FIRST YEAR PERFORMANCE FOR THE ROOF-MOUNTED, 45-KW PV-ARRAY ON OBERLIN COLLEGE'S ADAM JOSEPH LEWIS CENTER

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ABSTRACT

The curved roof of Oberlin College's, all-electric, *Environmental Studies Center* sports a 4,700 ft^2, 45-kW, photovoltaic array consisting of 690, BP-Solar crystalline silicon modules arranged in 10 rows, each with a different tilt angle. The array is divided into three sub-arrays, each grid-connected through a 15-kW Trace inverter and a 15-kVA Square-D isolation transformer. The PV array produced 59,000 kW-hr of energy in its first full year of operation. Our own calculations, which incorporate manufacturer specifications for modules, inverters, and transformers, combined with TMY2 weather data for Cleveland, project that the array will produce 67,500 kW-hr annually, 12% higher than observed. Explanations for the performance deficit are suggested.

INTRODUCTION

The *Adam Joseph Lewis Center* (see Fig. 1) is a recently constructed, academic building, which has been offered as a model of sustainable architecture [1]. This 13,600 ft^2 classroom/office building on the *Oberlin College* campus incorporates a long list of green technologies including triple-pane glazing, geothermal heat pumps, CO_2 and motion sensors, efficient lights and daylight controls, energy-recovery ventilators, and an ecological on-site waste treatment system [2]. Construction on the building was completed in Jan. 2000 and its roof-mounted PV array became operational Nov. 15 that same year.

Fig 1. View of the south and east sides of the *Lewis Center*. PV array is installed on the main, curved roof.

One of the primary goals for this building is for its PV array, on an annual basis, to generate more energy than the building consumes [2]. The building architect, William McDonough & Partners, projected the building would consume 63,609 kW-hr of energy annually, corresponding to a site energy use of 16,000 Btu/ft^2/yr, about 21% that used by comparable conventional buildings [2]. The BP Solar array was projected by the manufacturer to produce 75,750 kW-hr annually.

During its first two years of operation the building's measured annual energy consumption was 190,000 kW-hr/yr, three times original projections [3]. A study of the final building design reveals that its HVAC systems differ significantly from assumptions used in the architect's energy projections. Energy projections based on actual construction drawings are consistent with measured performance [3]. Oberlin College has begun renovation of the HVAC systems to address some of the design flaws and reduce the building's energy consumption.

Here we consider the design and performance of the photovoltaic power system.

ARRAY DESCRIPTION

The main roof of the *Lewis Center* hosts a PV array designed by *Solar Design Associates*. The 434 m^2 grid-connected, PV-array consisting of 690, BP Solar model 585, metal-framed, crystalline silicon modules. An individual module has dimensions 118.8 cm x 53.0 cm and a rated power (at 20°C, AM1.5 illumination) of 85 W (18.0 V, 4.72 A), corresponding to a module efficiency of 13.5%.

The modules are arranged in 10 rows that run east-west, parallel the main building axis and are organized into three, nominally identical, sub-arrays as shown in the Fig. 2. Were it possible for AM1.5 illumination to simultaneously fall on each module the entire array would produce 58.7 kW. But since each of the 10 rows is mounted with a different tilt angle (see below) the output from each sub-array is expected to exceed 15 kW only on

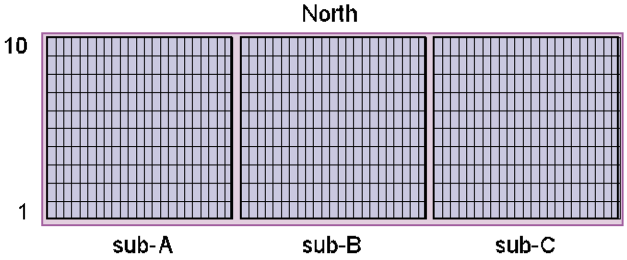

Fig 2. 690 modules are arranged in three identical, 15-kW sub-arrays, each with 10 rows.

a handful of occasions. All 23 modules in the same row of a sub-array are connected in series and the ten rows of each sub-array are connected in parallel.

