Passive Design in Residential Buildings: A Review of Current and Potential Technologies

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ABSTRACT

As residential housing increases with population growth and people expect larger homes, increasing amounts of energy are consumed to meet this demand. Passive design in buildings can provide huge energy savings in the usage phase using both basic and complex methods and technologies. A range of simple design methods are discussed to reduce artificial heating, cooling and lighting requirements within residential buildings. In further depth, upcoming technologies such as counter current heat exchange in ventilation and the use of phase change materials in building materials are analysed. The application of these methods to the Melbourne climate will be briefly analysed along with current building regulations and recommendations for the near future.

1. INTRODUCTION

Energy is vital in material production, building construction as well as household usage throughout the lifetime of a building. Over the past fifty years, residential buildings have gone throughout a great transformation phase to meet people's expected comfort levels. From the basic triple fronted brick veneers seen in Melbourne in the 1950s, we now see larger houses, using more materials, more complex construction, ducted heating and cooling with excesses of electronic appliances. Passive solar design can be implemented in residential houses to reduce the energy required throughout the usage phase of the building and move towards more sustainable energy use, often using concepts derived from systems found in nature.

This paper will explore some basic methods that are already being implemented to many new buildings to reduce energy usage through heating, cooling and lighting, as well as other newer concepts in techniques and technologies. These include counter current heat exchange and the use of phase change materials in thermal mass. Current building regulations will be analysed as well as recommendations for Melbourne, Victoria for the near future in regards to implementing passive solar design in all new residential buildings.

2. WELL KNOWN PASSIVE SOLAR TECHNIQUES IN PRACTICE

2.1 Orientation

For the southern hemisphere, a building should face towards the equator. Therefore, buildings in Melbourne should be orientated with the main living areas and windows facing true north between 15°W and 20°E (Reardon, 2008). This allows for the low winter sun to heat up the building and reduce heating requirements while keeping out the higher summer sun with the addition of eves.

2.2 Shading

In summer, large north facing windows may provide too much heat to a residential building. To reduce this problem, eves and retractable awnings may be installed to reduce the high summer direct radiation while letting in the low winter suns radiation.
Deciduous trees and vines loose their leaves in winter, therefore offering shade in the summertime and let the sun in the wintertime. These can be planted close to the north facing

wall and window to reduce the need for both cooling and heating in the respective seasons with a reduction of active heating by approximately 50% (Parker, 1983).

2.3 Double Glazing

Double glazing of windows is now almost standard practice and act as insulation for windows. This reduces heat flow in and out of a building by half (Energy Savings Trust, 2009). Therefore, northern windows should not be double glazed, as long as shading or eves are present.

2.4 Insulation

Wall and roof insulation reduces the movement of thermal energy from the internal space of a building to the environment. Therefore, heat losses during winter are reduced and less heat can infiltrate the building during summer. Up to 45% of heating and cooling energy can be saved through installing insulation in ceilings and roof while a further 20% is saved through wall insulation and 5% through floor insulation (McGee, 2008).

2.5 Thermal Mass

Using high density materials such as concrete and brick, this acts as a thermal mass and helps moderate the internal temperatures by averaging diurnal extremes (Reardon, 2008). In winter they store energy from the sun during the day and release it at night while in summer they act as a heat sink and help keep the internal environment comfortable. It is estimated that when compared to lighter weight building materials, they can save up to 25% of heating and cooling energy requirements (Sustainability Victoria, 2009).

2.6 Passive Illumination

Through the use of natural light in residential buildings, an energy saving can be made. However, natural light benefits human both psychologically and physiologically through the various spectrums and this benefit is often overlooked when designing new buildings. Robbins (1986) suggests that natural light has been associated with improved mood, enhanced morale, lower fatigue and reduced eyestrain.

2.6.1 Maximizing Natural Light

In order to maximise the natural light input, the visible transmittance must be high. Visible transmittance is an optical property that indicates the amount of visible light transmitted through the glass. Conventionally, glass windows have dominated natural light in residential buildings, but daylight does not penetrate deeply into the rooms from ordinary glass windows, falling almost exponentially with distance from the window (Edwards & Torcellini, 2002).

