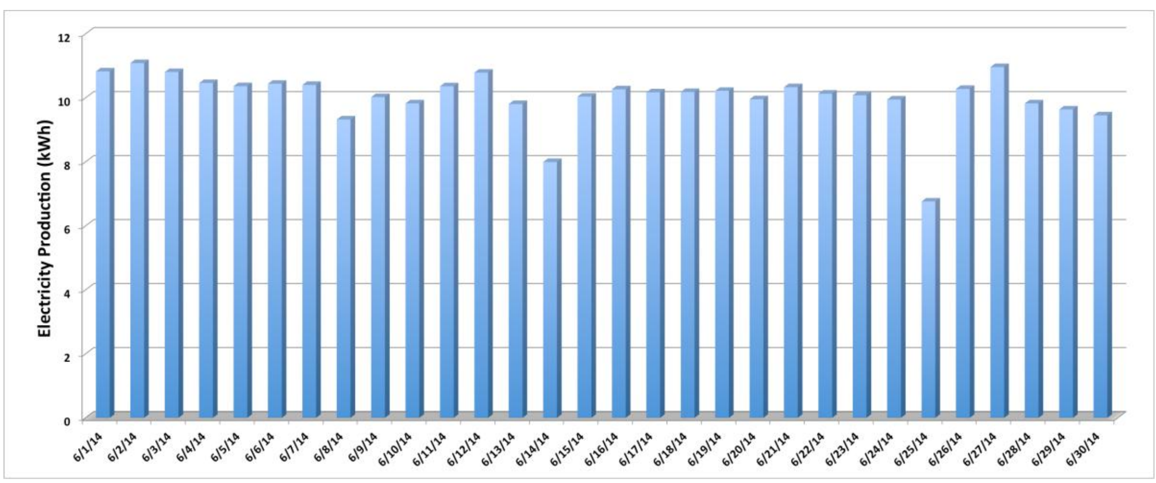
Electricity Generation of PVT System during Mar. 2014



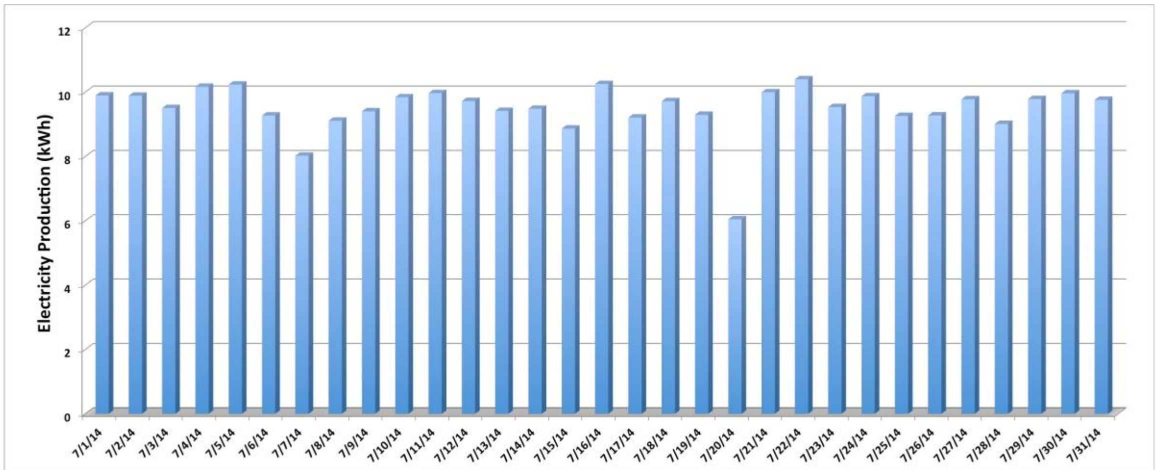
Electricity Generation of PVT System during Apr. 2014



Electricity Generation of PVT System during May 2014



Electricity Generation of PVT System during Jun. 2014



Electricity Generation of PVT System during Jul. 2014