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Analyzing Two Federal Building-Integrated Photovoltaic Projects Using *ENERGY*-10 Simulations

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ANALYZING TWO FEDERAL BUILDING INTEGRATED PHOTOVOLTAICS PROJECTS USING *ENERGY-10* SIMULATIONS

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ABSTRACT

A new version of the *ENERGY-10* computer program simulates the performance of photovoltaic systems, in addition to a wide range of opportunities to improve energy efficiency in buildings. This paper describes two test cases in which the beta release of *ENERGY-10* version 1.4 was used to evaluate energy efficiency and building-integrated photovoltaics (BIPV) for two Federal building projects: a 16,000-ft^2 (1,487 m^2) office and laboratory building at the Smithsonian Astrophysical Laboratory in Hilo, Hawaii, and housing for visiting scientists [three 1400-ft^2 (130 m^2) and three 1564-ft^2 (145 m^2) houses] at the Smithsonian Environmental Research Center in Edgewater, Maryland. The paper describes the capabilities of the software, the method in which *ENERGY-10* was used to assist in the design, and a synopsis of the results. The results indicate that *ENERGY-10* is an effective tool for evaluating BIPV options very early in the building design process. By simulating both the building electrical load and simultaneous PV performance for each hour of the year, the *ENERGY-10* program facilitates a highly accurate, integrated analysis.

INTRODUCTION

The U.S. Department of Energy (DOE) Federal Energy Management Program (FEMP) supports agencies in their efforts to make new Federal buildings energy efficient and to maximize the use of renewable energy. The *ENERGY-10* computer program has proved useful in setting goals and evaluating performance in the design of small (10,000 ft^2 or less) Federal buildings. The DOE Office of Building Technology, State and Community Programs, the National Renewable Energy Laboratory (NREL), Lawrence Berkeley National Laboratory (LBNL), and the Sustainable Buildings Industry Council (SBIC) have released a beta test version of *ENERGY-10*—version 1.4. This new version now has the capability to evaluate grid-tied photovoltaic installations as well as energy efficiency opportunities in buildings.

NOMENCLATURE

Aspect ratio: East/west dimension divided by north/south dimension

Solar heat gain coefficient (SHGC): Fraction of incident solar power transferred through a window as heat and light

ENERGY-10 AND TRNSYS COMBINED

ENERGY-10 is a software design tool for building energy analysis [1]. In version 1.4, a new feature simulates the performance of a photovoltaic (PV) system integrated into the envelope of a building. It allows the user to study hourly interactions between the building load and the PV array. The program distinguishes wall-integrated, roof-integrated, window-integrated, and standoff systems. The PV system description can include up to four building-integrated arrays and one standoff array, all fed through a single inverter. At present, only grid-connected systems (no battery storage) are modeled.

ENERGY-10 initially creates an “autobuild shoebox” based only on size (square footage), location, utility rates, type of heating and cooling system, and number of floors. The shoebox is useful for setting goals and strategizing before the design begins. As the design progresses, details are added and the shoebox is transformed into the evolving design. This provides many other capabilities to building designers, including making investigating the use of PV much easier and eliminating initial hurdles; providing comprehensive graphical output [2]; and having the ability to accommodate future technology, such as new PV products integrated into building elements or thin-film window coatings. The program integrates hourly analysis of thermal and electric systems; hourly schedules for lights, plug loads, etc.; hourly variable heating, ventilating, and air-conditioning (HVAC) loads responding to weather; hourly variable light dimming due to daylighting; and hourly PV system energy delivery [3].

The hour-by-hour simulation of PV performance in *ENERGY-10* uses the TRNSYS simulation program, written at the University of Wisconsin. *ENERGY-10* creates inputs and a weather file for TRNSYS and reformats the hourly output for study within *ENERGY-10*. The hourly electrical load fed to TRNSYS is the result of the thermal simulation, accounting for all weather-driven effects and occupant schedules, including time-varying HVAC loads and light dimming due to daylighting. In a two-step process, PV electrical energy is not subtracted from the thermal energy balance of the outermost layer but can be approximated by reducing the absorptivity of the outer layer where the BIPV is located by the PV efficiency (typically 10%).