2.6.2 Application of Natural Lighting – Skylights

An excellent way to provide natural light is through the use of skylights. These, in conjunction with the right glazing materials, can allow three times as much light as a common glass window of the same size. To increase their energy efficiency at least two panes and a heat reflecting coating must be added to the design (Lyons, 2008).

3. COUNTER-CURRENT HEAT EXCHANGE

Counter current heat exchange is a less well known system to recover thermal energy while maintaining ventilation. It is a mechanism used to transfer heat from one fluid to another flowing in the opposite direction using a thermally-conductive material between the flows. This can be applied to residential buildings to reduce heat losses. Figure 1 below explains the behaviour of this system.

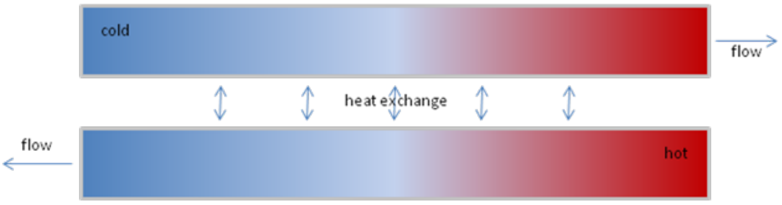

Figure 1. Counter current Heat Exchange Diagram. (Ash, 2000)

The diagram shows two streams separated by a thermoconductive membrane. The property transferred, which in this case is heat, is represented in Figure 1. As the two fluids run in opposite directions, it is possible for the system to maintain a constant gradient over the whole length. If the length is sufficient, all of the heat may be transferred, provided both the fluids have similar specific heat capacities. The configuration of a counter current heat exchanger makes it possible to transfer heat between the two liquids, that is, the hot fluid decreases in temperature while the colder fluid increases in temperature.

One such example of this occurring in nature is shown in the bumblebee, which is able to keep itself at a regular temperature by using counter current heat exchange and heat shunting mechanisms (Heinrich, 2004). The anatomy of a bumblebee creates a counter current heat exchanger between the blood flow between the thorax and abdomen. This allows the heat to remain in the thorax regardless of the blood flow.

3.1 Application for a Household

This basic counter current heat exchange system can be modified for use in an average household, such as a low energy ventilation system. Every household needs ventilation to obtain fresh air and prevent the build up of harmful substances and stale air in the building. By opening doors and windows, the humidity and amount of fresh air that enters the house cannot be controlled as these conditions vary according to the weather. Along with obtaining fresh air, a good ventilation system needs to remove stale air, which contains high levels of moisture and odours. The system is sensitive to temperature and consequently operates differently in winter than in summer.

3.1.1 Operation in Winter

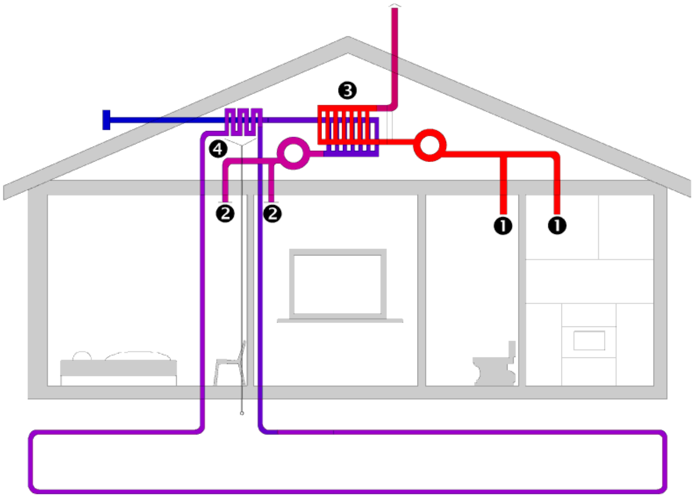

Figure 2. Operation in winter of a ventilation system using a counter current heat exchanger. (Rosemeier, 2008) See following paragraph for explanation of numbers in Figure 2.

