ANALYSIS OF THE BENEFITS OF PHOTOVOLTAIC IN HIGH RISE COMMERCIAL BUILDINGS

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ABSTRACT

Energy efficient glazing is necessary to reduce heat gains or losses that contribute to the high-energy use of buildings. However, high-rise commercial buildings that use energy efficient glazing are still consumptive. To reduce their energy use further, recent studies have integrated photovoltaic glazed window systems into the building shell. To understand the relationship between photovoltaic windows, energy use and human satisfaction, this paper presents a study of the effects of photovoltaic glazed windows on the energy use of large commercial buildings and includes an assessment of the overall human satisfaction of the workers within photovoltaic glazed office spaces. A prototypical building was used to develop the base case simulations for the DOE-2 energy simulation program and the PV F-Chart photovoltaic analysis program. By substituting the appropriate variables in the base case simulation for each site, the building was simulated to evaluate the impact of the PV glazing on the building's heat loss/gain as well as the amount of electricity that could be expected from the PV. To test for human satisfaction, a survey was performed to assess the overall preference of the subjects to the office spaces using the photovoltaic glazed windows. Finally, an overall assessment of the economic and non-economic impacts is also discussed (Sylvester, 1999).

INTRODUCTION

The Need for Energy Conservation

Despite the reduction in the per capita energy use and the steady increase in the GNP in the US, the consequences of future energy shortages and the resultant increases in energy costs (Kraushaar and Ristinen, 1993) can be seen in the recent blackouts in America's northeastern and pacific northwestern states during the summer of 1999. Therefore, we must continue to give immediate attention to predicted increases energy prices, while maintaining a stable economic and social structure for future generations. In this section, a discussion of the impacts of solar energy on government policies, deregulation of the utility industry, building construction, the energy use of commercial buildings, and social acceptance is presented.

Government Policy and Support

With governmental concerns over accelerating energy conservation, research of Building Integrated Photovoltaic (BIPV) systems has been congressionally mandated in the United States (Ashley, 1992). Additionally, major government demonstration programs using BIPV systems have been initiated in Austria, Germany, Switzerland and the Netherlands (Schoen & Blum, 1994).

With efforts to significantly increase the use of clean and renewable resources, President Clinton announced the Million Solar Roofs Initiative for the US in 1994. Working with businesses and communities, the U.S. Department of Energy plans to coordinate the installation of solar panels on one million new roofs by the year 2010. The President's program targets: 1) electric utilities and energy service organizations, 2) PV manufactures and PV infrastructure organizations, 3) community, city and corporate personnel, 4) community development organizations, 5) residential and commercial real-estate developers, 6) architects and energy consultants, and 7) local and regional financial institutions (UPG, 1997).

Likewise, the Department of Energy promotes partnerships between the public and private sectors to promote the development utility photovoltaic markets (UPG, 1997). The Technology Experience to Accelerate Markets in Utility Photovoltaics (TEAM-

UP) program funds ventures that develop sustainable markets and opportunities using PV applications. It also funds programs that take advantage of business opportunities with PV technologies and supports the expansion of utility PV markets through collective market actions or pre-commercial installations. With continued support from the government and increased public awareness, the use of photovoltaic systems is expected to increase and expand into new applications.

Deregulation of the Utility Industry

The Public Utility Regulatory Policies Act (PURPA) of 1978 and the Energy Policy Act (EPACT) of 1992 increased competition in the electric generation industry. PURPA requires utility companies with a need for more electricity to receive bids from alternative suppliers. EPACT deregulates the sale of electricity to promote competition among power sellers and to create lower electric rates (King, 1996) and extends the scope of non-utility producers by creating a new class of suppliers that are permitted to sell power in wholesale markets. EPACT also requires the owners of transmission facilities to provide independent suppliers with open access to the electric grid to transmit power to wholesale utility customers. With a shift from large, central power plants to smaller generating facilities, a restructured electricity industry is now poised to offer significant opportunities to increase the deployment of renewable energy using integrated PV systems (Brown et al., 1999).

When considering BIPV systems, it is now possible for an owner to use BIPV systems to provide some or all of the building's energy. As a power supplier, the owner can sell the electric energy produced by the PV system to the tenants of his or her building. Conventional or other renewable sources of electricity could then be used to provide the electricity not provided by the BIPV system. Conversely, this concept may not apply to all building management structures. Therefore, more research is required to develop feasible financial solutions for building owners and management groups.

