ENERGY-EFFICIENT BUILDING ENVELOPES—AN AUSTRALIAN PERSPECTIVE

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ABSTRACT

Although Australia is one of the few OECD countries without energy efficiency standards for commercial buildings, a number of studies have been and are being carried out in this area. An architecture research unit at an Australian university has developed a draft standard for energy-efficient design of the building envelope that is now being put through an expert committee consensus process through Standards Australia.

Australia is unique in that it is one of the few OECD countries with a cooling-dominated climate. A lack of comprehensive knowledge of the effects of envelope properties on the energy efficiency of commercial buildings in these climates necessitated the development of an Australian energy data set. This was done by carrying out more than 1,500 parametric computer simulation runs for nine Australian cities using the DOE-2.1 building energy simulation program.

Management of solar gain is identified as the critical factor affecting the energy efficiency of commercial building envelopes in Australian climates, which are mostly mild and warm. The effect of window system shading coefficient on annual cooling energy is shown to be significantly greater than the effect of thermal transmittance of windows and walls. Reduction of internal gain is also seen to lower the annual cooling energy required. This paper will briefly present the results of the simulation studies and discuss their implications on energy standards for Australia and its southeast Asian neighbors.

INTRODUCTION

In June 1992, the National Greenhouse Steering Committee (NGSC 1992), as part of the National Greenhouse Response Strategy, recommended that:

1. There should be rapid completion of work on the development of nonresidential building energy performance standards.
2. New energy labeling programs and energy performance standards for commercial and industrial equipment should be introduced where it is technically feasible to do so.

Several initiatives are being implemented to address these recommendations, three of which are (1) initial studies toward the development of a commercial building energy code, (2) an industry and government initiative to develop a window energy rating scheme, and (3) the creation of an Australian data set to characterize building envelope performance and develop envelope system trade-off procedures.

This paper deals with the third initiative listed. It first documents the rationale for the development of the building envelope data set and then presents a discussion of the results within the Australasian context.

DEVELOPMENT OF AN ENVELOPE DATA SET

Need for an Envelope Systems Performance Compliance Option

Three paths to compliance have been proposed for the commercial building energy code (SRCI 1993) being developed. These are similar to ASHRAE Standard 90.1 and are prescriptive, system performance, and whole-building performance paths. Some non-negotiable basic requirements are also being proposed. The prescriptive requirements are found by identifying lowest life-cycle choices for components in four building systems, namely, fenestration, opaque envelope, lighting, and mechanical systems. The methodology is explained by Eley (1993) and is similar to that used for the 1992 California Residential Energy Standards.

Discussion with a cross section of the building industry revealed that any standard being developed for Australia must necessarily be easy to understand and apply. A mere set of prescriptive rules for envelope design was considered extremely restrictive. Although there is a growing awareness of the benefits of detailed simulation studies, hourly simulation tools—which form the basis of whole-building performance methods—are not commonly used for commercial building design by architects

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or heating, ventilating, and air-conditioning (HVAC) system designers in Australia. A systems performance method based on trade-offs between components in each building system would therefore be the most frequently used compliance path in the short term, highlighting the importance of developing an easily applicable and user-friendly systems performance procedure.

Benefits of a Two-Step Strategy

Building energy standards should be dynamic documents that will enable periodic adjustment of the baseline for minimum acceptable performance levels in response to the development and acceptance of innovative, energy-conserving building products. To successfully adopt this strategy of continual upgrading, it was considered beneficial (Wilkenfeld et al. 1993) to decouple the cost-effectiveness criteria from the energy calculations. Such a performance-based efficiency standard must have at least two components:

1. a trade-off procedure that allows a designer to select different system combinations, provided the design meets a specified minimum performance level, and
2. a procedure to set minimum performance (or stringency) levels.

To be effective, it is imperative to have a simple, yet powerful trade-off procedure as the basis of the standard. Such a procedure should be able to predict energy use for a space based on material properties, internal loads, and climate. It would then be possible to independently set the minimum acceptable performance level of every system component (e.g., the shading coefficient of the fenestration) on any criteria, be it energy cost (with or without a levy for future societal costs), a specific energy performance point (e.g., maximum energy used for cooling in $MJ/m^2 \cdot yr$), or cost-effective construction based on a chosen economic scenario. For compliance, the energy performance of the proposed building envelope will have to equal or better the building envelope system made up of components with the minimum acceptable performance.

