

Photovoltaics for Buildings: New Applications and Lessons Learned

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Photovoltaics for Buildings: New Applications and Lessons Learned

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ABSTRACT

Photovoltaics (PV) for buildings system applications are experiencing exponential growth. This increased activity is the result of building owners becoming more confident with this new technology, designers becoming more comfortable incorporating PV into architectural and building electrical designs, decreasing PV system cost, the heightened public awareness of depleting conventional energy resources, and issues related to power reliability and stability. Usually, these systems meet primary objectives to offset building electrical loads, decrease building electrical demand, or provide continuous power supply during utility grid outages; but because of design flaws, installation errors, or improper maintenance, these systems can perform below the design expectations.

Currently, the performance of the PV systems integrated into the designs of three high-performance commercial buildings is under close observation. The rated capacities of these systems range from 7 kWp to 60 kWp. Two systems are roof-mounted systems and one is a roof-integrated system. All systems are grid-tied and one also doubles as the uninterruptible power supply (UPS) system for the building. These systems provide power to a classroom/laboratory building, a national park visitor center, and a retail store. This paper discusses experiences with these PV systems on commercial buildings and presents energy performance and solutions to resolve design and operation issues.

Introduction

In new construction, these systems should be integrated into the design process and integral to the building function. This integration method is part of the whole-building approach to design. The end result is integration of energy efficiency and renewable energy technologies into the building envelope and systems. To successfully understand and evaluate the complex interactions between potential design solutions, the design team completes detailed quantitative and qualitative analyses using hourly computer simulations. In addition, all pieces of a building design are thought of as a single system from the onset of the conceptual design through the completion of the commissioning process (Torcellini 1999, 2002). The design team must ensure that the building envelope and systems complement one another.

The whole-building design process goes beyond designing a high-performance building that has been optimized for energy efficiency (DOE 2002). A high-performance building also incorporates renewable energy technologies to further offset building electrical and thermal loads. Applying the whole-building design process during the design, construction, and commissioning phases minimized the energy usage of the three buildings discussed in this paper. In all cases, a PV system was an integral component of the overall design.

These buildings integrate energy efficiency and passive solar strategies including daylighting; solar gain load control; natural ventilation cooling; energy-efficient lighting; and energy-efficient heating; ventilating; and air-conditioning systems. The PV system was designed after the energy loads were minimized through good design. Minimizing the building loads increased the value of the PV systems because they were then able to offset a larger portion of the overall building electrical load. Put another way, there is not enough building roof area (at the current efficiencies of PV cells) to meet a significant portion of the typical building's electrical load unless loads are first minimized through very energy efficient design.

Case Studies—Three Commercial Buildings' Photovoltaic Systems

Researchers are currently evaluating the building energy performance, including the performance of the PV systems, of three commercial buildings: the Oberlin College Lewis Center for Environmental Studies in Ohio, the Zion National Park Visitor Center in Utah, and the BigHorn Home Improvement Center in Colorado.

Lewis Center for Environmental Studies

System description. The Oberlin College Lewis Center for Environmental Studies is a two-story, 12,590-ft² (1,170-m²) classroom and laboratory building (Figure 1). Construction was completed and the building was occupied in January 2000. The integrated building design includes daylighting and natural ventilation to offset building lighting and cooling loads, respectively; massive building materials to store passive solar gains; a ground-source heat pump system to meet most remaining cooling and heating loads; an energy management system to optimize the performance of building mechanical and electrical systems; and a system to process building waste water without sending the waste into a conventional sewage treatment plant. The building consumed 33.1 kBtu/ft²/yr (10.5 kWh/m²/yr) from March 1, 2001 through February 28, 2002, less than half of the average educational building use of 79 kBtu/ft²/yr (25 kWh/m²/yr) (EIA 1998).

