

Energy-10 PV: Photovoltaics, A New Capability

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*



NREL

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

NOTICE

The submitted manuscript has been offered by an employee of the Midwest Research Institute (MRI), a contractor of the US Government under Contract No. DE-AC36-99GO10337. Accordingly, the US Government and MRI retain a nonexclusive royalty-free license to publish or reproduce the published form of this contribution, or allow others to do so, for US Government purposes.

This report was prepared as an account of work sponsored by an agency of the United States government. Neither the United States government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States government or any agency thereof.

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>



ENERGY-10 PV: Photovoltaics, A New Capability

J. Douglas Balcomb, Research Fellow
National Renewable Energy Laboratory
1617 Cole Boulevard
Golden, Colorado 80401
doug_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

A new feature of the *ENERGY-10* design tool computer program is the ability to model and simulate the performance of a photovoltaic (PV) system that is integrated with the building. The hour-by-hour simulation of PV performance in *ENERGY-10* is carried out using the *TRNSYS* simulation program written at the University of Wisconsin. *ENERGY-10* creates an input deck and weather file for *TRNSYS* and re-formats 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 dimming of lights due to daylighting.

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

INTRODUCTION

ENERGY-10 is a design-tool computer program (Balcomb, 1997). A new feature is the ability to model and simulate the performance of a photovoltaic (PV) system that is integrated with the building. This is an energy-efficient strategy, appearing alongside the other 12 strategies in the *APPLY* dialog box. This new feature has been introduced in Version 1.4 of *ENERGY-10*. It adds a powerful and unique capability to the program, allowing the user to study the hourly interaction 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 are modeled.

The advantages of this capability for building designers will be:

- Investigating PV will be very easy, so *ENERGY-10* users will be drawn to PV
- Integrated analysis accounting for 8,760 hours
- Hourly schedules for lights, plug loads, etc.
- Time-variable HVAC loads responding to weather
- Time-variable light dimming due to daylighting
- Comprehensive graphical output
- The ability to accommodate future technology, such as new PV products integrated into building elements or thin-film window coatings.

The hour-by-hour simulation of PV performance in *ENERGY-10* is carried out using 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.

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 (1) the overall consequences of building electrical load requirements before and after the PV system contribution, (2) PV system output, and (3) 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. New plotting capabilities provide unprecedented 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 of PV system output, PV to the building, and PV sellback.

In Version 1.4, the PV implementation is done in a separate program called up by the main *ENERGY-10* program. For the most part, the transfers are automatic and transparent, requiring no action by the user. The APPLY function for PV is operational. Eventually, in Version 2 of *ENERGY-10*, PV will be fully integrated as a module of the main program, the RANK function will be implemented, and a graphical input routine will be incorporated, allowing a user to draw the building on the screen using the mouse.

IMPLEMENTATION

As with daylighting or thermal performance, calculating PV system performance is a complex process. TRNSYS is a powerful executive program that relies on an input “deck” to define the characteristics of the system to be simulated. The model is rigorous. It characterizes the PV module performance using its current-voltage (I-V) characteristics and temperature coefficients, searching each hour for the maximum power point. Arrays are defined as series-parallel connections of modules.

Embedding one program within another is a complex process. The procedure used relies on providing the required input information, in the correct format, and reformatting the TRNSYS output into a form suitable for *ENERGY-10*. The advantage of this approach is that no modifications were required in TRNSYS—it could be used “as is.” When new versions of TRNSYS are issued, they too can be used without modification.