Building Integrated Photovoltaics

Currently in the world of PV, self-healing semi-conductors are currently being developed to combat the harmful effects of radiation (Savage, 1999). This 'smart material' restores to its previous function after being damaged. Although still in development, these systems provide evidence of the dependable performance of PV systems beyond there currently life expectancies. In addition to these self healing modules, state of art integrated BIPV modules and thermal collectors have been develop by Solar Design Associates and United Solar with support of the Department of Energy (Wardell, 2000). Combining these two technologies to generate hot water and electric energy, higher efficiencies can be obtained that are similar to other co-generation methods of heat recovery in PV systems (Posnansky and Gnos, 1994, Clarke, et al. 1997, Gutschler, 1997).

To offset our predicted energy shortage, research and application of BIPV systems have been aimed at integrating PV elements directly into buildings (Ashley, 1992). Projected to provide up to 70% of a building's electric demand when designed for their optimal energy production, we can provide electric energy at the point of demand using BIPV systems. These systems convert sunlight into electricity and integrate with the energy use and structure of buildings as weathering skin, sun shading, and roof and window systems. Because they provide a viable alternative and renewable method for generating electric energy, BIPV systems can improve and secure our economic growth by reducing our dependence on non-renewable energy.

While roof mounted modules have been tested and used extensively, as seen in the solar roof programs around the world, efforts to integrate PV systems into facades have been hampered by several unsolved problems in the module design and the cost of wiring and framing (Bendel et al., 1994). Nonetheless, several demonstration projects are investigating PV systems as cladding and glazing for facades (Strong, 1994). In the United States, Advanced Photovoltaic Systems (APS) company integrated PV skylights and semi transparent curtain walls into their new manufacturing facility in Fairfield, California. In Germany, the Bavarian Environment Ministry uses amorphous silicon modules in the non-window areas of the facades. In Japan, Sanyo has installed a prototype PV façade in a building for the Tsukasa Electric Industry Company.

Energy Use of Commercial Building

Among commercial buildings, one of the largest energy users has been the tall building. Typically sealed enclosures without operable windows, tall buildings are oriented to match the prevailing street layout, and therefore, may not have an optimal solar orientation. To maintain a comfortable environment for the building's occupants, in southern climates, tall buildings depend on mechanical cooling and heating to compensate for heat gain from the sun or heat and humidity gains in ventilation air.

To offset the existing drain on non-renewable energy, commercial buildings will eventually have to increase their use of renewable energies and energy conserving technologies. Although current applications are few, BIPV systems are potentially one of the most useful renewable energy technologies because their cost is offset by the windows they replace. According to Kiss et al., (1995), PV systems using glass substrates, as compared to flexible PV modules using stainless steel substrates, are the most available PV products that can be immediately integrated into current building systems.

Societal Impacts

Despite the known benefits of photovoltaic systems, architects, builders and developers are still reluctant to use photovoltaic systems as integral building elements (Goethe, 1994) due to a lack of understanding about the economic and aesthetic aspects of BIPV systems. In order to address the economic and aesthetic concerns associated with PV systems, Kiss and Kinkead (1996) conclude that the economic and environmental benefits of BIPV products must be defined for the public and building community. In addition, we must understand what factors, such as aesthetics, will influence their acceptance (Kiss and Kinkead, 1996).

Finally, if society continues to demand architects to design in climates where ambient conditions are inhospitable, reducing energy consumption becomes paramount due to the continuous need for mechanical cooling and heating. Furthermore, if architects continue to seek new forms of architecture that are independent of the climate and orientation, renewable energy conservation methods must be utilized to provide as much renewable energy that is financially viable to operate such buildings. Thus, to improve the building's sustainability, an economic and psychological analysis of photovoltaic glazing in commercial buildings will lead to a better understanding of their potential to save energy and social acceptance.

