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Document Description

PV-BILD: A LIFE CYCLE ENVIRONMENTAL AND ECONOMIC ASSESSMENT TOOL FOR BUILDING-INTEGRATED PHOTOVOLTAIC INSTALLATIONS
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Notice

This report (CSS99-02R2) is a second revision of CSS99-02. Model results presented in the second revised report were computed using a zero degree tilt. Model results presented in the first revised report (CSS99-02R) were computed using a 6% module level conversion efficiency and 45° slope (but the insolation model was not accurate and underestimated the PV output). The simulation results in the original report are based on an 8% module level conversion efficiency, which represents the active area efficiency, and for a 45° slope. As expected the electricity generation decreased, payback time increased and the air pollution prevention decreased. These results did not change our observations or conclusions.

This document is available online: http://css.snre.umich.edu

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Executive summary

An elegant application of photovoltaic (PV) technology is in building-integrated designs (BIPV), in which the PV modules become an integral part of the building envelope. 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. A life cycle environmental and economic model and software tool was developed to assist in the evaluation and design of building-integrated photovoltaic installations. This tool, called the **P**hoto**v**oltaic-**B**uilding **I**ntegrated **L**ifecycle **D**esign tool or PV-BILD, calculates a set of life-cycle environmental impacts and benefits associated with a specified BIPV system while also evaluating the combination of conventional electricity and building materials that the BIPV system displaces. The environmental data categories investigated include energy, air pollutant emissions, water use, and waste generated. PV-BILD also calculates system energy performance metrics and system economic parameters.

PV-BILD currently includes data for two BIPV products (a shingle product and standing-seam metal roofing) and one inverter, as well as insolation and electric utility parameters for 15 cities around the United States. Results were generated for a reference BIPV system (2kW$_p$ shingle system with a 20 year life) for the 15 cities in PV-BILD. The electricity production efficiency (electricity output/total primary energy input excluding insolation) for a reference system ranged from 3.6 in Portland OR to 5.9 in Phoenix, AZ indicating a significant return on energy investment. The energy performance of this BIPV system is dramatically better than conventional electricity generation. The pollution prevention benefits of displaced conventional building material were negligible compared to the benefits from displacing conventional electricity generation for the reference system. The reference system had the greatest air pollution prevention benefits in cities with conventional electricity generation mixes dominated by coal and natural gas, not necessarily in cities where the insolation and displaced conventional electricity were greatest. Detroit had the highest mass of pollution prevention for all air emissions except methane and carbon monoxide.

The life cycle economic analysis determined the value of the air pollution prevention achieved by the BIPV system. The value of avoided air pollution without regulation of carbon emissions ranged from 1.8 cents/kWh in Detroit to 0.5 cents/kWh in Boston based on the unit damage costs incorporated in the model. With carbon regulation, the value of avoided air pollution ranged from 4.4 cents/kWh in Detroit to 1.4 cents/kWh in Boston based on a carbon compliance cost of $130/ton. The cost for the BIPV reference system was 30 cents/kWh in Detroit based on a 20 year service life. Even when avoided damage costs are included, the reference system is not economically competitive with conventional grid electricity. It should be noted that many other environmental costs associated with conventional electricity generation such as oil spills, nuclear wastes, and habitat destruction from hydroelectric dams were not included in this analysis. Even considering these factors, consumers motivated primarily by economic arguments are not likely to deploy BIPV systems until system cost comes down substantially or the cost of conventional electricity rises.

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 recognize the urgency 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 objective of developing tools and generating results 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)[2-4], 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 this 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 **L**ifecycle **D**esign tool, or PV-BILD. The PV- BILD tool is the primary product of this NSF/Lucent Technologies Industrial Ecology Fellowship research project.

Objectives & Significance

Project Objectives

The primary objective of the proposed research is to develop a multi-objective life cycle analysis software tool for BIPV design, planning and policy making, PV-BILD. This tool is based on a comprehensive set of interconnected modules characterizing environmental, cost, performance, regulatory, and policy factors influencing BIPV systems. The primary function of PV- BILD is to perform comparative assessments between BIPV systems and the functionally equivalent combination of conventional building materials and electricity generating systems. PV- BILD will be applicable to any type of grid-tied building integration configuration including walls, facades, roofs, light-filtration and screening elements and any type of PV technology such as crystalline, polycrystalline, or amorphous silicon as well as cadmium telluride (CdTe) and copper indium diselenide (CIS) thin films. Life cycle inventory and cost assessments of the displaced conventional building materials and electricity generation are included as well. Inclusion of these displaced systems is an integral part of any comprehensive evaluation of a BIPV installation and is necessary to determine the full benefits and any tradeoffs of the system.

This project began with the following specific objectives:

1. Development of a life cycle inventory (LCI) and life cycle cost (LCC) model for BIPV systems, as well as for the displaced conventional building materials and centralized electricity generating systems.

2. Determination of the salient performance, regulatory and policy factors influencing the inventory and cost models. Environmental, energy, and economic performance of BIPV systems are directly dependent on these factors.

3. Construction of the BIPV design and planning tool PV- BILD to measure:

a. BIPV pollution prevention factors for air pollutant emissions (greenhouse gases, NO_x, SO_2, particulates, VOCs), water effluents (heavy metals, suspended and dissolved solids, COD, BOD, oils and greases, phosphate, ammonia), and solid waste.
b. BIPV life cycle energy performance (energy payback time, electricity production efficiency).
c. BIPV economic performance (life cycle costs, including social benefits and costs) and the implications of various policy scenarios (such as national and international policy on marketable permits for various air pollution emissions).

4. Evaluation and testing of PV- BILD using existing and proposed sites.

Project Significance

The audience for this tool is expected to be policy makers, the PV industry, and the architecture and building professions. The expected value of this tool to these groups is highlighted below.

Policy Makers
- provide understanding of the full costs and benefits of integrating PV technology into a building envelope in comparison to conventional centralized electricity generating systems
- provide a basis for developing regulatory and economic instruments that encourage more sustainable energy technologies (particularly during electricity utility deregulation)
- provide a consistent (standardized) methodology for evaluating the full potential of different types of BIPV technology
- support the U.S. Department of Energy Million Roofs initiative

PV Industry
- provide guidance for improving design and application of PV
- provide specific data for communicating the full environmental and energy benefits of BIPV systems to policy makers and the public
- provide a consistent (standardized) methodology for evaluating the full potential of different types of BIPV technology

Architecture and Building Professions
- provide guidance for BIPV system design
- provide specific data for communicating the full environmental and energy benefits of BIPV systems to clients, colleagues, and the public

The research project will investigate the following novel areas:

1. Developing interconnected life cycle inventory and cost models for a multi-functional product system.
2. Developing a life cycle-based tool (PV- BILD) that integrates performance, economic and policy factors and evaluates their relative significance to inventory and cost results.
3. Measuring the life cycle energy and economic performance of amorphous silicon thin film BIPV systems.
4. Measuring the life cycle environmental performance (air and water pollutant emissions and solid waste) for amorphous silicon thin film BIPV systems.

Methodology

The two major components of this project are the construction of the PV-BILD tool and the collection of life cycle inventory data on BIPV products, inverters, conventional building materials, and grid electricity. Before a discussion of the PV-BILD model or the life cycle inventory, a section is presented that details the scope and boundaries of the study, as well as enumerating assumptions made and existing limitations in the product.

Scope and Boundaries

Functional Unit

Since PV-BILD compares photovoltaic building materials to the combination of conventional building materials and electricity generation, it is important to know that we are comparing appropriate quantities of each. The functional unit for this investigation is defined as both building protection for a specified surface area and the provision of electricity over a defined service lifetime. This functional unit of comparison has two components: a quantity of building material and a quantity of electricity. The amount of building material is determined when the user inputs the PV array area, the amount of electricity depends on the array area also, but also on array orientation, the particular PV product and inverter chosen (conversion efficiency) and the system's geographic location (insolation). All of these parameters are specified by the user. The functional unit on the photovoltaic building materials side also includes any balance of system (BOS) components required to generate utility-quality AC electricity (such as the inverter). The components of the functional unit are compared in Table 1.

• Table 1. Functional unit components

System Function	BIPV	Conventional
building protection	BIPV	shingles, metal roofing
electricity generation	BIPV+inverter+other BOS	regional electricity grid

There is an assumption about differences in service life between the BIPV product and the conventional building material. Currently, we assume that these two materials have the same service life, the system lifetime input by the user. This assumption seems reasonable given the two PV materials in the model now, one of which is designed to directly replace asphalt shingles, and the other is laminated to an existing metal roofing product. The BIPV product is also assumed to not deteriorate over its service life to the point that its ability to perform as building protection or electricity generator is impaired.

There are also some points that need to be made about the electricity component of the functional unit. PV-BILD presently contains data for electricity generation impacts on a regional basis. The regions used are those of the North American Electricity Reliability Council (NERC). The impacts for a given region are an aggregate of the entire region and so may (or may not) be representative of impacts for an individual utility company, city, or generating facility. Also, electricity generated by the PV system is assumed to displace generation in that NERC region but is not expected to significantly alter the mix of generating technologies in the region. The result of this assumption is that regional electricity generation inventory parameters (e.g., air pollutant emission factors) will not change with the addition of a residential size PV array. This assumption will need to be revisited when PV is deployed on a large scale or when electricity generation is inventoried on a scale smaller than NERC regions. Retail competition in the electric utility business will also be cause to revisit some of the assumptions in PV-BILD, since the displaced electricity may not be from the same location as the PV array.

The calculations in PV-BILD currently do not consider the fate of any materials after their service life has ended. One factor in the decision not to include end-of-life is the difficulty in accurately establishing the service life of BIPV products since they are relatively new. It is also not clear how the life of a BIPV product will end, whether by failing to produce electricity due to delamination or other age-related deterioration or by failing to serve as a functional building skin. Regardless of the failure mechanism, it is likely that at least amorphous silicon BIPV products will have fates similar to their conventional building material counterparts. Steel roofing will likely be recycled as steel scrap, shingles will end up either in a landfill or waste incinerator. In either case, the end-of-life impacts of BIPV materials are expected to be similar to conventional building materials. The major point left to be determined is the existence of a difference in service lifetime. In PV-BILD we assume that there is no difference in service lifetime.