Whereas synthetic loads have been used in other programs, the new PV capability helps *ENERGY-10* users evaluate how a PV system will offset realistic building electrical loads. If the PV system is integrated into the building skin, there will be thermal effects that are accounted for by changes in the building description, which is passed to the *ENERGY-10* thermal simulation engine. Thus, results produced by this tool show the overall consequences of building electrical load requirements before and after the PV system contribution, PV system output, and when and how much of the PV output is available to be sold back to the utility. These results are available as annual summaries and as typical monthly and hourly plots. Plots provide views of the 8,760 hours of data for 13 electrical variables that include disaggregated building loads (heating, cooling, lights, fan, plug loads) and PV system variables such as PV system output, PV to the building, and PV sellback.

The TRNSYS PV model [4] predicts the current-voltage (I-V) behavior of a flat-plate PV module, given the solar irradiance and ambient temperature. Arrays are defined as series-parallel connections of modules, with a tilt angle and orientation. The user can select detailed module descriptions from a library or define new module types. The PV balance-of-system is assumed to include an inverter operating as defined by a 10-point conversion efficiency curve. A simple dispatch strategy is applied: building load is offset by PV output and any excess is counted as sellback to the grid.

SMITHSONIAN ASTROPHYSICAL OBSERVATORY

The Smithsonian Astrophysical Observatory (SAO) Base Facility will include about 16,000 usable square feet of electronics laboratories, offices, and support space in the University of Hawaii’s Hilo Science Park. Figures 1 through 3 are illustrations of the concept design, dated January 2, 2001. Key assumptions consistent with standard ASHRAE 90.1 [5] were that lighting power is 1.78 W/ft^2; exterior walls are 6-in. steel frame; shear walls are 8-in. block; glazing is double-pane, aluminum frame with thermal break; floor-to-ceiling height is 14 ft on both floors; air conditioning is Package Terminal Air Conditioning; and occupancy is 19 persons upstairs and 12 persons downstairs. Based on utility bills from Hawaii Electric Light Company for other Smithsonian facilities in the area, the energy cost was taken as \$0.177/kWh and the demand cost as \$5.740/kW.

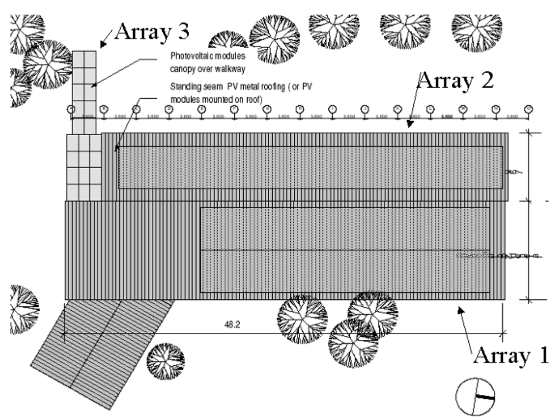

Figure 1. Plan view of SAO with PV integrated into standing-seam metal roof and walkway canopy.

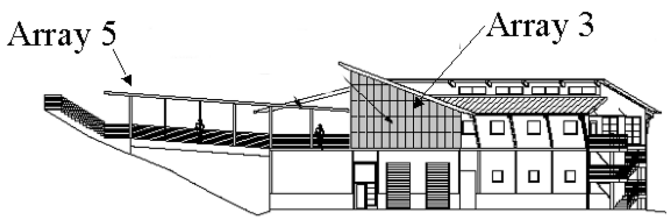

Figure 2. South elevation views of SAO with PV integrated into curtain wall glazing and walkway canopy.

Several recommendations to improve the energy efficiency of the building were evaluated both individually and in combination. The measures considered were these:

- Reduce installed lighting capacity from 1.78 W/ft^2 to 1.0 W/ft^2 through efficient equipment and architectural design of the lighting system.
- Modulate artificial lighting in response to available daylight through windows. Two control strategies were evaluated:
    - Continuous dimming
    - Three-step switching.
- Increase cooling system efficiency from energy efficiency rating (EER) 8.1 to EER 11.5.
- Use programmable thermostat to set up the cooling set temperature from 72°F (24°C) to 87°F (30°C) during unoccupied periods (setbacks from 5°F to 25°F were considered).
- Replace double-pane glazing [U = 0.49 Btu/hrft^2°F (2.78 W/m^2°C), SHGC = 0.77] with selective double pane glazing [U = 0.28 Btu/hrft^2°F (1.59 W/m^2°C), SHGC = 0.37].