In the following section, this paper reviews issues surrounding the design of photovoltaic glazing, their installation and maintenance in buildings, and how they affect owning and operating costs of commercial buildings. In addition, a review of the state of the art energy simulation software is discussed, as well as methods for predicting the photovoltaic system's thermal and electrical performance. In the following section, the review of literature discusses the effects of windows on people and the measurement tools that are used to determine the level of human satisfaction

METHODOLOGY

The Design

This study targeted commercial buildings with 100% glazing and 20 or more floors. These buildings were simulated on a selected urban site - one within each census region (West, Midwest, South, and Northeast). Based on 1992 US Census Data, the selection of the sites was limited to those with populations greater that one million people to ensure appropriate characteristics such as the existence of large business districts, downtown development, and significantly large buildings. Furthermore, in census regions where more than one city met the selection criterion, the city with the largest population was chosen. The selected cities are as follows:

Table 1. Selected Sites for Each Census Region

Census Region:	City:
South	Houston
West	Los Angeles
Northeast	New York
Midwest	Detroit

Using a typical high rise building and city block, this study used a forty-story building surrounded by buildings one-half its height. Because of their density and grid layout, general characteristics of the city block, as observed from maps, are: small-building footprints, multi-lane roadways with off-street parking and setbacks for pedestrian sidewalks. To determine the dimensions of the typical city block mentioned above, downtown Houston was used as a basis for all four cities. After a review of the appropriate maps and building sites, this study used a building footprint of one hundred by one hundred square feet, adjacent six-lane roadways with off street parking and a twenty foot setback for pedestrian sidewalks (Figure 1).

To determine the building's height, a survey of high-rise structures within each downtown business district was conducted. In general, various data were available regarding historical and prominent buildings within each downtown area. However, very little comprehensive data existed for Houston, regarding the building's sizes. For Detroit, no statistical data was available for review regarding its high-rise buildings. Nonetheless, using the compiled data, representing mainly Los Angeles and New York, the average height of high-rise buildings was determined to be 42 stories. Thus, a 40-story building was used in this study. After a survey of the photographs of downtown buildings and the city skyline of the selected cities, the surrounding buildings in this study were set at one half the height of the 40-story high-rise building discussed earlier.

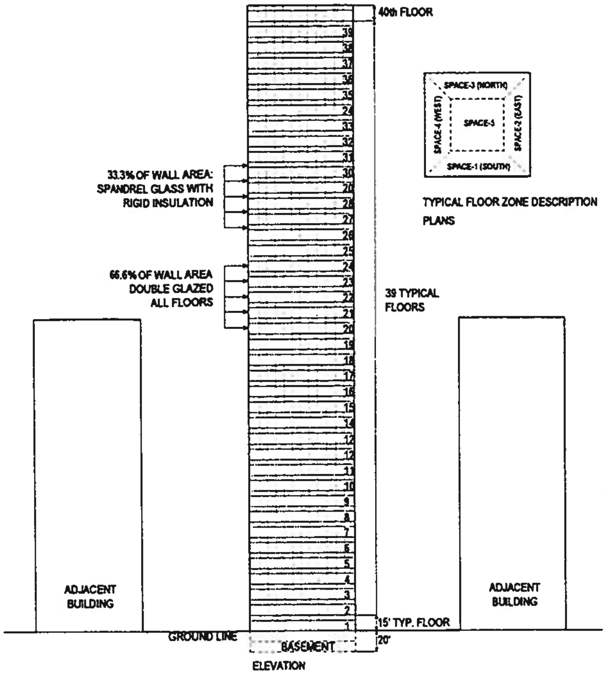

Figure 1. Typical High Rise Building

In general, the building is a steel frame structure with four-inch concrete floors and roof, a fifteen feet floor to floor height, and ten feet ceilings. The curtain wall is 100% glass, with typical floors containing five vertical feet of spandrel glass and ten feet of windows. The interior of the building has typical partitions for the interior spaces and suspended acoustical tile ceilings with recessed fluorescent lights. Occupancy of the building was determined using 100 square feet per person for perimeter spaces and 200 square feet per person for core areas.

The Experiments

Based on the cities selected, the prototype building, and the site configuration, the following models were developed: 1) the window experiment and simulation 2) the resource assessment, 3) the energy simulation, 4) the economic analyses, 5) and the human assessment. These are discussed further in the following paragraphs. See Appendix for the flow charts of the procedures.