For a winter scenario shown above, stale air is ducted from areas of the house that produce odours and air of low quality ([1] e.g. the kitchen and the bathroom). From outside the house, fresh air is pumped into the house that is delivered into the rooms where needed ([2] e.g.

living room and bedrooms). The fresh air is heated by using a counter current heat exchanger [3] using the exhaust air from the kitchen and bathroom. The input air is heated before reaching the counter current heat exchanger by a simple heat exchanger that goes through the ground [4].
In locations where the difference between the ground temperature and the ambient air temperature is not sufficiently large enough, it is recommended that an underground heat exchanger not be installed since its contribution can be considered negligible.

3.1.2 Operation in Summer

As mentioned above, the counter current heat exchanger system can be used in summer as shown in Figure 3 below.

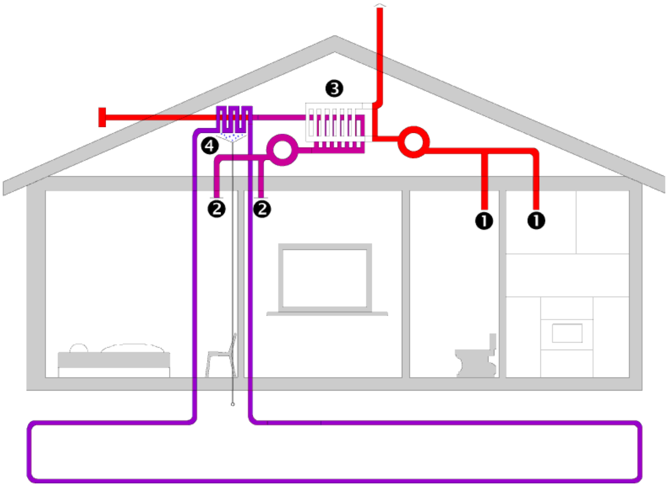

Figure 3. Operation in summer of a ventilation system using a counter current heat exchanger. (Rosemeier, 2008) See following paragraph for explanation of numbers in Figure 3.

Stale air is ducted from areas of the house that produce smell and low quality air ([1] e.g. the kitchen and the bathroom). From outside the house, fresh air is pumped into the house that is delivered into the rooms where needed ([2] e.g. living room and bedrooms). In contrast to the winter system, there is no need for the counter current heat exchanger [3]. Wind from outside is cooled by a heat exchanger that goes through the ground. As the wind is cooled, it will experience some condensation, resulting in a decrease its humidity level.

4. THE USE OF PHASE CHANGE MATERIALS AS A THERMAL MASS

4.1 Background of Phase Change Materials

The use of thermal mass in passive design as described above is essential to maintain adequate temperatures throughout the day and night. Utilising materials which have a melting point close to room temperature can be effective in stabilising the temperature of a building due to their large latent heat capacity. The latent heat of melting is the large amount of energy that is absorbed or released as a material changes phase from a solid to a liquid or vice versa (Farid & Khudhair, 2003). Phase change materials (PCM) absorb large amounts of latent heat at a constant phase transition temperature and are ideal at assisting in passive heat storage and temperature control (Huang et al., 2006). PCM encapsulated materials such as wallboards, typically have a volumetric thermal storage capacity 5 times greater than that of masonry (Pieppo, 1990; Neeper, 2000). The use of PCMs to store coolness have been developed for air conditioning applications, where cold is collected and stored from ambient air at night, and released into the building during the hottest hours of the day. This concept is known as free cooling (Cabeza et al., 2002).

While the technology has been explored since before 1980, it has yet to establish itself as a commonly implemented technique of sustainable building practice. Technology has been limited in its use in residential buildings as few companies are yet to develop PCM materials suitable for use, though it has been successfully implemented in similar temperature control applications including in electronics and the storage of perishable items (Huang et al., 2006). Currently available in Australia is the Knauf Micronal® PCM SmartBoard™ (Knauf, 2009), which has been implemented successfully in the 6 star Green Star rated Charles Sturt University building (Award Magazine, 2009), among other projects.

