PV-BIDPAT: AN EVALUATION AND DESIGN TOOL FOR BUILDING-INTEGRATED PHOTOVOLTAIC INSTALLATIONS

Geoffrey Lewis
Gregory Keoleian
Center for Sustainable Systems
The University of Michigan
430 E. University, Dana Building
Ann Arbor, MI 48109-1115
Email: glewis@umich.edu
gregak@umich.edu

ABSTRACT

This paper discusses the development of a software tool called PV-BIDPAT, that is used to evaluate, design, and plan building-integrated photovoltaic (BIPV) installations. The tool consists of life cycle inventory and life cycle cost components and performs comprehensive calculations of the environmental costs and benefits of BIPV technology. These calculations compare BIPV to the functionally equivalent combination of conventional building materials and grid electricity. Currently there are two roofing products and one module-level inverter in the PV-BIDPAT library. An example case for a 2kW array of PV shingles in the Detroit, MI area showed significant benefits for the BIPV system in lower resource and energy use, as well as reduced air emissions.

1. INTRODUCTION

Currently, only a very small percentage of U.S. electricity is generated from renewable, potentially sustainable sources (hydropower - 8.6%, wood - 1.1%, geothermal - 0.5%, wind - 0.1%, solar - 0.03%).[1] Producing electricity from non-renewable coal, natural gas, fuel oil, and nuclear fuel is not a sustainable practice. Environmental impacts associated with these unsustainable electricity generating systems include release of greenhouse gases, acidification, dispersion of air pollutants such as mercury, formation of smog and ground-level ozone, and the generation of long-lived radioactive waste. Unfortunately, when decisions are being made about new electricity generation capacity, short-term economic factors predominate and these environmental impacts are of secondary importance. Though there are reasons to believe that this situation is slowly changing (Kyoto protocol for reduction of greenhouse gas emissions, SO2 emissions permit trading), many also believe that there is no time to waste in the shift to renewable energy sources.

Research projects at the Center for Sustainable Systems (CSS) at the University of Michigan (formerly the National Pollution Prevention Center) have the aim of generating results and tools to inform energy planners and decision makers of the full benefits of renewable energy technologies. CSS projects (including the current research) have been examining photovoltaic (PV)[2,3,4], hydrogen, and fuel cell technologies. CSS projects are typically based on industrial ecology and life cycle design concepts. Industrial ecology focuses on the systematic analysis of global, regional, and local material and energy flows associated with a product system or economic sector. Life cycle design is a method for integrating environmental requirements into product development and management while also considering cost, performance, regulatory and policy requirements.[5,6]

An elegant application of PV technology is in building-integrated designs (BIPV), in which the PV modules become an integral part of the building envelope.[7] BIPV systems perform the traditional architectural functions of walls and roofs (weather protection, structural, and aesthetic) while performing the additional function of generating electricity. BIPV systems displace conventional building materials and utility-generated electricity and do not require additional land area or supplementary support structures. Several different manufacturers are currently supplying BIPV roofing and facade elements.

Current design and planning of BIPV systems does not adequately address many life cycle issues related to materials production, manufacturing, use and end-of-life management. These issues include life cycle energy performance, pollution prevention benefits, and related cost savings. A number of investigators besides the authors have studied the life cycle energy performance of PV devices, [8-13] but the current work looks to broaden the scope of PV system studies beyond energy. A comprehensive accounting of the full benefits of BIPV in comparison with conventional building materials and fossil/nuclear electricity generating technologies is the primary focus of this project. This comprehensive accounting takes place within the structure of a computer software tool, the **P**hoto**v**oltaic-**B**uilding **I**ntegrated **D**esign and **P**olicy **A**ssessment **T**ool, or PV-BIDPAT. The PV-BIDPAT tool is the primary product of this NSF/Lucent Technologies Industrial Ecology Fellowship research project. This paper discusses the structure and operation of PV-BIDPAT, the data it contains to date (March 15th, 1999), some selected results, and a brief outline of the work to be done before the project is completed.

2. DESCRIPTION

PV-BIDPAT comprises a comprehensive set of interconnected modules that characterize environmental, cost, performance, regulatory, and policy factors influencing BIPV systems as well as the material end energy flows through these systems over their life cycles. The structure of PV-BIDPAT is strongly controlled by the modular nature of these data.

