Responsive shading and energy efficiency in office buildings: an Australian case study

Myles E Bunning[1], Robert H Crawford[1]

[1]University of Melbourne, Melbourne, Australia

ABSTRACT: Solar radiation allowed to be transmitted to air-conditioned space through a building's glazing can be a major contributor to the total annual energy requirement for cooling a building. Without the presence of a sufficient barrier to absorb or reflect the radiation transmitted through the glazing, significant resources are committed to providing air-conditioning and maintaining lighting levels. Shading acts as a barrier to solar radiation; however, for shading to further reduce energy demand by being responsive, it is required to be automated so that it modifies the amount of shading provided according to external conditions. The operational energy component of the building's life cycle energy is to be examined for internal and external responsive venetians for a case study building. As part of this study the impact of venetian shading upon the sizing of the HVAC as well as the differences between temperate and sub-tropical climates is also assessed. Overall, the use of smaller HVAC systems in conjunction with external responsive venetian shading was shown to reduce the building's annual operational primary energy by up to 27% in comparison to a static shading option. By examining the energy impacts of responsive shading, this study provides guidance for energy efficient building design.

Conference theme: Buildings and energy
Keywords: energy efficient buildings, shading design, bioclimatic architecture, responsive shading

INTRODUCTION

The energy transfer between the internal and external surfaces of a building façade, particularly related to glazing, is attributable to a large proportion of the heating and cooling demands. Carmody *et al.* (2003, p. 9) estimates that 12% of all energy use in commercial buildings in the United States is attributable to windows. Until the introduction of energy efficiency provisions for commercial buildings in the 2006 Building Code of Australia, the amount of shading and glazing of office building facades was left largely unregulated. This may have contributed to the finding by the Australian Low Energy Highrise Report (LEHR) (Warren Centre 2009) survey that 26 out of the 98 buildings sampled from the more premium end of Australia's office market and having an average age since construction of approximately 21 years, only showed evidence of light external shading. The conduction of heat through the fenestration system, which includes both the glass and the frame, together with the heat gains and losses due to transmission of radiation, presents challenges in the design of fenestration systems. The choice of fenestration system is also dependent on the occupants desire for daylighting. To meet the variety of demands brought about by both weather conditions and the preferences of office occupants, there is opportunity for use of controlled shading which can respond to dynamic requirements. This paper aims to compare the operational energy resulting from the use of static and responsive shading systems that balance the demands of reducing overheating, maintaining daylight and shield from glare for an office building. Part of this comparison will involve determining the degree to which different shading systems can alleviate the burden on HVAC systems. The comparison of distinctly different locations using a case study building will offer an insight into how climate and latitude may influence the selection of a shading system in the Australian context.

1. BACKGROUND

Static fenestration systems have great benefit for those situations in which concerns about glare or daylight distribution and light uniformity are secondary to those of heat gain reduction. Responsive shading, which is a system that can change its configuration to suit its circumstance, does not necessarily have the same heat gain limitations. Through adjustment of venetian blind tilt, direct solar radiation from any direction can be occluded or permitted to temper thermal gains. Selkowitz *et al.* (2003) suggests that a 'subtle shift' from static design solutions using innovative glazing to making the façade responsive, interactive and even intelligent is occurring. Whilst horizontal venetians can have the effect of blocking too much light, their ability to increase the uniformity of daylighting through inter-reflection between profiled slats is a significant benefit of directionally selective shading devices.

Venetian blind systems placed externally can be susceptible to wind loading, especially for upper floors of high-rise buildings. However, venetian blinds expose smaller continuous areas to wind loads, making them less vulnerable to damage than external textile roller blinds (Herkel *et al.* 2007). Developments in the profile of directionally selective shading such as horizontal venetian blinds have allowed for greater rigidity within slats. Some product manufacturers recommend that the distance between the exterior glazing and the start of the horizontal profile of the slat be no more the 50 mm. Such tight tolerances between the façade and the blinds might not be necessary for all slat profiles. Claims have been made that certain aluminium extrusions have been designed to have the strength to withstand typhoons (Yokota *et al.* 2007).

The energy savings and acceptance of operable internal and external blind systems by the occupant is highly sensitive to the control system adopted. Statistical models of manual controls of shading systems have been devised to compare manual and automated control modes (Littlefair *et al.* 2010; Reinhart 2004). One of the key findings, which impacts upon attempts to represent manual controls statistically comes from a recent behavioural study by BRE in the UK of daylight use in open-plan offices. The study found that 'blinds down lights on' (BDLO) state occurs regularly unless blinds are opened routinely by cleaners or security staff (Bordass *et al.* 1994).