As is the case for the *Georgia Tech Aquatic Center* [4, 5] the roof-mounting surface is curved rather than flat (see Fig. 3). Tilt angles, listed in Table 1, range from 20°S for Row 1 (south edge) to 9°N for Row 10 (north edge). Owing to their different tilt angles each row will produce a different output current.

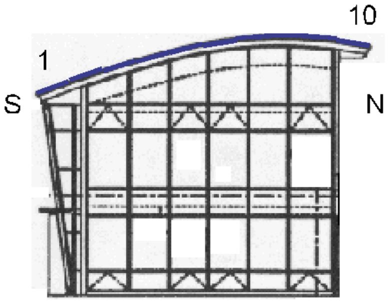

Fig 3. View of east end of the main building showing 10 rows of modules mounted on curved roof.

Row	Tilt Angle	Row	Tilt Angle
1	20°	6	9°
2	19°	7	4°
3	17°	8	0°
4	16°	9	-4°
5	14°	10	-9°

Table 1. Tilt angles for the 10 rows of PV modules. Row 1 is on south edge while Row 10 is on north edge of roof.

Each of the three sub-array outputs is connected to its own 15-kW Trace-Xantrex model PV-15208 power inverter, which produces a 208 VAC, 3-phase output. The output of each inverter is connected to a *Square-D*, model 15T85HBIS 15-kVA isolation transformer. The three transformer secondaries are connected in parallel to the 208 VAC, 3-phase building power circuit. A "billing meter" records ac energy flow out of the PV system. While inverters automatically shut down when PV power drops below a preset level, isolation transformers remain continuously connected to the grid resulting in nighttime energy loss not recorded by this meter.

Transformer power loss data were provided by the vendor. A fit to the data shows that the power loss, P_{Loss}, for each of the 15-kVA transformers is represented by

$$P_{Loss} = P_0 + \alpha P^2 , \qquad (1)$$

where P_0 = 290 W and α = 1.9 x 10^{-6}, where P_{Loss} and P are both expressed in Watts. The combined transformer losses are 2.1 kW when inverters produce their maximum combined 45 kW power.

An inverter is set from the factory to shut down should its output fall below 300 W. Its output power never exceeds 15 kW. A typical Inverter efficiency curve is shown in Fig. 4.

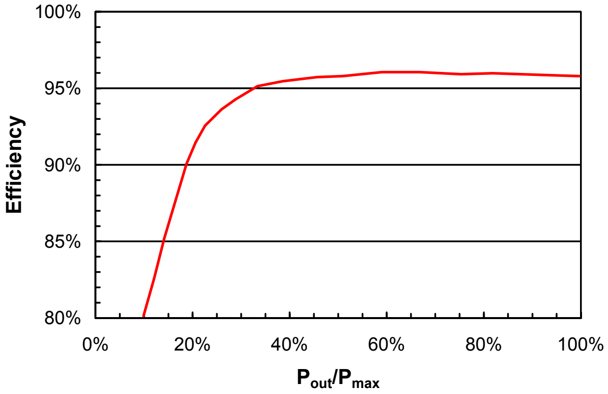

Fig 4. Typical inverter efficiency graphed versus percentage of the rated ac output (15 kW), courtesy of Xantrex Technology Inc.

PROJECTED PERFORMANCE

We have combined the above loss information for the inverters and transformers, along with BP Solar performance specifications for the silicon modules with 8760 hour, TMY2 weather data for nearby Cleveland, OH to project the hourly output for the PV-array. These calculations, which also take into account local temperature and increased reflection for oblique angles, yield an annual system (arrary/inverters/transformers) output of 67,500 kW-hr. The inverters (7.2%) and transformers (6%) together are responsible for a 13.2% reduction in system output. The nighttime transformer core losses further reduce this figure by 4,300 kW-hr since the transformers remain connected to the grid. The projected monthly energy production is graphed in Fig. 5 (dark bars) and listed in Table 2.

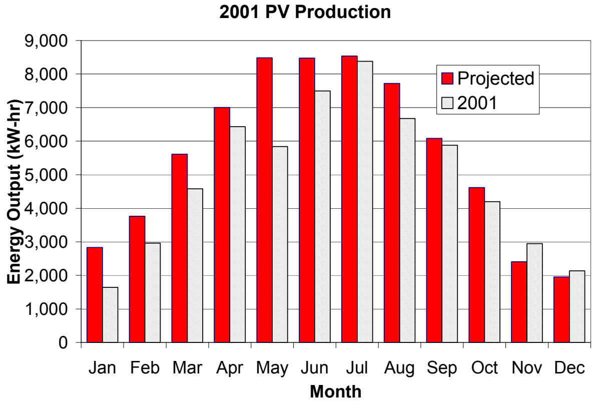

Fig 5. Projected (dark) and measured (light) monthly energy production for the year 2001.