Rationale Behind the Trade-Off Procedure

Flexibility in facade design is of paramount importance to architects, since the facade is a major contributor to the external appearance of a building. While prescriptive performance limits for roofs and floors may not attract much criticism (these elements are not wholly visible in many commercial buildings), any attempt to prescribe the choice of vertical facades would certainly attract opposition from architects. Conversely, a trade-off procedure that inherently allows a high degree of flexibility in facade design has the potential to be quickly accepted by designers and architects.

Sander et al. (1993) have developed a simple model to predict heating and cooling energy based on envelope thermal properties using a newly created data set for Canada (Crawley 1992). These equations consider the effect of fenestration shading coefficient, fenestration thermal transmittance, window-to-wall ratio, internal gain, and thermal transmittance of the opaque facade to predict the heating and cooling energy required by building perimeter zones. (Energy use in the interior zones of a building are not affected by climate and therefore do not play a part in determining the energy efficiency of building envelopes.) A cooperative study by Canadian and Australian research teams has shown the model to be applicable irrespective of climate, HVAC system configuration, and operational schedules (Cornick et al. 1995).

Development of the Simulation Data Base

A data base was developed for nine Australian locations based on a similar methodology. The results were used to develop a simple and effective systems performance trade-off procedure for the building envelope. In March 1994, the Australian research unit submitted its findings (Prasad et al. 1994). Equations to predict the heating and cooling loads for perimeter zones facing cardinal orientations in nine locations were developed and reported. These equations were used to form the basis of a trade-off procedure as described, and a proposed standard for the envelope systems performance option was drafted along with examples and worksheets. Designers were given prescriptive values for the thermal transmittance for roofs and floors but were allowed the freedom to select an appropriate combination of window-to-wall ratio, fenestration shading coefficient (with overhang credits), fenestration thermal transmittance, and thermal transmittance of the opaque facade, provided the design equaled or exceeded the thermal performance of a specified envelope configuration.

One-hundred and forty-four DOE-2 simulation runs were carried out for each location to develop the data base from which the equations were developed. The middle floor of a three-story building, with one interior zone and four perimeter zones oriented in the cardinal directions, was used for the study. Similar building models in a single-story configuration have been used in previous studies (PNL 1983; BSG 1986; Wilcox 1991).

Each zone was modeled with its own packaged single-zone HVAC system equipped with an enthalpy-controlled economizer to enable energy analysis on a zone-by-zone basis. A gas-fired furnace provided heating. The heating input ratio for the gas furnace and the energy input ratio for the cooling compressor were set to unity for the simulation runs so that heating and cooling efficiency could be accounted for separately.

The locations include all the state and territory capitals and thus account for a large portion of the commercial building activity in the country. Together these locations cover all the major climate types in Australia, except for the few Snowy Mountain locations for which complete weather data are not yet available. Table 1 lists climatic details of the locations modeled.

Comparing the climatic parameters of Australian locations with locations in the United States, Canada, and southeastern Asia (see Table 2) yields some useful observations. Only Canberra and Hobart have more than 1,667 heating degree-days (HDD) 18 (3,000 HDD65), the minimum at which mandatory insulation is required for an unheated floor slab and walls below grade as per ASHRAE Standard 90.1-1989. On the other hand, not a single U.S. location listed in Appendix C of ASHRAE Standard 90.1-1989 has anywhere near the 3,450 CDD18 (6,210 CDD65) of Darwin, with the highest being Honolulu, located outside the continental U.S., with 2,306 CDD18 (4,150 CDD65). Table 2 gives the hottest and coldest climates listed in Appendix C of ASHRAE Standard 90.1-1989. Similar conclusions can be drawn by examining the 25 Canadian locations used for developing the energy data base for the new building energy code (NRCC 1995). Table 2 lists parameters for an extreme climate (Yellowknife) and two other locations in Canada.

Table 1 Climate Indicators for Locations Used to Develop the Australian Dataset

Location	HHD18	CDD18	VSN/ VSS	Latitude
Australia				
Adelaide, South Australia	1007	584	11.8	34.9 S
Alice Springs, Northern Territory	618	1668	12.6	23.8 S
Brisbane, Queensland	232	1228	11.0	27.5 S
Canberra, Australian Capital Territory	2160	241	12.0	35.3 S
Darwin, Northern Territory	0	3450	10.4	12.4 S
Hobart, Tasmania	2062	37	10.5	42.9 S
Melbourne, Victoria	1423	244	9.9	37.8 S
Perth, Western Australia	665	811	11.6	31.9 S
Sydney, New South Wales	743	556	11.1	33.5 S