Building physicists have demonstrated energy savings with control of fenestration devices based on solar sensors (Kim *et al.* 2009; Lee *et al.*1998; Roche 2002). The differing effects of various shading types on HVAC operational energy (Hammad & Abu-Hijleh 2010; Rosencrantz 2003) and other functional requirements which influence their selection (James 2006) has been established in previous studies.

2. SELECTION OF CASE STUDY BUILDING AND SHADING ALTERNATIVES

In order to quantify and compare the operational associated with various shading types, a building simulation model was used. With this model, it was then possible for various shading scenarios to be tested across different locations. The use of a single case study allowed operational energy benefits of different shading types to be modelled without variations to other parameters such as building geometry or orientation, which would mask the impact of weather conditions.

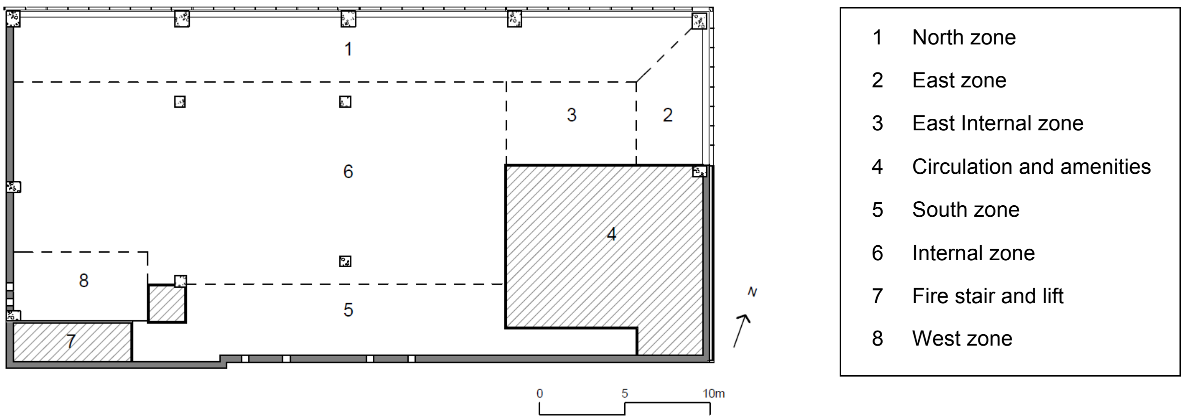


Figure 1: Zoning of typical office space levels 5-11 for case study building

The case study building chosen is located in the central business district of Melbourne, Australia and consists of 8,343 sqm of floor area over 12 floors and 2 basement levels. Of the 12 floors of the selected building, levels 5 to 11 were zoned as office space as shown in Figure 1. The other occupied floors were dedicated to non-office functions. In conjunction with the 2009 façade replacement, the HVAC system was also upgraded. The existing façade was replaced with new argon filled double glazed units with a low-e coating on the second surface from the outside. The overall *g*-value of 0.60 and a transmittance of the visible spectrum of 0.72 for the glass was achieved with this specification. Separate HVAC systems with a combined plant room were installed for the top seven floors of office space and the five floors below, which were to serve a judicial function and included meeting and mediation rooms for dispute resolution. The base case cooling system utilised a primary central hydronic system consisting of a water cooled condenser and cooling tower. This equipment supplies chilled water to the secondary central hydronic system. This secondary system consisted of an air-water system using active chilled beams to transfer radiant heat away from the room as well as supplementary cooling using re-circulated and outside air. A set point of ±2 degrees Celsius around a fixed value of 22 degrees was established during the design process as being an acceptable 'comfort band'.

Venetian shading is unique in its capacity to capture diffuse light and also redistribute it in a way that reduces the possibility of glare. The optically complex nature of venetian blinds affects the way that energy transfer is calculated. The solar heat gain coefficient (SHGC) varies not only as a function of the glazing, but also as a function of the direction of incoming solar radiation. Particularly for north facing glazing, this means that the SHGC value can vary throughout the year according to incident angles. With the concern about the amount of operational energy associated with maintaining illuminance and thermally comfortable set points, venetian blind operation which is responsive to incident angles of diffuse and direct radiation becomes more critical.