The window properties of the photovoltaic glazing were simulated using Window 4.1 (LBL, 1997) and its transmittance was validated through experimentation. PV F-Chart was used to calculate the electric output of the photovoltaic façade (F-Chart Software, 1997). These data were offset by average hourly monthly shading values calculated by DOE 2.1E and validated using 3D Studio Max software (Autodesk, 1996). The DOE 2.1E program, (LBL, 1980), was used to measure the energy consumption of commercial buildings using window library files created using Window 4.1. An economic analysis of the four sites compared the shading effect (effects caused by surrounding buildings), the non-shading effects (effects with no surrounding buildings), and the type of window treatment (single pane clear, Low-E, and photovoltaic coatings). The analysis was performed using a simple payback analysis method, which is the investments costs divided by the annual savings.

In the human assessment, the subjects were 200 males and females obtained from a university population with an average age of 20 years. This study was limited to overall satisfaction for a window and non-window view in office spaces using PV windows. Measurement of overall satisfaction was accomplished by surveying the individuals after exposure to the simulated environments using a time lapse video for one day. This study used the simulated solar irradiation levels for the summer solstice (June 21) for each census region, as generated by PV F-Chart (F-Chart Software, 1997).

A 2 x 4 x 2 factorial analysis of variance analyzed the design (SAS Institute, Inc., 1992). Independent variables are window transparency and position. Window transparency is the window treatment at the varying levels of 40% and 100% transmittance (clear glass). As a blocking factor, position will account for the effects of a window view to measure the effect of window transparency and non-window view to measure the effects of visual light transmittance. Dependent variables are human responses to the window treatments and visual light transmittance. Visual light transmittance is dependent upon window transparency. Fixed variables are the office environment, view through the window, window location and size, time of day and sky conditions.

RESULTS

In this section, a summary of each part of the study is presented. Overall, this section presents the results of the window properties, the PV resources assessment, the energy simulation, the economic analysis, and the human assessment. Additional information about the analyses can be found in Sylvester (1999).

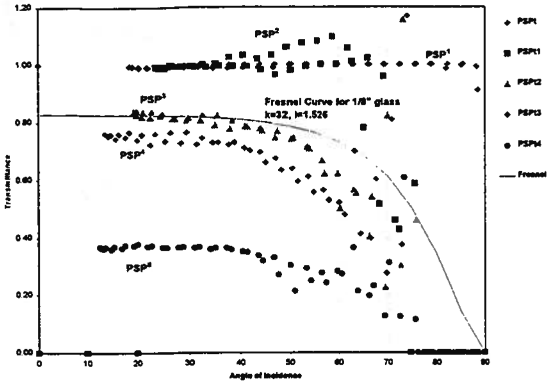

Figure 2. Angle of Incidence vs. Transmittance - Measured
PSP¹ is the measure with no box.
PSP² is the measure with the box added to the test bench.
PSP³ is the measure with the glass and frame added the box.
PSP⁴ is the measure with the transparent film added to the glass
PSP⁵ is the measure with the PV added to the transparent film.

Window Properties

The study was conducted using a test box located on the Solar Test Bench at Texas A&M University. The test box experiment used 1/8 inch glass with a covering that approximated the optical properties of the PV window material. To measure the transmittance of the prototype, the study measured the solar radiation for five conditions. They were: 1) pyranometer only (calibration), 2) pyronometer with test box, 3) pyranometer with test box and clear 1/8 inch glass, 4) pyranometer with test box, clear 1/8 inch glass and substrate, and 5) pyranometer with test box, clear 1/8 inch glass and substrate with PV film. These are now referred to as PSP¹, PSP², PSP³, PSP⁴, and PSP⁵ respectively. The data were recorded over an eight-month period and only clear days were selected for analysis.

In Figure 2, the results of the transmittance experiment show a measured transmittance of approximately 38% for the PV glazing which was determined using prototype PV material and designed using transmittance formulas for PV glazing (Nishikawa, 1994). PSP³ are the results of 1/8" clear glass; PSP⁴ is the measure with the transparent film added to the glass; and PSP⁵ is the measure with the PV added to the transparent film. The resultant curve (Duffie & Beckman, 1999) is shown for 1/8" glass as a solid line.

