February 2001 • NREL/CP-550-29638

Conference Paper

Hourly Simulation of Grid-Connected PV Systems Using Realistic Building Loads

Preprint

J.D. Balcomb and S.J. Hayter
National Renewable Energy Laboratory

N.L. Weaver
InterWeaver Consulting

To be presented at the American Solar Energy Society (ASES) National Solar Conferences Forum 2001
Washington, D.C.
April 21–25, 2001

National Renewable Energy Laboratory

1617 Cole Boulevard
Golden, Colorado 80401-3393

NREL is a U.S. Department of Energy Laboratory
Operated by Midwest Research Institute • Battelle • Bechtel

Contract No. DE-AC36-99-GO10337

Available electronically at http://www.doe.gov/bridge

Available for a processing fee to U.S. Department of Energy
and its contractors, in paper, from:
U.S. Department of Energy
Office of Scientific and Technical Information
P.O. Box 62
Oak Ridge, TN 37831-0062
phone: 865.576.8401
fax: 865.576.5728
email: reports@adonis.osti.gov

Available for sale to the public, in paper, from:
U.S. Department of Commerce
National Technical Information Service
5285 Port Royal Road
Springfield, VA 22161
phone: 800.553.6847
fax: 703.605.6900
email: orders@ntis.fedworld.gov
online ordering: http://www.ntis.gov/ordering.htm

Printed on paper containing at least 50% wastepaper, including 20% postconsumer waste

Hourly Simulation of Grid-Connected PV Systems Using Realistic Building Loads

J. Douglas Balcomb, Research Fellow
National Renewable Energy Laboratory
1617 Cole Boulevard
Golden, Colorado 80401
douglas_balcomb@nrel.gov

Sheila J. Hayter, P.E., Task Leader
PV in Buildings Program
National Renewable Energy Laboratory
1617 Cole Boulevard
Golden, Colorado 80401
sheila_hayter@nrel.gov

Norman L. Weaver
InterWeaver Consulting
PO Box 775444
Steamboat Springs, Colorado, 80477
norm_weaver@nrel.gov

ABSTRACT

ENERGY-10 is a design-tool computer program. A new feature of *ENERGY-10* described in this paper is the ability to model and simulate the performance of a photovoltaic (PV) system that is integrated with the building. An integrated simulation program is desirable because a building's electrical load is highly variable nature. Realistic load estimation requires a detailed simulation to account for the variable nature of both the weather and the building occupancy. The *ENERGY-10* PV program links the *ENERGY-10* load simulation with a TRNSYS PV simulation, eliminating most of the time-consuming chores that would be encountered using separate programs.

This is one of two companion papers that describe the *ENERGY-10* PV design tool computer simulation program. The other paper is titled "*ENERGY-10* Photovoltaics: A New Capability" and is being presented at the same conference by the same authors. Whereas this paper focuses on the PV aspects of the program, the companion paper focuses on the implementation method. The case study in this paper is a commercial building application, whereas the case study in the companion paper is residential application with an entirely different building-load characteristic. Together they provide a balanced view.

INTRODUCTION

There are many programs available that can be used to simulate the performance of a photovoltaics (PV) system, based on a description of the system and an hourly weather file. Such programs are generally adequate for estimating the energy that will be produced over a time period, such as a year. This may be all the information that is needed. For example, the user may be interested in sizing a system to provide a given number of kWh in a year. The simulation results provide the hourly output and the total.

Building integrated PV (BIPV) systems are among those applications for which the user might require more information. For example, he or she might want to know how the PV system meets the hourly building load. This, of course, requires knowing not only the hourly output of the PV system but also the hourly detail of the building electrical load. Building electrical loads tend to peak in the afternoon on hot, sunny summer days when air-conditioning loads are high. This is just the time when a PV system tends to generate peak or near-peak output. If the cost of electricity from the grid is increased at this time, for instance, through a time-of-day rate, then the value of the PV system might be enhanced. This can be a very large effect. The avoided cost of electrical energy purchases during such a peak might be several times greater than the average cost. Whether this cost is passed along to the consumer or not depends on the rate structure. Often it is not, but sometimes it is.