Technology Included

The BIPV products considered in PV-BILD are both manufactured by United Solar and are produced almost identically. They are triple-junction thin film amorphous silicon photovoltaic cells deposited on stainless steel and encapsulated in a polymer composite. The only differences between the two products are the materials included in the final lamination step. The stabilized conversion efficiency (solar radiation to electricity) of these materials was taken to be 6% based on the manufacturer's laboratory and field experience, and did not vary with temperature or account for degradation of PV performance over time (more important for amorphous than crystalline or polycrystalline silicon). These products were unique at the time data were collected for this project, though several manufacturers produce BIPV products using crystalline and polycrystalline cells deposited on glass. Other thin film BIPV products are also becoming available and it is one of the primary goals of the research team to include inventories of these other BIPV products in PV-BILD. Other manufacturers of BIPV products include Solarex, Atlantis Energy, and APS.

The primary difference between available inverters is size, both power rating and physical dimensions. The inverter included in PV-BILD is a small, currently available Advanced Energy Systems 250 Watt model. The efficiency of this inverter was assumed to be 95% based on full load operation, and did not vary with load. Smaller inverters are assumed to have lower burdens than larger, higher power inverters, though larger inverters may have lower burdens on a per-Watt basis. PV-BILD multiplies the unit burdens for the inverter by the number of inverters required for a specified PV array power output. The components used in all inverters are similar, differing mainly in size. Since use of the smaller inverters can result in the elimination of DC wiring and other related hardware, they may be more familiar for most electricians to work with than the larger units. This tradeoff between single large centralized inverters and distributed smaller inverters is another main interest the research team wishes to pursue in the future.

The conventional building materials included in PV-BILD are composite asphalt shingles and Galvalume metal roofing. These materials are widely used and representative of the choices available for roofing products.

Geographic Extent

United Solar produces the BIPV products at two facilities. The photovoltaic material is produced in Troy, Michigan, the final assembly and lamination steps occur in Tijuana, Mexico, and the finished products are stored in San Diego, California.

Advanced Energy Systems, as of the date data were collected, produced the MI250 inverter in Wilton, New Hampshire.

The boundaries of the NERC electricity regions used in PV-BILD are illustrated in Figure 1 below. The mix of generating technologies in each of these regions is discussed in the life cycle inventory section.

- Figure 1. North American Electricity Reliability Council (NERC) regions

Time Period

Data for United Solar BIPV products and the AES inverter were collected in 1997 and 1998 and is representative of current manufacturing practices. Regional electricity technology mixes, and the regional impacts that result from them, are based on electricity generation data from 1996. The asphalt shingle material data are from 1995.

Life Cycle Inventory

Life cycle inventory data were gathered from a variety of sources in accord with ISO 14040 guidelines. Material and energy resources 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. Any deviations from this tracking process are reported explicitly.

The inventory models were constructed using Ecobalance, Inc.'s TEAM life cycle assessment software. The associated DEAM database was also a source for much of the life cycle data used for material production, transportation and energy. TEAM was used to assemble a separate model for each component of the product system. When each component model was complete, the list of overall impacts for that component was exported to the PV-BILD file (in Excel) for use in inventory calculations.

Data categories

Inventory data can be grouped into several environmental categories. All inventory data collected is included in PV-BILD but only a portion of it is currently displayed in the output. The list of data categories, subcategories, and components that are displayed can be easily modified, though the user cannot currently specify this list. For this demonstration of PV-BILD, the selection of air emissions, energy, solid waste, and water use shown in Table 2 were selected to appear in the output. This study focused on air emissions and not water pollutant emissions because unit damage costs for water pollutants were not available for inclusion in the model.

• Table 2. Data categories, subcategories, and components included in PV-BILD output

Data Category	Subcategories (Components)
Air Emissions	Criteria air pollutants (CO, Pb, NO2, O3, PM-10, SO2)
	Greenhouse gases (CO2, CH4, other greenhouse gases)
	Other toxic air pollutants (Hg)
Energy	Feedstock
	Process
	Renewable
	Non-renewable
	Total Primary Energy
Solid Waste	Total solid waste
Water	Total used

Components of the product system

The following sections describe in detail the life cycle data collected for each component of the product system, assumptions made, and any missing data.

Grid electricity

Inventory data on conventional electricity generation are compiled from Ecobalance, Inc.'s TEAM life cycle assessment software and associated DEAM database. These inventory data include precombustion and combustion impacts and utilize EPA AP-42 emission factors. Electricity generation inventory 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 3 lists the mix of generating technologies (as a percentage) in each NERC region (Miami was in the SERC region at the time of data collection).

TABLE 3 Mix of generating technologies (as a percentage) in each NERC region in 1996

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

The inventory data for electricity generation account for losses in transmission and distribution but do not include the environmental impacts associated with constructing power plants. These impacts are considered to be small in comparison with the environmental impacts from the combustion of fossil fuels over the plant's lifetime.

BIPV products

UniSolar provided data for the two BIPV products presently included in PV-BILD, SHR-17 shingles and ASR-128 standing seam metal roofing. Data collected from United Solar include a complete bill of materials for both products and information on energy, resource use, and emissions for the manufacturing facility. The inventory for the standing seam metal roofing product only included the photovoltaic material and not the conventional standing seam roofing product to which it is laminated since this roofing system component is not displaced by the use of UniSolar's ASR-128. A detailed description of UniSolar's manufacturing process for amorphous silicon PV products (identical to those used in the BIPV products studied here) can be found in Lewis and Keoleian[4].

Using the bill of materials and the Ecobalance DEAM database, an inventory of material production impacts was assembled. Data were not available for all of the materials used in these BIPV products, but data for 98% of the mass of the PV shingle and 95% of the PV standing seam metal roof were included. No data were available for Tefzel, a polymer used in encapsulation, and this one material was responsible for most of the remainder of the uninventoried mass. Data were also unavailable for some of the gases used in the deposition of the photovoltaic structure, but these materials are used in such small quantities that the impacts associated with their production are likely to be small on a mass basis.

Measurements of electricity use were taken from each process machine on a per module basis to determine manufacturing process energy requirements. Impacts due to this electricity use were assigned based on the NERC ECAR region, the location of the United Solar plant. Complete data for plant overhead energy (lighting, heating, etc.) were not available in this study and so could not be included. Water use and interplant packaging data were included, though some other process material data were not. These omissions were not expected to affect results very much due to the small quantities of these materials. An alternative means of evaluating manufacturing process energy (not used here) is to divide the total plant energy requirements by the number of modules produced to find energy burdens on a per module basis. Burdens associated with administrative and research and development activities could also be allocated to the PV system.

Impacts associated with transportation of materials to the United Solar plants were included when the location of a supplier was known. This was the case for 95% of the mass of the PV shingle and 97% of the mass of the PV standing seam metal roofing. Impacts for transporting products and protective packaging by diesel truck between the United Solar plants in Troy, MI and Tijuana Mexico were included in the inventory, as were impacts for transporting completed PV shingles from the manufacturing plant to the point of use. The distance used for this final transportation link was from Tijuana to the average of the nearest (Los Angeles) and farthest (Boston) cities included in the model.

These BIPV products were assumed to have no material or energy requirements during the use phase, and end-of-life considerations were discussed in the section on the system functional unit above.

Inverter

Although there are a variety of inverters currently being manufactured, no inventory data are publicly available for any of them. AES provided data for the one inverter included so far, the MI-250 microinverter, a 250 watt module-level unit. The inventory only accounts for material production burdens since manufacturing burdens for assembly of the inverter were not available. Data included a complete bill of materials and specifications for custom parts, though not all parts of the inverter were included in the inventory calculations. Excluded were parts for which data were unavailable or of suspect quality, namely most of the electronic components (integrated circuits, resistors, capacitors, and inductors). This omission is expected to be significant since production of electronic components is generally resource intensive. The inverter inventory did include all structural parts (aluminum extrusions and covers), some electronic components, and the printed wiring board (PWB) fabrication process. Data for the PWB fabrication process and the electronic components are from the Ecobalance, Inc. EIME database. No transportation burdens were assigned for the inverter components since suppliers and their locations were not known. Transportation impacts for the completed inverter from the AES facility in Wilton, NH to the point of use by diesel truck were included. The distance used for this transportation link was from Wilton to the average of the nearest (Boston) and farthest (Los Angeles) cities included in the model.

At the time of this study, a major project was underway to develop LCA modules for electronic components. The Ecobalance, Inc. EIME database is the only potential source for modeling inverter electronic components. We intend to incorporate the remainder these data into the inverter model once they have been developed and verified.

Conventional building materials

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. Since Ecobalance is also the source of the BEES database, these data are comparable with all of the BIPV material data. Asphalt shingles were assumed to have been transported 500 miles by diesel truck, an estimate of the distance from one of the many production plants to the point of use.

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.

Peer review process

A panel of individuals was assembled to perform a peer review for this project. The members of the panel and their affiliations are shown in Table 4.

• Table 4. PV-BILD peer reviewers

Peer Reviewer	Affiliation
Dr. Jonathan Bulkley	Professor of Resource Policy, School of Natural Resources and Environment, University of Michigan
Dr. Kurt Brandle	Professor Emeritus, College of Architecture and Urban Planning University of Michigan
Susan Monroe	Architect, Facilities Planning and Design, University of Michigan
Robert Pratt, PE	Principal Engineer Energy Technology Assessment Team Detroit Edison
Dr. Marc Ross	Professor of Physics College of Literature, Science, and the Arts University of Michigan
Richard King	PV Energy Technology Program U.S. Department of Energy

Copies of the PV-BILD program and explanatory documentation were sent to the peer reviewers periodically over the course of the project. The reviewers provided comments and questions that guided the development process. The peer reviewers were also given the opportunity to review any project reports or papers that were to become publicly available, such as the paper given at the American Solar Energy Society annual meeting in June, 1999.