Figure 1. Lewis Center for Environmental Studies South Façade and PV Array

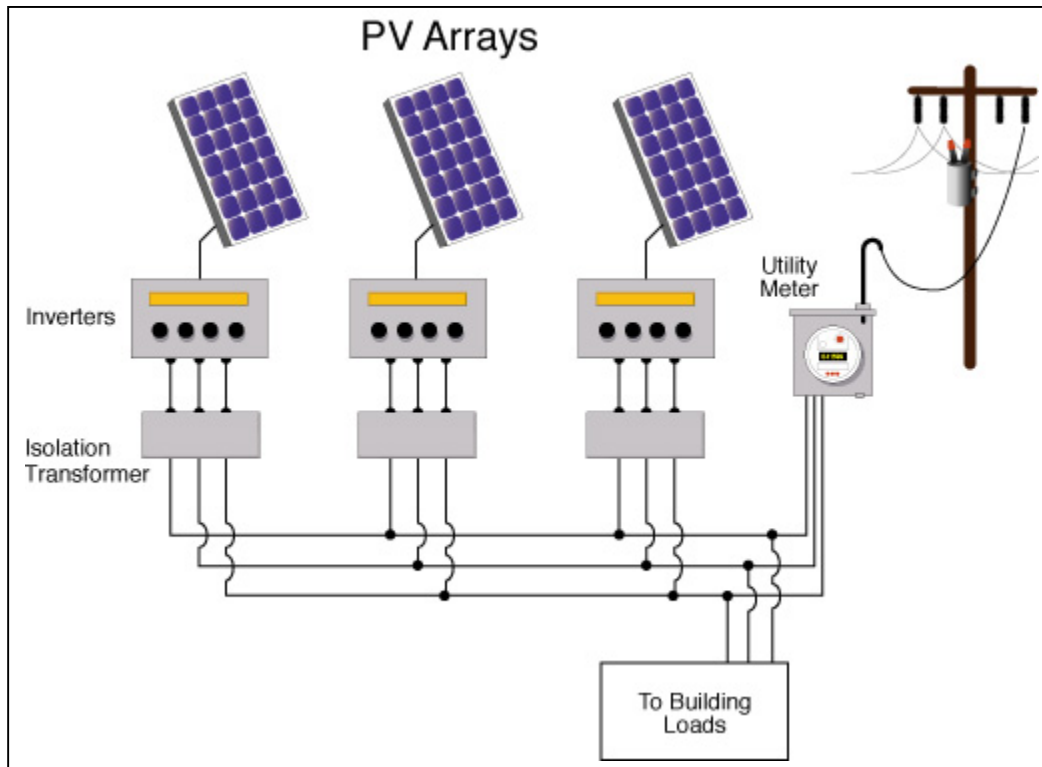


The vision of the Lewis Center was to make the building a net-energy exporter. As a result, the design team first minimized the building's energy intensity by integrating energy-efficient strategies into the whole-building design, and then investigated the potential of a PV system to offset building electrical loads and provide excess power to the local utility grid. The design team covered the building's roof with a PV array. The final PV system design was a 60-kW, 3-phase, grid-tied system with no battery storage.

The PV array is a roof-mounted system integrated into the architectural design of the building. The standoff array tilt follows the roof curvature, which varies from facing 5° north to 20° south. The array comprises 690 85-W single-crystalline modules divided equally into three sub arrays. The sub arrays are configured identically—23 modules per string orientated east to west and 10 strings in parallel from north to south. Each sub array is rated for 19.54 kW (414 V DC and 47.2 A).

Each sub array is linked to its own 15-kW, 3-phase, grid-tied inverter (Figure 2). The inverters are connected to the building's main distribution panel through 15-kVA isolation transformers, one transformer for each of the three inverters. Note that the combined capacity of the inverters is smaller than the rated capacity of the modules to make more efficient use of the inverters. It is rare that the sub array outputs exceed the 15-kW rating of each inverter.

Figure 2. Lewis Center for Environmental Studies PV System Configuration



Excess power produced by the PV system feeds into the utility grid. The local utility does not offer net-metering agreements. The exported power is currently “given” to the utility.

Monitoring equipment to measure the Lewis Center for Environmental Studies PV system performance consists of DC Watt transducers located between each sub array and the corresponding inverter, an AC Watt-hour meter between the system AC disconnect and the building main distribution panel, and an AC Watt-hour meter downstream of the main distribution panel.

Photovoltaic system performance. Figure 3 summarizes the building’s average daily electrical energy loads per month. This information is based on actual performance data. The line representing the percent of the total building energy load met by the PV system indicates that the PV system produced more power than was needed to meet the building’s demands during two months and that more than two-thirds of the building’s electrical loads were offset by the PV system during an additional 4 months.

Figure 3. Lewis Center Normalized Monthly Energy Summary

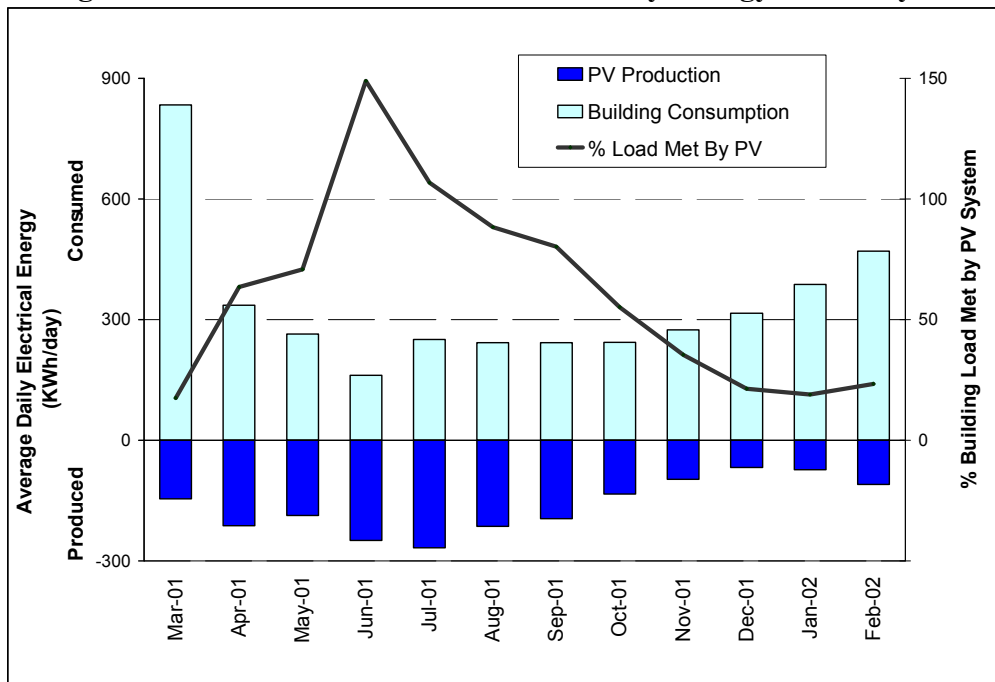


Table 1 summarizes the estimated system production loss and the associated percent of lost production during the year the system was evaluated.