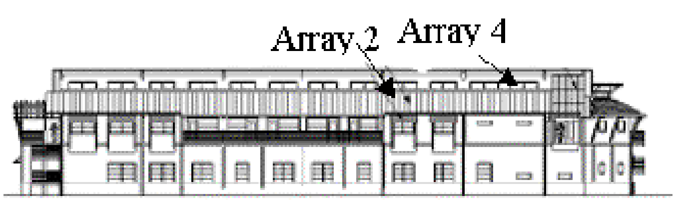

Figure 3. West elevation view of SAO with PV integrated into standing seam metal roof and curtain wall.

Taken together, these recommendations could reduce annual energy use from 1,563,001 kBtu/year (458 MWh/year) at a cost of $88,585/year to 970,576 kBtu/year (284 MWh/year) at a cost of $55,222/year. Energy use per square foot of floor area is reduced from 91.0 to 56.5 kBtu/ft^2/year (287 to 178 kWh/m^2/year).

After the energy efficiency measures were incorporated, photovoltaics were considered to provide electric power. Because of the uniform solar resource and high avoided cost of energy, Hawaii represents an excellent opportunity to demonstrate photovoltaics, which convert sunlight directly to electricity. Insulating value is not significant for the thin roof and window BIPV materials considered here. Photovoltaic devices would be integrated into architectural elements of the building, such as the roof, curtain wall, and walkway canopy:

- *Array 1 and Array 2:* The large expanse of roof facing east and west is the location for standing-seam metal roofing with Unisolar ASR128 modules. Each module is 16 in. wide (metal pan width) and 18.3 ft long. Array 1 consists of two rows of modules on the wider east roof for a capacity of 22.5 kW. Array 2 consists of one row on the west roof with a capacity of 15.1 kW. Each module is 48 V dc (open circuit) and they can be wired in series in groups of 12 to produce 576 V dc (open circuit). The operating voltage would be 33 V dc per module for 396 V dc operating voltage.
- *Array 3 and Array 4:* The south (Array 3) and west-facing (Array 4) glass curtain walls are the location for ASE 30-DG-UT panels with partial transmissivity. The glass panels, 1.2 m long by 0.6 m wide, have a power output of 27 W each. Each has an open-circuit voltage of 60 V dc, and they can be wired in series in groups of 10. Array 3 is 1.1 kW and Array 4 is 0.4 kW.
- *Array 5*: The walkway canopy is covered with ASE 300 modules 1.28 m wide and 1.89 m long, each rated at 300 W. Each has an open-circuit voltage of 60 V dc; they can be wired in series in groups of 10.

Table 1. ENERGY-10 report showing detail on each of the 5 BIPV arrays on the SAO.

Total PV Array Area, ft² / m²	8264 / 768
Total PV Rated Output, kW	45.4
Total Inverter Rated Capacity, kW	105
Array 1	
BIPV Type / Rated Power, kW	Roof-Integrated / 22.5
No. of Modules	176
Area (ft^2) /Azimuth /Tilt	4334 / 90 / 20
Array 2	
BIPV Type / Rated Power, kW	Roof-Integrated / 15.1
No. of Modules	118
Area (ft^2) /Azimuth/Tilt	2906 / 270 / 20
Array 3	
BIPV Type / Rated Power, kW	Wall-Integrated / 1.1

No. of Modules	43
Area (ft^2) /Azimuth/Tilt	333 / 180 / 90
Array 4	
BIPV Type / Rated Power, kW	Wall-Integrated / 0.4
No. of Modules	15
Area (ft^2) /Azimuth /Tilt	116 / 270 / 90
Stand-Off (Array 5)	
BIPV Type / Rated Power, kW	Stand-Off / 6.6
No. of Modules	22
Area (ft^2) /Azimuth/Tilt	574 / 0 / 0
PV Simulation Results:	