When a PV simulation action is initiated, the following sequence of events occurs:

1. The hourly electrical load of the building, which has been previously calculated using the CNE thermal simulation engine, is formatted for TRNSYS. CNE is the thermal simulation engine in *ENERGY-10* (Wilcox and Barnaby, 1997).
2. A TRNSYS weather file is created for the location. This is done using the hourly information in the *ENERGY-10* weather file.
3. A TRNSYS input “deck” is created using a template supplied by the University of Wisconsin and information about the PV arrays in the PV description and PV library.
4. TRNSYS is called using the files described above, and the simulation creates an hourly results file, after which control transfers back to the PV program.
5. The TRNSYS hourly results file is reformatted into a binary file. This is the file that produces the graphical results.
6. The CNE output file described in step #1 and the TRNSYS output file described in step #5 are merged to create an hourly ASCII file. This file can be opened in a spreadsheet program.
7. Finally, the CNE hourly output file is reformatted into a binary file named to correspond to the current project residing in the project subdirectory.

The files in steps 6 and 7 are accessed by the plotting routines in *ENERGY-10*, providing powerful ways to display the results annually, monthly, daily, or hourly.

All these steps are programmed into *ENERGY-10* and happen automatically. This not only saves time for the user but also increases reliability.

CASE STUDY

The *ENERGY-10* PV program can be appreciated by studying some results. We chose to evaluate a 2000-sq. ft. two-story house in Denver. As is usual in *ENERGY-10*, we started with a *reference case* building, which uses typical construction practice and applied 10 energy-efficient strategies: improved glazing, shading, energy-efficient lights, improved insulation, air tightening to

reduce infiltration, added thermal mass, passive solar heating, 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 103,000 Btu/sq. ft. per year to 22,000 Btu/sq. ft. per year. Annual electrical use is reduced from 12,200 kWh to 6,100 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.

We want to design a “zero-net-electrical-energy” house—that is, 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 $6100/8760/0.20 = 3.5$ kW. This 300-sq. ft. array would fit easily on the 1,000-sq. ft. building roof (a system for the *reference case* building would cost nearly twice as much to install, but that 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 6,100 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 slightly undersized. We increased the number of modules by one to 33 units, each with a rated power of 110 W made up of crystalline silicon cells. This is selected from the *ENERGY-10* PV default library of 13 module types.

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.

The hourly details are available, both in a large file that can be imported into a spreadsheet and visually in *ENERGY-10* PV.

GRAPHICAL OUTPUT

An important feature of *ENERGY-10* PV is a rich set of graphic outputs that provides an in-depth view of the operation of the PV system *vis-a-vis* the building electrical load. Several of the dozens of options are shown in Figs. 1–5.

CONCLUSIONS

The case study illustrates an example in which the PV system provides 50% of the building load at the time it is needed, drawing on the grid for the remaining 50%. However, the system feeds roughly the same amount back into the grid at times when the system output exceeds the building load. The result is 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 an office-building application in the companion paper¹ shows a 55%/45% split instead of a 50%/50% split. The timing is quite different, highlighting the need to carry out detailed joint simulations.

Implementing joint thermal/PV simulations illustrates the difficulty of marrying two different computer simulation engines in one package. The alternative approach of programming a new simulation tool from scratch would have been even more difficult. However, having TRNSYS on board in *ENERGY-10* will have advantages in the future for simulation of solar hot-water systems, which is a strength of the program.

STATUS

Version 1.4 was sent to reviewers for beta test in November 2000. 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.

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.
- Christensen, C. (September 1984). *Digital and Color Energy Maps for Graphic Display of Hourly Data*. SERI/TP-253-2461. Available NTIS: DE85000526.
- Klein, S. A. (1996). *TRNSYS - A Transient Simulation Program*. Madison, WI, Solar Energy Laboratory, Univ. Wisc. Madison..
- Wilcox, B. A., J. R. Barnaby, and P. W. Niles (1992). *CNE Users Manual*, Berkeley Solar Group, Oakland, CA.