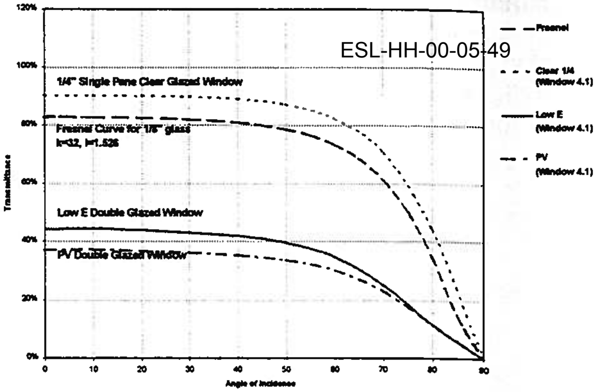

Figure 3. Angle of Incidence vs. Transmittance - Simulated

Using the Window 4.1 software, clear single pane glazing, Low E double glazed and PV double glazed windows were evaluated. For the clear single pane and Low E glazing, standard window types were chosen from the glazing library of the window software. To simulate the effect of the PV glazing, a double glazed window was constructed using 1/4" clear glazing. Furthermore, a transmittance of 40% was applied to the second layer for windows that were used in hot climates and the third layer for windows that were used in cold climates. The window properties were then calculated and saved for input into the DOE-2 window library (Figure 3). The transmittance curves from the Window 4.1 library are also shown for ¼" single pane clear and Low-E glazing.

PV Resource Assessment

In the resource assessment, the results show that the PV glazing performed best for the unshaded condition as compared to shaded. Specifically, Los Angeles shows the greatest electricity production of all sites; Houston was next and then Detroit; and last, New York shows the lowest production levels. In view of these urban centers, it is important to note that undesirable atmospheric conditions caused by air pollution and smog may significantly affect the available solar irradiation and should be studied further. Nonetheless, in this study the shading caused by the adjacent buildings significantly reduced the electricity production of the PV glazing by 34%. Overall, the shading by surrounding buildings reduced the electricity production of the PV glazing by 34% (Figure 4).

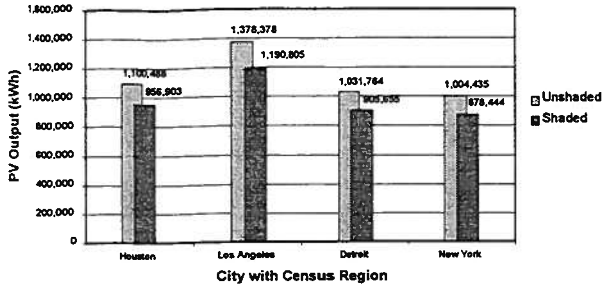

Figure 4. Annual PV Electric Production

Energy Simulation

In this study, the DOE-2 samp2.inp file produced an unreasonably low, annual energy use mainly due to unreasonable assumptions about operation and temperature schedules, which completely shut down the building during unoccupied periods. After modification of the samp2.inp file, the energy use of the building increased to levels comparable to buildings from the LoanSTAR database (Turner et al., 1998). Based on the modified DOE.2 samp2.inp file, results show that buildings using single pane clear glazing were most consumptive for both conditions. In agreement, studies show that the PV glazing performs similar to Low-E glazing in reducing the energy consumption of buildings (Sylvester, 1999).

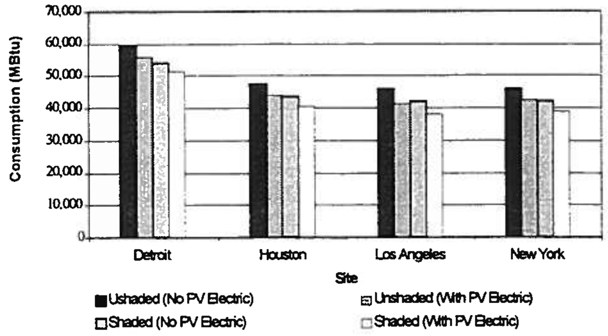

Figure 5. Annual Energy Consumption for All Sites

The electric energy produced by the PV glazing made the building slightly less consumptive than buildings using Low-E glazing. Overall, the mostly vertical PV glazing, with no shading effects caused by surrounding buildings, met 21% of the electricity needs of the building, while the PV glazing that considered shading from surrounding buildings satisfied 14% of the electric needs of the building (Figure 5).