PV System Output, kWh	51361
PV Sellback, kWh	411
PV Output of Each Array before Power Conditioning Losses (inverter inefficiency)	
Array 1, kWh	25076
Array 2, kWh	16736
Array 3, kWh	723
Array 4, kWh	261
Array 5, kWh	10309
Total, kWh	53105
Total Bldg Electric Load, kWh	284279
Supplied by PV, kWh	49305
Supplied by Grid, kWh	234973
Peak PV Net Output, kW, time	23.4 Feb 28 12:00
Peak PV Output to Bldg, kW, time	23.4 Feb 28 12:00
Peak PV Sellback to Grid, kW, time	4.1 Oct 5 13:00
Bldg Peak Elec., kW, time	77.0 Sep 9 8:00
Bldg Peak PV Coincident Output, kW	13.8
Bldg Net Elec. Peak, kW, time	65.0 9/16 7:00

The total building electric load is reduced from 458,045 kWh/year to 284,279 kWh/year through the efficiency measures. Of this, 49,305 kWh/year is supplied by PV, and 234,973 kWh/year is supplied by the electric utility. Thus, solar provides 17% of the building energy requirements. The peak PV net power output is 23.4 kW, on February 28 at 12:00 noon. This is about half the installed rated power of 45.4 kW, indicating the effect of non-optimal orientations (tilt and azimuth) and also differences in temperature and insolation from standard rating conditions. The building electrical peak is 77 kW on September 9 at 8:00. At that time, the building peak PV coincident output is 13.8 kW, reducing the peak load to the utility to 63 kW.

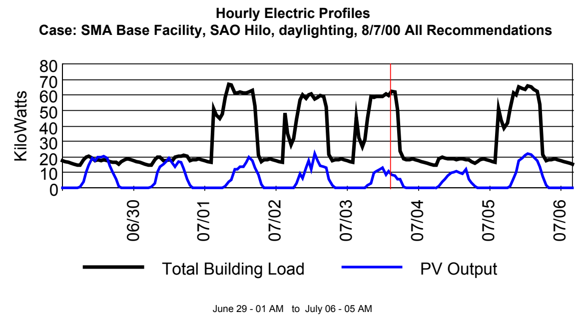

Figure 4. *ENERGY-10* report showing PV output and total building electrical load for the first week in July.

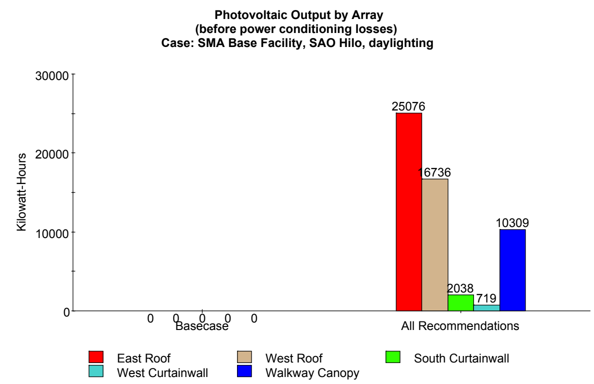

Figure 5. *ENERGY-10* report showing annual DC energy delivery of each of the five BIPV arrays on the SAO.

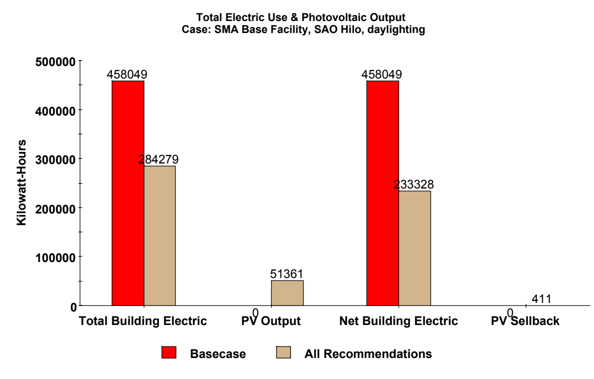

Figure 6. *ENERGY-10* report showing annual energy use of SAO basecase, energy efficiency improvements, and BIPV savings.