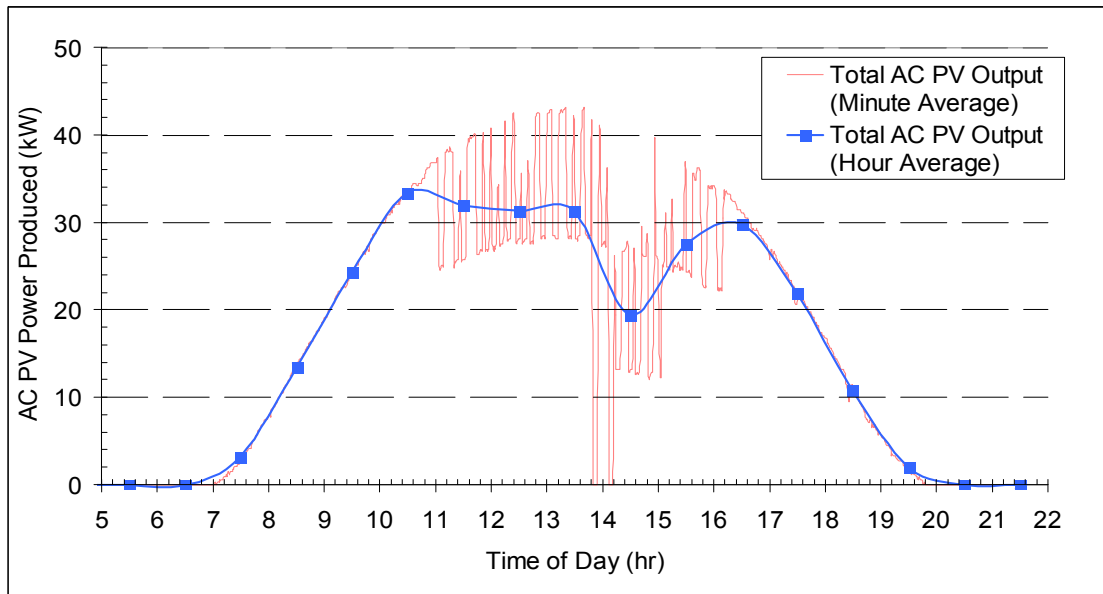
Table 1. Performance Degradation Summary

PV System Performance Degradation Description	Estimated PV Production Lost (kWh)	Percent of Total PV Production
Transformer Stand-By Losses ¹	4363	7.3
Inverter Faults ²	708	1.2
Snow ³	769	1.3
Operation and Maintenance ⁴	879	1.5

1. The PV system inverters and transformers consume power to remain operational. During the night, when the PV array is not producing electricity, these balance of system (BOS) components consume a constant 900 W to 1000 W of utility-provided power.
2. Inverter shutdowns are attributed to the system power output exceeding the inverter maximum allowed power setting during high insolation periods (Figure 4) and to circuit breaker trips caused by high inrush currents required to re-energize the transformers during a loss of power.
3. Accumulated snow does not slide off the array because a large portion of the PV array is nearly horizontal.
4. The inverters were intentionally shut down when current-voltage curve trace measurements and meter verification were conducted. Unscheduled shutdowns occurred as well, such as an incident when the inverters were accidentally shut off during a weekend.

Careful examination of the PV system performance showed that on some days, the inverters would shut down repeatedly for short periods (Figure 4). Daily hourly average power production data appeared to show that a cloud had passed by in mid afternoon, not that there was a system performance issue. The system performance problem was seen when reviewing the minute-by-minute performance data. On cool, sunny days, the PV system supplied more power to the inverter than its capacity. The result was an over-voltage fault. Work is still being done to rectify this situation.

Figure 4. PV AC Power Output for Three Sub Arrays on April 28, 2001



The solution to the problem of snow accumulating on the array is to change the array tilt. This solution is not possible for this building, but should be considered when designing PV systems for other buildings in climates in which snow accumulation is expected. The curved array also reduces system output in two ways: a) part of the array is at a sub-optimal tilt, and b) the inverters are wired such that panels from all tilts feed each inverter. In this configuration the panels at the least favorable angle for each string govern the output of the entire string. Organizing the strings in the longitudinal direction instead of in the transverse direction could have solved this problem. However, a larger inverter would have been needed for the most favorably tilted string.

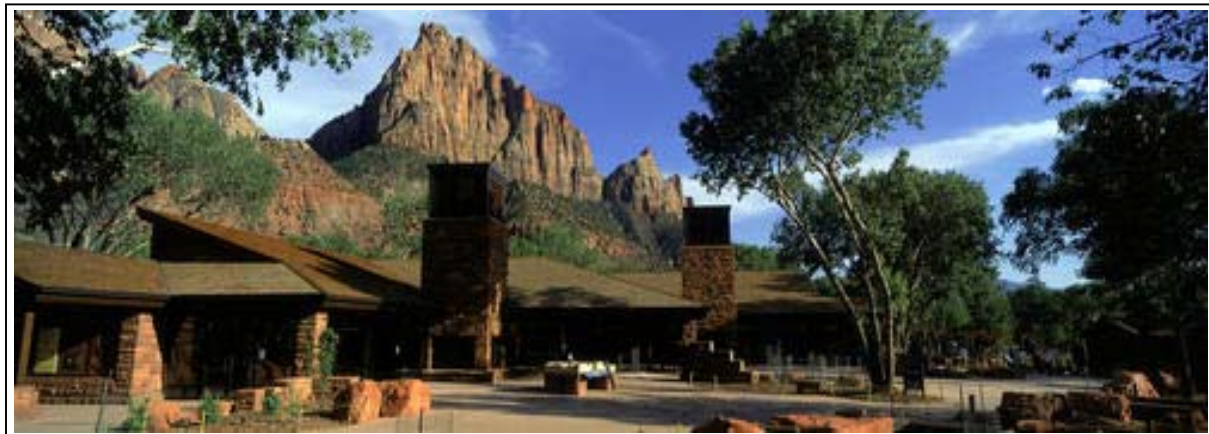
The monitoring period for this PV system is completed so planned system shutdowns will not occur as often in the future. Fewer operation and maintenance system shutdowns will result than during the evaluation year.