ECONOMICS

Despite the fact that Los Angeles has the greatest PV electricity production, the study shows that buildings located in Detroit and Houston glazing showed the quickest payback for both shaded and unshaded effects (Table 2). This is due to the benefits of solar controlled window glazing in climates with extreme hot and cold temperatures. Furthermore, when the reduced size of the chiller is not considered, the simple payback for the building using PV glazing is 17.5 and 15.5 years for the shaded and unshaded conditions.

Table 2. Simple Payback with no Capital Recovery

	Shaded			*Unshaded*		
	Clear	Low E	PV	Clear	Low E	PV
Detroit	NA	3.63	13.28	NA	3.23	11.73
Houston	NA	4.66	16.35	NA	4.10	14.79
Los Angeles	NA	5.73	19.90	NA	5.29	17.84
New York	NA	5.74	20.73	NA	5.29	18.65
National Average		**5.38**	**17.57**		**4.48**	**15.75**

Table 3. Simple Payback Analysis with Capital Recovery

Site	*Shaded*			*Unshaded*		
	Clear	Low E	PV	Clear	Low E	PV
Detroit	NA	2.87	12.44	NA	2.56	10.99
Houston	NA	3.68	15.32	NA	3.24	13.86
Los Angeles	NA	4.54	18.65	NA	4.18	16.71
New York	NA	4.54	19.43	NA	4.19	17.47
National Average		**4.25**	**16.46**		**3.54**	**14.76**

When considering capital recovery, the payback is only reduced by one year, as with the investment tax credit (Table 3 and Table 4. The greatest effect on the payback of PV systems is achieved when using a 5-year depreciation method. As shown in Table 5, the average payback was reduced 11.6 and 10.4 years for the shaded and unshaded conditions. It is important to note that further study is required to develop more accurate and reliable cost data that reflect our current technologies such as wiring, framing and power conditioning methods. Overall, when considering all economic benefits, the PV glazing payback time was reduced by approximately 34%. In comparison, the buildings using PV glazing had a payback time that was twice that of Low-E. This difference indicates that Low-E glazing should be integrated within the PV system to make a more cost effective and efficient system.

Table 4. Simple Payback Analysis with Investment Tax Credit

	Shaded			Unshaded		
	Clear	Low E	PV	Clear	Low E	PV
Detroit	NA	2.87	11.18	NA	2.56	9.88
Houston	NA	3.68	13.77	NA	3.24	12.45
Los Angeles	NA	4.54	16.76	NA	4.18	15.02
New York	NA	4.54	17.46	NA	4.19	15.70
National Average		**4.25**	**14.79**		**3.54**	**13.26**

Table 5. Simple Payback Analysis with 5-Year Depreciation

	Shaded			Unshaded		
	Clear	Low E	PV	Clear	Low E	PV
Detroit	NA	2.87	9.55	NA	2.56	8.44
Houston	NA	3.68	11.76	NA	3.24	10.64
Los Angeles	NA	4.54	10.33	NA	4.18	9.26
New York	NA	4.54	14.91	NA	4.19	13.41
National Average		**4.25**	**11.64**		**3.54**	**10.44**

Human Assessment

In the human assessment, the mean result for the arousal effect shows that the subjects were only slightly aroused. In the case of the view shown, the students preferred a sitting position facing the window to one facing the door. In addition, the students preferred the spaces using the clear glass windows to the spaces using windows with 40% transmittance (Table 6). To interpret these data, a score of 4.5 represents a normal, everyday feeling. A score higher that this indicates that the subjects felt more aroused or pleased and a lower score indicates that the subjects felt sleepier or unpleased. These measurements are based on a scale from 1 to 9. The analysis of variance shows that that all the treatment means at levels of VIEW, LOCATION, and GLAZING were significantly different. That is, the variations in the test stimuli were being detected (Table 7).

For the pleasure response, the overall mean result shows that the subjects were only slightly pleased. Similar to the results for arousal, the students preferred a sitting position facing the window to the view facing the door. In addition, they preferred the spaces using the clear glass windows to the spaces using the windows with 40% transmittance (Table 8). In the analysis of variance for the final study, only VIEW had significantly different treatment means, while levels of LOCATION and GLAZING did not (Table 9). Overall, although people prefer clear windows to those with 40% transmittance, windows with 40% transmittance do not create significantly stressful or unpleasant feelings in people.