2.1 PV-BIDPAT Structure

A simplified schematic of PV-BIDPAT is shown in Figure 1. The life cycle inventory (LCI) model component (the upper half of the figure) contains several sets of modules that quantify material and energy resource inputs as well as waste and pollutant outputs associated with BIPV and conventional electricity generation and building material systems. One set (on the left) characterizes individual BIPV products built with various PV technologies (amorphous, crystalline, and crystalline silicon, CdTe & CIS thin film) for both roofing and façade applications. Another set of modules (on the right) characterize building materials (fiberglass asphalt shingles, galvanized metal roofing, curtain wall panels, glazing components) displaced by the BIPV system. A third set of modules characterizes

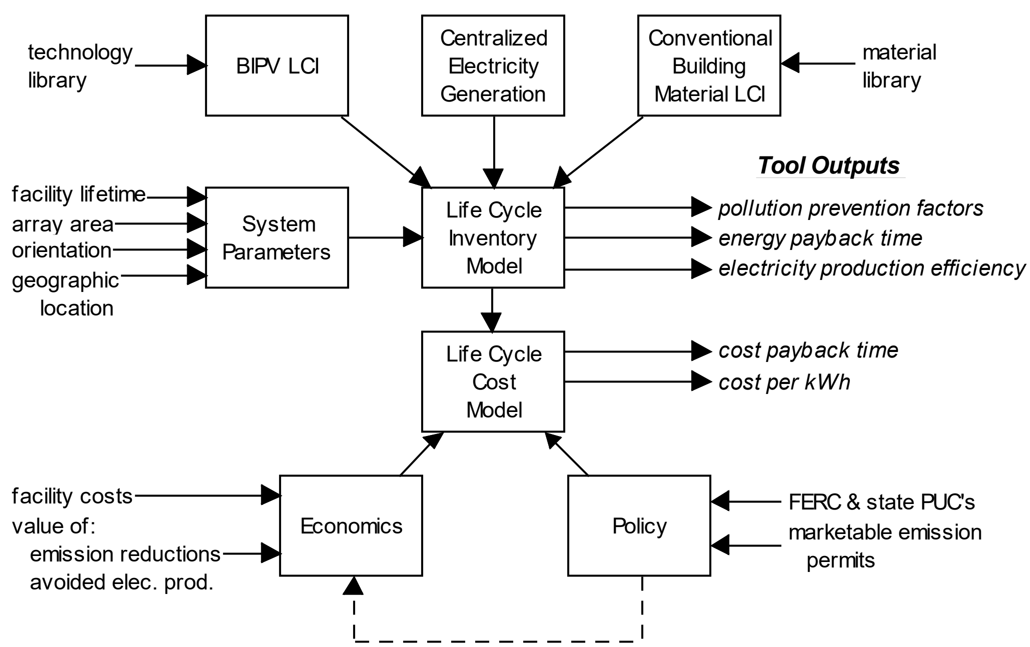

Fig. 1: A simplified schematic of PV-BIDPAT

conventional electricity generation ('the grid') by National Electricity Reliability Council (NERC) region. The final part of the LCI model is a user interface for specifying BIPV system parameters. The interface allows selection of a particular BIPV product and inverter (module, string, or array), the displaced conventional building material, geographic location, array size, tilt, and system lifetime. PV-BIDPAT currently contains data for two UniSolar amorphous silicon roofing products (shingle and galvanized steel standing seam), an AES module-level inverter, and the appropriate displaced building materials.

The lower half of Figure 1 illustrates the structure of the life cycle cost component of PV-BIDPAT. The economics module (on the left) contains information on system capital and operating costs as well as a valuation of the environmental costs of pollutant emissions and avoided electricity purchases. The policy module (on the right) allows modification of some underlying assumptions (net metering or not, valuation of currently unvalued emissions such as CO_2).

Once all of these modules are assembled and data for a particular BIPV installation has been entered, the tool generates several metrics as output. These metrics include pollution prevention factors, energy payback time, electricity production efficiency,[2] cost payback time, and cost per kWh.

2.2 PV-BIDPAT Operation

PV-BIDPAT is currently configured in Microsoft Excel. The data are contained in spreadsheets and the tool is implemented in Visual Basic. The user interface is a form with pull-down menus and boxes for input data. A preliminary version of the user interface is shown in Figure 2.