PV-BILD model

Structure

A simplified schematic of PV-BILD is shown in Figure 2. 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 constructed using various PV technologies (amorphous, polycrystalline, 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 conventional electricity generation (the 'grid') by NERC region. The final part of the LCI model is a user interface for specifying system and economic 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, and system lifetime. PV-BILD currently contains life cycle data (described in detail below) 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 2 illustrates the structure of the life cycle cost component of PV-BILD. The economics module (on the left) uses a significant portion of the user interface to collect data on system capital costs, value of displaced material, electricity price, and interest rate, as well as providing for the input of unit damage costs for several air pollutant emissions. The policy module (on the right) collects data on the value of any system subsidies and on compliance costs for carbon emissions, and allows a choice in the CO_2 emission regulatory policy (CO_2 emissions either regulated or not). Other policy scenarios resulting from Federal Energy Regulatory Commission

(FERC) or state Public Utility Commissions (PUC) can be explored using the existing model structure.

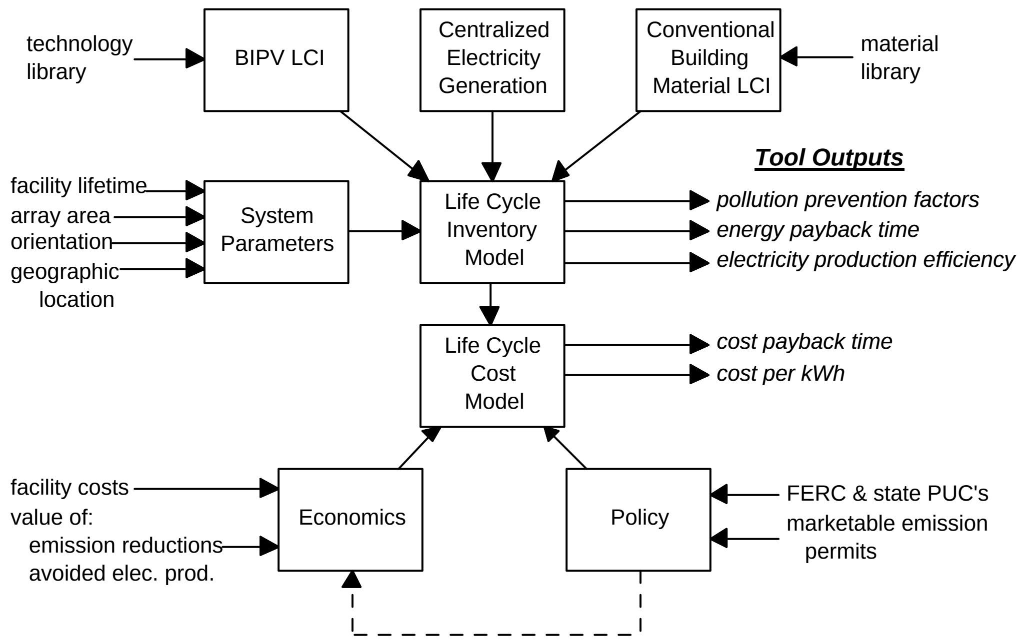

Figure 2 PV-BILD block diagram

Running PV-BILD

Running PV-BILD is a very straightforward process. Open PV-BILD.XLS either from within Excel or from the Windows Explorer. The file opens and the PV-BILD input form (seen in Figure 3) loads. This form is divided into two main areas, the PV data on the left and the economic data on the right. Details on the actual calculations performed by PV-BILD can be found in later sections, this section describes filling out the input form.

Using either the tab key or the mouse, the user fills in all of the open pull-down and text boxes, some of which contain default values. The first pull-down box allows a choice of cities, each one of which has an associated NERC region and average insolation, both of these not visible. The BIPV product and inverter pull-downs are next, both of which have associated conversion efficiencies, also not visible. Next are text boxes for the PV array area and slope, two parameters used in the electricity production calculation and to determine how much conventional building material is being displaced. The area is input in square meters. Currently, the PV-BILD insolation model is based on a horizontal deployment or zero slope. Options for evaluating the system performance at other slope values will be addressed in a future version of this model.

Once the PV choices have been made, the economic parameters are filled in. 'System cost' is the dollar total of the PV material, inverter(s), and any other balance-of-system materials. 'Value of subsidies' includes the present value (in dollars) of any buy-down, tax incentive, or rebate – anything that effectively reduces the system cost. The 'Value of displaced mat'l' box is filled in with the dollar value of the conventional building material that the BIPV material is replacing, the cost of the shingles you didn't have to buy, for example. "Electricity price' is the retail rate paid for the electricity being displaced and is used to calculate the value of this displaced electricity, assuming a net metering arrangement where PV electricity is valued at the utility's retail rate. This

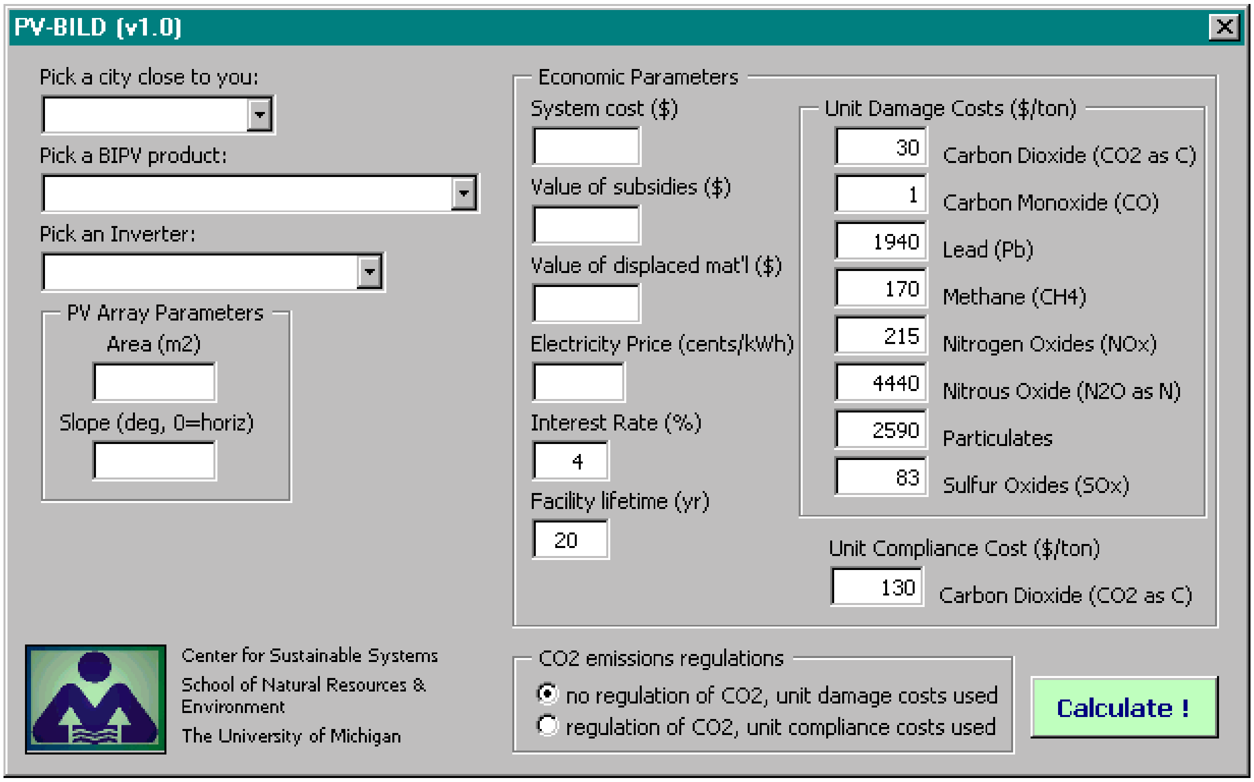

Figure 3 PV-BILD input form with default economic values, as described in Economic Calculations section

assumption can also be described as the situation where all PV-generated electricity is used on-site and reduces demand for utility-generated electricity at the retail rate. The ‘Interest rate’ box contains the interest rate, in percent, used in the present value calculations and has a default value of 4%. The ‘Facility lifetime’ box is filled in with the number of years the PV system is expected to last and has a default value of 20 years.

The next group of input boxes is labeled ‘Unit damage costs’. These boxes contain the amount of damage each of these airborne emissions is thought to cause to human health, in dollars per ton, and all of them contain default values. Notice that the unit damage cost for CO2 is actually per ton of carbon, likewise the unit damage cost for N2O is per ton of nitrogen. The last input box is for the ‘Unit compliance cost’ of CO2 (again, per ton of carbon) and is an estimate of what it would cost a facility to comply with a cap on carbon emissions. The last choice on the input form is an option button used to choose whether carbon emissions are regulated or not. All of these economic parameters and the calculations that use them will be discussed in much more detail shortly, a discussion that includes the determination of the default values.

All of the boxes are necessary, if any of them is left blank the program will not run. Once all of the boxes are filled in, the ‘Calculate !’ button is pressed, the program performs its calculations and places the results in an output Excel file called Results.xls. This output file is the topic of the section entitled “Organization of PV-BILD output".

Insolation model

Incident solar radiation (insolation) is the ‘fuel’ for photovoltaic systems and is currently modeled using National Renewable Energy Laboratory (NREL) data for yearly average global horizontal insolation in Wh/m^2/day[14]. Table 5 illustrates the cities currently available in PV-BILD, their associated NERC region, and global horizontal insolation. These data assume no shading or ground reflection component.

TABLE 5 Cities currently in PV-BILD, with NERC region, global horizontal insolation, and state average cost per kWh

City	NERC Region	Insolation ($Wh/m^2/day$)	Cost/ kWh (cents)
Atlanta	SERC	4582	7.2
Boston	NPCC	3910	10.6
Boulder	WSCC	4576	7.4
Chicago	MAIN	3868	10.3
Detroit	ECAR	3779	8.6
Fort Worth	ERCOT	4891	7.2
Los Angeles	WSCC	4946	10.3
Miami	SERC	4833	8.0
Minneapolis	MAPP	3892	7.2
New York City	NPCC	3991	13.9
Oklahoma City	SPP	4762	6.2
Philadelphia	MAAC	3987	9.3
Phoenix	WSCC	5733	8.2
Portland (OR)	WSCC	3517	5.9
Raleigh	SERC	4395	7.9

The insolation model will be developed in the future to address changes in the slope of the PV array. An option that seems to strike a reasonable balance between accuracy and computational intensity is to perform an hourly simulation of sun position relative to the PV array for one day every month and use the resultant electricity production data for the entire month. This will require that the PV array azimuth be known in addition to the slope.