For the results of the operational energy modelling to be sufficiently differentiated, two Australian locations were chosen to exemplify significantly different weather and solar exposure characteristics. The climate characteristics considered to have direct relevance to the relationship between energy requirement and venetian blind control included the hottest and coolest average monthly temperature, the diurnal temperature swing, the average number of cloudy days, the highest average monthly direct solar radiation and the minimum and maximum sun altitudes at solar noon. The climates of Melbourne and Brisbane were selected to represent different extremes of climate. It was noted that Brisbane has a more tropical climate than Melbourne with more partly cloudy days. An expected ramification of these differences for the case study building is that humidity will have more of an impact on HVAC requirements in Brisbane. The high number of partly cloudy days in Brisbane is also likely to heighten the risk of glare for a highly glazed facade.

2.1. The base case shading scenario

The shading system adopted as a base case for the case study building is a combination of a static louvred overhang projecting 700 mm form the facade and a manually operable, yet unused, venetian blind located internally, as shown in Figure 1.

The base case manual control draws from reported occupant behaviour including the 'blinds down lights on' (BDLO) case (Bordass *et al.* 1994). The configuration is defined as a uniform slat angle of 45 degrees during the cooling demand period with artificial lighting operating continuously at 12 W/m^2. The optical properties of the base case venetian blinds are assigned according to measurements recorded by Kuhn and Helde (2002) for silver cloud aluminium slats. The solar reflectance value for the slats is 0.486 and the visible reflectance value is 0.488. Slats are positioned with the pivot point of the slat a distance of 150 mm from the glazing. These environmental conditions are considered to be a sub-optimal scenario in terms of both visual comfort and energy. This scenario is still conservative since no direct sunlight within the room is permitted, even though this would inevitably occur when venetians were manually operated. There is little evidence to suggest that occupants are influenced by the amount of solar radiation when they operate blinds. It is conceivable that rather than controlling direct sunlight on sunny days, manually operated venetian blinds could result in considerably more direct solar radiation to be transmitted to the interior than with a static venetian blind angled at 45 degrees as well as less daylight during overcast periods.

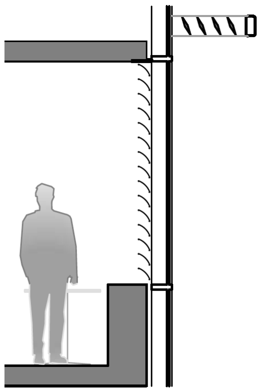


Figure 2: Base case shading applied to north and east facade

2.2. The responsive shading scenarios

Two responsive shading scenarios were considered in order to isolate the relative operational energy differences occurring from the use of automated shading placed on either side of external glazing and compare these results to a static base case. System A is positioned externally with 100 mm spacing from the glazing to the edge of the venetian blade. Figure 2 shows the configuration and features of the external responsively operated shading system and outlines the basis for how the venetian blind control strategy was selected.

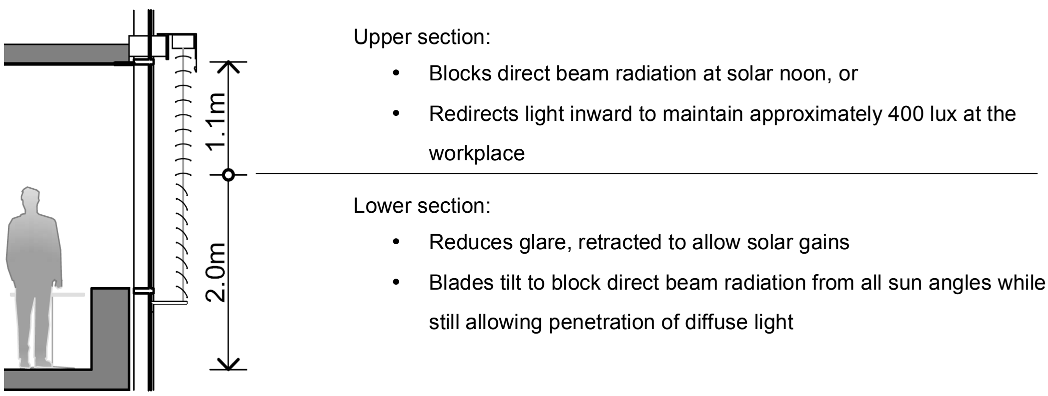
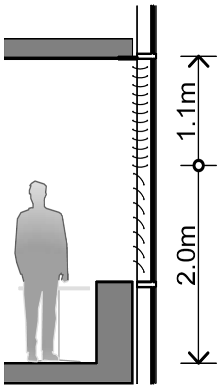