Zion Visitor Center

System description. The Visitor Center Complex at Zion National Park in southwest Utah exemplifies the National Park Service's commitment to promote conservation and to minimize the building's impact on the natural environment. The building design incorporates energy-efficient features including daylighting, natural ventilation, evaporative cooling (using cooltowers), passive solar heating, solar load control with engineered overhangs, computerized building controls, and an uninterrupted power supply (UPS) system integrated with the PV system. These features form the integrated energy solution that met the project goals to design a building that costs 70% less for energy than a building designed to meet the minimum requirements of the applicable energy code (USGVT 1995). The building's energy performance has been evaluated since it was occupied in May 2000.

The complex includes a retail bookstore, visitor orientation, backcountry permitting functions, staff support areas, and restroom facilities. It was decided early in the design process to permanently house much of the exhibit space outside under shade structures. The restroom function (Comfort Station) was also separated from the main Visitor Center building to improve pedestrian traffic flows. Landscaping in the outdoor exhibit areas and between the buildings created outdoor rooms, increasing the effective space available for visitor amenities (Figure 5). Two conditioned buildings were constructed: an 8475-ft² (787-m²) main Visitor Center building and a 2756-ft² (256-m²) Comfort Station. The integrated design resulted in a building complex that costs \$0.45/ft² (\$4.84/m²) to operate and consumes 26.9 kBTU/ft²/yr (8.5 kWh/m²/yr). The typical building of this type in 1995 consumed about 76 kBTU/ft²/yr (24 kWh/m²/yr) (EIA 1998).

Figure 5. Zion Visitor Center



The design team anticipated the addition of a future PV system during the design process. The roof on which the system was to be mounted was pitched at a slope to maximize PV performance. Wiring conduit and roof brackets were also included in the

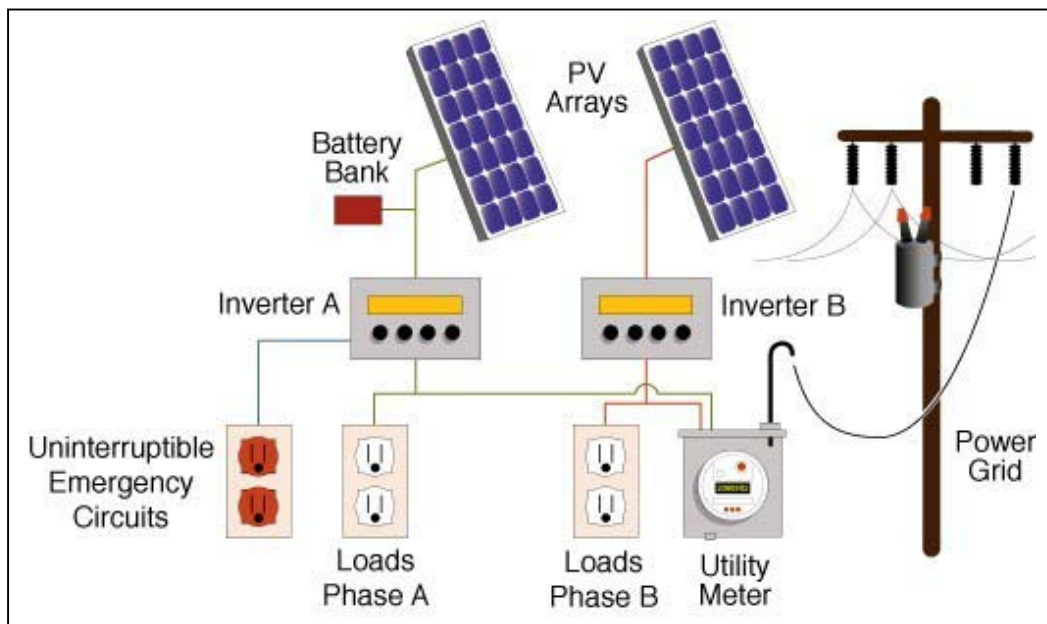
initial design and installed during construction. Unreliable power at the park’s remote location created a need for a building UPS system. The inverter for the UPS system was selected to be capable of receiving power from a PV system. This decision ensured compatibility with a future PV system. Just after completing the building construction, funds became available to purchase a 7.2-kW PV array. Proper advance planning resulted in a quick installation of the PV modules and integration of the PV array with the building structure and electrical system.

The roof-mounted, grid-tied PV system is mounted to the south roof of the Visitor Center nearly flush with the 4/12-pitched roof (18.4°). The array is composed of 24 300-W modules divided equally into two sub arrays. The sub arrays are configured identically—an east array and a west array. Each sub array is rated for 3600 watts and consists of three parallel strings comprising four modules in series to create a 48-V system. Figure 6 diagrammatically shows that one sub array charges the building UPS system batteries and the other is tied directly to the building electrical panel. The UPS system contains 200 Ah of battery capacity.