HDD18 = Heating-Degree-Day 18°C
CDD18 = Cooling-Degree-Day 18°C
VSN/VSS = Average annual solar irradiation, MJ/m^2·day, incident on a vertical surface oriented facing the sun, i.e., North (in Southern Hemisphere) or South (in Northern Hemisphere

Table 2 Climate Indicators for Locations in USA, Canada, and Southeast Asia

Location	HHD18	CDD18	VSN/ VSS	Latitude
USA				
McGarth, Alaska	8260	1	9.6	~68 N
Honolulu, Hawaii	0	2306	10.6	21 N
Canada				
Yellowknife, North Western Territories	8600	26		62.5 N
Windsor, Ontario	3687	273		42.3 N
Toronto, Ontario	4218	224	8.3	43.7 N
Southeast Asia				
Bangkok, Thailand	0	3652	10.4	13.7 N
Kuala Lampur, Malaysia	0	3495	2.6	3.1 N

HDD18 = Heating-Degree-Day 18°C
CDD18 = Cooling-Degree-Day 18°C
VSN/VSS = Average annual solar irradiation, MJ/m^2·day, incident on a vertical surface oriented facing the sun, i.e., North (in Southern Hemisphere) or South (in Northern Hemisphere

In sharp contrast, the Australian locations listed in Table 1 require much less heating, and the dominant energy use in most locations is for cooling. Similar conclusions are also applicable to many southeast Asian locations, two of which are listed in Table 2.

Brief Description of Envelope Parameters and Predictor Equations

The model to predict energy use for heating and cooling in building perimeter zones uses the three parameters given here. The formulation of the three parameters that account for (nonsolar) transmission heat loss or gain through the envelope (U), solar gains (V), and internal loads (W) are described by Crawley (1992):

facade thermal transmittance, W/m^2·K,

$$U = [A_w \times U_w + A_g \times U_g] / A_t; \tag{1}$$

solar aperture, dimensionless,

$$V = \frac{A_g}{A_t} \times SC_g; \tag{2}$$

internal gain parameter, W/m^2,

$$W = I \times \frac{A_f}{A_t}; \tag{3}$$

where

A_w = opaque facade wall area (m^2);
A_g = fenestration system area (inclusive of frame area, etc.) (m^2);
A_t = gross wall area, opaque plus fenestration (m^2);
A_f = floor area associated with perimeter, approximately 5 m (16.4 ft) deep (m^2);
U_w = opaque facade wall U-factor (W/m^2·K);
U_g = fenestration system U-factor (W/m^2·K);
SC_g = fenestration system shading coefficient, dimensionless, where shading coefficient is defined as the ratio of the solar heat gain of the fenestration system to that of a standard reference window of single-pane double-strength glass, irradiated in the same way and under the same environmental conditions;
I = design heat gain from lights, people, and equipment (W/m^2 of perimeter floor area).

Heating is estimated by predicting the seasonal heating requirement (H_{00}) of a perimeter space without considering solar and internal gains. Factors for solar gain

(*SGRF*) and internal heat generation (*IGRF*) are then used to estimate the reduced heating requirement. Cooling is estimated as two parts—the base cooling load (C_0) due to solar gain and internal load, plus a correction term (ΔC) accounting for envelope losses or gains. Thus,

$$Q_{heating} = H_{00}\,[f(U)] \times SGRF\,[f(V)] \times IGRF\,[f(W)] \tag{4}$$

and

$$Q_{cooling} = C_0\,[f(V, W)] + \Delta C\,[f(U)]\,. \tag{5}$$

The functions of *V*, *W*, and *U* in Equations 4 and 5 use location- and orientation-specific constants that are derived from the simulation data base created from multiple DOE-2 runs where each parameter is varied over a specified range while the other two are held constant. Cornick and Sander (1993) discuss the derivation of the energy predictor equations in detail, and the brief description presented is only in the interest of completeness.

RESULTS AND IMPLICATIONS FOR WARM CLIMATES

This section presents some of the simulation results that were generated and analyzes the implications for building efficiency codes developed for warm and hot locations.

Large Cooling Energy Needs vs. Small Heating Energy Needs

Unless otherwise mentioned, the following apply to Figure 1 and all following figures.