Figure 3: System A shading applied to the north and east facade



Upper section (highly reflective):

- Blocks direct beam radiation at solar noon, or
- Focuses light towards the ceiling to maintain approximately 400 lux at the workplace

Lower section

- Reduces glare or set at horizontal to create a thermal buffer during the day in the heating demand period, or
- Blocks incident direct beam radiation, while still allowing penetration of diffuse light

Figure 4: System B shading applied to the north and east facade

System B is an internal responsively operated venetian with 20 mm spacing between the glazing and the venetian blade as illustrated in Figure 3.

The systems and control strategies described in Figures 1-3 are the basis for the simulation of energy consumption throughout a representative meteorological year for both Brisbane and Melbourne. The size of the HVAC system necessary for both responsive shading systems A and B was determined by modelling peak loads during heating and cooling design day conditions in EnergyPlus. Heating and cooling by both convection and radiation was delivered by means of hydronic skirting heaters and active chilled beams. Such a system is likely to be more commonly utilised in buildings requiring high levels of efficiency in the future (Badenhorst 2003).

3. METHOD

The analysis method used to determine the operational energy of the case study building for each of the shading scenarios, combines the easy to use interface of DesignBuilder with additional functionality of EnergyPlus. The additional functionality included the cooled beam module to simulate radiant cooling devices and the ability to input a detailed control schedules generated from weather data. The method for determining the slat angle of the blinds is calculated daily based on sky condition and sun angle, and converted to an average monthly schedule for each hour in the day. The method also allows the opportunity to make an assessment of the impact of annual changes in recorded weather and assist in evaluating the contribution that shading design may have in mitigating greenhouse gas emissions relating to operational energy.

Although there is no accepted standard method for control of shading, automated venetian blind position was determined by considering the following variables in combination and at various time intervals:

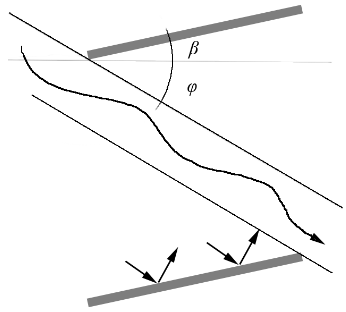
- Sky clearness
- Hourly Solar zenith angle
- Orientation of the window

Each hour was categorised into those which were overcast, those which were partly cloudy and those which were clear, according to the model for sky clearness described by Perez *et al*. (1990). For each day, the results for each hour of sunlight were averaged to determine whether the day could be classified as fine. On clear sky days the calculations were made to preference blocking direct solar radiation and reflected glare from the slats while on overcast days, blind angles which preference daylight penetration during overcast periods were chosen. A slat tilt of 45 degrees, which reduced glare was selected for partly cloudy periods unless the cut off slat angle was less than 45 degrees or direct solar penetration was considered desirable during the winter months.

Two dimensional analysis of the relationship between sun angle, flat slat angle and the front transmittance of direct solar radiation is well established. When the front transmittance of incident direct solar radiation by the venetian blind reaches zero, the ventian blind is found to be in the cut-off position. For sun angles projected onto the vertical plane normal to the window between the horizon at 0 degrees and directly overhead at 90 degrees, the state at which direct solar cut-off just occurs can be expressed as a relationship between sun angle and the tilt of the slat as derived by Tzempelikos (2008) and presented in Equation 1.

$$\beta = 90-2\,\varphi \qquad \text{Equation 1}$$

Where β represents the slat tilt from a horizontal position and the solar profile angle φ represents the sun angle projected on a vertical plane normal to the window. For the example shown in Figure 4 the tilt angle would need to be increased for the sun to be occluded at the given solar profile angle. For solar profile angles below 45 degrees, an approximation of the appropriate cut-off angle for direct radiation was determined using Equation 1 so as to keep the slat surface normal to the sun. This slat angle was further adjusted in the manner described below to compensate for other requirements besides direct solar cut-off. These relationships are based on the assumption that the spacing between the slats is equal to the slat width and that the thickness of the slat is negligible.