Simulations show that inverters truncate output power to their 45-kW maximum for only 152 hours of the year resulting in an energy loss of only 70 kW-hr.

Month	Energy (kW-hr)	Month	Energy (kW-hr)
Jan	2,834	Jul	8,538
Feb	3,763	Aug	7,722
Mar	5,609	Sep	6,082
Apr	7,007	Oct	4,617
May	8,485	Nov	2,404
Jun	8,474	Dec	1,953
		Total	**67,488**

Table 2. Projected monthly ac energy production from PV system (not counting nighttime transformer losses).

MEASURED PERFORMANCE

Actual array performance for 2001 is graphed as the light bars in Fig. 5. These and data for an additional 6 months are listed in Table 3. The total energy generated during 2001 was about 59,000 kW-hr, roughly 12% lower than projected. Some of the winter deficit may be attributed to un-melted snow on the array, which is not accounted for in the simulations. About 1,200 kW-hr of the May deficit is due to the array being inadvertently disconnected for 3+ days. After correcting for these known deficiencies the measured 2001 performance remains 8% below projections.

Month	Energy (kW-hr)	Month	Energy (kW-hr)
Nov	507	Aug	6,678
Dec	1,130	Sep	5,880
Jan-01	1,643	Oct	4,197
Feb	2,960	Nov	2,947
Mar	4,579	Dec	2,135
Apr	6,430	Jan-02	2,304
May	5,840	Feb	3,125
Jun	7,496	Mar	3,746
Jul	8,381	Apr	5,075

Table 3. Measured energy production since installation Nov. 15, 2000.

An obvious question is whether or not the performance deficit is simply due to lower-than-average solar insolation for the period investigated. An ongoing monitoring effort is in place to record actual weather and solar irradiance data for direct comparison with PV energy output. But even without these data this explanation is doubtful. In all but 2 of the 17 full months for which data are available the measured performance was below projections.

One clue to the nature of the problem is found by comparing, on a daily basis, projected energy with measured energy output. Consider measured and calculated daily outputs for March 2001. There is, of course, no reason to expect that the actual weather on, say March 3, was identical to that contained for that day in the TMY2 data file. But we do expect the range of weather experienced in March 2001 to be captured by the TMY2 file. Hence, if we compare the measured and simulated daily PV output for the month of March, sorted in order of output, we might expect the "best days" for the simulation to agree with the "best days" in the measured performance, and so on.

Fig. 6 shows such a comparison for the 31 days of March 2001 sorted by output. Dark bars represent measured daily output while light bars correspond to simulations. The graph shows good agreement for the "best days" but simulations are consistently higher than measurements for the "worst days." Corresponding graphs for other months show similar trends. The result suggests that the simulation is quite accurate for clear, sunny conditions, but over-estimates energy production for overcast days when sunlight is mainly diffuse and the array operates well below its full-power rating. However, we cannot rule out the possibility that actual insolation is lower than that found in TMY2 weather files.

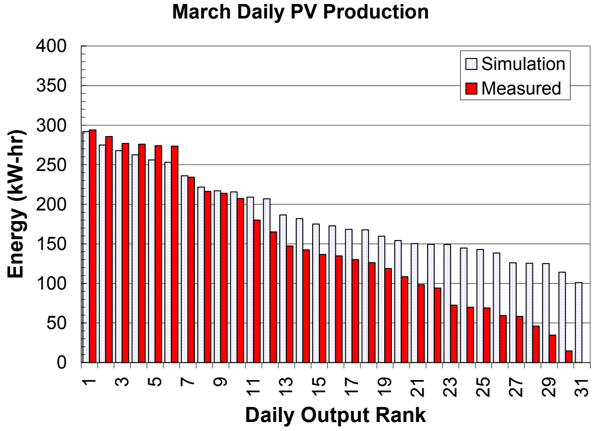

Fig 6. Comparison of measured (dark) and simulated (light) daily energy generation for March 2001, ordered from highest to lowest output.