PV simulation programs typically characterize the building electrical load in rather simple ways. One common technique is to identify a daily load profile and simply use it every day of the year. More sophisticated techniques might use a different daily profile on different days, for example, one profile in the winter and a second profile in the summer, or one profile on weekdays and another on weekends.

The reality of building electrical loads is that they vary widely in ways that are impossible to characterize so simply. Each building is different, and the load is different on each day of the year. Whereas many typical buildings with large loads can be characterized with reasonable accuracy, buildings that incorporate a PV system are likely to be exceptions. These buildings would have been designed to minimize all loads through strategies such as daylighting, improved glazing, and shading, with equipment strategies, such as high-efficiency HVAC, improved controls, economizer cycle, and thermal mass. In fact, on some days, a highly optimized building using a combination of strategies might come close to eliminating lighting and air-conditioning loads.

Understanding the electrical load of such a low-energy building requires using either monitored building data or simulating the building in some detail. Such a simulation must take into account details of the building, such as window placement, typical occupancy schedules, light dimming due to daylighting, and HVAC system performance. An adequate building simulation is more complex than a PV simulation. A program, such as DOE2 (Buhl et al, 1994) would be needed. Using monitored data does not provide a feasible alternative because data would be needed for a building that is very similar to the building in question. These data are expensive to obtain and probably are not in hand when the information is needed.

Using a program like DOE2 is a major undertaking. Not only is it necessary to develop a building model, but it is also necessary to format the hourly output so it can be used as input to the PV simulation. The whole process can take weeks to complete, discouraging designers from even starting the process.

The need identified here is for a single computer simulation program that integrates a building's thermal and electrical performance simulation with the PV simulation. Moreover, the program should be easy, fast to use, and accurate. This paper describes such a program: *ENERGY-10* PV.

ENERGY-10 **PV**

ENERGY-10 PV is a new simulation tool that provides the capability to analyze building-integrated, grid-connected PV systems. The distinguishing characteristic of this tool is that the hourly electrical load of the building is calculated using a comprehensive hourly simulator. The electrical load in the new tool is realistic, accounting for scheduled plug loads, lights, and complex interactive effects including:

1. Thermal heating and cooling loads and fan power, calculated in response to hourly typical meteorological year (TMY2) weather data and hourly schedules of occupancy and thermostat settings and accounting for heat storage in building materials,
2. Dimming lights in response to available daylight based on illumination from windows and the response of realistic dimming sensors,
3. The thermal consequences of reduced light energy,
4. Changes in the thermal envelope due to BIPV components, and
5. Changes in the solar heat transmission and visible transmittance of windows caused by using window-integrated PV components.

The new tool was created by adding PV simulation capability to the *ENERGY-10* program (Balcomb, 1997), a design tool for architects, engineers, and energy consultants that provides the ability to evaluate envelope strategies such as insulation, glazing, shading, air-tightness, and passive solar heating, with equipment strategies, such as high-efficiency HVAC, improved controls, economizer cycle, reduced duct leakage, and thermal mass. *ENERGY-10* employs comprehensive daylighting and thermal simulation engines. There are more than 1,400 registered users of *ENERGY-10,* and the program is being used as a teaching tool in 44 colleges and universities, primarily in architectural and engineering curricula. The principal advantages of *ENERGY-10* are that it is fast, accurate, and easy to use. Evaluations that would take hours or days with other tools can be carried out in minutes.

The hour-by-hour simulation of PV performance is carried out in ENERGY-10 using the TRNSYS simulation program, written at the University of Wisconsin (Klein, 1997). The hourly electrical load fed to TRNSYS is the result of the daylighting and thermal simulations done prior to the PV simulation. ENERGY-10 creates an input deck and weather file for TRNSYS and reformats the hourly output for study within ENERGY-10. 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 are modeled.

ADVANTAGES OF *ENERGY-10* PV

There have been two distinct groups of designers interested in efficient buildings: a small group that specializes in PV and a larger group concerned with efficiency in general. The PV community is increasingly interested in integrating the PV system with the building and is well aware of the need to minimize the electrical load as a first priority. To this group, the building represents a convenient platform for their system that offers the cost advantage of a dual use for a building element, such as the roof or a shade awning over a window. Most of the second group, while interested in PV as a new technology, have often paid little serious attention because they are wary of high installation costs.