While currently, there are no studies on PCM use in Melbourne, the University of Auckland, New Zealand (Farid, 2007), is undergoing research into developing a gypsum wallboard containing PCM suitable for New Zealand weather conditions. The use of PCMs in buildings has also been studied by several other researchers such as Khudhair (2003), Cabeza et al (2003), Castillon et al (2006) and Huang et al (2006), while commercially available products have been developed by companies such as BASF (Castellon et al., 2006). It can be concluded that PCM gypsum wallboard is a viable alternative to concrete and bricks as a thermal mass, and is likely to become more widespread in its use for sustainable buildings.

Studies by Kendrick and Walliman (2006) have shown that the effect of PCMs on daytime temperature is quite substantial, with a typical reduction of 4 – 5 °C on very hot days. However, it is important to note that the cooling effect of PCMs will only be present if the whole cycle takes place, whereby the PCM is cooled and recrystallised before the next day (Castellon et al., 2006). Night ventilation is useful in this regard and could be implemented in the Melbourne climate, though the use of air conditioning overnight may be preferred if there are a succession of very hot days, as can be common in the summer months in Melbourne. Figure 4 below shows an example of the effect PCMs have on the temperature in a room. It can be concluded that PCMs are quite effective at keeping the temperature within a comfortable range for a large percentage of the duration.

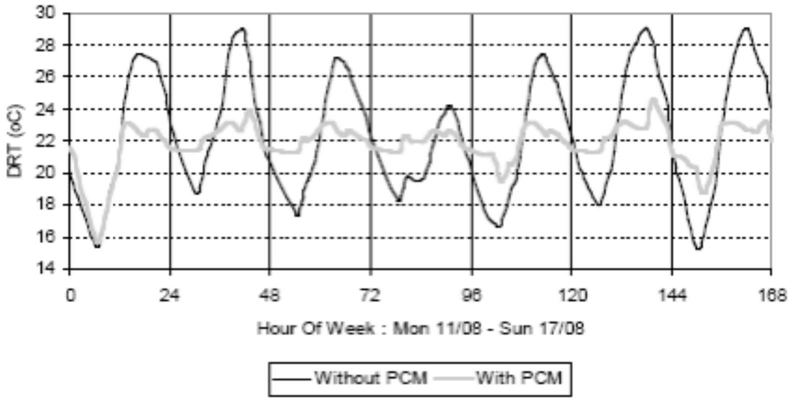

Figure 4. Effect of PCM on temperature profile for residential conditions. (Kendrick & Walliman, 2006).

The light weight structure of many residential buildings has resulted in these houses having a low thermal mass, leading to high temperature fluctuations (Cabeza et al., 2002). As PCMs do not require considerable mass to deliver adequate temperature control, they may present a solution to this problem, both in future construction and the retrofitting of buildings. Masonry walls have traditionally been used for passive storage but do not always sufficiently stabilise temperature swings due to their limited thermal capacity, and are often inappropriate for retrofits due to the large mass needed (Peippo et al., 1990). Additionally, the energy required to produce PCMs is only a fraction of that required to produce blocks, bricks or concrete with the same storage heat capacity (Kendrick & Walliman, 2006).

4.2 Phase Change Materials Suitable for Residential Building Applications

Studies by Peippo (1990), Neeper (2000) and Kendrick & Walliman (2006) have concluded that the optimal diurnal storage occurs with a PCM melt temperature 1 – 3 °C above the average room temperature. Therefore a melt temperature of between 20 and 24°C would be appropriate. Along with having a desirable melting temperature, a number of other properties are essential in an effective phase change material, those of which are summarised in Table 1 below. PCMs useful for building applications can be divided into two main groups: inorganic materials (e.g. hydrated salts) and organic materials (e. g. fatty acids and their derivatives and paraffins) (Table 2). Salt hydrates, though cheaper than organic materials, have a tendency to supercool (drop below its freezing temperature without the transition to solid occurring) and the components do not melt congruently, resulting in segregation (Farid & Khudhair, 2003).