Inventory Calculations

Once the life cycle inventory data for all of the components included in the functional unit have been collected, the calculation of the net impacts proceeds directly. The impacts for the BIPV products are installed in PV-BILD on a per unit area basis. When the user inputs an array area, the impacts are appropriately multiplied. The array area also determines the impacts for the displaced conventional building material, since this is also stored per unit area.
The calculation of inverter impacts is slightly more involved. Since the only inverter currently installed in PV-BILD is rated at 250 watts, it is possible that quite a few of them will be needed on a larger system. Once the array area is input and a BIPV product is selected, the nominal power output of the array is calculated. This power is divided by the rating of the inverter to determine how many inverters are necessary. Currently, the result of this calculation is not rounded up, effectively allowing fractional inverters.

Determining the impacts from displaced grid electricity is a fairly straightforward process. The amount of electricity produced by the PV system per year is calculated after the system parameters have been input. This calculation multiplies together the array area in square meters, the average insolation from the selected city in kWh/square meter/day (modified by the cosine of the array tilt), the PV conversion efficiency, the inverter conversion efficiency, and 365 days/year. The result of this calculation (kWh/year) is multiplied by the system lifetime in years to give the number of kWh produced by the BIPV system over its lifetime. The impacts for the displaced electricity depend both on the number of kWh and on the NERC region of the selected city. The grid electricity production impacts are stored by NERC region on a per kWh basis. Multiplying the

NERC region impacts by the number of kWh produced by the BIPV system results in the net impacts of displacing that quantity of grid electricity.

The last step in determining the net impacts for the BIPV system is a simple addition. First, the impacts from the BIPV product and the inverter are summed, resulting in the "investments" in the BIPV system. Then the impacts from the displaced building material and grid electricity are summed, resulting in the "credits" for the system. Then the investments are subtracted from the credits to give the net total impacts for the BIPV system. Positive values indicate a net credit; i.e. the BIPV system is an improvement over the combination of conventional material and grid electricity.

One additional calculation is performed in PV-BILD at this point. The net impacts are divided by the BIPV system's lifetime electricity production to give the net impact or credit per kWh. These values can be thought of as pollution prevention factors since they measure the amount of pollution prevented for every kWh the BIPV system generates (thereby displacing a conventional grid kWh and its associated impacts).

System Performance Metrics

Electricity Produced

The amount of electricity produced by a specified system in a given location over its lifetime is the first system performance metric calculated. It is calculated by multiplying the electricity generated per year by the system lifetime. As described in the section on economic calculations, the present value of the cost of this electricity is also calculated using the average electricity cost per kWh in the appropriate NERC region.

Energy Payback Time

Energy payback time in years was calculated by PV-BILD using Equation 1 that, in simple terms, divides the amount of energy invested in the BIPV system by the amount of energy the system generates in a year. Equation 1 considers this calculation in more detail. The variables used are defined as follows: E_{mat} = energy to extract, process, and transport raw materials to the manufacturing facility for all system components; E_{fab} = energy to fabricate system components from these materials and transport them to the use site; E_{inst} = energy required for system installation (assumed to be 0); E_{elm} = energy required for any end-of-life management activity (assumed to be 0); E_{gen}/yr = energy generated by a system in one year; and $E_{o\&m}$/yr = energy used annually for operation and maintenance (also assumed to be 0).

- $$\text{Payback time} = \frac{E_{mat} + E_{fab} + E_{inst} + E_{elm}}{E_{gen}/yr - E_{o\&m}/yr} \qquad \text{Equation 1}$$

Electricity Production Efficiency

Electricity production efficiency is calculated by summing the energy produced by a generating system over its lifetime (E_{gen}(lifetime)), and dividing it by the sum of the energy inputs required to manufacture and transport (E_{mat} + E_{fab}), install, operate and maintain (E_{iom}, which = E_{inst} + (system lifetime)($E_{o\&m}$/yr)), and dispose of or reclaim it at the end of its lifetime (E_{elm})(Equation 2). E_{iom} and E_{elm} were assumed to be zero for this analysis; in actuality both are likely to be small numbers. E_{elm} might even be negative (an energy benefit, not a cost).

- $$\text{Electricity production efficiency} = \frac{E_{gen}(\text{lifetime})}{E_{mat} + E_{fab} + E_{iom} + E_{elm}}$$ Equation 2

Electricity production efficiency is presented as a ratio. A system that generates more energy than it requires as inputs over its lifetime has an electricity production efficiency greater than 1. This is a necessary but not sufficient condition for a sustainable system.

Economic Calculations

From an economic perspective, the BIPV system generates two types of benefits: generation of electricity and displacement of air pollution emissions and other external costs of electricity production at thermal power plants. Previous sections have illustrated the quantification of these physical flows. In this section, we convert these physical flows to monetary values. A primary assumption of the analysis is that BIPV systems provide a constant service flow over their lifetime.

Electricity production

We have already seen how the electricity production of a BIPV system is calculated. Inside PV-BILD, production is calculated on an annual basis and then multiplied by the system lifetime. For the determination of the economic value of this generation, the annual benefits are discounted as a recurrent service over the system lifetime and the net present value of this service is calculated using Equation 3.

- $$Elec_{NPV} = Elec_{gen} * Elec_{price} * \left(1 - \frac{1}{(1 + \text{Int rate})^{\text{sys lifetime}}}\right) \Big/ \text{Int rate}$$ Equation 3

Where:
$Elec_{NPV}$ = net present value of electricity produced
$Elec_{gen}$ = annual electricity generation
$Elec_{price}$ = electricity price
Int rate = annual interest rate used for discounting
sys lifetime = system service lifetime

The electricity price used in the PV-BILD model was the regional average cost for conventionally generated electricity. This valuation is based on the "net metering" regulatory policy in place in several states under which utilities pay PV electricity generators retail rates for PV electricity production. The 4% interest rate used as a default value in PV-BILD is closest to the real, riskless interest rate observed in financial markets, though any interest rate may be used.

A private decision-maker that placed no value on pollution reduction would compare the present-value benefits of electricity production to the present-value costs of purchasing, installing, and maintaining the PV shingle system. A social decision-maker, in contrast, would consider the benefits of pollution reduction.

Pollution reduction

By displacing electricity production at thermal power plants, a BIPV system reduces air pollution emissions and other external costs (e.g., water pollution and land degradation) of thermal power plants and the life cycle of fossil-fuel use. This section describes the damage function approach to measuring pollution costs and illustrates the calculation of the economic benefits of pollution reduction induced by a BIPV system. As noted above, a private decision-maker typically does not incorporate pollution impacts into energy-use decisions. Economically inefficient decisions are the consequence of the failure to consider pollution impacts.

Studies that comprehensively estimate the environmental damage costs of electricity generation typically employ a damage function approach. This approach involves five major steps[16]:

1. estimate the emissions and other environmental stresses specific to the technology and fuel type being studied;
2. estimate changes in the relevant measures of environmental quality as functions of the emissions, etc.;
3. estimate the physical effects of changes in environmental quality on the relevant receptors, for example, increases in the incidence of disease as a function of increases in air pollutant levels;
4. apply unit values from the literature to convert physical effects to monetary damages for each end point;
5. aggregate damages across all receptors and end points.

The first step, as described in item 1, is to estimate the change in emissions. The next step, which combines items 2 through 4, uses the economics literature to identify marginal damage costs per unit emitted for major pollutants associated with electricity generation. Finally, as in item 5, overall damages are estimated and reported as social benefits of the reduction in pollution emissions.

The damage-function approach is an example of the benefit-transfer method used in environmental economics. In this method, original results developed for one study are transferred to other, similar studies. This method recognizes that development of original estimates of pollution damage functions would be a very expensive and time consuming undertaking.

A major assumption made in this economic analysis relates to the diverse stationary and mobile sources of air pollutant emissions modeled. Unit damage costs for air pollutant emissions from electricity generation were applied to all air pollutant emissions (e.g., from transportation). Damage costs from transportation emissions will vary depending on the route traveled and may differ significantly from damage costs associated with electricity production, but more detailed economic modeling was beyond the scope of this study.

A second limitation arises from the need to use two studies to obtain unit damage costs for all of the major air pollutants considered here, since no single economic study that encompassed this project's complete list of air pollutants was available. Consequently, comparability of unit damage costs across studies remains an issue not addressed explicitly here.

Determining unit damage costs of air pollutants.

This section focuses on marginal damage costs per unit of pollutant emissions. Estimates based on previous studies are identified for application of the benefits-transfer method. Recognizing that any such estimates are inherently associated with a high degree of uncertainty, ranges of estimates are considered whenever possible.

Marginal damage cost estimates for particulates, carbon monoxide (CO), sulfur oxides (SO_X), nitrogen oxides (NO_X), and lead (Pb) are applied from Banzhaf et al[17]. Their study analyzes the air pollution externalities associated with electricity generation in the Midwest, with a specific focus on making the results transferable to other locations and contexts. Their regional basis and techniques make the results appropriate for transfer to this study. Using air dispersion models, meta-analyses of damages from other studies, and Monte Carlo simulations, Banzhaf et al. derive confidence intervals for marginal damages from selected pollutants. Their study considers damage costs related to effects on human health, agriculture, visibility, and materials. Upstream and downstream externalities in the fuel cycle (e.g., damages from fossil-fuel extraction or fly ash waste processing after coal burning) are not incorporated. Other studies suggest that this is a relatively minor omission because air pollution damage costs constitute the vast majority (80-90%) of total damage costs.[16]

Acknowledging that damage estimates are highly sensitive to population size in affected areas, Banzhaf, et al. report results for three different scenarios[17]:

- *rural scenario*, which primarily involved the addition of a 400 MW pulverized coal plant in the western, rural part of Minnesota;
- *metropolitan fringe scenario*, which involved the same plant located just to the west of Minneapolis/St. Paul;
- *urban scenario*, which involved an increase in the emissions of two older coal plants in the Twin Cities area.

We apply results from all three scenarios developed in Banzhaf, et al[17]. Our low scenario is the midpoint of the confidence interval in the rural scenario. Similarly, the mid and high scenarios use the midpoints of the confidence intervals for their metropolitan fringe and urban scenarios, respectively. (A further elaboration of our study would be to incorporate the 5% and 95% points of the confidence intervals into the analysis to explicitly reflect uncertainty over unit damage costs). Estimates are taken directly for particulates, carbon monoxide, sulfur dioxide, and lead. Estimates are used for nitrogen oxides that recognize the additional role of NO_x in the formation of secondary particulate matter and ozone. Damage cost estimates from these scenarios are contained in Table 6, along with the default values used in PV-BILD.

