THE SIMULATION OF BUILDING INTEGRATED PHOTOVOLTAICS IN COMMERCIAL OFFICE BUILDINGS

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ABSTRACT

Building Integrated Photovoltaic (BIPV) system implementation is on the rise worldwide. A computer modeling tool was developed to predict BIPV system power generation in commercial buildings. This tool utilizes hourly weather data files and complex Electric Utility tariff structures to predict BIPV system power output as well as providing economic analysis. A number of cities and building facade angles were modeled to test the predictive nature of this tool. A 35 degree photovoltaic (PV) module tilt angle (90° being vertical) proved to be the most efficient design, with simple economic paybacks ranging from 31 to 39 years. The results closely agreed with previously published data on PV generation, thereby validating the tool's accuracy. Furthermore, this tool has built-in flexibility to adapt quickly to changes in PV technology and Electric Utility tariffs.

INTRODUCTION

There has been growing international interest in the implementation of photovoltaic (PV) power systems in commercial buildings, which generally involve either building integrated PV (incorporated into the building roof and facades) or stand-alone PV panels. In dense urban environments, where security and expensive real estate are often major concerns, building integrated PV (BIPV) systems have the distinct advantage of being an intrinsic component of a building's overall structure and electrical system. In addition, BIPV systems are being utilized more and more by major architectural firms for their aesthetic and conceptual qualities.

A major hurdle to a widespread participation in the commercial PV movement is the unknown economic cost of implementing PV panels in a commercial environment. In addition, the modeling tools and analytical data associated with commercial PV are lacking relative to those associated with traditional building energy systems.

METHODOLOGY

A modern six-story office building was utilized as the base building model for this study. This building has a 30 meter by 20 meter rectangular footprint, with the long orientations of the building facing due South and North. The floor to floor height is 4 meters for each story, while the gross square footage of this building measures 3,600 square meters. The facade for each floor consists of vision glass 2.1 meters in height, with 1.8 meters of vertical spandrel between floors (this spandrel/glass combination is typical of many modern office buildings being designed in the United States today). Insulated PV panels are installed in place of where conventional structural spandrel panels would normally be in a conventional building.

Because all the geographical locations modeled are above 30 degrees North latitude, the East and West facades are shaded by the building itself for significant portions of the day, which dramatically decreases module output [Kovach and Schmid (1996)]. Furthermore, the North facade receives almost no solar radiation for a considerable portion of the year. Therefore, to achieve a reasonable economic payback, the modeled building has PV collectors installed on the South Facade only.

PV modules typically have a manufacturer's rated power output value in Watts (at 25° C) for a specific size panel. This value can vary significantly, depending on the performance of the panel. Since the panels are located on a building in a congested urban environment an allowance factor of 0.94 is needed to account for the decreased efficiency of the panels due to dirt accumulation on the panel surfaces. Furthermore, at high ambient temperatures PV performance decreases according to equation (1) [Kuwano and Takeoka (1990)].

$$P = P_{25} \bullet [-0.5\% \bullet (t - 25° C)] \qquad (1)$$

where P_{25} is the manufacturer's rated power output of the PV module and t represents the ambient temperature.

The panels are all wired into a DC to AC power inverter, which has a manufacturer rated efficiency.

PV cell performance varies with the spectral distribution of solar radiation. This spectral distribution varies in turn with the solar location, season, local weather conditions, altitude, and time of day [Hirata and Tani (1995)]. To account for these variations TMY2 hourly weather data obtained from the United Sates National Climatic Data Center (NCDC) was utilized. This hourly data represents a number of weather parameters (temperature, wind speed, etc.) for a typical year of weather for a specific geographic location. This typical weather year is considered a „representative year", as it is extrapolated by the NCDC from a 23 year period of climatic data.

SIMULATION OF BIPV PERFORMANCE

The hourly TMY2 weather data for a number of cities around the United States was imported into a newly created Microsoft Access database. Programming code was developed utilizing Visual Basic to calculate the power generated by the BIPV system for each hour of the year. The Visual Basic code prompts the user to enter: the number of PV modules; the size of each PV module (in square meters); the cost of each module; and the maufacturer's rated power per PV module (in Watts). These inputs are utilized by the software code to calculate the PV collector efficiency. The user also inputs the city and the inverter efficiency.

The code accesses the solar location as well as the drybulb temperature, the horizontal solar radiation, and direct radiation figures directly from the specified city's weather database. This data is utilized, along with the PV collector efficiency and tilt angle (90° being vertical) to produce 8,760 hourly PV power output calculations spanning from January 1 through December 31. The code proceeds to adjust these PV output figures further to account for inverter losses and panel dirt accumulation as discussed above. These hourly results are summed to achieve monthly power output figures (in kWh per square meter of PV modules).

Inputs for the baseline building included 162 PV modules, 2 square meters per module, a manufacturer's power rating of 240 Watts per module (120 Watts per square meter of module), and a 93% inverter efficiency. The results, described as annual power output per square meter of PV module, is displayed in Figure 1 for the baseline building in the city of Los Angeles.

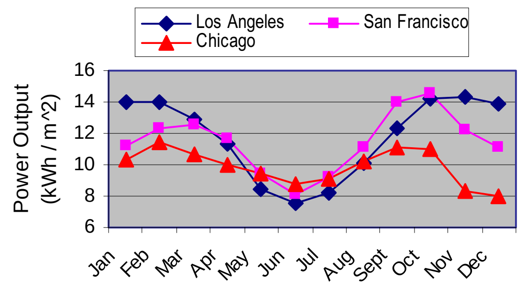

Figure 1: Vertical BIPV Power Output

Similarly, simulations were executed for the cities of San Francisco and Chicago, utilizing the appropriate TMY2 weather data files (Figure 1).