The UPS system is connected to a set of emergency circuits that power the computer equipment, cash registers, window actuators, cooltower pumps, and telephone switch. During power outages, the computer equipment, cash registers, and telephone switch are the minimum equipment required to continue business functions, and the window actuators and cooltower pumps ensure continued operation of the building cooling system, while the daylighting system provides sufficient light. The result is that the building remains functional during daytime hours, even during the frequent power outages experienced by the Park.

Excess power produced by the PV system feeds into the utility grid. Zion National Park has a net-metering agreement with the local utility. This agreement was the first net-metering agreement to be placed in the state of Utah.

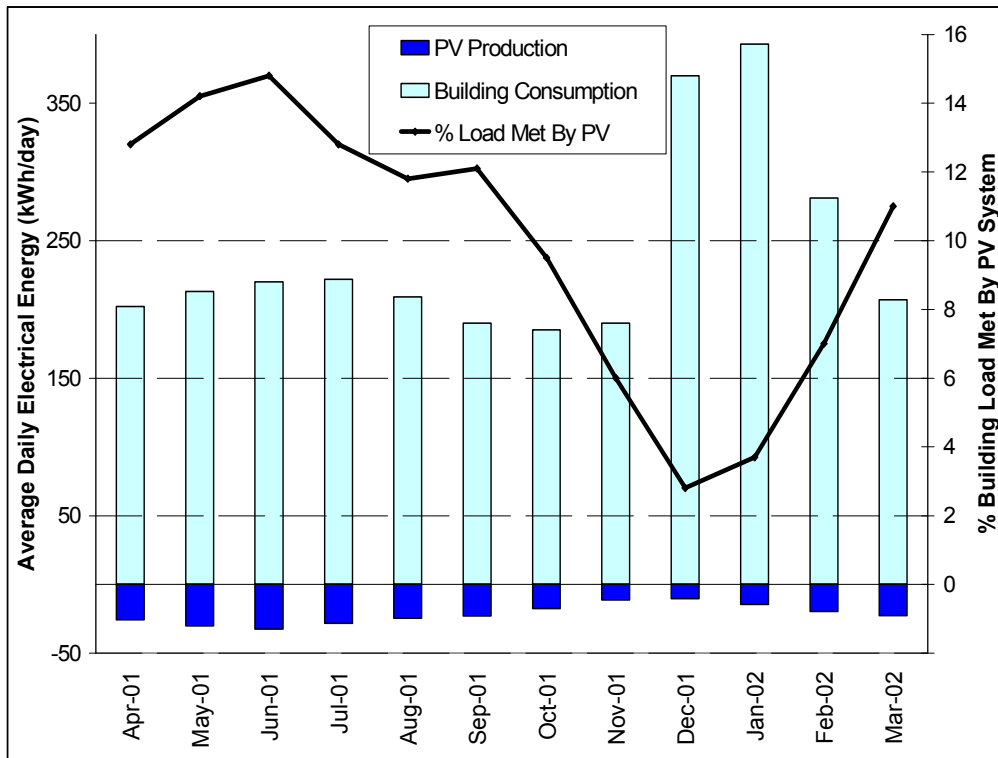
Figure 6. Zion Visitor Center PV System Configuration



Zion Visitor Center PV system monitoring equipment consists of watt-hour transducers measuring the energy of the emergency panel UPS and the power to and from the main distribution bus. This data indicates the net energy produced (or consumed) by the PV system and related components. Energy flows are recorded every 15 minutes.

Photovoltaic system performance. Figure 7 summarizes the building average daily energy loads per month and is based on actual utility data. The PV system offsets approximately 13% of the loads during the spring and summer months. It offsets less than 5% of the load during the winter. Total building loads were higher in the winter because of the heating load.

Figure 7. Zion Visitor Center Normalized Monthly Energy Summary



During the monitored year, the PV system produced a net 7832 kWh (building normalized to 2.4 kBTU/ft²/yr (760 Wh/m²/yr). The PV system offsets about 7% of the total annual energy load. The PV system is a high-value feature to the building even though it displaces a small part of the total energy load. It provides sufficient power for continued business operations during extended daytime grid power outages without relying on power stored in the UPS system battery bank. This system met 40 power outages ranging from 1 second to 8 hours during the monitoring period.

The utility disconnects are often preceded by multiple brownouts and on/off cycles. Even though the inverter has the capability to switch almost instantaneously between utility and PV or battery power, it has had difficulties making this switch because of the erratic power conditions during electrical storms. The result has been some power interruptions on the UPS circuits. Changing the cutout voltages on the inverter has improved, but not eliminated, this situation.