- TABLE 6 Estimate of unit damage cost per ton of emission, 1998$

Air Pollutant Emission	Damage Cost Scenario			PV-BILD
	Low	Mid	High	value
Carbon Dioxide (as C)	9.73	29.97	69.54	30
Carbon Monoxide	0.33	1.12	1.77	1
Lead	451.77	1939.08	3724.75	1940
Methane	76.24	169.57	327.31	170
Nitrogen Oxides	70.50	216.02	717.43	215
Nitrous Oxide (as N)	1252.73	4441.75	10990.67	4440
Particulates	753.52	2590.52	5786.78	2590
Sulfur Oxides	18.61	82.91	160.18	83

Air emissions of mercury associated with conventional electricity generation are also of interest and were tallied in the inventory calculations above. A study estimates the marginal damage costs of mercury emissions by using a similar damage function approach across rural, suburban, and urban scenarios.[22] This study contains a single value for the unit damage cost of mercury emissions, as opposed to the ranges found for air emissions in other studies. This single value could not be corroborated in the literature and was inconsistent with the unit costs for the other emissions in the model when considering relative toxicity. As a result of this difficulty, mercury emissions were not included in the economic calculations in PV-BILD.

Beyond the pollutants already mentioned, electricity generation is associated to a large degree with greenhouse gas (GHG) emissions. While studies such as those conducted by Banzhaf, et al. do not contain estimates of GHG damage costs, other studies provide evidence that damages from GHG emissions are likely to be substantial. Two approaches have been used to estimate per-unit damage costs of greenhouse gases. One approach takes the shadow price from a dynamically efficient trajectory of GHG emissions.[18, 19] This is commonly reported as the efficient carbon tax, as carbon dioxide is the primary greenhouse gas. The second approach is to compute the actual marginal social cost of GHG emissions.[20, 21] We adopt the second approach in this study and apply the estimates of Fankhauser. As discussed below, Fankhauser's estimates using the marginal-social-cost approach are similar to other estimates in the economics literature, including those generated using the shadow-price approach.[a]

[a] Nordhaus and Yang (1996, p. 745) note, "The results [on the economic damages from climate change in their study] in the aggregate do not differ markedly from the other major estimates…", and proceed to reference Fankhauser's estimates. They also remark, "Estimates of the economic impacts or damages from climate change are sparse at this stage."

Fankhauser's model includes both market-based and non-market damages. For the market-based component, GHG damages grow in proportion to global Gross National Product. For the non-market component, GHG damages grow relative to global Gross National Product, but include a positive income elasticity to reflect the positive income elasticity of non-market goods and services. Three greenhouse gases are modeled: carbon dioxide, methane, and nitrous oxide. Fankhauser explicitly models uncertainty over GHG damages, and thus produces estimates at the mean, lower 5^{th} percentile, and upper 95^{th} percentile of a confidence interval. The upper and lower bounds of these confidence intervals for the period between 2000 and 2010 are applied as the range of damage estimates. The 5^{th} percentile is used in our low scenario; the mean is used in the mid scenario, and the 95^{th} percentile is used in the high scenario. All results are included in Table 6 along with the default value used in PV-BILD. Estimates for carbon dioxide (CO_2) and nitrous oxide (N_2O) are reported in tons of carbon and nitrogen, respectively, as is customary in the literature.

Particular care must be taken with per ton damage estimates for CO_2. Power plants that burn fossil fuels emit as much as 1000 times more CO_2 than any other air pollutant.[22] Estimates for damages per ton of CO_2, therefore, can greatly influence measurements of the damage cost of emissions. Estimates in the literature range from approximately $5 to $124 per ton for the period between 1991 and 2000, with the majority below $40.[18, 20, 21, 23-27] Fankhauser's range in the 1991-2000 period (between $6.2 and $45.2 per ton) is consistent with the majority of results from research in this area. While obtaining accurate damage estimates for nitrous oxide and methane is also important, the damages arising from these pollutants are a small fraction of total emission damages from electricity generation. Hence, overall damages are not very sensitive to estimates for these other greenhouse gases.

Determining unit compliance cost of CO_2

Additional evaluation of CO_2 emission reductions focuses on the effect of the regulatory baseline in analysis of pollution damage costs. When a pollutant is unregulated or regulated using a performance-based standard, marginal damage cost is the correct way to monetize changes in emissions. In contrast, when a pollution regulation takes the form of a cap or ceiling on aggregate emissions, then marginal compliance cost becomes the correct way to monetize changes in emissions. [28] The rationale is that, given the cap, a unit of emission reduction will only generate a corresponding unit of emission increase. Consequently, damage cost will not change. In this case, the value of emission reduction to the economy is that marginal compliance cost will be avoided.

In the case of CO_2 emissions, the issue of regulatory baseline concerns treatment of the Kyoto Protocol. The initial set of carbon benefit measures is computed as if a verifiable treaty on CO_2 emissions is not in place. In contrast, a second regulatory baseline assumes that provisions of the Kyoto Protocol are in place. The protocol sets an emission cap for CO_2 and suggests that a transferable permit system for CO_2 be implemented among Annex I countries. [29, b] Based on the range of values presented by the U.S. Department of Energy in 1998, PV-BILD uses a default value of $130/ton for the unit compliance cost of CO_2.[29]

Using unit damage and compliance costs

Now that unit damage and compliance costs have been determined, we will illustrate how they are used to calculate the total net present value of emission reductions. The benefits of these reductions are computed in two steps. First, annual benefits for each emission are calculated as

[b] A similar analysis could be conducted with SO_2 emissions. The 1990 amendments to the Clean Air Act establish a cap on aggregate SO_2 emissions by electric utilities and an SO_2 permit trading system. This analysis was not conducted for two reasons. First, the SO_2 benefits are a minor component of aggregate pollution reduction benefits. Second, the average SO_2 allowance price (which will closely approximate marginal compliance cost) has been, since the inception of the program, in the range of $100 to $200 per ton, which is the unit damage cost of SO_2 in the high scenario. (In contrast, estimates of marginal compliance cost with the Kyoto Protocol are significantly higher than carbon's unit damage costs.) Thus, such an analysis would not generate additional insight.

the product of unit damage cost (UDC) and the annual quantity of emission reduction attributable to the BIPV system (NER). This quantity is also called the avoided annual damage cost (AADC), Equation 4.

- $AADC = UDC * NER$ Equation 4

Second, the annual benefits are discounted over the system lifetime to obtain present-value benefits, as in Equation 3. By summing the present value for each emission, we calculate the total net present value of emissions reductions. A similar calculation is performed for the carbon compliance cost.

Economic system performance metrics

In PV-BILD, there are two main economic system performance metrics, the system net present value and the system cost per kWh. Each of these metrics can then be calculated either as a "social" metric using damage/compliance costs, or as a "private" metric using a subsidy. The specific calculations for all of these economic metrics are reviewed here.

First though, the way that the carbon compliance cost is used in the calculation of system performance metrics needs to be explained. As discussed above, compliance cost only comes into play if the scenario being considered includes a cap on carbon emissions, as signaled by the option button on the PV-BILD input form. If that is the case, carbon damage cost is replaced by carbon compliance cost in the calculation of system performance metrics. Regardless of the scenario, the term damage/compliance cost is used to refer to this quantity.

The system private net present value sums the present value of the electricity generated by the BIPV system, the avoided conventional material cost, and the value of any subsidies, and then subtracts the system cost. This is the present value a private individual would realize. Negative values indicate an uneconomical system.

The system social net present value likewise sums the electricity net present value and the avoided material cost, but then adds the avoided damage/compliance costs instead of the system subsidy before subtracting the system cost. This is the cost that a social decision-maker would look at and, as above, negative values imply an uneconomical system.

The cost per kWh metric is calculated three different ways in PV-BILD, all of them very similar. This metric is calculated because it is commonly used to compare electricity-generating systems. System cost per kWh subtracts the cost of avoided conventional building material from the system cost and divides the result by the energy produced by the system over its lifetime. Private cost per kWh also subtracts the subsidy from the system cost and avoided material cost before dividing by energy produced. Social cost per kWh is identical to private cost per kWh with the only difference being the replacement of the subsidy in the calculation with the damage or compliance cost.

Organization of PV-BILD output

An example of Results.xls, the Excel output file from PV-BILD, can be seen in Figure 4 on the next page. This file is a single worksheet divided into four sections. The upper left contains the inventory calculations that are used to determine net impacts from the use of a BIPV system. To the right of this area is a small section that reiterates the selections from the user input form so it is plain what system the results pertain to. Directly below the inventory calculations is a damage and compliance cost calculation section. The final section, below the damage and compliance costs, is the section containing the system performance metrics.