DISCUSSION

The performance deficit must therefore be associated with mechanisms that are not important on sunny clear days. This rules out such things as poor module performance or wiring losses.

Here we eliminate two possible explanations for the 8% performance deficit. The first is voltage mismatch between the 10 rows of a sub-array. The second is inverter losses at low power.

Our simulation assumes that, when each of the 10 rows are wired in parallel, each row is still able to achieve the maximum power for its incident radiation. Because of the variation in tilt angles, however, there are conditions under which the front rows receive considerably more light than the back rows, leading to a significant variation in the optimal voltage between front and back rows. Since they are wired in parallel, rows will be forced to operate at the same voltage, leading to sub-optimal performance. This should be more important when the sky is clear and the sun is low in the sky, which occurs in winter or in early morning and late evening. This is not expected to be important when the sky is overcast.

We have employed Sandia's *IVTracer v1.0* software to produce I-V curves for the 10 rows under conditions found in the TMY2 data files for which this voltage mismatch should be most important [6]. We find the reduction in power is, at most, a few percent, for the 20 or so hours (out of the 4000 daylight hours) when Row 10 receives a third or less the insolation received by Row 1. Hence we conclude the affect of this voltage mismatch is negligible.

Manufacturer specifications are not precise when inverters are operated below 20% capacity. We have performed simulations assuming zero inverter efficiency when operated in this range and find annual output is reduced by, at most, 3,500 kW-hr. Sub-optimal inverter performance at low power cannot explain the performance deficit. However, sub-optimal inverter performance at higher power cannot be ruled out.

It is interesting to calculate the loss in performance associated with the curved roof design. Suppose, for instance, that the 690 modules were mounted in a single plane tilted south at an angle given by L – 15º = 26º (where L is the latitude). The increased annual array output (before the inverters) is just 5%. This is the cost of integrating the PV array into the architectural features of the building – surprisingly low because Oberlin, on an annual basis, receives relatively little direct sunlight. Much of the annual sunlight is diffuse and, with diffuse light, the north-tilted rows perform as well as the south-tilted rows.

Consider the energy payback time associated with this PV array. This requires an estimate of the energy required to fabricate the array. We find two numbers in the literature for crystalline Si modules (not including metal frames): 2,400 to 7,600 MJ/m^2 [7] and 2,700 MJ/m^2 [8]; we adopt the latter. Assuming the 434 m^2 array achieves its projected annual energy production of 67,500 kW-hr the energy payback time is calculated to be 4.8 years. Based on 2001 performance and including nighttime transformer losses the payback time is 6.0 years. Both are significantly less than the 20 year module warranty

The monetary payback time is a different matter. The estimated array cost (including inverters, transformers, and installation) is $420,000. The cost of electricity from the local power company is roughly $0.08 per kW-hr. Hence, the cost savings associated with the annual projected energy production is about $5,400. At 6% interest the annual debt service alone on the capital investment is $25,000. Clearly the monetary payback time for the array is infinite.

We note that nighttime transformer losses could be eliminated by the installation of a contactor circuit for disconnecting the system from the grid at night. This would result in an annual savings of $340. Such a modification would be cost-effective.

SUMMARY AND CONCLUSIONS

In summary, we have described the roof-mounted, 45-kW, crystalline Si PV array on Oberlin College's *Adam Joseph Lewis Center* and presented data for its first 18 months of operation. We have also simulated energy production using manufacturer's specifications and TMY2 weather data. Annual energy production for 2001 was measured to be 59,000 kW-hr. Nighttime transformer losses reduced this further by an estimated 4,300 kW-hr (or 6%). Annual energy production is 12% below our projections. About one third of the deficit is easily explained. The rest could be associated with sub-optimal inverter performance, an over-emphasis of diffuse light in the simulations, or simply lower-than-average insolation during the measurement period. Additional measurements are required to sort these out.

The array (less metal frames) has been shown to have an energy payback time of 5-6 years based on literature estimates for the energy used to manufacture crystalline Si modules. Simulations show that the non-optimal curved mounting is responsible for only a 5% reduction in performance.

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