Table 1. Important characteristics of energy storage materials. (Cabeza et al. 2002).

Thermal Properties	Physical Properties	Chemical Properties	Economic Properties
Phase change temperature fitted to application	Low density variation	Compatibility with container materials	Cheap and abundant
High change of enthalpy near temperature of use	High density	No phase separation	
High thermal conductivity in both liquid and solid phases (although not always)	Small or no undercooling	Non-toxic, non-flammable, non-polluting Stability	

Readily available fatty acids are considered the most suitable for residential buildings as their melting point can be easily modified to suit the application, while the cost still remains reasonable (Peippo et al. 1990). Although fatty acids have a lower heat storage capacity per unit volume, they are physically and chemically stable with good thermal behaviour (Farid & Khudhair, 2003). Organic materials also have a tendency to decompose over time and are often highly flammable. These problems can be overcome by adding antioxidants to the PCM to prevent deterioration (Peippo et al. 1990), adding fire retardants or using halogenated PCM compounds such as brominated hexadecane or octadecane is self extinguishing (Farid & Khudhair, 2003). Possible toxicity issues may have to be assessed. Table 2 below shows PCMs that are suitable for implementation into building materials.

Table 2. Hydrated salts and organic PCMs suitable for buildings. (Farid & Khudhair, 2003).

PCM	Melting point (°C)	Heat of fusion (kJ/kg)
KF · 4H2O Potassium fluoride tetrahydrate	18.5 – 19	231
$CaCl_2 \cdot 6H_2O$ Calcium chloride hexahydrate	29.7	171
$CH_3(CH_2)_{16}COO(CH_2)_3CH_3$ Butyl stearate	18 - 23	140
$CH_3(CH_2)_{11}OH$ Dodecanol	17.5 – 23.3	188.8
$CH_3(CH_2)_{16}CH_3$ Tech. grade octadecane	22.5 – 26.2	205.1
$CH_3(CH_2)_{12}COOC_3H_7$ Propyl palmitate	16 – 19	186
45% $CH_3(CH_2)_8COOH$ / 55% $CH_3(CH_2)_{10}COOH$ 45/55 Capric-lauric acid	17 – 21	143

4.3 The Application of Phase Change Materials in Residential Buildings

PCMs can be integrated into a number of mediums including concrete, plasterboard and furniture. This paper will focus on the storage of phase change materials in the air pockets of gypsum plasterboard, which typically account for approximately 40% of the volume of the board. It was discovered that PCM concentrations of up to 25% were suitable for this application, with higher concentrations leading to some PCM leakage over the temperature cycles (Kendrick & Walliman, 2006). Analysis by Farid & Khudhair (2003) has shown that adding PCM to the gypsum board by an immersion process has the potential to achieve higher heat storage capacity than adding wax filled pellets to the wallboard during its manufacture, with a tenfold increase in energy storage capability for the storage and discharge of heat when compared with the standard gypsum wallboard (Farid & Khudhair, 2003).

The gypsum wallboard infused with PCM can be installed in place of ordinary wallboard during new construction or rehabilitation of a building. Farid & Khudhair (2003) reached the conclusion that the installation of PCM wallboard would incur little or no additional costs in place of ordinary wallboard. As the Knauf Micronal® PCM SmartBoard™ available in Melbourne is manufactured in Germany (Knauf, 2009), it is likely that a locally produced material will be much cheaper due to lower transportation costs. As PCMs are produced from readily available substances such as paraffin waxes (Farid & Khudhair, 2003), it is possible for appropriate materials to be produced locally. Furthermore, with new products becoming available the cost is likely to decrease as a result of a more competitive market. While the initial cost of using PCM wallboard is likely to be more expensive than other commonly used materials, the decrease in reliance on heating and cooling will provide energy savings, making this a more financially attractive option. Important, but not easily expressed in terms of economic benefit, is the increased thermal comfort that PCM wallboards may provide (Peippo et al, 1990).