SMITHSONIAN ENVIRONMENTAL RESEARCH CENTER

The Smithsonian Environmental Research Center (SERC) is a 4200-acre environmental research facility located on Chesapeake Bay in Edgewater, Maryland. SERC's interdisciplinary research applies short-term and long-term studies to examine the ecological landscapes of linked ecosystems, especially those impacted by human activities.

The institute's mission requires that impacts due to site operations be minimized, a justification for considering PV. The overall project proposes constructing a visiting scientist housing complex consisting of three two-story houses, three one-story accessible houses, a laundry building, and a seminar/conference building. Each housing unit consists of two bedroom/bathroom modules and a shared kitchen/eating area and living room space. The fully developed housing complex will provide accommodations for up to 24 researchers. SERC is committed to providing as much clean, reliable power from renewable sources as is economically feasible. Since a large component of the mission at SERC is to educate the thousands of visitors each year, an educational opportunity about renewable energy exists. For brevity, only the analysis of the two-story housing units is presented [6].

The basecase (reference case) is a hypothetical case based on the requirements of ASHRAE 90.2–1993, Energy Efficient Design of New Low-Rise Residential Buildings [7]. Some key assumptions include a ceiling R-value of 30 $ft^2hr°F/Btu$ (0.19 $W/m^2°C$); wall R-value of 15.8 $ft^2hr°F/Btu$ (0.36 $W/m^2°C$); floor R-value of 21.3 $ft^2hr°F/Btu$ (0.27 $W/m^2°C$); fenestration R-value of 2 $ft^2hr°F/Btu$ (2.8 $W/m^2°C$); and an air-conditioning EER of 7.6, minimum. Lighting power is assumed at 1.2 W/ft^2 (13 W/m^2). Exterior walls are 2x4 wood frame with insulated sheathing and wood siding. Windows are double-pane, aluminum frame with thermal break. Floor-to-ceiling height is 9 ft (2.7 m). The floor plan is a simple rectangle with an aspect ratio of 0.75. Windows are equally distributed on all exterior walls. Air conditioning and heating are provided by a split system with electric furnace, and the ducts run through the unvented crawlspace. Occupancy is assumed at 400 ft^2/person. The current (2001) electric rate from Delmarva Power & Light utility company, averaging $0.092/kWh, is used in the analysis. Natural gas is not available at the site.

Results of the *ENERGY-10* simulation for the 1,400 ft^2 (130 m^2) one-story basecase building indicate that the peak cooling load is 4 tons; the peak electrical load is 14.9 kW; and annual energy use intensity averages 65.7 $kBtu/ft^2$/year (207 kWh/m^2/year). Basecase energy use results in an annual cost of $2,478/year.

The schematic design incorporates several features to improve energy performance over the basecase:

- House orientation: Largely east and west, with the large façades and windows facing north and south to reduce summertime solar gains and admit winter sun
- Insulation: The 6-in. wall provides R-17.7 insulation, a higher R-value than the 15.8 $ft^2hr°F/Btu$ (0.36 $W/m^2°C$) prescribed by code
- Wood frames and low-e glass: Used to reduce the window heat loss coefficient from U = 0.49 to U = 0.28 $Btu/ft^2hr°F$ (1/6 $W/m^2°C$)
- Energy-efficient lighting equipment: Specification of fluorescents where possible is estimated to reduce interior lighting from 280 W to 210 W, and exterior lighting from 56 W to 42 W
- Daylighting: Provided in almost every room, mitigating the daytime use of electric light
- Programmable thermostats
- Whole-house fan
- Insulated hot water piping
- Low-flow showerheads
- Energy-efficient appliances.

The following measures were also recommended to further improve the performance of the schematic design:

- Ground-source heat pump
- Solar water heating
- Drain water heat recovery
- Structural insulated panel construction
- Infiltration measures.