The movement toward BIPV systems is increasingly bringing these designers together and reducing the distinction between the groups. The PV group has become sophisticated about using other energy-efficient strategies. The larger, energy-efficiency group has become aware of an increasing demand for integrating PV with their designs.

The key advantage of *ENERGY-10* PV is that it brings these groups even closer. One tool can serve both functions, and do it better and far more quickly than the individual tools used previously.

Designers who might be evaluating a variety of strategies, such as those previously implemented in *ENERGY-10,* can easily fold in a study of PV. There is no need to learn a separate program or even know much about PV. With a few mouse clicks they can do an evaluation and be studying detailed results in minutes. This will broaden the pool of designers who can do a PV evaluation by tenfold. The group who started out doing PV evaluations will have a tool for doing a better job evaluating other strategies readily at hand—even strategies that reduce fuel consumption—which might have been of only peripheral interest previously.

The second advantage is that the evaluation will be much more realistic and therefore more likely to produce an optimized building design, accounting for a proper balancing of load reduction and supply. The highly variable nature of building electrical loads is much more accurately characterized than with previous models that performed PV simulations only. The optimization process, which would have been prohibitively time consuming using other tools, now becomes tractable.

The third advantage is that the dual nature of building elements used for PV cells can more readily be modeled. A good example is a PV window. The PV cells block much of the window, reducing visibility and solar transmittance. *ENERGY-10* PV already includes default window types with such characteristics, and users can easily add others. Furthermore, new technologies such as "power windows" can be accommodated within the framework of the program. (The term "power windows" is used here to describe windows that serve both as unobstructed view windows, albeit with somewhat reduced transmittance, and as a PV module, albeit with somewhat reduced efficiency. There could be major cost advantages in a power window because the window serves as both the mounting structure and the substrate for the PV, which is simply a coating on the window. Power windows are not yet available, but may be feasible.)

CASE STUDY

The *ENERGY-10* PV program can be appreciated by studying some results. We chose to evaluate a 3000-sq. ft. two-story office building in Denver. As is usual in *ENERGY-10*, we started with a *reference case* building, which uses typical construction practice and applied 12 energy-efficient strategies: daylighting, improved glazing, shading, energy-efficient lights, improved insulation, air tightening to reduce infiltration, added thermal mass, passive solar heating, economizer cycle, high-efficiency HVAC, improved HVAC controls, and reduced duct leakage. This second building is called the *low-energy case*. The effect of these strategies is dramatic, reducing the energy use by 79%, from 204,000 Btu/sq. ft. per year to 43,000 Btu/sq. ft. per year. Annual electrical use is reduced from 72,000 kWh to 15,500 kWh. Admittedly the *reference case* results are rather high, but that is irrelevant because it is the *low-energy case* that is our starting point for the PV evaluation.

Suppose we want to design a "zero-net-electrical-energy" building—a building with a grid-connected PV system that generates as much electricity in one year as the building requires. It is simple to estimate the required size of the PV system if we have an estimate of the annual capacity factor (the ratio of the power generated to the energy generated if the system were to produce its rated power continuously). Capacity factors vary, but a value of 20% is feasible for a good system in Denver at near-optimum orientation. The required capacity is 15,500/8,760/0.20 = 8.84 kW. This 824-sq. ft. array would fit easily on the 15,000-sq. ft. building roof (a system for the *reference case* building would be five times larger. However, this is irrelevant because we should not consider this option).

If all we are interested in is sizing the PV system, then we don't need *ENERGY-10* PV. However, if we want to know *when* the 15,500 kWh are generated in relation to *when* it is needed, *when* the system feeds back into the grid, and *when* the peaks occur, then we need an integrated analysis. This is where *ENERGY-10* PV becomes valuable.

In the first *ENERGY-10* PV calculation, we found that the system is a little undersized because the capacity factor turns out to be only 19% instead of 20%. We then tried a 9.3-kW system tilted at 40 degrees and oriented due south. This consists of 84 modules in a 12 x 7 array made up of crystalline silicon cells each with a rated power of 110 W, selected from the *ENERGY-10* PV default library of 13 modules. The results are shown in Table I. (imported directly from the *ENERGY-10* PV output).