Table I. Summary Results

PV cell output, kWh	6750		
PV System Output, kWh	6245		
PV Sell-back, kWh	3170		
Total Bldg Electric Load, kWh	6117		
Supplied by PV, kWh	3075		
Supplied by Grid, kWh	3042		
Peak PV Net Output, kW, time	3.6	at	3 / 6 12:00
Peak PV Output to Bldg, kW, time	2.3	at	7 / 17 12:00
Peak PV Sell-back to Grid, kW, time	3.2	at	3 / 6 12:00
Bldg Peak Elec., kW, time	2.4	at	9 / 1 17:00
Bldg Peak PV Coincident Output, kW	0.2	same	
Bldg Net Elec. Peak, kW, time	2.3	at	10 / 5 18:00
PV Annual Capacity Factor	0.20		

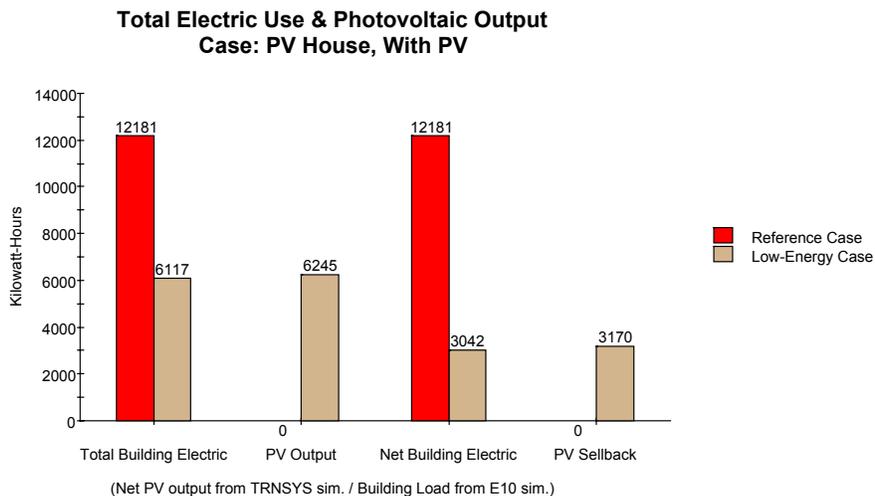


Figure 1. The first output graph in *ENERGY-10* PV, which is displayed by default after a PV simulation, gives the big picture, showing the annual performance.

Hourly Electric Profiles
Case: PV House, With PV, Low-Energy Case

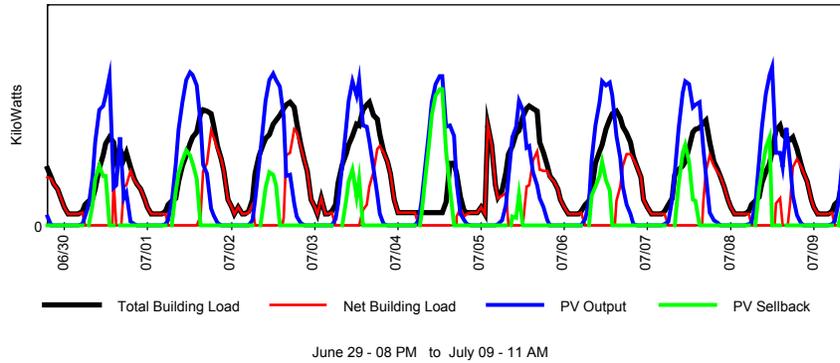


Figure 2. An example of the hourly output option. Any time length of the data can be viewed. Note the variable nature of the day-to-day behavior even within one short period.