ENERGY-10 cannot currently model some of these recommended measures; in those cases, the savings are either not included in the estimate (insulated water piping, energy-efficient appliances, whole-house fan), or are calculated by hand and estimated by reducing the associated load (ground-source heat pump [8], low-flow shower heads, drain water heat recovery [9], solar water heating).

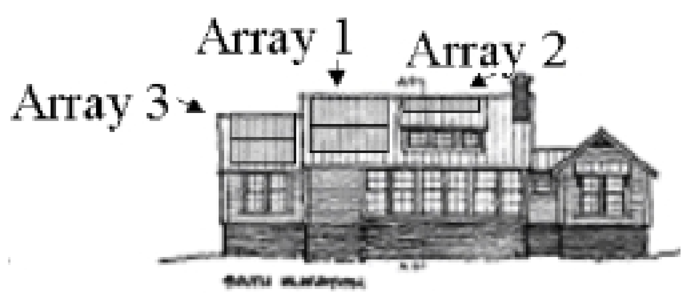

Figure 7. Schematic design of SERC one-story housing unit by Architrave PC with three standing-seam BIPV arrays added to south-facing roof.

Photovoltaics are integrated into the building roof to further reduce the load. The site is wooded, and some trees would have to be removed to mitigate shading. The south-facing roof is the location for standing-seam metal roofing with Unisolar ASR-64 modules [10]. Each module is 16 in. (0.4 m) wide (metal pan width) and 9.5 ft (2.9 m) long. There are two rows of modules on the living room roof and the bedroom roof, and one row of modules on the roof of the clerestory section in the living room. The insulating value of the BIPV materials is not considered. Each module is 24 V dc (open circuit), and they can be wired in series in groups of two to produce 48 V dc (open circuit). The operating voltage would be 17 V dc per module for 34 V dc operating voltage.

Table 2. *ENERGY-10* report showing detail of the three BIPV arrays on the SERC one-story housing units.

Total PV Array Area, ft² / m²	612 / 57
Total PV Rated Output, kW	3.1
Total PV Annual AC Output, kWh	3688 (3195 to house, 493 to grid)
Annual Building Load, kWh	23194
Annual Supplied by Grid, kWh	19999
Living Room South Roof	
BIPV Type / Rated Power, kW	Standing seam, roof-integrated, ASR-64 modules, 64 W each, two rows / 1.3 kW
No. of Modules	20
Area (ft^2) /Azimuth/Tilt	255 / 0 / 3
Annual DC Output, kWh	1402
Living Room Clerestory Roof	
BIPV Type / Rated Power, kW	Standing seam, roof-integrated, ASR-64 modules, 64 W each, one row / 0.6 kW
No. of Modules	10
Area (ft^2) /Azimuth/Tilt	128 / 0 / 18
Annual DC Output, kWh	881
West Bedroom South Roof	
BIPV Type / Rated Power, kW	Standing seam, roof-integrated, ASR-64 modules, 64 W each, two rows / 1.2 kW
No. of Modules	18
Area (ft^2) /Azimuth/Tilt	230 / 90 / 38
Annual DC Output, kWh	1644

Of a total building electric load of 23,194 kWh per year, 3,195 kWh would be supplied by PV and 19,999 kWh would be supplied by the electric utility. Thus, solar would provide 14% of the building's power requirements. The peak PV net output is 2.1 kW, on March 19 at 11:00 am. The building electrical peak is 18.9 kW on January 31 at 3:00 am. At that time, the PV system is not producing power to reduce the peak load. Figure 8 shows annual energy use of a code-compliant basecase, the schematic design for the house, a case with all efficiency measures included, and a case with BIPV added.

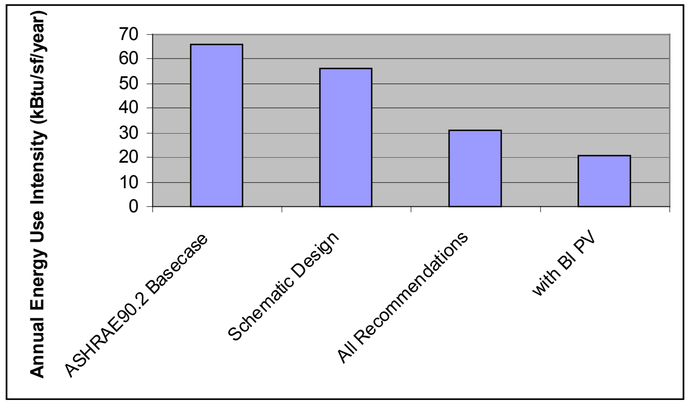

Figure 8. Annual utility energy use intensity (Btu/ft^2/year) of basecase, schematic design, all efficiency measures, and BIPV for one-story SERC housing unit.