The critical information added by the *ENERGY-10* PV calculation that would not be available from a PV-only simulation is the sellback amount and the timing. There is no way to obtain these numbers without a detailed hour-by-hour comparison of the building load with the PV system output. The results would be different if the timing of the building load were different. In our case, a lot of the sellback occurs on weekends and holidays when the building is unoccupied and the loads are small.

The hourly details are available, both in a large file that can be imported into a spreadsheet and visually in *ENERGY-10* PV. There are many built-in graphing options that provide detailed insight into all of the building load components and the PV system supply. Two of these are shown in Figs. 1 and 2.

PV SIMULATION

The TRNSYS simulation model is quite sophisticated. It uses a current voltage (I-V) curve characterization of the modules accounting for the instantaneous cell temperature. Specifications carried in the *ENERGY-10* PV database and transferred to the PV simulation are:

Rated power
Length
Width
Open-circuit voltage
Closed-circuit current
Maximum power point voltage
Maximum power point current
Voltage temperature coefficient
Current temperature coefficient
Tau-alpha factor
Bandgap, ev
Number of cells in series.

The system characteristics are system voltage, soiling, mismatch, and the inverter power and inverter efficiency at 10 equally spaced fractions of rated power. In the present program, which simulates grid-connected systems, the controller is assumed to achieve cell operation at the maximum power point.

STATUS

ENERGY-10 PV has been released as a beta-test version of *ENERGY-10*, called Version 1.4, in November 2000. This version implements the simulations as two separate programs, one to carry out the building simulation and the other to perform the PV simulation. It is akin to the process described in the introduction where two programs are used. The significant advantage in Version 1.4 is that the process is automated, reducing the time required to get results from weeks to minutes. For example, one automated step is converting the building simulated electrical loads into the format required by the TRNSYS program. This step is transparent to the user, happening in a fraction of a second. Another example is that the weather file used in the *ENERGY-10* simulation is converted to the weather file format required by TRNSYS, assuring that the two simulations are done with exactly the same hourly weather data, a result that would be difficult to guarantee if different programs were used.

Having said this, it must be admitted that Version 1.4 is not as seamlessly integrated as we would like. Ultimately, one would want a single program in which the building physical description used for the thermal simulation is identical to the physical description used for the PV simulation. This cannot be guaranteed in Version 1.4 because the programs are separate. In the initial automatic setup, the two descriptions will be consistent, but the user can make changes that lead to inconsistent descriptions. Version 2 of *ENERGY-10* is currently being programmed. Among other significant changes, the two programs will be merged so that PV will function seamlessly, much as any other energy-efficient strategy. In Version 1.4, it is assumed that the cells are not shaded, although the Version 2 implementation will incorporate shading as well as simulating systems with batteries. In the meantime, Version 1.4 provides a powerful tool that can provide critical information about the expected system performance.

Preliminary beta-test results are in. Although the program operates properly giving good answers, the reviewers found that it is significantly more difficult to learn than *ENERGY-10* itself. This is inherent in the two-program implementation. As a result, Version 1.4 will not be distributed to all *ENERGY-10* users. Licensed users can obtain the beta-test version on request.

CONCLUSIONS

ENERGY-10 PV fills a need to use realistic building electrical loads when performing simulations of BIPV systems. Although the implementation in *ENERGY-10* Version 1.4 provides a useful tool on an interim basis, the full integration in Version 2 will overcome some awkwardness that comes about as a result of the interaction between two separate executable programs.

The case study illustrates an example in which the PV system provides 55% of the building load at the time it is needed, drawing on the grid for the remaining 45% of the building load. However, the system feeds roughly the same amount drawn from the grid back into the grid at times when the system output exceeds the building load. This result describes a "zero-net-electrical-energy building"—one that makes no net demands on the utility grid. *ENERGY-10* PV provides a unique tool that can be used to study the hour-by-hour behavior of such a system.

The case study of a residential-building application in the companion paper[1] shows a 50%/50% split instead of a 55%/45% split. The timing is quite different, highlighting the need to carry out detailed joint simulations.