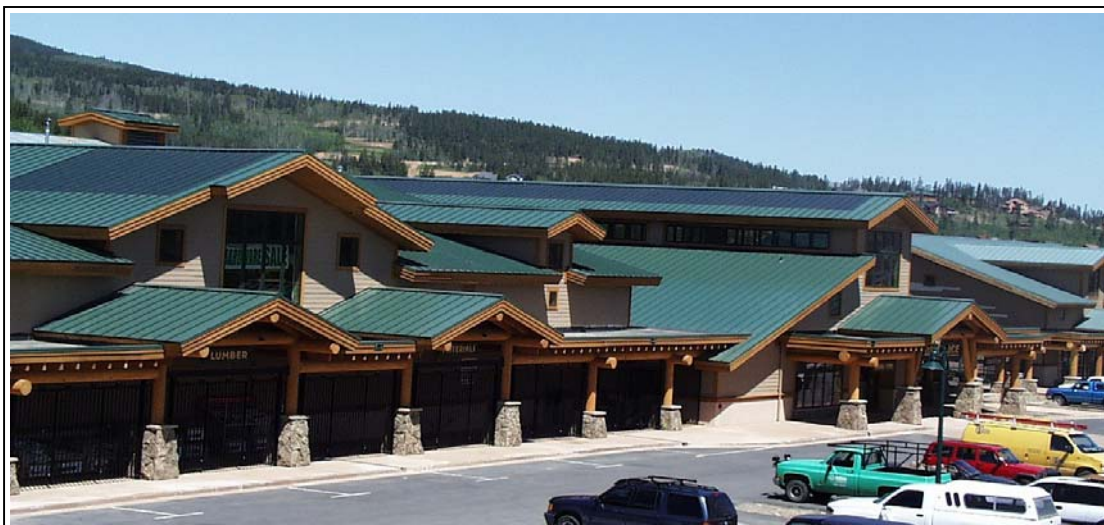
The concept of designing a building to be ready for the addition of a future PV system was quite successful for the Zion Visitor Center project. The PV system performance matched the design expectations. Performance is degraded somewhat because a tree partially shades the west set of modules late in the afternoon; this effect has not been quantified and there is no intention to remove the tree.

BigHorn Home Improvement Center

System description. The BigHorn Home Improvement Center consists of an 18,500-ft² (1720-m²) hardware store retail area and a 22,780-ft² (2120-m²) indoor lumberyard and warehouse. The building is located at 9000 ft (2740 m) above sea level. The business owner was committed to using renewable energy and a building design optimized for energy use. Aggressive daylighting and smart envelope design in the retail area allow the use of natural ventilation to meet all the cooling loads. The daytime lighting load in the warehouse is almost entirely met by daylighting except during very cloudy periods. The electric lighting load in the retail area is further reduced by cluster arrangements of eight compact fluorescent lamps per fixture. The lamps can be turned on in pairs to provide five levels of lighting. The heating system in the retail area is a hydronic radiant floor system with natural gas-fired boilers. An energy management system controls the lights, natural ventilation, and heating system to optimize performance. The warehouse is partially heated by a transpired solar collector.

An 8.88-kW, thin-film PV system is integrated into the standing-seam metal roof (Figure 8). The roof-integrated PV system is a durable and practical solution for buildings in this alpine climate because of the high amount of snowfall and ice buildup on the roof. The system consists of 18 120-W modules and 105 64-W modules.

Figure 8. BigHorn Home Improvement Center

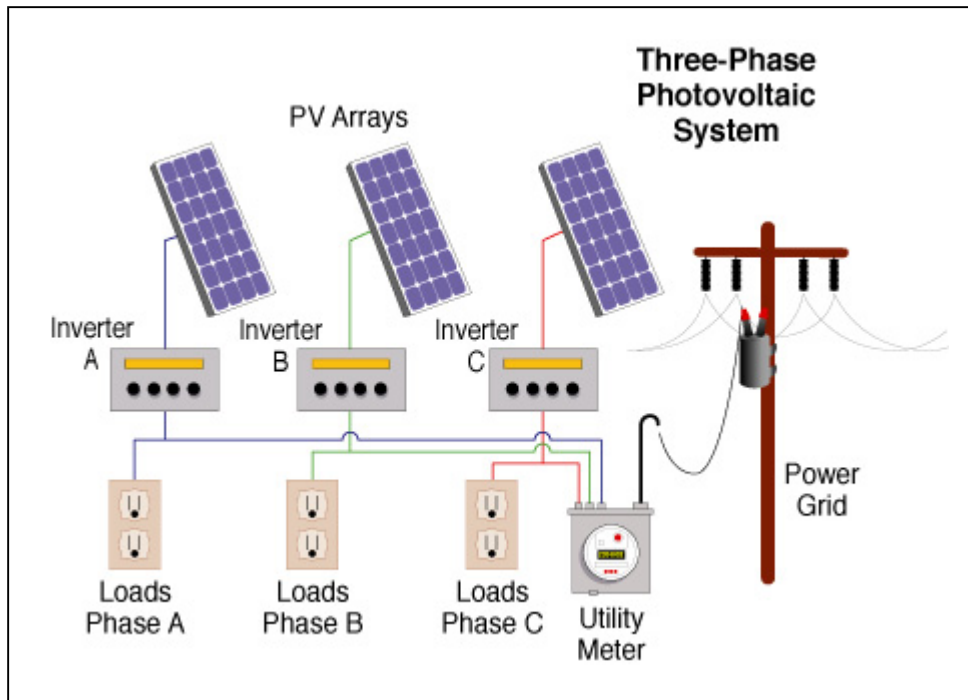


Strings consisting of 3 modules in series are wired in parallel to form three arrays, each having similar output. Originally, the power output for all three arrays was nearly identical. To accomplish this equal power output, two arrays (the Phase-B and Phase-C arrays) each consisted of 48 64-W modules and the third array (the Phase-A array) was

configured with 18 120-W modules and 9 64-W modules. Later, the arrays were rewired so that the 120-W modules make up the Phase-A array and the 64-W modules are divided almost evenly between the Phase-B and Phase-C arrays.

Each array is connected to its own inverter and each inverter is tied to a separate phase of the three-phase electrical system (Figure 9). The inverters have no internal battery back up, so an external circuit consisting of four 12-V batteries is used to maintain the inverter memories at night. The battery backup is tied to the Phase-A inverter.