1. A COP of 3 for cooling and a gas furnace efficiency of 0.8 have been included in the annual cooling and heating energy numbers displayed.
2. Annual cooling and heating energy in MJ/m^2·yr are based on the floor area associated with the perimeter zone in question.
3. The total internal heat gain (*I*) from lighting, equipment, and people is 30.4 W/m^2 (2.8 W/ft^2) based on the floor area associated with the perimeter zone in question. Note that *I* is different from the internal gain parameter *W*, which is relative to the vertical facade area.
4. All figures are based on results of the actual DOE-2 runs, not on derived results from the energy predictor equations (Equations 4 and 5).

Figure 1 shows the variation of the annual heating and cooling energy needs with solar aperture, *V*, for east-facing perimeter zones in Canberra, Darwin, and Sydney. Cooling energy is shown along the positive y-axis, while heating energy is shown as negative.

Two observations can be immediately made from Figure 1 for each location. First, the annual cooling energy required increases linearly (at constant *W* and *U*) with increasing solar aperture, *V*. Second, the annual heating energy required decreases nonlinearly with increasing solar aperture. Both these effects are physically consistent, i.e., increased solar gain (due to increased fenestration area or use of glazing with higher shading coefficient) results in greater cooling energy needed in summer and less heating energy required in winter as the useful fraction of solar gain offsets the heating energy requirement.

Similar curves are seen for the other cardinal orientations, as shown in Figure 2, for Sydney. The zone oriented away from direct sun (south zone in the Southern Hemisphere) has a predictably different response, with lower cooling and higher heating requirements compared to the north-, east-, and west-facing zones.

Commercial buildings in Australia tend to have large amounts of glass on their facades. Even suburban office buildings are generally designed as "a slice of a CBD building in a landscaped site" (Thomas et al. 1994) (CBD [central business district] buildings are a general reference to multi-story glass facade buildings common in city centers). Consider two possible building configurations represented by $V = 0.2$ and $V = 0.4$. Since solar aper-

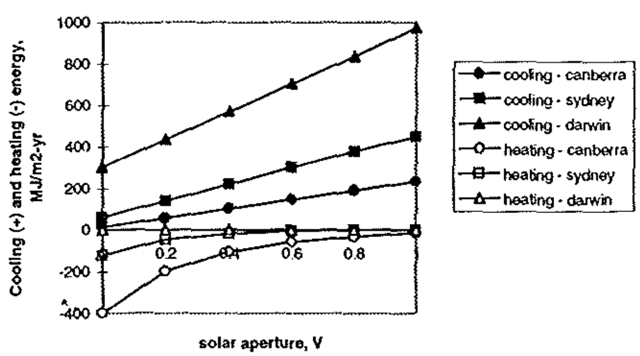

Figure 1 Solar aperture, V, vs. cooling and heating energy for east-oriented perimeter zones at three Australian cities; I = 30.4 W/m², U = 2.3 W/m²·K.

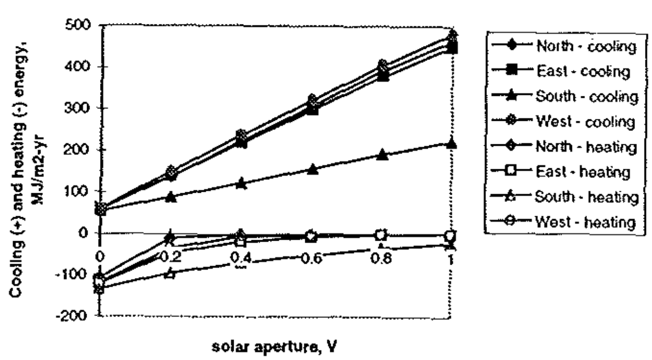

Figure 2 Solar aperture, V, vs. cooling and heating energy for perimeter zones at Sydney; I = 30.4 W/m², U = 2.3 W/m²·K.

Table 3 **Example Commercial Building Configurations**

Solar Aperture, *V*	0.2	0.4
WWR	0.80	0.60
SC	0.25	0.67

ture (V) is the product of the window-to-wall ratio (WWR) and the shading coefficient (SC) of the fenestration system, two example combinations for these parameters are given in Table 3. The first combination is typical of an almost all-glass-facade building with reflective glazing (e.g., bronze), while the second configuration has a shading coefficient/fenestration area combination typical of office buildings fitted with tinted glazing.

The perimeter zones of the building in Sydney (see Figure 1) require about three times as much energy for cooling when compared to the energy for heating, for $V = 0.2$ in the north-, east-, and west-facing zones, and this ratio rises to almost 11 for $V = 0.4$. Even in the south zone, oriented away from direct sun, cooling needs are greater than heating for typical values of solar aperture, e.g., $V > 0.2$. Note that Sydney requires more heating (has more HDD) and less cooling (has less CDD) than Alice Springs, Brisbane, and Perth (from Table 1). Thus the ratio of annual cooling to heating energy in all of these locations is higher than that of Sydney. Buildings in Darwin have enormous cooling loads and require no heating.