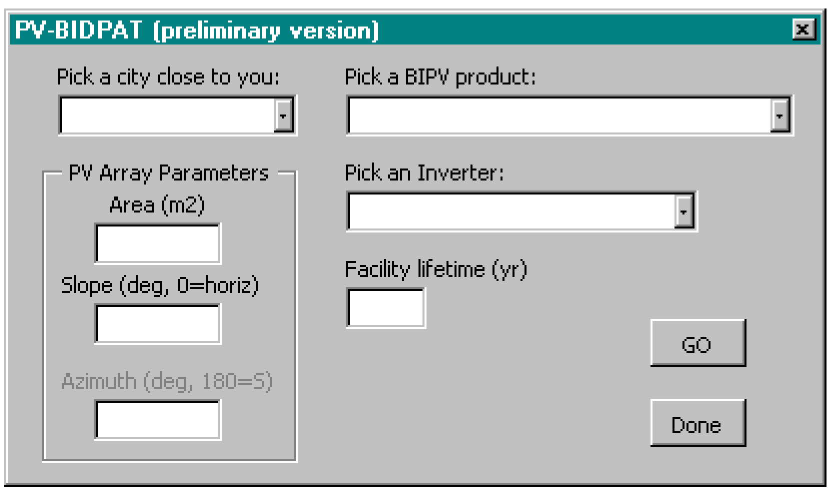

Fig. 2: PV-BIDPAT user interface

In this version of PV-BIDPAT, the user begins by making a geographic location selection from a pull-down menu, followed by filling in the array area and tilt angle. (When the method for modeling insolation is improved, array azimuth will also be an input). The user then selects a BIPV product and inverter from pull-down menus and fills in the facility lifetime, clicks the GO button and the results are calculated and saved to a separate Excel file. Data for another case can be entered and new results can be calculated or the user can click the Done button to exit. Data were not complete for the cost components, so they were not included in PV-BIDPAT as of this writing.

The calculation of results is fairly straightforward. Insolation ($Wh/m^2/day$) is multiplied by the area of the array, the cosine of the tilt angle, the PV conversion efficiency, the inverter conversion efficiency, and 365 days/year. This number is divided by 1000 to yield production of the PV array in kWh/year and then multiplied by the facility lifetime to give total kWh generated. A profile of total investments is calculated as the sum of the environmental impacts associated with the selected BIPV product and inverter. A profile of total credits is likewise calculated as the sum of the environmental impacts associated with the displaced conventional building material and electricity generation. These profiles are a measure of total environmental impacts over the facility lifetime. A net total is calculated as total investments minus total credits, with net benefits for the BIPV system showing up as negative quantities. An example of this calculation is presented in the results section.

2.3 Data

Life cycle inventory data were gathered from a variety of sources in accord with ISO 14040 guidelines. Materials are tracked from their source "in the ground" to their entry into the product system under investigation, materials leaving this system are tracked to another product system (via reuse or recycling) or back to the environment in the form of emissions or waste. Energy also is tracked from original resource through transportation, processing, generation and use. The sections that follow describe the main data types used in PV-BIDPAT.

2.3.1 Insolation

Incident solar radiation or insolation is currently modeled using National Renewable Energy Laboratory (NREL) data for yearly average global horizontal insolation in $Wh/m^2/day$.[14] This simple approximation will be modified so that an hourly simulation for one day every month is performed in the final version. These data assume no shading. Table 1 illustrates the cities currently available, their associated NERC region and insolation.

TABLE 1. CITIES CURRENTLY INCLUDED IN PV-BIDPAT, THEIR NERC REGION, AND INSOLATION.

CITY	NERC Region	Insolation ($Wh/m^2/day$)
ATLANTA	SERC	4582
BOSTON	NPCC	3910
BOULDER	WSCC	4576
CHICAGO	MAIN	3868
DETROIT	ECAR	3779
FORT WORTH	ERCOT	4891
LOS ANGELES	WSCC	4946
MIAMI	SERC	4833
MINNEAPOLIS	MAPP	3892
NEW YORK CITY	NPCC	3991
OKLAHOMA CITY	SPP	4762
PHILADELPHIA	MAAC	3987
PHOENIX	WSCC	5733
PORTLAND (OR)	WSCC	3517
RALEIGH	SERC	4395

2.3.2 Grid Electricity

Data on conventional electricity generation are compiled from Ecobalance, Inc.'s TEAM life cycle assessment software and associated DEAM database. These data are grouped by NERC region, each one of which has its own average mix of generating technologies (coal, natural gas, nuclear, hydro) and thus, its own profile of resource use and emissions per kW generated. Table 2 lists the mix of generating technologies (as a percentage) in each NERC region.

TABLE 2. MIX OF GENERATING TECHNOLOGIES (AS A PERCENTAGE) IN EACH NERC REGION.

NERC region	coal	Nat. gas	heavy fuel oil	nuclear	hydro
ECAR	89.2	0.3	0.3	9.7	0.5
ERCOT	47.0	36.4	0.2	16.1	0.3
MAAC	52.1	3.1	3.2	39.7	1.9
MAIN	58.8	1.1	0.4	38.3	1.4
MAPP	72.6	0.6	0.5	16.0	10.2
NPCC	21.0	12.3	12.5	36.6	17.5
SERC	57.6	4.8	3.4	29.2	5.0
SPP	57.6	23.5	0.6	16.0	2.0
WSCC	35.3	8.2	0.2	13.0	43.3

2.3.3 PV Material

UniSolar provided data for the two BIPV products included so far, SHR-17 shingles and ASR-128 standing seam metal roofing. Data included a complete bill of materials for both products and information on energy, resource use, and emissions for the whole manufacturing facility, prorated for each product.

