Final Project Report:

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

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Energy Institute

July, 2015
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SUSTAINABLE 2ND CENTURY

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California Public Utilities Commission
California Solar Initiative: Research, Development, Demonstration, and Deployment Program

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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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ACKNOWLEDGEMENTS

The authors and researchers would like to thank the following: Itron, Carmel Partners, CP Construction West, UC Davis Institute of Transportation Studies, Carol Kruger, Ernie Hoftyzer, Roberta Devine, and Helen Barr. Additionally, Gwen Caramanica, CeCe Coyle and Jeff de Ropp provided time and expertise to support the individual project demonstrations in their respective departments. The UC Davis Design and Construction Management team and the UC Davis Plug-in Hybrid & Electric Vehicle Research Center provided valuable services and match funding for the Aggie Smart Home. Wireless Glue Networks Inc., and SMA America whom donated equipment and engineering expertise to the Aggie Smart Home. Lastly Mark Rutheiser and the rest of the UC Davis Real Estate Services team contributed tremendous knowledge and guidance in coordinating the project’s many complex contracts, agreements and construction activities.
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.
# Table of Contents

Abstract 4  
Executive Summary 8  
  Task 1 Demo 1 – Battery Buffered Electric Vehicle Charging Station 8  
    Results 9  
  Task 1 Demo 2 – Single Family Home Energy Storage 10  
    System Performance 10  
  Task 2 – Integration of AMI with Solar PV and other DER Technologies 15  
  Task 3 Demo – 1: Multifamily PVT Integration 16  
  Task 3 Demo 2: Single Family Home PVT Integration 18  
Introduction 22  
Project Goals and Objectives 23  
  Target Area One-Improved PV Production Technologies 23  
    Project Goals 23  
    Project Objectives 24  
Results 25  
  Task 1 Demo 1 – Battery Buffered Electric Vehicle Charging Station Demonstration 25  
    Introduction 25  
    Project Objectives 25  
    Project Summary 25  
    Conclusions and Recommendations 27  
    Public Benefit to California 28  
  Task 1 Demo 2 – Single Family Home Energy Storage 29  
    Introduction 29  
    Project Objectives 30  
    Project Summary 30  
    Key Findings 33  
    Conclusions and Recommendations 34  
    Public Benefit to California 35  
  Task 2 – Integration of AMI with Solar PV & Other DER Technologies 37  
    Introduction 37  
    Project Objectives 37
Project Summary 37
Key Findings 38
Conclusions and Recommendation 41
Public Benefits to California 41
Task 3 Demo 1 – Multifamily PVT Integration 42
Introduction 42
Project Objectives 42
Project Summary 42
Key Findings 43
Conclusions and Recommendations 47
Public Benefit to California 49
Task 3 Demo 2 Single Family Home PVT Integration 50
Introduction 50
Project Objectives 50
Project Summary 50
Key Findings 51
Conclusions and Recommendations 54
Public Benefits to California 55
References 56
Appendix 57
Appendix A – Task 1 Demo 1-Battery Buffered Electric Vehicle Charging Station Demonstration 57
Appendix B – Task 1 Demo 1-Single Family Home Energy Storage 57
Appendix C – Task 2-Integration of AMI with Solar PV & other DER Technologies 57
Appendix D -Task 3 Demo 1- PVT integrations, Demo 2-Single family home PVT integrations 57
List of Figures

Figure 1: System Data Collected First Week of Operation............................................................ 9
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................................................................. 11
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................................................................. 12
Figure 4 House demand data; b PV energy harvested, over 8 months........................................... 13
Figure 5 Net energy. Positive value means PV energy harvested is greater than house demand, negative value is vice versa ........................................................................................................................................ 14
Figure 6: Heat generations from PVT, heat pump, and water heater, respectively .......................... 17
Figure 7: Heat generation ratio from PVT, heat pump, and water heater, respectively........................ 17
Figure 8: Effective energy factor of PVT system each month ............................................................. 18
Figure 9: Heat generations from PVT and natural gas heater, respectively .......................................... 19
Figure 10: Heat generation ratios from PVT and natural gas heater, respectively .............................. 19
Figure 11: Monthly heat delivery, heat loss and effective energy factor of PVT system ..................... 20
Figure 12: Average monthly electricity generations per panel from available data ......................... 21
Figure 13: Solar Powered EV Charging Station Equipped with Battery Storage ............................. 26
Figure 14 Solar Powered EV Charging Station Equipped with Battery Storage ............................. 27
Figure 15: Second use of vehicle battery as stationary energy storage .............................................. 29
Figure 16: System diagram .................................................................................................................. 31
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 ........................................................................................................ 32
Figure 18. Sample of system operation on 12/01/2013.................................................................... 34
Figure 19: Design schematic and photos of the integrated PVT system installed at West Village ........ 45
Figure 20: Monitoring data from October 2013 ................................................................................. 46
Figure 21: Appliance off-peak scheduling savings .......................................................................... 47
Figure 22: Instrumentation plan and photos of the PVT system installed at Aggie Village ................ 52
Figure 23: Electricity Generation of PVT System during September and October ............................ 53
Figure 24: Temperatures and flow rates plotted versus time during October 2013 ............................ 54