Figure 9. BigHorn PV System Configuration

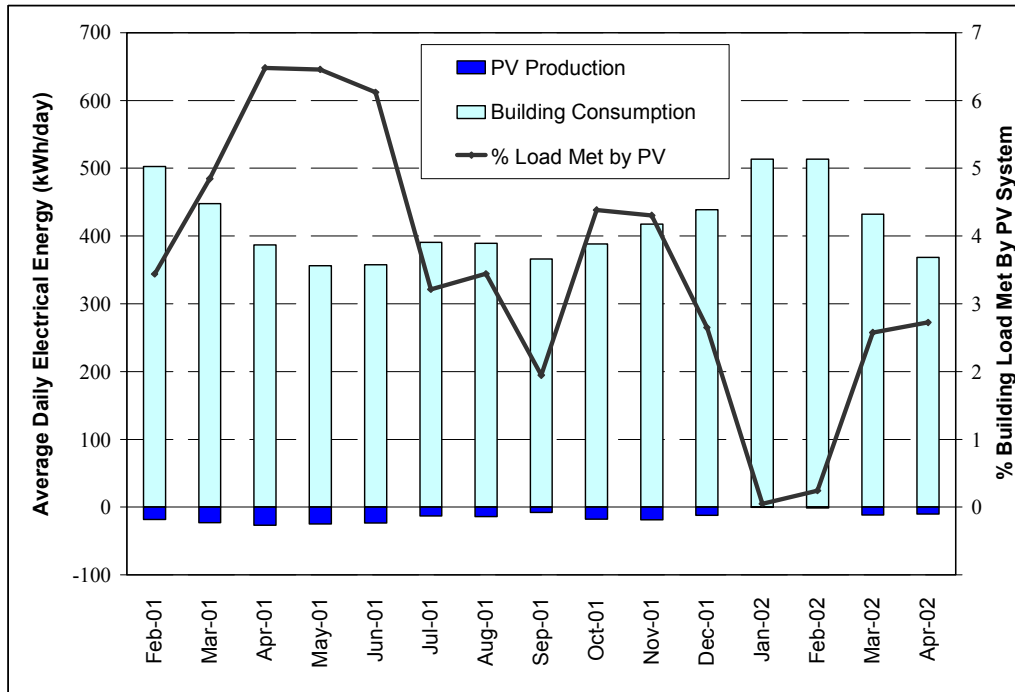


The major electrical loads are monitored with current transformers and watt-hour transducers, which are connected to a dedicated data logger and the building energy management system. Data is recorded at 15-minute intervals.

Photovoltaic system performance. During system installation, the roofing crew damaged all the lower wattage modules (105) because they penetrated the junction boxes of every module as they secured the modules to the roof. The roofing crew was familiar with standing-seam metal roofs, but had never installed PV-integrated standing-seam roof modules. It is standard practice for this particular crew to penetrate standing-seam roof modules in three locations, equally spaced along the top of each module, when attaching them to the roof. The crew was told that installing PV-integrated standing-seam modules was the same as installing standing-seam modules without PV. The lack of guidance given to a roofing crew unfamiliar with the product resulted in damaging the PV modules to the point that they could not provide power to the building. The damaged modules were replaced shortly after the damage was discovered.

Figure 10 summarizes the building average daily electrical energy loads and PV system production per month. The percent of the total building electrical load met by the PV system peaked around 6.5% in April 2001.

Figure 10. BigHorn Center Normalized Monthly Energy Summary



The inverters do not have maximum power point (MPP) tracking ability. Cell temperature affects the output of the amorphous-silicon PV modules only slightly; however, the peak power-point voltage drops as the cell temperature rises. Because the modules are integrated into the insulated roof of the BigHorn Center, there is little heat loss off the backside of the modules and the cell temperatures can exceed 140°F (60°C). The float voltage on all three inverters was fixed at 50 VDC.

A battery back-up circuit is tied to the Phase-A inverter to supply power to the inverters during the night so that they do not lose their memory. This external battery backup required the Phase-A inverter to be set at 50 VDC. The Phase-B and Phase-C inverters were also set at 50 VDC to match the Phase-A setting.

The 50-VDC inverter settings did not match the arrays' maximum power points. In addition, the Phase-A array MPP trends differed from that of the Phase-B and Phase-C arrays because the Phase-A array configuration consisted of both 120-W and 64-W modules. A system analysis performed in May 2001 showed that the system was losing 30%-40% of its potential output because of the lack of MPP tracking and because of the way in which the modules were wired together.

The first solution to these problems was to rewire the arrays. The Phase-A array was rewired to consist only of 120-W modules and the 64-W modules were divided between the Phase-B and Phase-C arrays. The phase-A inverter was kept at 50 VDC to match the battery circuit requirement. The Phase-B and Phase-C inverters were set to 40

VDC to more closely correspond to the MPP of these arrays on clear sunny days. The changes were so successful that the DC current on Phase-B and Phase-C arrays approached the rating of the DC circuit breaker of the inverters (60 A).

A fault in the battery back-up circuit results in nighttime power loss to the Phase-B and Phase-C inverters. When this fault occurs, the inverters lose their memory and fail to start up again the following morning and a manual restart is necessary. The especially poor performance in January and February was because the Phase-B and Phase-C inverters were offline most of the time; only the Phase-A array provided power to the building. Cloudy days and snow partially covering the Phase-A array further reduced module performance. Because of the roof design, snow buildup is more of a problem for the Phase-A array than the Phase-B and Phase-C arrays.

The optimal solution to improve the PV system performance is to replace the inverters with dedicated grid-tied units having MPP tracking capability. It is estimated (conservatively) that the system will perform 30% better after installing new inverters. This change is planned for the near future.