The building in Canberra is seen to have higher heating energy needs as compared to cooling (Figure 1). This is particularly so in the south orientation (in the Southern Hemisphere), which does not receive direct solar access (not shown). In the other orientations, there is only a marginal difference between the total heating and cooling needs. Of the nine Australian locations modeled, Hobart always requires more heating than cooling, Melbourne has slightly more heating, while Adelaide has marginally greater cooling energy requirements.

The focus of this study is on the unique results for the warmer locations, and results for Canberra are used only to highlight this distinction. Note that although the CDD18 for Canberra are similar to those for Toronto (see Table 1), the HDD18 are about half, highlighting the fact that even Australia's coldest major city cannot be classified as a really cold climate.

The Marginal Benefit of Facade Thermal Transmittance

Equations 1 through 3 suggest there are three parameters that can be varied in an effort to improve the envelope energy efficiency of a building:

1. Controlling solar gain into the building by changing the solar aperture parameter, V. This can be done by varying either the WWR (feasible at a conceptual design stage) or the choice of fenestration, i.e., select a fenestration system with an appropriate shading coefficient. Figure 1 shows linearly increasing cooling loads and a nonlinear decrease in heating load with increasing solar aperture. In warmer climates, where the energy required for cooling is significantly higher than the energy required for heating, the priority is clearly to reduce the energy required for cooling, i.e., to reduce solar aperture.
2. Controlling internal heat generation by choosing to install efficient electric lighting systems, promoting the use of energy-efficient equipment, etc. Figure 3 is a plot showing the effects of increasing internal loads for exactly the same building configurations as Figure 1; the y-axis scale for MJ/m^2·yr is also identical. The data points for $I = 30.4$ W/m^2 (2.8 W/ft^2) represent the building configuration for $V = 0.4$ shown in Figure 1. The relationships are similar to those in Figure 1, i.e., linearly increasing cooling loads and nonlinearly decreasing heating loads with increasing internal loads, although the dependencies seem to be not as strong as for solar aperture. Again, the total cooling to heating energy ratio is informative. Even with no inter-

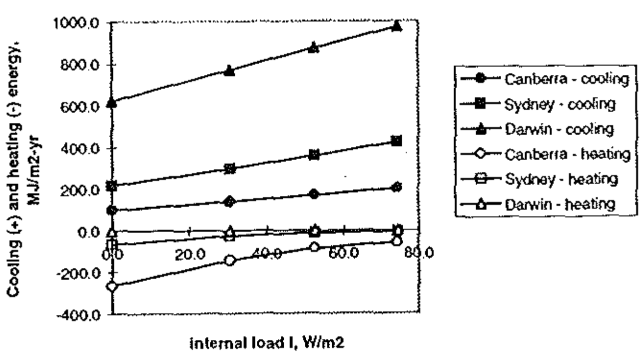

Figure 3 *Internal load, I, vs. cooling and heating energy for east-oriented perimeter zones at three Australian cities; V = 0.4, U = 2.3 W/m^2·K.*

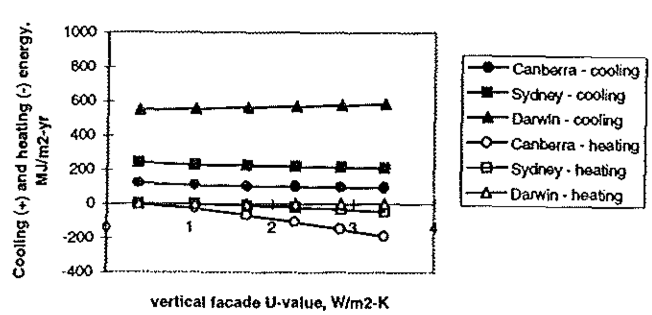

Figure 4 *Facade thermal transmittance, U, vs. cooling and heating energy for east-oriented perimeter zones at three Australian cities; V = 0.4, I = 30.4 W/m^2.*

nal loads at $I = 0\ W/m^2$ ($0\ W/ft^2$), the annual cooling energy needed is 3.4 times the heating energy needed for Sydney.