ACKNOWLEDGEMENTS

Funding to support development of the PV addition to *ENERGY-10* was provided by the PV Domestic Markets & Applications Project, Richard King, Department of Energy Program Manager. General funding for *ENERGY-10* is from the DOE Office of Energy Efficiency and Renewable Energy, Drury Crawley, Program Manager.

The TRNSYS routines in *ENERGY-10* PV were provided through the office of Prof. William Beckman at the University of Wisconsin. The DVIEW plot implementation is by Tom Lambert.

ENERGY-10 is distributed by the Sustainable Buildings Industry Council as part of the *Designing Low-Energy Buildings with ENERGY-10* package. (SBICouncil@SBIC.org or www. sbicouncil.org.)

REFERENCES

Balcomb, J.D. (September 1997). *Energy-10: A Design Tool for Buildings*, Building Simulation'97, International Building Performance Simulation Association, Prague.

Klein, S. A. (1996). *TRNSYS - A Transient Simulation Program*. Madison, WI , Solar Energy Laboratory, Univ. Wisc. Madison..

W.F. Buhl, B. Birdsall, A.E. Erdem, K.L. Ellington, and F.C. Winkelmann, LBL and Hirsch and Associates (1994), *DOE-2 Basics*, Version 2.1E, *LBL-35520*. Available from the National Technical Information Service.

Table I. Summary Results

PV cell output, kWh	17182	
PV System Output, kWh	15976	
PV Sell-back, kWh	7351	
Total Bldg Electric Load, kWh	15552	
Supplied by PV, kWh	8625	
Supplied by Grid, kWh	6927	
Peak PV Net Output, kW, time	9.8	at 3 / 6 12:00
Peak PV Output to Bldg, kW, time	6.9	at 9 / 6 12:00
Peak PV Sell-ack to Grid, kW, time	8.4	at 2 / 16 12:00
Bldg Peak Elec., kW, time	7.6	at 8 / 30 13:00
Bldg Peak PV Coincident Output, kW	5.3	same
Bldg Net Elec. Peak, kW, time	6.0	at 10 / 28 17:00
PV Annual Capacity Factor	0.19	

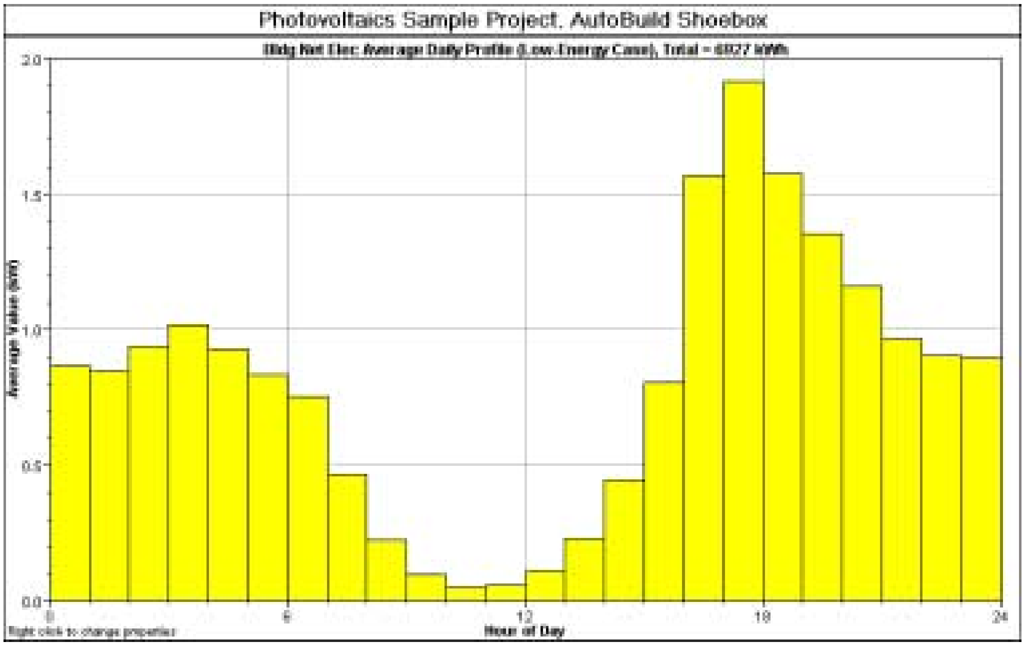

Figure 1. Building net energy, showing the total energy drawn from the grid over the whole year during each hour of the day. Note how different this is from the residential profile shown in the companion paper, which is nearly zero all day and peaks much later in the evening.