Another set of simulations was executed with the assumption that the BIPV collectors were set at a tilt angle of 35 degrees from vertical. The Visual Basic code automatically adjusts for this new PV angle and the result is increased direct solar radiation striking the PV collectors. To achieve this angle for the collectors an architect might either design the entire Southern curtain wall at the desired angle or separate and hang the PV collectors at an angle from the vertical facade. Due to the PV collector angle being closer to true perpendicular to the direct solar radiation, the PV output results shown in Figure 2 improved significantly over the vertical PV orientation (Figure 1).

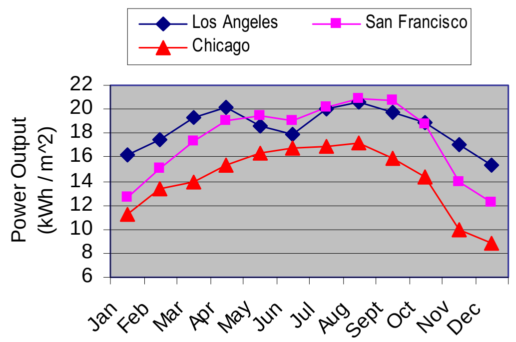

Figure 2: 35 deg. Tilt BIPV Power Output

SIMULATION OF BIPV ECONOMICS

After creating a BIPV analysis tool the next logical step was to develop an economic payback analysis for BIPV systems. Since many electric utility tariffs in the United States involve complex rate structures often incorporating multiple demand and transmission charges, it is often difficult to develop a payback analysis for the BIPV system using only PV output generation figures. Therefore, it was determined that the computer calculation tool must include these rate structures to adequately perform a feasible economic analysis.

Since all three cities studied are served by different Electric Utility providers, and therefore have different rate structures, a data array was developed for each city's unique Utility tariff. These arrays were entered into the Microsoft Access Database system and include the demand and transmission charges for each hour of the day for each of the 12 calendar months. Additional Visual Basic code was written to access this array for each hour of the year to compute the net worth, based on current retail electricity rates, of the electric power generated by the BIPV system.

A price of US$1380 per 2 square meter PV module (US$5.75 per rated Watt) was assumed and input into the base building simulation. The annual net worth of the PV production is indicated in Table No. 1 and listed in US$ per rated power output (Watts) of the PV modules. The PV angle has also been varied which illustrates the relationship between PV tilt angle and PV efficiency. The simple economic paybacks in years for the systems have also been computed (Table No. 2).

Table 1: Net worth of IBPV Power Genererated Annually (in US$ / Watt)

PV Tilt angle (90 = vert)	Los Angeles	San Francisco	Chicago
90	0.098	0.108	0.097
60	0.143	0.167	0.146
30	0.174	0.184	0.148
0	0.148	0.172	0.136

Table 2: Simple payback of IBPV System (in years)

PV Tilt angle (90 = vert)	Los Angeles	San Francisco	Chicago
90	59.0	53.1	59.5
60	40.1	34.5	39.4
30	33.0	31.2	38.8
0	38.8	33.5	42.3

ANALYSIS

The computer modeling tool performed well in predicting PV power generation. Figure 1 illustrates the effect of a very small angle between a vertical PV surface and the sun during the summer months. There is a dramatic decrease in PV power from May through September.

Figure 2 reveals a 104% improvement for the three cities over the vertical PV results by utilizing a 35° tilt for the PV collectors. Furthermore, Chicago's PV production trails behind California production 20-50% due to steady cloud cover seen throughout the year.

The payback analysis (Table 2) periods at first seemed high at over 30 years, although they closely agreed with other published results. A powerful way to reduce the payback is to investigate rebate programs sponsored by government and private agencies. In the city of Los Angeles at the present time the local electrical utility is offering up to $5 per installed rated Watt of solar modules. Utilizing this incentive, the payback for the Los Angeles base-building solar modules would be a reasonable 6 to 10 years.

Table 1 also points to the fact that climate is not the sole factor in determining the economic payback. Chicago had 21% less PV power generation in a vertical BIPV system than Los Angeles (Figure 1) did over the course of a year. However, the simple payback was essentially the same due to Chicago's lower commercial electricity rates.

The computer estimating tool ran each simulation in less than 10 seconds on Pentium 400 PC. Since the weather files are especially data intensive, the simulation processing time may increase significantly on a slower machine.

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CONCLUSIONS

This paper has shown the computer modeling tool developed has a strong capability to predict BIPV system power generation, as well as useful economic results. The strongest feature of this tool is it's use of hourly weather data files and it's inclusion of complex Utility tariff structures. A missing piece, however, to this modeling tool is the exclusion of a user friendly front-end to input utility schedules. However, an accompanying user's manual with a step-by-step procedure on creating unique utility schedule databases would be an adequate substitute.

The long simple payback times for BIPV systems predicted with the computer tool should spur architects, engineers, and other building professionals to develop new methods to significantly lower costs in the future. This tool is flexible enough to adapt quickly to changes in PV equipment technology, architectural design, and Utility rate structures.

REFERENCES

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NOMENCLATURE

AC Alternating Current

DC Direct Current

BIPV Building Integrated Photovoltaic

kW kiloWatt – a measure of instantaneous electric demand

kWh kiloWatt – hours, a measure of electricity consumption

m meter

P Power produced by a Photovoltaic Collector

PV Photovoltaic

TMY2 Typical Meteorological Year – Hourly weather data file

US$ = United States dollars (currency)