Source: (Tzempelikos 2008)

Figure 5: Solar profile angle and slat angle for a flat slat venetian blind

When the fraction of the slat that has direct solar radiation exposure is too large for solar profile angles greater than 45 there is greater risk of reflected glare. Equation 2 is derived from the description by Chaiwiwatworakul *et al*. (2009) description of slat surfaces visible from an interior point and gives the relationship between slat angle and solar profile angle to achieve a static ratio of shaded to unshaded slat.

$$\varphi = \tan^{-1}\left(\frac{\frac{u}{d}\cos\beta}{1-\frac{u}{d}\sin\beta}\right) \qquad \text{Equation 2}$$

Where:

φ	is the sun angle projected on a vertical plane normal to the window
β	is the slat tilt from the horizontal slat position
u	is the unshaded depth of the slat and
d	is the depth of the slat

To identify the appropriate control for responsive shading, information about the sky condition needs to be interpreted. The hours requiring differing shading tilts were determined by classifying the slat tilt ranges into according to the level of clearness following the model developed by Perez *et al.* (1990). Table 1 shows how this was classification was assigned for upper and lower blinds and for different times of day.

Table 1: Control modes, clearness conditions and slat tilt range

Control mode	*Control mode description*	*Clearness condition**	*Slat tilt Range*
A	Sunny	$\varepsilon > 2.8$	0 - 85
B	Partly cloudy (cloudy day until 1pm)	$1.2 < \varepsilon < 2.8$	45 - 85
C	Cloudy (cloudy day)	$\varepsilon < 1.2$	0 - 0
D	Cloudy (non-cloudy day)	$\varepsilon < 1.2$	0 - 45
E	Partly cloudy (cloudy day after 1pm)	$1.2 < \varepsilon < 2.8$	0 - 85
F	Partly cloudy (non-cloudy day)	$1.2 < \varepsilon < 2.8$	0 - 85 Summer 45 - 85 Winter
G	Upper blind tilt (sunny)	$\varepsilon > 2.8$	-35 - 75
H	Upper blind tilt (partly cloudy)	$1.2 < \varepsilon < 2.8$	0 - 75
I	Upper blind tilt (cloudy)	$\varepsilon < 1.2$	0 - 75

* The three clearness categories are reduced from eight discrete sky clearness categories as defined in Perez *et al.* (1990). A clearness index of less than 1.2 is consistent with an 'average' overcast condition. The upper limit of the overcast condition with a clearness index of 1.2 is above the lowest of the eight sky clearness categories between 1 and 1.065. A clear sky is defined in this paper as above a sky clearness category of 5, where a category of 8 is the highest sky clearness category.

During the winter half year, the control mode was modified to allow a greater proportion of the solar radiation to be transmitted for profile angles lower than 45 degrees. This was achieved within the control modes shown in Table 2 by adjusting the calculated direct solar cut-off angle for the summer half year to not exceed 45 degrees. In the case of partly cloudy weather in the afternoon in Melbourne, the slat angle was permitted to approach the horizontal position as the profile angle approached 45 degrees. Extra passive solar heating during afternoons within this winter period was not considered necessary for Brisbane. For any hours classified as partly cloudy on cloudy days after 1pm, the slat tilt was set to 45 degrees from horizontal in Brisbane for the north west facing facade. Throughout the year, night-time slat tilt for Brisbane was set to 0 degrees from horizontal. For the winter half year in Melbourne, a slat angle of 75 degrees at night was selected to reduce heat loss from the venetian blind assembly. The same control mode was considered appropriate for both external and internal venetian blinds.

Table 2: Control modes, clearness conditions and slat tilt range from September through to March

Sun position	*Slat tilts (degrees from horizontal) for each control mode*								
	A	***B***	***C***	***D***	***E***	***F***	***G***	***H***	***I***
Non incident (daytime)	0	45	0	0	45	45	0	45	0
0 <φ <15	85	85	0	0	85	85	90-2φ	45	0
15<φ <45	90-2φ	45	0	0	45	45	0	45	0
45<φ <60	90-φ*	45	0	90-φ*	45	90-φ*	10- φ/2	45	0
60<φ <90	90-φ*	45	0	90-φ*	45	90-φ*	85	85	85
Night	0	0	0	0	0	0	0	0	0

* If slat angle results in more than three quarters of the top of the slat being unshaded (for example), then the alternative slat tilt result from Equation 2 to satisfy the requirement for the minimum proportion of slat shading is substituted.