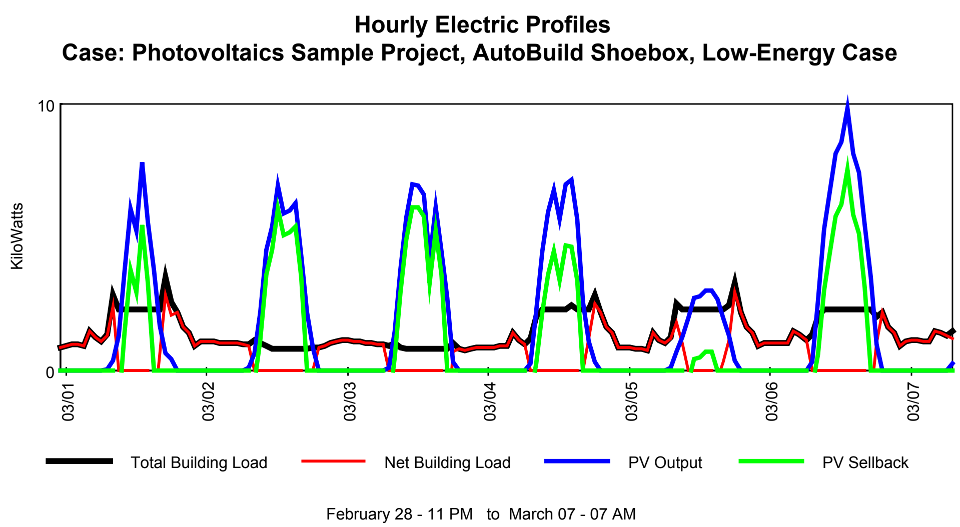

Figure 2. An example of the hourly output option. Any length of the data can be viewed. Note the variable nature of the day-to-day behavior even within one short period. Note the weekend on the second and third day.

REPORT DOCUMENTATION PAGE

Form Approved
OMB NO. 0704-0188

1. AGENCY USE ONLY (Leave blank)	2. REPORT DATE February 2001	3. REPORT TYPE AND DATES COVERED Conference Paper

4. TITLE AND SUBTITLE
Hourly Simulation of Grid-Connected PV Systems Using Realistic Building Loads

5. FUNDING NUMBERS
BET1.7001

6. AUTHOR(S)
J. Douglas Balcomb, Sheila J. Hayter, and Norman L. Weaver

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
National Renewable Energy Laboratory
1617 Cole Blvd.
Golden, CO 80401-3393

8. PERFORMING ORGANIZATION REPORT NUMBER
NREL/CP-550-29638

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

10. SPONSORING/MONITORING AGENCY REPORT NUMBER

11. SUPPLEMENTARY NOTES

12a. DISTRIBUTION/AVAILABILITY STATEMENT
National Technical Information Service
U.S. Department of Commerce
5285 Port Royal Road
Springfield, VA 22161

12b. DISTRIBUTION CODE

13. ABSTRACT *(Maximum 200 words)*
This is one of two companion papers that describe the *ENERGY-10* PV design tool computer simulation program. The other paper is titled "*ENERGY-10* Photovoltaics: A New Capability." Whereas this paper focuses on the PV aspects of the program, the companion paper focuses on the implementation method. The case study in this paper is a commercial building application, whereas the case study in the companion paper is a residential application with an entirely different building load characteristic. Together they provide a balanced view.

14. SUBJECT TERMS
ENERGY-10 PV; grid-connected PV; computer simulation

15. NUMBER OF PAGES

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
Unclassified	Unclassified	Unclassified	UL

NSN 7540-01-280-5500

Standard Form 298 (Rev. 2-89)
Prescribed by ANSI Std. Z39-18
298-102