List of Tables

Table 1. System operation statistics ................................................................................................. 10
Table 2: Normal vs. non-normal demand data from Aggie Smart Home ........................................ 14
Table 3: List of data logging server ................................................................................................. 31
Table 4: Energy management decision making table ........................................................................ 32
Table 5: System operation statistics ............................................................................................... 33
Table 6: Technical comparison of optimized PV, PV + ST, and PVT + PV arrangements ............... 43
Table 7: The financial evaluations of optimized PV, PV + ST, and PVT + PV arrangements .......... 44
Table 8: Heat flow (kWh) in PVT system during October 2013 ....................................................... 46
Table 9: Heat flow in PVT system during October 2013 ................................................................. 54
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 spirit, 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 to 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 967 kWh 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>
<thead>
<tr>
<th>PV System</th>
<th>Operation Hours (system on)</th>
<th>1483 Hours</th>
</tr>
</thead>
<tbody>
<tr>
<td>(09/2013 to 12/2013)</td>
<td>Energy Harvested</td>
<td>967 kWh</td>
</tr>
<tr>
<td></td>
<td>CO2 Saved</td>
<td>1639 lbs.</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Battery Pack</th>
<th>Peak Usage Shifted</th>
<th>63 kWh</th>
</tr>
</thead>
<tbody>
<tr>
<td>(11/2013 to 12/2013)</td>
<td>Peak Usage Bill Saved (@0.3$/kWh)</td>
<td>18.9 $</td>
</tr>
<tr>
<td></td>
<td>Extended Battery Life</td>
<td>11 Cycles</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Grid Interaction</th>
<th>Electricity Bill Saved (@0.15$/kWh)</th>
<th>145.5 $</th>
</tr>
</thead>
<tbody>
<tr>
<td>(09/2013 to 12/2013)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

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.
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.
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.
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.
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.

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

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 2nd 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 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.
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.
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 $\frac{Q_{PVT}}{Q_{delivered}}$. 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](image)

**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](image)

**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 in 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 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.
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.

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 m² 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 LiFePO4 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.
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.

### Table 3: List of data logging server

<table>
<thead>
<tr>
<th>Data Acquisition Service</th>
<th>Access</th>
</tr>
</thead>
<tbody>
<tr>
<td>1) Aggie Village Home Server via SSH protocol</td>
<td>ssh <a href="mailto:gsf@ucdavisvillage.no-ip.biz">gsf@ucdavisvillage.no-ip.biz</a></td>
</tr>
<tr>
<td>2) Tigo Energy via Tigo live view service</td>
<td><a href="http://www.tigoenergy.com/">http://www.tigoenergy.com/</a></td>
</tr>
<tr>
<td>3) SMA webbox server</td>
<td><a href="http://ucdavisvillage.no-ip.biz:3334/">http://ucdavisvillage.no-ip.biz:3334/</a></td>
</tr>
<tr>
<td>4) Obvius smart panel server</td>
<td><a href="http://ucdavisvillage.no-ip.biz">http://ucdavisvillage.no-ip.biz</a></td>
</tr>
<tr>
<td>5) Battery data server via FTP</td>
<td>FTP://ucdavisvillage.no-ip.biz</td>
</tr>
<tr>
<td>6) Live data webpage</td>
<td><a href="http://ucdavisvillage.no-ip.biz:9000/">http://ucdavisvillage.no-ip.biz:9000/</a></td>
</tr>
</tbody>
</table>

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.
<table>
<thead>
<tr>
<th>Input 1</th>
<th>T</th>
<th>F</th>
<th>N</th>
<th>T</th>
<th>F</th>
<th>N</th>
<th>T</th>
<th>F</th>
<th>N</th>
<th>T</th>
<th>F</th>
<th>N</th>
</tr>
</thead>
<tbody>
<tr>
<td>Input 2</td>
<td>T</td>
<td>T</td>
<td>T</td>
<td>F</td>
<td>F</td>
<td>F</td>
<td>T</td>
<td>T</td>
<td>T</td>
<td>F</td>
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<td>F</td>
</tr>
<tr>
<td>Input 3</td>
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<td>T</td>
<td>T</td>
<td>T</td>
<td>T</td>
<td>F</td>
<td>F</td>
<td>F</td>
<td>F</td>
<td>F</td>
<td>N</td>
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<tr>
<td>Action</td>
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<td>C</td>
<td>F</td>
<td>D</td>
<td>S</td>
<td>D</td>
<td>F</td>
<td>C</td>
<td>C</td>
<td>D</td>
<td>S</td>
<td>S</td>
</tr>
</tbody>
</table>

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.