3.1. Daylight and glare modelling

To simulate artificial lighting controlled by dimmer switches, illuminance levels at 1.7m and 3.7m from the facade were determined using EnergyPlus. The reduction of energy between the energy requirement to keep lights on throughout working hours and the requirement for maintaining the target illuminance was calculated. Using the same reference points, glare measurements for the operational energy analysis were calculated using EnergyPlus. A maximum glare index of 22 on the logarithmic daylight glare scale is recommended for general office work (Winkelmann & Selkowitz 1984). In the case that glare results from the simulation exceeded the recommended limit during the occupancy period, the control strategy during these periods of high glare was reviewed to achieve greater uniformity of illuminance.

3.2. HVAC peak load and energy usage

The chilled beam sizing method was cross-checked against active chilled beam design for the same case study building that had previously been prepared for construction in Melbourne. The EnergyPlus model was used to calculate the controlled flow of air and water through heating and cooling coils, dampers and fans to simulate the energy consumption of the system. Within the Cooled Beam module, allowance was made for a water loop serving skirting panel radiators within each perimeter zone.

4. RESULTS AND DISCUSSION

For this analysis, the peak heating and cooling load and sizing information was calculated first to determine the system description for which the operational energy was to be simulated.

Table 3: Chilled beam sizing supply air rates and chilled water flow rates for Melbourne and Brisbane

	Beam length (m)	Quantity of Beams			Total length per floor (m)			Supply Air Flow Rate (l/s/beam)			Hrs cooling set point. not met		
		Base	System A	System B	Base	System A	System B	Base	System A	System B	Base	System A	System B
Melbourne													
East Perimeter	2.1	21	14	21	6.3	4.2	6.3	25.2	22.0	25.2	147	85	312
North Perimeter	3	112	49	119	48	21	51	27.0	25.0	25.0	123	55	94
Brisbane													
East Perimeter	2.1	28	14	28	8.4	4.2	8.4	30.0	25.2	30.0	303	124	345
North Perimeter	3	119	63	126	51	27	54	27.0	27.0	27.0	257	202	248

The sizing of the chilled beams involved the determination of the quantity and length of the beams as well as the flow rates of the water and air passing through them. Supply air-flow and chilled water flow rates were modelled with reference to the Frenger Active calculator, which was the process utilised for the original as-built design. Although the same water-cooled chiller size of 650kW was required for both Melbourne and Brisbane, using the responsive venetian system was found to result in a 50kW difference in the chiller size between the two locations with the largest chiller size of all required for System B in Brisbane. Boiler sizes remained constant for each shading system, although the case study building located in Brisbane required a boiler size of 400kW instead of 450kW, which was required in Melbourne.

4.1. Operational energy requirements

Primary operational energy results are based on a primary energy factor of 3.4 for electricity supplied in Victoria and 3.1 for electricity supplied in Queensland (ABS 2001). The primary energy requirements, composed of both plant, artificial lighting electricity and gas requirements for System A, were 27.0% less than the base case for Melbourne and 26.8% less for Brisbane. For System B, 16.5% less primary energy than the base case was required in Melbourne and 18.8% less primary energy than the base case was required in Brisbane. Although responsive internal venetians (System B) required slightly less artificial lighting than external responsive venetians (System A), the modest heating energy savings made by placing the responsive venetian internally were outweighed by the increase in energy requirements associated with the additional cooling loads. The reduction in energy demand from the chiller and cooling tower amounted to 42% for exterior responsive venetians in Melbourne relative to the base case chiller and cooling tower energy demand. Internal responsive venetians only reduced primary energy from the chiller and the cooling tower by 12% under the same Melbourne conditions.