3. Decreasing the thermal transmittance (it is not usual to increase thermal transmittance) of the vertical facade, either by adding insulation to the opaque walls or by the use of double glazing, thermally broken frames, etc. This option is shown in Figure 4. In keeping with Figures 3 and 4, the y-axis scale has been kept constant to allow intuitive visual comparisons. The data points for $U = 2.3\ W/m^2{\cdot}K$ are the same as for $V = 0.4$ in Figure 1 and $I = 30.4\ W/m^2$ ($2.8\ W/ft^2$) in Figure 3.

The most striking observation that can be made from the results shown in Figure 4 is the change in the direction of the slope of the lines. Canberra and Sydney show slightly increased cooling energy needs as the thermal transmittance of the vertical facade is reduced. The results for Darwin follow conventional wisdom, and a reduction of facade thermal transmittance does indeed show a small reduction of annual cooling energy. Cooling is again seen to be linearly dependent on facade thermal transmittance (although the dependency is very small), while heating is nonlinear. To get some quantitative feel for the relationships shown in Figures 1, 3, and 4, it is useful to compute the change required to the variable on the x-axis of each these figures to effect a reduction of 1 $MJ/m^2{\cdot}yr$ (.09 $kBtu/ft^2{\cdot}yr$) in annual cooling energy. These are listed for Sydney in Table 4.

Although these quantities do not have identical units and are not strictly comparable, the information in Table 4 allows some important qualitative judgments to be made. A reduction of 1 part in 390 of the solar aperture, *V*, drops the energy needed for cooling as much as 1 part in 2.75 for internal gain, *I*. In contrast, "bettering" the facade by decreasing its thermal transmittance by 1 part in about 10 increases the cooling energy required by the same amount.

Table 4 **Reduction in Parameter Required to Reduce Cooling Energy by 1 $MJ/m^2{\cdot}yr$; Sydney, East Orientation**

Parameter	Change Required	Units
Solar aperture, *V*	0.0026	ratio
Internal load, *I*	0.3634	(W/m^2)
Facade Thermal Transmittance, *U*	–0.0957	($W/m^2{\cdot}K$)

Implications for Commercial Building Envelope Energy-Efficiency Standards in Warm Climates

This discussion leads to some interesting inferences. In warm, temperate, and hot locations (five of the nine Australian locations selected), energy required for cooling is many times more than that required for heating in typical multilevel commercial office buildings. Changing the solar aperture (i.e., window-to-wall ratio and/or fenestration system shading coefficient) offers the greatest potential for reducing annual cooling energy, followed by a reduction of the building's internal loads.

On the other hand, reducing the vertical facade's thermal transmittance in such climates can increase the annual cooling energy required, albeit by a very small amount. This is probably due to small temperature differentials between the ambient and cooled spaces and internally driven buildings (although a fairly conservative total internal load of 30 W/m^2 (2.8 W/ft^2) was used to demonstrate these findings). Such buildings store heat during the day and tend to cool down at night when the plant is shut down, the building is unoccupied, and night temperatures fall below the cooling setpoint. Adding insulation to the facade restricts this "free cooling" cycle, resulting in slightly increased cooling energy.

Only in extremely hot climates, such as Darwin, does adding insulation to the vertical facade result in a marginal reduction of cooling energy. This is probably due to ambient temperatures being higher than the cooling thermostat setpoint, even at night. There is mainly heat gain into the building at most times and little opportunity for "free cooling." Additional insulation in the vertical facade will marginally reduce the small proportion of conductive heat gain into the building.

CONCLUSIONS

Selection of fenestration systems for commercial office buildings in warm climates similar to many locations in Australia assumes critical importance and should be addressed explicitly by energy-efficiency codes and standards applicable to warm and hot locations.

Second, energy efficiency of commercial office buildings in warm climates is not a strong function of facade thermal transmittance. Therefore, simple OTTV (overall thermal transmittance value) type calculation procedures would be considered inappropriate as a basis for energy-efficient building envelope standards in Australia. Originally developed for cold climates, such procedures place a great deal of importance on limiting envelope thermal transmittance values. In warmer climates, as adapted for the Southeast Asian nations, the shading coefficient term is by far the most significant in the OTTV equation. In such climates, comparable to warm Australian locations (see Tables 1 and 2), these standards become "implicit shading coefficient standards" (Koldrup and Eley 1992).

Envelope trade-off procedures for such locations could be at once simplified and offer a significantly higher level of design flexibility by adopting explicit trade-offs between the fenestration shading coefficient (or solar heat gain coefficient) and window-to-wall ratios. The procedure described in this paper can be used as a basis for developing such trade-offs.

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