<table>
<thead>
<tr>
<th>PV System (09/2013 to 12/2013)</th>
<th>Operating Hours (system on)</th>
<th>1483 Hours</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy Harvested</td>
<td>967 kWh</td>
<td></td>
</tr>
<tr>
<td>CO2 Saved</td>
<td>1639 lbs.</td>
<td></td>
</tr>
<tr>
<td>Battery Pack (11/2013 to 12/2013)</td>
<td>Peak Usage Shifted</td>
<td>63 kWh</td>
</tr>
<tr>
<td></td>
<td>Peak Usage Bill Saved (@ $0.30/kWh)</td>
<td>$18.90</td>
</tr>
<tr>
<td></td>
<td>Extended Battery Life (charge cycles)</td>
<td>11 Cycles</td>
</tr>
<tr>
<td>Grid Interaction (09/2013 to 12/2013)</td>
<td>Total electricity Bill Savings (@0.15$/kWh)</td>
<td>$145.50</td>
</tr>
</tbody>
</table>

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 usage 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 accustomed to approving energy storage in homes, the National Electric Code does have guidelines and standards which make permitting and approval fairly straightforward, 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 make 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 hours.

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. More sophisticated 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.

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

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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**

*Simsulations 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 m²) 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).

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**Technical Comparison – 3 bed home**

<table>
<thead>
<tr>
<th>Parameters</th>
<th>PV (w/ heat pump)</th>
<th>2 ST + PV</th>
<th>3 ST+PV</th>
<th>PVT+PV (heat pump)</th>
<th>PVT+PV (boiler)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electricity Produced (≥ 6356 kWh AC)</td>
<td>6709</td>
<td>6351</td>
<td>6468</td>
<td>6272</td>
<td>6562</td>
</tr>
<tr>
<td>Heat Produced (≥ 3775 kWh)</td>
<td>3864</td>
<td>3731</td>
<td>3753</td>
<td>3672</td>
<td>4144</td>
</tr>
<tr>
<td>Electricity used for heat (kWh)</td>
<td>1434</td>
<td>376</td>
<td>259</td>
<td>870</td>
<td>1216</td>
</tr>
<tr>
<td>No. PV panels</td>
<td>23</td>
<td>19</td>
<td>19</td>
<td>10</td>
<td>12</td>
</tr>
<tr>
<td>Area (m²)</td>
<td>28.61</td>
<td>23.64</td>
<td>23.64</td>
<td>12.44</td>
<td>14.93</td>
</tr>
<tr>
<td>No. ST panels</td>
<td>-</td>
<td>2</td>
<td>3</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Area (m²)</td>
<td>-</td>
<td>4.82</td>
<td>7.23</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>No. PVT panels</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>12</td>
<td>12</td>
</tr>
<tr>
<td>Area (m²)</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>15.96</td>
<td>15.96</td>
</tr>
<tr>
<td>Total Area (m²)</td>
<td>28.6</td>
<td>27.64</td>
<td>30.87</td>
<td>28.4</td>
<td>30.89</td>
</tr>
</tbody>
</table>

Table 6: Technical comparison of optimized PV, PV + ST, and PVT + PV arrangements
Financial Comparison – 3 bed home

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

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

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.

<table>
<thead>
<tr>
<th>Unit: kWh</th>
<th>Total Heat Delivery (kWh)</th>
<th>Recirculation Loss (kWh)</th>
<th>Useful Hot Water Delivered (kWh)</th>
<th>PVT Heat Delivery (kWh) (Percent)</th>
<th>Heat Pump Heat Delivery (kWh) (Percent)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Oct. 1st – 31th</td>
<td>994.9</td>
<td>463.5</td>
<td>531.4</td>
<td>567.9 (57%)</td>
<td>99.4 (10%)</td>
</tr>
</tbody>
</table>

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 and domestic hot water demand of the dishwasher, clothes washer, dryer, sinks and showers

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.

![Credits saved by scheduling appliances to off-peak hours](image)

**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](image)

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](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

<table>
<thead>
<tr>
<th>Unit: kWh</th>
<th>PVT Glycol Loop (PVT heat exchanger efficiency)</th>
<th>System delivered</th>
<th>Natural Gas Heater (Fraction)</th>
<th>PVT (Fraction)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Oct. 1st – 30th</td>
<td>71.1 (58.4%)</td>
<td>48.8</td>
<td>7.3 (14.9%)</td>
<td>41.5 (85.0%)</td>
</tr>
</tbody>
</table>

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.