Table 6. Means Response for Arousal

	Window View						Non Window View				
	Houston	Detroit	Los Angeles	New York	*Mean*		Houston	Detroit	Los Angeles	New York	*Mean*
100	5.05	6.72	5.78	6.77	6.08	100	6.13	4.98	6.35	5.47	5.73
40	2.58	4.79	5.41	5.00	4.45	40	3.17	4.41	4.10	3.22	3.73
					5.26						4.73

Overall Mean: 5.00

Table 7. ANOVA for Arousal

Source	DF	ANOVA SS	Mean Square	F Value	Pr > F
View	1	221.01	221.01	64.59	0.0001
Location	3	267.11	89.04	35.46	0.0001
Glazing	1	1127.31	1127.31	309.76	0.0001
View *Location	3	130.90	43.63	14.84	0.0001
View*Glazing	1	4.38	4.38	1.59	0.2110
Location*Glazing	3	133.47	44.49	15.35	0.0001
View*Location*Transmittance	3	177.90	59.30	20.72	0.0001

Table 8. Means Response for Pleasure

	Window View						Non Window View				
	Houston	Detroit	Los Angeles	New York	*Mean*		Houston	Detroit	Los Angeles	New York	*Mean*
100	6.19	6.51	5.64	5.97	6.08	100	5.49	5.63	4.9	5.7	5.43
40	4.6	6.14	6.15	6.09	5.74	40	4.27	5.1	5.18	4.36	4.73
					5.91						5.08

Overall Mean: 5.5

Table 9. ANOVA for Pleasure

Source	DF	ANOVA SS	Mean Square	F Value	Pr > F
View	1	191.36	191.36	56.64	0.0001
Location	3	35.83	11.94	3.07	0.0287
Glazing	1	76.08	76.08	7.39	0.0082
View *Location	3	9.57	3.19	0.91	0.4384
View*Glazing	1	77.05	77.05	26.61	0.0001
Location*Glazing	3	126.23	42.08	10.68	0.0001
View*Location*Transmittance	3	128.48	42.83	15.43	0.0001

Overall, the results of the final study show that students prefer clear windows to those with a lower transmittance. Although there are significant differences in the mean responses for the varying window types, the subjects were only slightly aroused and pleased as indicated in the overall mean scores. Thus, the windows with a 40% transmittance are not perceived to create negative effects.

CONCLUSIONS

It is well known that people prefer daylight and windows in their environments (Biner and Butler, 1989). However, the primary function can be is overshadowed by economic factors associated with thermal properties of windows that may adversely affect human satisfaction of office workers. Consistent with this, architects must avoid presumptuous decisions that are based on market standards. By obtaining information on the current preferences of building occupants, architects expand their search of excellence to relating human acceptance to window or glazing types. More importantly, effects of windows on worker performance and preference, as indicated by this study, may be linearly related to the amount of light they transmit, the is either due to the size or by transmittance of the window.

Results from this study show that there is much work to be done to effectively analyze all effects of PV glazing in buildings. Thus, this section discusses the recommended future work to improve the simulation of PV glazing buildings. Although the assessment measures in this study have been proven reliable, more studies should be conducted for spaces that are used by the elderly or people who are psychologically stressed. Such studies should investigate the effect of age on human preference to PV glazing and the effect of low transmittance on the well being of hospital patients.

With respect to the window properties, this study has validated and created preliminary information to begin modeling PV glazing within energy simulation software. However, testing of the actual PV element is required to accurately define the thermal and optical properties of double glazed PV windows.

For the resource assessment, the PV electricity generated was reduced by 50% due to the vertical orientation. Thus, studies using alternative façade designs, such as those by Kiss (1993) are expected to improve the PV production. In this case, the façade design must reduce the angle between the incident light of the sun and the face of the module. Another method to improve the effectiveness of the PV is the reclamation heat generated within the double glazed system. This is expected to be most beneficial to cold climates.

In terms of economics, with economic factors included, the buildings using PV glazing still had a payback time that was twice that of Low-E. This indicates that Low-E glazing should always be included when designing windows. Future study should investigate the development of a hybrid system that integrates the PV and Low-E glazing within the same window system. This is presumed to make a more cost effective and efficient system. In addition, further study should investigate using a less expensive PV material. Furthermore, life cycle costs of these systems should be conducted to factor the continual contribution of electricity to the building.

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