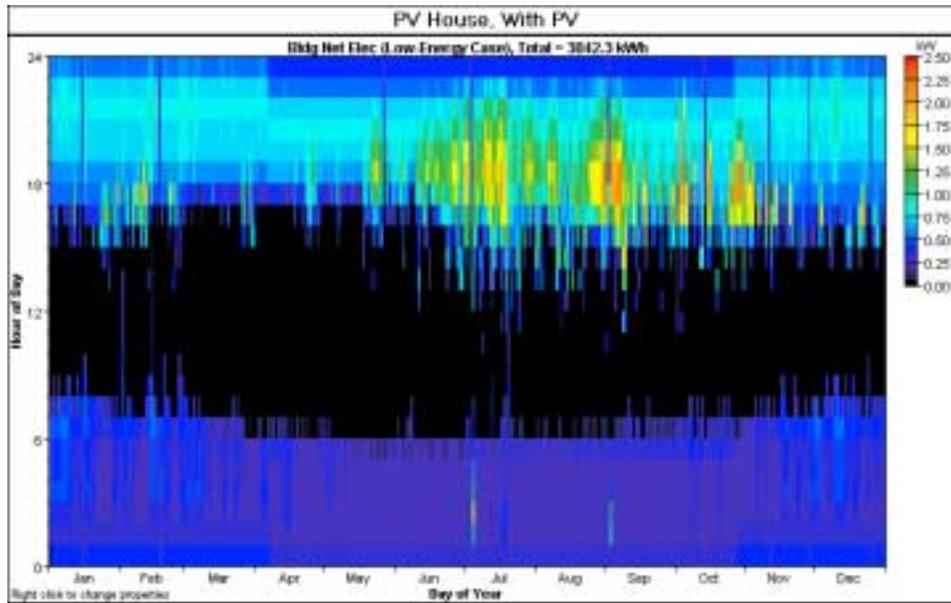


Figure 3. A DVVIEW plot (Christensen, 1994). This plotting technique shows both the time-of-year and the time-of-day behavior on one graph. The horizontal axis is the day of the year. The vertical axis is the hour of the day. The value of the variable, in this case the electricity purchased from the grid, is shown by color, as indicated on the scale at the right. Here we can see that the building uses little energy during the day, and that the peak backup electricity is early evening in three clumps in July, September, and November. Any of 13 variables can be viewed in this format.

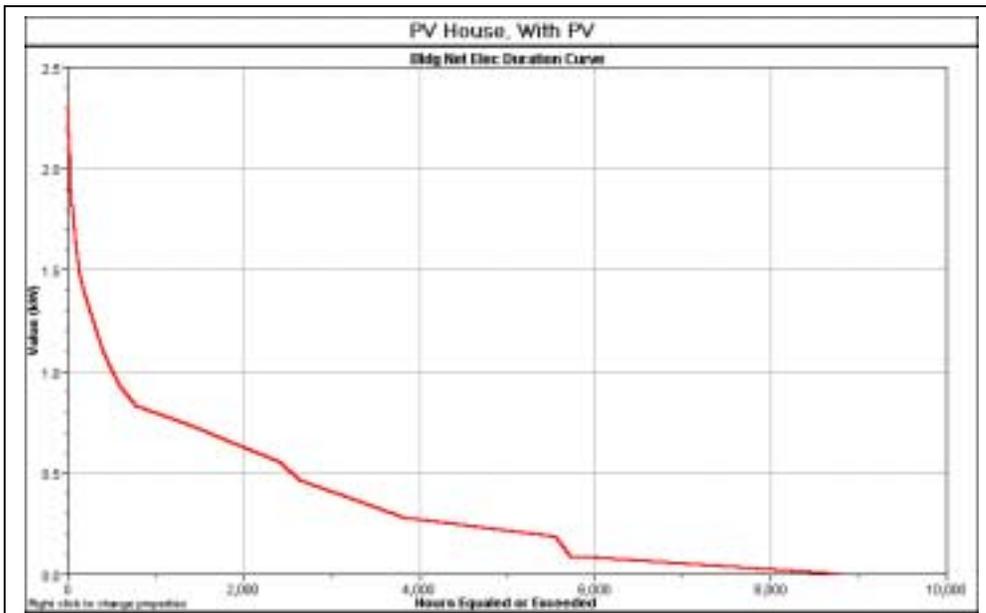


Figure 4. The load duration curve for building net energy. This is of interest to utilities, showing the number of hours a particular load is exceeded as a function of the load.