2.3.4 Conventional Building Materials

Environmental inventory data on conventional building materials are compiled from the National Institute of Standards and Technology's (NIST) BEES program.[15] BEES is an acronym for Building for Environmental and Economic Sustainability and is a software package that compares pairs of conventional building materials (asphalt vs. fiber cement shingles, for example). The BEES database contains an inventory of the energy, resource use, waste and emissions per unit of building material and is the source of the asphalt shingle data. Materials that occur in both conventional and BIPV installations were not included since they have no net effect on the comparison. Materials that fall into this category are roofing felt, nails, and galvanized metal standing seam roofing. The galvanized roofing is in this category since the same material is used by UniSolar to produce their BIPV product, so the only difference is the PV laminate.

2.3.5 Balance-of-System Materials

AES provided data for the one inverter included so far, the MI-250 microinverter, a 250 watt module-level inverter. Data included a complete bill of materials and specifications for custom parts. These data have not been converted to a list of impacts, so the inverter is not yet included in the calculation of results. The environmental benefits of the BIPV system will be reduced when this balance of system component is included.

3. RESULTS

Since the focus of this paper is the presentation of the PV-BIDPAT tool, its construction and operation and the data it contains, only one set of preliminary results are presented here. Presentation and analysis of more complete and comprehensive results based on the refined PV-BIDPAT tool will be reported in future publications.

The example presented here is a 2kW array of PV shingles (360 ft^2 or 33.444 m^2 area) on a 45 degree roof surface in Detroit, Michigan. It assumes an 8% PV conversion efficiency, a 95% inverter conversion efficiency, and a 20 year product lifetime (the current warranty period for this PV product). Table 3 contains results for some selected

TABLE 3. SELECTED RESULTS FOR A DETROIT 2kW SHINGLE ARRAY EXAMPLE

	unit	PV shingle	inverter	total investment	Asphalt shingle	ECAR	total credit	net total
Resource use								
Coal	kg	777		777	6	26819	26825	-26048
Natural gas	kg	5948		5948	33	172	205	5743
Oil	kg	156		156	86	329	415	-259
Air emission								
CO2	kg	2414		2414	146	64295	64441	-62027
HC	kg	9		9	11	184	185	-176
SO2	kg	15		15	1	387	388	-373
NOx	kg	9		9	0.4	219	219	-210
Particulate	kg	31		31	12	269	281	-250
Energy								
Fuel	MJ	29965		29965	2462	772310	774772	-744807
Feedstock	MJ	7256		7256	3087	0	3087	4169
Total primary	MJ	37221		37221	5550	772310	777859	-740638

material and energy flows. Negative values in the net total column indicate lower burdens for the BIPV system; positive values indicate lower burdens for the asphalt/grid electricity system.

An examination of the net total column reveals that the BIPV system enjoys significant environmental benefits compared to the conventional electricity generating and building material combination. It is much more energetically efficient to make electricity with PV than by burning fossil fuels, as the total primary energy row in Table 3 shows. A total of 740 GJ of primary energy is saved over the life of the system. In addition, 62 metric tons of CO_2, 176 kg of HC, 370 kg SO_2, 210 kg NO_x and 250 kg of particulate emissions are avoided. Again it should be emphasized that the inclusion of the inverter in inventory modeling will reduce these benefits somewhat. There is a large credit for coal and a somewhat smaller credit for oil, while the BIPV system uses more natural gas than the asphalt/grid electricity combination. Natural gas is used for a rather small proportion of the power generated in the ECAR region (0.3%) and is the feedstock for the polymers used in the BIPV shingles. The polymers are also the explanation for the feedstock energy showing up as a “cost” of the BIPV system.

The air emissions, especially CO_2 are strong evidence for expanding the adoption of BIPV systems. The cost of the currently unmonetized CO_2 emissions would have a dramatic effect on the economics of this type of system, were they included. The air quality improvements from the reductions in HC, SO_2, NO_x and particulates are also significant considering damage and health costs due to acidification and smog formation.

4. ONGOING AND FUTURE WORK

The data collection effort is ongoing. A main priority is to fill in the currently existing data gaps (refinement of some PV materials, the inverter assessment, the economic and cost parameters). The policy and economic components also need to be completed before PV-BIDPAT is fully functional.

Future work will be focused on collecting data for other BIPV products, inverters, and conventional building materials to expand the functionality and usefulness of PV-BIDPAT. By providing early feedback on the life cycle environmental and economic performance of BIPV systems, industry and policy makers will be better informed in guiding improvements in these systems.

5. ACKNOWLEDGMENTS

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