Article	Units	BIPV Prod	Inverter	Investment (C + D)	Displaced bldg mat	Grid elec	Credit (F + G)	Net total (H - E)	Total/kWh
(r) Coal (in ground)	kg	792.91	92.31	885.22	0.19	28918.88	28919.07	28033.85	5.24E-01
(r) Natural Gas (in ground)	kg	6051.61	58.39	6110.00	0.97	185.97	186.94	-5923.06	-1.11E-01
(r) Oil (in ground)	kg	244.78	71.97	316.75	2.58	354.48	357.06	40.30556	7.54E-04
(r) Uranium (U, ore)	kg	0.02	0.01	0.02	0.00	0.14	0.14	0.114546	2.14E-06
Water Used (total)	liter	9076.21	9336.93	18413.14	0.80	571.12	571.92	-17841.2	-3.34E-01
(a) Carbon Dioxide (CO2, fossil)	g	2738950.50	618322.00	3357272.50	4352.21	69330448.00	69334800.21	65977528	1.23E+03
(a) Carbon Monoxide (CO)	g	1659.49	792.67	2452.16	5.69	15935.77	15941.46	13489.3	2.52E-01
(a) Hydrocarbons (except methane)	g	873.35	700.77	1574.11	3.18	5001.98	5005.17	3431.052	6.42E-02
(a) Hydrocarbons (unspecified)	g	3571.86	262.15	3834.01	21.39	1555.66	1577.05	-2256.96	-4.22E-02
(a) Lead (Pb)	g	6.99	1.31	8.31	0.00	36.64	36.64	28.32844	5.30E-04
(a) Mercury (Hg)	g	0.04	0.00	0.04	0.00	1.35	1.35	1.312365	2.45E-05
(a) Methane (CH4)	g	5541.94	1394.53	6936.47	7.39	191850.80	191858.19	184921.7	3.46E+00
(a) Nitrogen Oxides (NOx as NO2)	g	12416.63	1577.01	13993.63	11.67	235977.91	235989.58	221995.9	4.15E+00
(a) Nitrous Oxide (N2O)	g	83.16	11.32	94.48	0.28	1565.37	1565.65	1471.163	2.75E-02
(a) Particulates (unspecified)	g	31326.68	1478.98	32805.66	349.23	289696.91	290046.13	257240.5	4.81E+00
(a) Sulfur Oxides (SOx as SO2)	g	15448.23	13499.94	28948.17	26.30	416966.53	416992.83	388044.7	7.26E+00
Waste (total)	kg	685.37	152.16	837.54	0.00	12412.30	12412.30	11574.77	2.17E-01
E Feedstock Energy	MJ	7434.93	523.00	7957.93	92.27	0.00	92.27	-7865.65	-1.47E-01
E Fuel Energy	MJ	34481.08	6955.90	41436.98	73.60	832795.63	832869.22	791432.2	1.48E+01
E Non Renewable Energy	MJ	41595.58	6438.58	48034.16	165.57	831296.31	831461.88	783427.7	1.47E+01
E Renewable Energy	MJ	283.35	806.32	1089.67	0.30	1499.75	1500.05	410.3781	7.68E-03
E Total Primary Energy	MJ	41916.30	7529.57	49445.87	165.87	832795.63	832961.50	783515.6	1.47E+01

Results for:
DETROIT
8.60 cents/kWh
UniSolar SHR17
AES MI-250
20 year lifetime
34.00 sq m area
0.00 deg slope
4 % interest rate
$16,000 system cost
$1,000 subsidy
$100 displaced building material

Avoided Pollution Damage Cost Calculation

Air Emission	Unit cost ($/ton)	Avoided annual damage cost ($)	Present value ($)
(a) Carbon Dioxide (CO2 as C)	$ 30.00	$ 29.75	$ 404.34
(a) Carbon Monoxide (CO)	$ 1.00	$ 0.00	$ 0.01
(a) Lead (Pb)	$ 1,940.00	$ 0.00	$ 0.04
(a) Methane (CH4)	$ 170.00	$ 1.73	$ 23.55
(a) Nitrogen Oxides (NOx as NO2)	$ 215.00	$ 2.63	$ 35.75
(a) Nitrous Oxide (N2O as N)	$ 4,440.00	$ 0.23	$ 3.11
(a) Particulates (unspecified)	$ 2,590.00	$ 36.72	$ 499.04
(a) Sulfur Oxides (SOx as SO2)	$ 83.00	$ 1.78	$ 24.12
	Total	**$72.84**	**$989.97**

Avoided CO2 Compliance Cost Calculation

	Unit cost ($/ton)	Avoided annual compliance cost ($)	Present value ($)
	130	**$128.93**	**$1,752.14**

System Performance Metrics

electricity produced, lifetime	**53463**	kWh
present value of electricity produced	**$3,124.29**	
energy payback time	**5.14**	years (total primary energy in / energy produced per year)
electricity production efficiency, BIPV	**3.89**	(electricity produced / total primary energy, BIPV+inverter)
electricity production efficiency, grid	**0.23**	(electricity produced / total primary energy in)
system private net present value	**-$11,775.71**	(electricity pres val+avoided mat'l cost+subsidy-system cost)
system social net present value	**-$11,785.74**	(electricity pres val+avoided mat'l cost+avoided damage/compliance cost-system cost)
system cost per kWh	**0.30**	dollars/kWh (system cost-avoided mat'l)/energy produced
private cost per kWh	**0.28**	dollars/kWh (system cost-avoided mat'l-subsidy)/energy produced
social cost per kWh	**0.28**	dollars/kWh (system cost-avoided mat'l-damage/compliance cost)/energy produced

Figure 4 Results.xls example

Inventory calculation

The inventory calculation section is a fairly straightforward spreadsheet layout. The leftmost column contains a list of "Articles", the most elemental units used in the analysis of impacts. These inflows and outflows are compared between BIPV and conventional systems. Many of the articles have prefixes in parentheses; these prefixes indicate either a resource (r) or an air emission (a). Energy articles are preceded by a capital E. Column B contains the measurement units for the articles. The next two columns contain the impacts associated with the production of the BIPV material (column C) and inverter(s) (column D). Column E sums the impacts from the BIPV and inverter columns to give the total impacts from the BIPV side of the functional unit. Likewise, columns F and G contain the impacts on the other side of the functional unit, the conventional building material and the displaced grid electricity, followed in column H by the sum of these two. The values in column I are net totals resulting from subtracting the impacts for the BIPV system from the impacts for the displaced electricity and material. Positive values in this column indicate a net BIPV system credit for that article, an amount of pollution prevented in other words. Negative values indicate that the BIPV system has larger emissions or usage than the displaced conventional system for that article.

Damage/compliance cost calculation

The damage and compliance cost section comprises four columns: a list of pre-selected airborne emissions, their associated unit damage costs from the input form; an avoided annual damage cost calculated from the inventory amount above, and the unit damage cost, assuming impacts distributed equally over the system lifetime; the present value of that annual cost given the system lifetime and interest rate. These calculations have been discussed in more detail above.

System performance metrics

The system performance metrics are divided into three groups. The top group displays the amount of electricity produced by the BIPV system over its lifetime and the present value of that electricity at the specified interest rate and electricity price. The second group contains the energy payback time for the BIPV system (how long it takes to generate the amount of energy it took to make the system) and the BIPV electricity production efficiency (how much energy the BIPV system produces per unit of energy it took to make the system). For comparison, this group also displays the electricity production efficiency of the NERC region for the city specified on the input form. The final group of system performance metrics is all economic and includes the system private net present value and system social net present value. The final three metrics in this group are electricity cost per kWh calculated on three different cost bases. Again, all of these calculations are described in more detail above.

Results

A series of results were generated with PV-BILD to illustrate the type of analyses that it was designed to assist. These results were all generated with the same "reference" system chosen to be representative of a residential rooftop installation. This system comprised 34 square meters of United Solar SHR-17 PV shingles (an array rated at approximately $2kW_p$) deployed horizontally and AES MI-250 inverters. Global horizontal insolation data in Table 3 were used to calculate electricity generation for the BIPV reference system. A zero tilt application was assumed for modeling purposes although such applications are not practical for the shingle system. Generally for BIPV systems, a tilt angle equal to the latitude normally maximizes annual electricity generation. The system lifetime was 20 years and a 4% interest rate was used in all economic calculations. The system cost was taken to be $16,000 based on the retail cost of the BIPV product and inverter at the time the results were generated. The system subsidy was assumed to be $1,000 and the value of displaced conventional building materials was $100, based on the retail cost of asphalt shingles. PV-BILD was run for all 15 cities using the reference system and the results were grouped by system performance metric.

Electricity Produced, Electricity NPV

The total number of kilowatt-hours (kWh) of electricity generated by the reference system in the 15 cities currently included in PV-BILD was calculated, and the results are collected in Table 7. These results, which are a function of insolation in these cities, indicate the amount of kWh that do not need to be supplied by the conventional electricity grid due to the operation of the BIPV system.

• Table 7. Electricity produced (kWh) by the reference system over its 20 year lifetime, by city

City	kWh produced, lifetime
Atlanta	45840
Boston	39120
Boulder	45780
Chicago	38690
Detroit	37800
Fort Worth	48930
Los Angeles	49480
Miami	48350
Minneapolis	38940
New York	39930
Oklahoma City	47640
Philadelphia	39890
Phoenix	57350
Portland	35180
Raleigh	43970

These results mirror the insolation data from Table 5. Since the only difference between the different cases considered was their insolation, the kWh produced follows directly from insolation. The lifetime generation data contained in Table 7 above were split into equal annual increments over the 20-year system lifetime and the net present value (NPV) of this electricity was calculated at a 4% interest rate. The electricity cost used in the NPV calculation was the average for the state in which each of the cities in the table are located (i.e., the Michigan average cost was used for Detroit). These state average costs are contained in Table 5 above. The results of the NPV calculation are collected in Table 8.

• Table 8. Net Present Value (at 4% interest rate and state average cost per kWh) electricity produced by the reference system over its lifetime, by city

City	Electricity NPV
Atlanta	$3,170
Boston	$3,980
Boulder	$3,260
Chicago	$3,830
Detroit	$3,120
Fort Worth	$3,390
Los Angeles	$4,900
Miami	$3,720
Minneapolis	$2,690
New York	$5,330
Oklahoma City	$2,840
Philadelphia	$3.560
Phoenix	$4,520
Portland	$1,990
Raleigh	$3,340

These results are slightly more complicated than the lifetime electricity generated. Since the cost of electricity is part of this calculation, cities with high costs have high NPV even if they didn't have tremendously high lifetime generation (see New York). On the other hand, cities with low costs and low generation have low NPVs (see Portland) while those with low cost and high generation have moderate NPVs (Boulder).

Energy Payback Time

The results of the energy payback time calculation are contained in Table 9. These values indicate the number of years it takes the reference system to generate the amount of energy that it took to manufacture the system originally.

• Table 9. Energy payback time (years) for the reference system, by city

City	Energy Payback Time, years
Atlanta	4.24
Boston	4.97
Boulder	4.24
Chicago	5.02
Detroit	5.14
Fort Worth	3.97
Los Angeles	3.93
Miami	4.02
Minneapolis	4.99
New York	4.87
Oklahoma City	4.08
Philadelphia	4.87
Phoenix	3.39
Portland	5.52
Raleigh	4.42

These results also mirror the insolation, just like lifetime generation above. Since the reference system is used for all cities, the only variable affecting energy production is insolation. Cities with high insolation have shorter energy payback times.