Conclusions

Design teams for the three commercial buildings described in this paper followed a whole-building design process to optimize building energy performance and integrate PV into their building's architectural and energy designs. The design objective was to maximize the PV power contributions to the buildings. Through detailed monitoring and evaluation of the PV system performance and the overall building energy performance, researchers successfully identified why the problems occurred and implemented or proposed solutions to the problems. In one of the examples discussed in this paper, the PV system produced more power than the building electrical requirements during part of the year. Table 2 summarizes the issues discussed in this paper. Other lessons learned are:

- Planning for a future PV system during the building design phase of the Zion Visitor Center allowed for a smooth addition of the PV system. This experience shows that a PV system can be integrated into a building some time after the building is constructed if proper planning for that PV system occurs during the design phase.
- The Zion PV system is large enough to maintain normal business operations during extended grid-power outages. As a result, the PV system is of great value to the building operators, even though it offsets a small part of the building's annual electrical load.
- The Lewis Center PV array covers the entire roof of the building. The building design minimizes energy performance, yet the annual building electrical load is still larger than the annual PV system production. More research is needed both in optimizing building energy performance and PV system performance before construction and operation of a zero-energy commercial building.
- Designers minimized the energy consumption for all three buildings. As a result, the PV systems offset greater portions of the annual electrical loads for each building than they would have for buildings that were not high performance.

Table 2. Performance Degradation Summary

Issue	Description	Solution
System design/ integration issues		
Mismatch between PV system output and inverter capacity.	PV system output exceeds the inverter's maximum power setting (inverter faults on over input capacity)	Specify inverters that closely match the anticipated PV system output. Most inverters can function when power input exceeds the inverter rated input by up to 25%. Verify allowed settings with inverter manufacturer.
Mismatch between selected inverter and system type	The inverters specified for a grid-tied PV system did not have MPP tracking capabilities and memory retention.	Ensure that the selected inverter matches the system type. An inverter meant for off-grid applications may not work well for a grid-tied application, and vice versa. If a UPS system is to be charged by a PV system, ensure that the UPS system inverter is capable of accepting power input from a PV system.
Mismatch of modules in an array	Modules rated with different power outputs were wired together in one array	Whenever possible, modules comprising a PV array should have equal power output ratings.
Strings with panels at different altitude angles.	The panels at the least favorable angle govern output for the entire string.	Design for optimal orientation. Organize strings such that panels of similar orientation are strung together.
Snow accumulation	Snow accumulated on the PV array results in decreased system performance	Evaluate snow accumulation potential during the design phase. Design the PV array to minimize snow accumulation and ensure that accumulated snow can easily slide off. Account for decreased power production because of accumulated snow when estimating annual power production.
Shaded array	Landscaping or other obstruction shades part of the array, decreasing system performance	Evaluate array shading potential during the design phase. If potential shade obstructions cannot be removed or relocated, then redesign the array so that it is not shaded. Account for decreased power production because of shade when estimating annual power production.
Misinformed system installers	Roofing installers were not aware that their practices damaged the roof-integrated PV modules	Understand the standard practices trades people installing PV system components use to complete their work. Clearly communicate how these practices may need to be adjusted when installing PV system components.
System Operation Issues		
BOS parasitic losses	PV system components draw power, decreasing the PV system usable power output during the day and using grid-supplied power during the night	Minimize the nighttime parasitic losses by maximizing the transformer efficiencies. Investigate using a timer/photocell to shut off BOS components that draw power. Daytime parasitic losses are part of the cost of operating a PV system. Account for these parasitic losses. Select BOS components to minimize these losses.
System shutdowns	Planned (e.g., for maintenance) and unplanned system shutdowns, usually resulting from inverter shutdowns	Plan in advance for maintenance shutdowns and try to complete as many maintenance procedures as possible during one shutdown. Carefully evaluate the PV system performance to identify reasons for unplanned shutdowns. Plan shutdowns during nighttime hours.

The buildings described in this paper reflect the problems and solutions commonly experienced with PV systems. These examples demonstrate the importance of integrating PV system design into the whole-building design process and the necessity to thoroughly evaluate the as-built PV system to maximize its performance. PV systems are ready for prime time and should be a standard consideration during a building design process. However, designers should understand the effects of design, integration, and

operation problems, such as those described in Table 2, and account for unavoidable design and performance imperfections when estimating anticipated system output. It is important not to overstate expected performance. The experiences gained from studying the three buildings described in this paper exemplify the need to continue careful evaluation of PV systems.

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13. ABSTRACT (<i>Maximum 200 words</i>) Photovoltaics (PV) for buildings system applications are experiencing exponential growth. This increased activity is the result of building owners becoming more confident with this new technology, designers becoming more comfortable incorporating PV into architectural and building electrical designs, decreasing PV system cost, the heightened public awareness of depleting conventional energy resources, and issues related to power reliability and stability. Usually, these systems meet primary objectives to offset building electrical loads, decrease building electrical demand, or provide continuous power supply during utility grid outages; but because of design flaws, installation errors, or improper maintenance, these systems can perform below the design expectations. Currently, the performance of the PV systems integrated into the designs of three high-performance commercial buildings is under close observation. The rated capacities of these systems range from 7 kWp to 60 kWp. Two systems are roof-mounted systems and one is a roof-integrated system. These systems provide power to a classroom/laboratory building, a national park visitor center, and a retail store. This paper discusses experiences with these PV systems on commercial buildings and presents energy performance and solutions to resolve design and operation issues.				
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