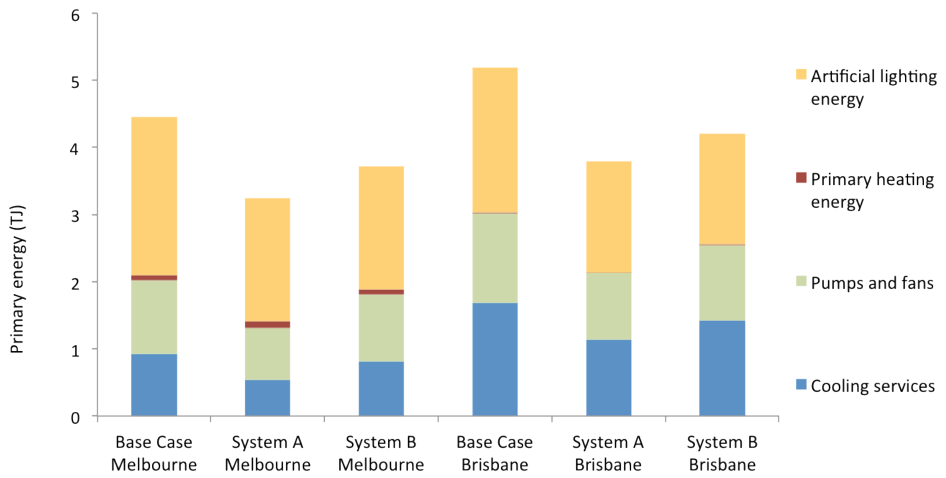


Figure 6: Annual primary operational energy consumption

4.2. Monthly heat gain through glazing

The conditions that bring about the greatest difference in heat gain from the north facing windows between the directionally selective static shading and responsive shading were found to be relative to not only the amount of solar radiation incident, but also the angle of the sun. The solar angle was consistently below 45 degrees, between March and September for Melbourne and between May and July in Brisbane and at these times, the static shade was least effective in comparison to venetians that could track the path of the sun. The bulk of the heat gain through the northern glazing for the base case occurred during the afternoon for non-cloudy days in both locations. A significant difference between the base case heat gain during afternoons of non-cloudy days and afternoons of cloudy days was observed in Brisbane. This is consistent with the character of Brisbane weather during March, which is influenced by the diurnal cycle of the tropics and typically involves afternoon cloud cover. The daily heat gain during cloudy and non-cloudy periods varied more significantly for the base case with static shading in comparison to System A. This was particularly evident during March for Brisbane when the heat gain during cloudy periods for System A and the base case were similar, while during partially cloudy and clear periods, the afternoon heat gains were substantially greater for the base case. Because the control mode is configured to be able to preference heat load reduction - a factor of the prevailing diurnal weather conditions rather than momentary solar levels, there is greater scope for control of heat gain through the glazing with this approach than one which relies only on solar sensors.

4.3. Inter annual variation

The advantages of responsive shading at lower solar angles are increased during unseasonably warm weather during shoulder seasons. Unseasonably warm periods occur in phases, which can be tracked by the Southern Oscillation Index. This index varies with the temperature of the surface of the tropical eastern Pacific Ocean. A swing of the southern oscillation index into a negative phase signifies an El Niño period. During these episodes the eastern two-thirds of Australia is typically in drought during spring (Wang & Hendon 2007).

From the El Niño periods reported in the 15 year period after 1995, with the exception of Brisbane in September, all the records for the selected months of February and October for Melbourne and March and September for Brisbane exhibit a tendency toward mean monthly daily global solar exposure being greater than the corresponding weather file global solar exposure which is representative of a typical year. This suggests that responsive venetian shading, which is able to compensate for the variable sky conditions during El Niño and La Niña periods, will reduce heat gain most effectively compared to a static system during the shoulder seasons in Melbourne and during the spring in Brisbane during El Niño periods.

CONCLUSION

The combination of sky condition and sun angle parameters in the control modes of an external venetian was found to result in a reduction in annual primary energy usage during operation for the case study building of up to 27% in comparison to a base case office building with static shading. There was no evidence of significant differences in annual energy reductions between Melbourne and Brisbane apart from the period of the year when the maximum reductions occurred. The definition of automated shading adopted by the BCA, which prescribes the requirement that it be operated automatically in response to solar radiation level, may be a limiting factor in the determination of control modes for venetian blinds designed to accommodate multiple parameters.

Responsive venetians may be most efficient in reducing cooling loads during El Niño periods. In comparison to static shading, responsive venetians also allow better control of glare and heat gain reduction for low sun angles during various weather conditions. Further simulations to determine the energy savings possible during past recorded El Niño and La Niña periods would assist in assessing the full potential of these shading devices. Within the broader context of energy supply, reduction of peak demand of electricity for cooling realised with responsive venetians, can dissuade the future growth of power generation infrastructure. This may allow for the diversion of resources towards renewable energy generation alternatives to greenhouse gas emitting fossil fuels.

ACKNOWLEDGEMENT

The contribution of Dr Eckhart Hertsch, Adrian Rowe and Dr Eddy Rusly in providing their technical knowledge and critique is hereby gratefully acknowledged.

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