Electricity Production Efficiency

The results of the electricity production efficiency calculation for both the reference BIPV system and the conventional grid are collected in Table 10. The conventional grid results are calculated for each NERC region so cities in the same NERC region have the same electricity production efficiency. The values in the table are the ratio of energy outputs from a generating system to energy inputs to the system, with all energy measured on a primary basis. Values greater than 1 indicate that a system generates more energy over its lifetime than it consumes.

• Table 10. Electricity production efficiency for the reference system and NERC region, by city

City	Electricity Production Efficiency	
	BIPV system	NERC region
Atlanta	4.72	0.26
Boston	4.03	0.30
Boulder	4.71	0.36
Chicago	3.98	0.25
Detroit	3.89	0.23
Fort Worth	5.04	0.26
Los Angeles	5.09	0.36
Miami	4.98	0.26
Minneapolis	4.01	0.25
New York	4.11	0.30
Oklahoma City	4.90	0.26
Philadelphia	4.11	0.26
Phoenix	5.91	0.36
Portland	3.62	0.36
Raleigh	4.53	0.26

The BIPV system electricity production efficiencies also track the insolation available in each of the cities considered. Since the energy inputs were identical for all of these systems and the only other determinant of electricity production efficiency for a BIPV system is its energy output, this is not a surprising result. It is useful to compare the BIPV systems against the conventional electricity generation represented by NERC region data. Since the conversion of fossil fuels into electricity via combustion is only about 30% efficient and there are further losses in transmission and distribution of centrally generated electricity, current conventional generation cannot approach the efficiency of the distributed BIPV systems considered here.

Pollution Prevention Benefits

Air pollution prevention benefits provided by the reference system in 6 of the 15 cities in PV-BILD are presented in Tables 11 and 12. These cities were chosen to be diverse in conventional generation mix and insolation. Table 11 contains the mass of air pollution emissions avoided. Table 12 contains the mass per kWh of electricity generated by the reference BIPV system. The negative lead emissions value for Boston indicates that more lead is released into the environment from production of the BIPV system than from the NPCC electricity grid and the production of the displaced conventional roofing.

• Table 11. Total mass of air pollutant emissions avoided by the reference system over a 20 year period, in grams

Air Emission	Mass of air pollutants avoided (grams)					
	Boston	Boulder	Detroit	Phoenix	Portland	Raleigh
Carbon Dioxide (CO2 as C)	2.42E+07	3.27E+07	6.60E+07	4.19E+07	2.44E+07	5.23E+07
Carbon Monoxide (CO)	6.55E+03	7.48E+03	1.35E+04	9.99E+03	5.18E+03	1.14E+04
Lead (Pb)	1.11E+00	9.26E+00	2.83E+01	1.37E+01	5.20E+00	1.93E+01
Mercury (Hg)	3.24E-01	6.11E-01	1.31E+00	7.76E-01	4.61E-01	9.86E-01
Methane (CH4)	6.34E+04	9.97E+04	1.85E+05	1.27E+05	7.50E+04	1.47E+05
Nitrogen Oxides (NOx as NO2)	6.14E+04	1.03E+05	2.22E+05	1.33E+05	7.63E+04	1.69E+05
Nitrous Oxide (N2O as N)	4.38E+02	6.95E+02	1.47E+03	8.94E+02	5.12E+02	1.13E+03
Particulates (unspecified)	4.53E+04	1.07E+05	2.57E+05	1.42E+05	7.45E+04	1.87E+05
Sulfur Oxides (Sox as SO2)	8.08E+04	1.71E+05	3.88E+05	2.22E+05	1.25E+05	2.87E+05

• Table 12. Total mass of air pollutant emissions avoided by the reference system, in grams per kWh

Air Emission	Mass of air pollutants avoided per unit electricity generated (grams/kWh)					
	Boston	Boulder	Detroit	Phoenix	Portland	Raleigh
Carbon Dioxide (CO2 as C)	4.37E+02	5.06E+02	1.23E+03	5.16E+02	4.90E+02	8.41E+02
Carbon Monoxide (CO)	1.18E-01	1.16E-01	2.52E-01	1.23E-01	1.04E-01	1.83E-01
Lead (Pb)	2.01E-05	1.43E-04	5.30E-04	1.69E-04	1.04E-04	3.11E-04
Mercury (Hg)	5.85E-06	9.45E-06	2.45E-05	9.57E-06	9.27E-06	1.59E-05
Methane (CH4)	1.15E+00	1.54E+00	3.46E+00	1.56E+00	1.51E+00	2.36E+00
Nitrogen Oxides (NOx as NO2)	1.11E+00	1.60E+00	4.15E+00	1.64E+00	1.53E+00	2.72E+00
Nitrous Oxide (N2O as N)	7.92E-03	1.07E-02	2.75E-02	1.10E-02	1.03E-02	1.82E-02
Particulates (unspecified)	8.19E-01	1.65E+00	4.81E+00	1.75E+00	1.50E+00	3.01E+00
Sulfur Oxides (SOx as SO2)	1.46E+00	2.64E+00	7.26E+00	2.73E+00	2.51E+00	4.61E+00

The value of these air emission pollution prevention benefits was then calculated by considering the annual amount of each of 8 criteria air pollutants not emitted due to the use of the reference system in each of these cities and the unit damage cost for these emissions, except for mercury which was discussed above. The default values for these damage costs, which are held constant across the cities in this analysis, can be seen in Figure 3 above. Using the resulting annual avoided emissions cost, the system lifetime and a 4% interest rate, the present value of these avoided emissions was calculated. This calculation was performed assuming both no regulation of carbon emissions and again assuming regulation of carbon emissions, as described in the section on economic calculations. The resulting values are collected in Table 13.

• Table 13. Damage cost value of BIPV air emission pollution prevention benefits, by city

City	Avoided damage cost, present value	
	w/o C regulation	with C regulation
Boston	$260	$754
Boulder	$449	$1,118
Detroit	$990	$2,338
Phoenix	$585	$1,440
Portland	$325	$823
Raleigh	$750	$1,818

These results are a function of the mass of air emissions avoided by the BIPV system in each city considered. The mass of avoided air emissions in turn depends on insolation but more strongly on the relative cleanliness of the mix of conventional electricity generating technologies in that city's NERC region. A city like Detroit has a high avoided damage cost since, even though it has lower insolation because it is in a NERC region dominated by coal and has high air emissions. So every kWh displaced by BIPV in Detroit avoids a large amount of air emissions. Within a NERC region, the city with the largest insolation has the highest avoided damage cost. Boulder, Phoenix, and Portland are all in the same region and the results for these cities track their insolation values.

System Net Present Value

The system net present value is calculated two separate ways reflecting the interests of a private individual and a social decision-maker. The results of these calculations are contained in Table 14. These calculations are described in the economic calculation section above, but those descriptions are repeated here. The system private net present value sums the present value of the electricity generated by the BIPV system, the avoided conventional material cost, and the value of any subsidies, and then subtracts the system cost. This is the present value a private individual would realize and negative values indicate an uneconomical system.

The system social net present value likewise sums the electricity net present value and the avoided material cost, but then adds the avoided damage/compliance costs instead of the system subsidy before subtracting the system cost. This is the cost that a social decision-maker would look at and, as above, negative values imply an uneconomical system.

• Table 14. System net present value, both private and social, by city

City	System Net Present Value	
	private	social
Atlanta	-$11,740	-$11,940
Boston	-$10,920	-$11,660
Boulder	-$11,640	-$12,200
Chicago	-$11,070	-$11,430
Detroit	-$11,780	-$11,790
Fort Worth	-$11,510	-$11,770
Los Angeles	-$10,000	-$10,510
Miami	-$11,180	-$11,350
Minneapolis	-$12,200	-$12,390
New York	-$9,570	-$10,300
Oklahoma City	-$12,060	-$12,210
Philadelphia	-$11,340	-$11,740
Phoenix	-$10,380	-$10,800
Portland	-$12,910	-$13,580
Raleigh	-$11,560	-$11,810

From a purely economic viewpoint, the reference system is not cost effective in any of the cities considered. Cities with higher cost electricity (New York) fare slightly better, as do cities with higher insolation (Phoenix). There are, however, a number of benefits provided by BIPV systems that are not included in these calculations. Electric utilities benefit from peak demand reductions and a reduced need to upgrade transmission and distribution equipment. Individuals who install BIPV systems frequently place a significant value on accepting responsibility for the effects of the electricity they use. BIPV systems reduce conventional electricity generation impacts such as nuclear waste and habitat destruction resulting from damming streams and rivers for hydroelectric plants. The United States government sees benefit in a thriving domestic PV industry and in reducing the need for military presence to protect access to foreign fossil fuel feedstock. Finally, the damage costs included in PV-BILD are a select set of human health impacts only. Even considering all of these factors, individuals motivated primarily by economic arguments are not likely to deploy BIPV systems until system cost comes down substantially or the cost of conventional electricity rises.

Cost per kWh

The results of the cost per kWh calculations are collected in Table 15. These calculations are described in the economic calculation section above but this description is repeated here. The cost per kWh metric is calculated three different ways in PV-BILD, all of them very similar. System cost per kWh subtracts the cost of avoided conventional building material from the system cost and divides the result by the energy produced by the system over its lifetime. Private cost per kWh also subtracts the subsidy from the system cost and avoided material cost before dividing by energy produced. Social cost per kWh is identical to private cost per kWh with the only difference being the replacement of the subsidy in the calculation with the damage/compliance cost.

• Table 15. Reference system, private, and social cost per kWh, by city

	System cost, $ per kWh		
City	**system**	**private**	**social**
Atlanta	0.25	0.23	0.23
Boston	0.29	0.27	0.28
Boulder	0.25	0.23	0.24
Chicago	0.29	0.27	0.28
Detroit	0.30	0.28	0.28
Fort Worth	0.23	0.22	0.22
Los Angeles	0.23	0.21	0.22
Miami	0.23	0.22	0.22
Minneapolis	0.29	0.27	0.27
New York	0.28	0.26	0.28
Oklahoma City	0.24	0.22	0.22
Philadelphia	0.28	0.26	0.27
Phoenix	0.20	0.18	0.19
Portland	0.32	0.30	0.31
Raleigh	0.26	0.24	0.24

These results mirror those above for system net present value, although they are cast in a more understandable form. It is straightforward to compare these values with the familiar cost of electricity on our electric utility bills. The same arguments above apply here as well.