CONCLUSIONS

In these two case studies, *ENERGY-10* was used to facilitate the evaluation of energy efficiency measures and photovoltaics measures very early in the design process. Making it easy to consider these measures increases awareness among architects and designers. As the design develops, *ENERGY-10* results identify and justify cost-effective measures, resulting in optimal building designs and high customer satisfaction. The estimate of annual energy delivery for the five systems on the SAO by *ENERGY-10* is 4.6% higher than that of the widely accepted PV F-Chart method [11], as shown in Figure 9.

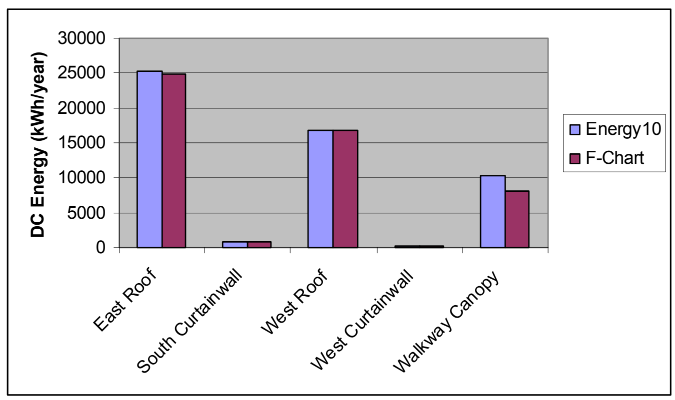

Figure 9. Comparison of annual dc energy delivery for five arrays on the SAO, as predicted by both *ENERGY-10* and F-Chart.

For both of these facilities, the Smithsonian Institution has reasons to consider photovoltaics beyond simple cost effectiveness. Nevertheless, budgets are strained, and the final designs may include photovoltaics only in smaller demonstration systems. For example, a recommended alternative design for the SAO incorporating BIPV only over the entry canopy is illustrated in Figure 10.

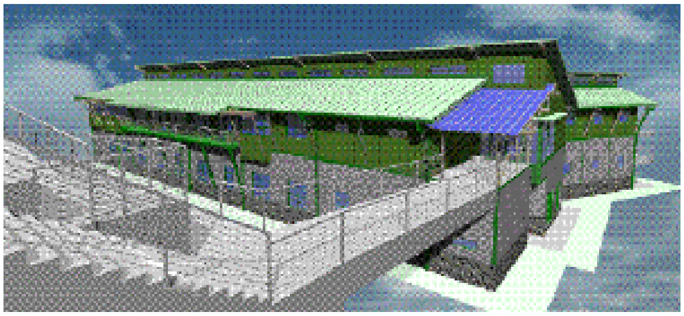

Figure 10. Rendering of SAO featuring small BIPV entry canopy to maximize demonstration benefits at reasonable cost (Source: Kiss+Cathcart Architects PC).

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13. ABSTRACT *(Maximum 200 words)*
A new version of the *ENERGY-10* computer program simulates the performance of photovoltaic systems in addition to presenting a wide range of opportunities for users to improve the energy efficiency of building designs. This paper describes two test cases in which the beta release of *ENERGY-10* version 1.4 was used to evaluate energy efficiency and building-integrated PV for two Federal building projects: an office and laboratory building at the Smithsonian Astrophysical Laboratory in Hawaii, and housing for visiting scientists at the Smithsonian Environmental Research Center in Maryland. By simulating both the building electrical load and simultaneous PV performance for each hour of the year, the *ENERGY-10* program facilitates a highly accurate, integrated analysis.

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