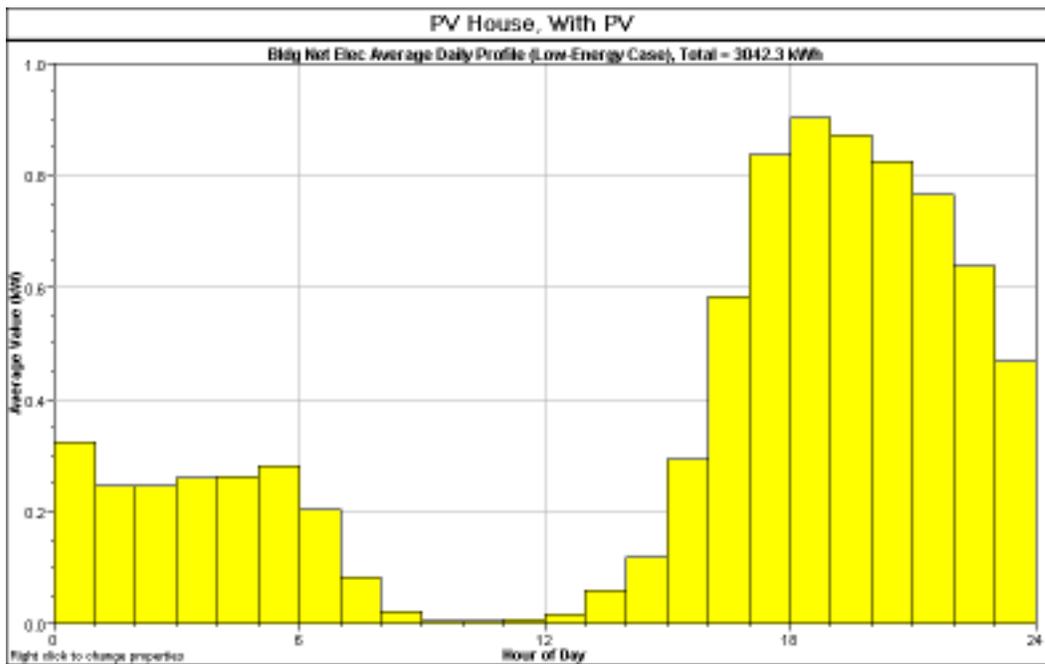


Figure 5. Another view of building net energy, showing the average total energy drawn from the grid over the whole year during each hour of the day.

REPORT DOCUMENTATION PAGE			Form Approved OMB NO. 0704-0188	
Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302, and to the Office of Management and Budget, Paperwork Reduction Project (0704-0188), Washington, DC 20503.				
1. AGENCY USE ONLY (Leave blank)	2. REPORT DATE February 2001	3. REPORT TYPE AND DATES COVERED Conference Paper		
4. TITLE AND SUBTITLE <i>ENERGY-10 PV: Photovoltaics, A New Capability</i>			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-550-29637	
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 (<i>Maximum 200 words</i>) This is one of two companion papers that describe the <i>ENERGY-10 PV</i> design-tool computer simulation program. The other paper is titled "Hourly Simulation of Grid-Connected PV Systems Using Realistic Building Loads." While this paper focuses on the implementation method, the companion paper focuses on the PV aspects of the program. The case study in this paper is a residential building application, whereas the case study in the companion paper is a commercial application with an entirely different building load characteristic. Together, they provide a balanced view.				
14. SUBJECT TERMS <i>ENERGY-10 PV; design tools; PV; computer simulation programs</i>			15. NUMBER OF PAGES	
			16. PRICE CODE	
17. SECURITY CLASSIFICATION OF REPORT Unclassified	18. SECURITY CLASSIFICATION OF THIS PAGE Unclassified	19. SECURITY CLASSIFICATION OF ABSTRACT Unclassified	20. LIMITATION OF ABSTRACT UL	