Scenarios

In addition to the results calculated above, several scenarios were considered using PV-BILD and the reference system described above. The first scenario was determining which of the 15 cities in PV-BILD had the maximum air emission pollution prevention benefits, on a mass basis. The second scenario sought to determine the subsidy required to bring the system private net present value to the break-even value of $0. The third scenario likewise was seeking the damage cost necessary to bring the system social net present value to break-even.

Pollution Prevention Benefits

This scenario examined the pollution prevention benefits calculated by PV-BILD to find the locations for which the reference system had the greatest beneficial impact. Only air emissions were considered in this scenario. The three cities with the greatest pollution prevention benefits are collected in Table 16 by air emission.

- Table 16. Cities with the three greatest amounts (by mass) of air emission pollution prevention

Air Emission	**Pollution prevention benefits, ranked by mass of avoided emission**		
	most	**second most**	**third most**
Carbon Dioxide (CO2 as C)	Detroit	Oklahoma City	Miami
Carbon Monoxide (CO)	Fort Worth	Oklahoma City	Detroit
Lead (Pb)	Detroit	Minneapolis	Miami
Mercury (Hg)	Detroit	Minneapolis	Miami
Methane (CH4)	Fort Worth	Oklahoma City	Detroit
Nitrogen Oxides (NOx as NO2)	Detroit	Oklahoma City	Miami
Nitrous Oxide (N2O as N)	Detroit	Oklahoma City	Miami
Particulates (unspecified)	Detroit	Minneapolis	Miami
Sulfur Oxides (SOx as SO2)	Detroit	Minneapolis	Miami

These results follow closely the proportion of coal and natural gas in each of these cities' NERC regions, with coal being more important. Detroit (89.5% coal and natural gas) was the only city in the ECAR region and had the highest mass of avoided air emissions for nearly all species considered. Fort Worth at 83.4% coal and natural gas, Oklahoma City at 88.1%, Minneapolis at 73.2% and Miami at 62.4% (and the highest insolation in the SERC region) were the only other cities represented in these results of the top 3 cities. The reference BIPV system has the greatest pollution prevention benefit in these cities because they have generating mixes with more air emissions than the other cities included in PV-BILD. This point is important for policymakers in areas with difficulty meeting federal air quality standards.

Subsidy or Damage Cost for $0 NPV

The second scenario took the perspective of a private individual with the aim of finding what subsidy would be necessary to make the system cost effective in present value terms. A cost-effective system is defined as one having a private net present value of $0. This scenario was conducted for the 6 cities shown in Table 17 and for interest rates of both 1% and 4%.

- Table 17. Subsidy required to make the reference BIPV system cost effective (i.e., have a $0 private net present value)

City	**subsidy required for $0 private NPV**	
	1% interest rate	**4% interest rate**
Boston	$10,610	$11,920
Boulder	$11,580	$12,640
Detroit	$11,750	$12,780
Phoenix	$9,900	$11,380
Portland	$13,250	$13,910
Raleigh	$11,470	$12,560

The third scenario examined system value from a social decision-maker's vantage point to determine what damage costs are necessary to make the system cost effective in present value terms. A cost-effective system is defined as one having a social net present value of $0. This scenario was likewise conducted for 6 cities and interest rates of 1% and 4%. Since the system cost, NPV of electricity generated, and value of displaced materials are the same as in the $0 private cost scenario and the only difference in the damage cost calculation is that damage cost replaces subsidy, the results are identical to those found in Table 17. This is in agreement with expectation, as the social decision maker would seek to make the subsidy equal to the externalities, in this case the damage cost.

Conclusions

A life cycle environmental and economic model and related software tool PV-BILD were developed to evaluate the performance of building-integrated photovoltaic systems relative to conventional building materials and electricity generation. The model successfully integrates life cycle inventory data for the BIPV and conventional products with economic unit damage cost to measure net environmental impacts, electricity generation, system energy performance and economic metrics. PV-BILD can be applied to evaluate various BIPV technologies, though a life cycle inventory analysis of each technology is required. The model presently has the capability of comparing BIPV systems with conventional electricity generation in 15 cities across the United States. Another application of this tool is to estimate the pollution prevention benefits of a particular BIPV installation, which can then be used to educate building occupants and visitors about this technology.

The application of the life cycle modeling of BIPV was demonstrated for two UniSolar amorphous silicon PV roofing products, a shingle product and standing-seam metal roofing. The electricity production efficiency (electricity output/total primary energy input excluding insolation) for a reference system ($2kW_p$ shingle system with a 20 year life) ranged from 3.6 in Portland OR to 5.9 in Phoenix, AZ indicating a significant return on energy investment. Lower values of this metric are expected as life cycle modeling becomes more comprehensive, for example by including more inverter electronic components. Nevertheless, the energy performance of this BIPV system is dramatically better than conventional electricity generation for these cities (0.36 electricity production efficiency).

The analysis of pollution prevention benefits provided by the BIPV system yielded unexpected results. The reference BIPV system had the greatest air pollution prevention benefits in cities with conventional electricity generation mixes dominated by coal and natural gas, not necessarily in cities where the insolation and displaced conventional electricity were greatest. Detroit had the highest mass of pollution prevention for all air emissions except methane and carbon monoxide.

The pollution prevention and economic value of displaced conventional building material for the reference system was negligible compared to the benefits from displacing conventional electricity generation. In the case of the standing-seam roofing product, there are no displaced conventional building materials since the identical metal roofing material is required for both systems. There are, however, significant advantages that accrue from eliminating the support structure required for non building-integrated PV arrays, as shown in previous work by the authors.[2-4]

The life cycle economic analysis determined the value of the air pollution prevention achieved by the BIPV system. Economic calculations highlighted the point that there are many values of BIPV systems, such as pollution prevention, that are not included in decision making processes. The value of avoided air pollution without regulation of carbon emissions ranged from 1.8 cents/kWh in Detroit to 0.5 cents/kWh in Boston based on the unit damage costs incorporated in the model. With carbon regulation, the value of avoided air pollution ranged from 4.4 cents/kWh in Detroit to 1.4 cents/kWh in Boston based on a carbon compliance cost of $130/ton. This study identified several limitations in the economic modeling of air pollution. One major limitation is that literature values of unit damage costs vary widely. An OTA review found environmental costs of conventional electricity generation varied from 0 to 10 cents/kWh.[30]

The cost for the BIPV reference system was 30 cents/kWh in Detroit based on a 20-year service life. Even when avoided damage costs are included, the reference system is not economically competitive with conventional grid electricity. It should be noted that many other environmental costs associated with conventional electricity generation were not included in this calculation. Even considering these factors, individuals motivated primarily by economic arguments are not likely to deploy BIPV systems until system cost comes down substantially or the cost of conventional electricity rises.

PV-BILD may be used both to highlight the particular benefits of different BIPV technologies and the policy changes that would be necessary for energy generating systems to be compared on an equitable basis. Examples of the types of policies that could be examined are carbon taxes, tax credits, buydown programs, or other subsidies.

Future work

As with the first version of any software, there are many facets of PV-BILD that would be improved by more refinement and effort. Some of these improvements are relatively simple programming changes, others require major data collection and research.

First, the smaller details. PV-BILD writes output to the same file, Results.xls, every time it is run. It would be better if the program gave the user the option of selecting a file name instead of forcing them to rename Results.xls after every run. Also, the program doesn't have any error checking on the inputs provided by the user on the input form so that improper data entries cause a crash. Adding error checking to the program would be useful.

Another improvement involves including material and energy inputs for operation and maintenance in the model. This addition should not affect results for BIPV systems very much, but inverters do break and PV arrays in certain situations may need to be cleaned occasionally. It would also be useful to allow the user to specify a factor for degradation of PV performance over time (more important for amorphous than crystalline or polycrystalline silicon).

The last of the more minor changes involves the insolation model. PV-BILD currently starts with daily global horizontal radiation, averaged for the entire year, and reduces it by the cosine of the array slope to model the reduction in effective horizontal area. This very simple approximation although it is not too deleterious in comparative scenarios, should be improved. This raises the question of how accurate the insolation model needs to be. We do not believe, for this application, that full-year hourly simulations of solar input are required. Perhaps hourly simulations of one day every week or two or even once a month would provide a good compromise between accuracy and computational intensity.

Once we start considering the changes that would have the greatest positive effect on the utility of PV-BILD, we find that these tasks involve a bit more effort. The single largest improvement in PV-BILD will result from the inclusion of life cycle data for more BIPV products and inverters. The tool is still very useful with the small library it now contains, but there is no doubt that it would benefit greatly from a larger library of products. Some manufacturers may be concerned that providing confidential product or process data would reduce their competitive ability or enable potentially unfavorable comparisons to be made. Every technology and every manufacturer has strengths and weaknesses. This tool highlights strengths and identifies weaknesses so that they may be improved to the manufacturer's benefit, and we are experienced at maintaining the confidentiality of sensitive data.

Another modification that would expand the utility of PV-BILD involves the way that impacts from grid electricity are handled. NERC regions are currently used as the unit of grid electricity. Unfortunately these regions are very large and smaller scale variation in fuel mix and emissions is lost since impacts are aggregated over the entire region. Using geographic regions smaller than a NERC region or, ultimately, allowing the user to specify a fuel mix would improve the accuracy and applicability of the results. There are complications in allowing the user to specify a fuel mix since transportation of fuels and transmission of electricity need to be accurately accounted for as well. With retail competition apparently coming to electric utilities, we need to consider that displaced generation may not be local in the near future and plan to accommodate this eventuality in PV-BILD. This modification would allow the modeling of a specific utility or even a specific generating plant as the source of the displaced electricity generation.

A useful modification is apparent in the determination of default values for damage and compliance costs. Currently these are midrange values from the economics literature and do not vary with city or with the urban, suburban, or rural location of the system under consideration. It is a positive step to acknowledge that these damage and compliance costs vary with location, but it is much more difficult to establish what these costs would be in different locations. There may be some areas, such as the South Coast Air Quality Management District in southern California, where these costs may be easier to identify. Perhaps the appropriate strategy would be to determine the areas for which these costs are relatively available and include them in the model, and use the default values from the literature for the remaining areas. Adding the option of including annual property taxes on the BIPV system would also improve the economic accuracy of the model.

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