5. APPLICATION IN MELBOURNE

5.1 Climate conditions in Melbourne

The city of Melbourne is situated at a latitude of 37.8° south, with a mild temperate climate. The mean monthly temperature ranges from a minimum of 10.4°C in July to a maximum of 21.2°C in February (BOM, 2007). Table 3 below shows the range of temperatures experienced in Melbourne, and assuming that buildings must remain close to 20 - 24°C to maintain maximum comfort that humans have grown accustomed to, heating is required in the winter months and cooling required in the summer months in order to maintain comfortable temperatures within the buildings.

Table 3. Melbourne's Annual Temperature Summary (BOM, 2007). (All values given in dry bulb temperature (°C))

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
Extreme maximum	43.3	43.2	41.0	33.8	27.7	20.8	23.1	26.5	30.7	34.5	40.3	41.9	43.3
Mean daily maximum	25.8	26.5	24.0	20.5	17.3	14.4	13.9	15.3	17.3	19.7	21.8	24.2	20.1
Mean	20.6	21.2	19.2	16.1	13.6	11.0	10.4	11.5	13.2	15.1	17.0	19.1	15.7
Mean daily minimum	15.4	15.8	14.3	11.7	9.8	7.6	6.8	7.6	9.0	10.5	12.2	13.9	11.2
Extreme minimum	8.5	8.7	6.7	4.2	2.1	0.0	-0.8	0.3	2.0	3.9	4.0	7.5	-0.8
Mean diurnal range	10.4	10.7	9.7	8.8	7.5	6.8	7.1	7.7	8.3	9.2	9.6	10.3	8.9

5.2 Application of Passive Design for Melbourne Climate

Melbourne's variable climate requires residential buildings to be heated and cooled throughout the year to maintain comfort levels. All current passive solar design methods discussed in this paper are useful to Melbourne residences and are currently being implemented in many new residential buildings. Northern facing houses provide great energy savings in winter providing the land allows for such orientation. This, combined with shading through eves and awnings prevents overheating in summer. Double glazing, insulation and thermal masses reduces the movement of thermal energy.

Counter current heat exchange ventilation may provide some benefits to Melbourne residences, but its application may be limited, with many consumers opting for more well known and proven technologies. PCMs in building materials show great promise, especially houses preferring more lightweight materials that seem to be a trend in suburban Melbourne.

6 VICTORIAN BUILDING REGULATIONS – GREEN BUILDINGS

6.1 Current

The building regulations in Melbourne dictate the grounds on which passive buildings can be built. Building design and construction must comply with the Building Act 1993, *Building Regulations 2006* (the Regulations) and the *Building Code of Australia 2006* (the BCA) unless exempted.

"Green" buildings are part of the Victorian Government's strategy to reduce greenhouse gas emissions. A major achievement in the promotion of sustainable development was through the development of the Green Star rating system which assesses the environmental performance of buildings including the energy and water efficiency, resident health and resource conservation. The Green Building Council of Australia aim to promote the advance in technologies and design practices associated with "Green" building designs (Building Commission, 2008). According to the Australian Green Building Mission, Australia is as technologically equipped as North America and Europe, however does not commercially distribute the concept as well as other continents. It is expected that over the next few years, sustainable development will become exponentially increasingly popular as business decisions are influenced by factors such as the environment and health (Australian Green Building Mission, 2003)

In 2005, the 5 star standard was introduced for new homes. It is estimated that if all homes in Victoria were converted to 5 star ratings, the annual savings would be up to is up to $40 million as well as up to 600,000 tonnes of green house gases. Energy efficiency levels for heating and cooling through the upgraded buildings are expected to increase by 40-50 per cent when compared with old insulation regulations that have been in force since the early 1990s (Building Commission, 2008). Since the majority of households in Victoria are older dwellings, the improvement of energy efficiency will greatly reduce the impact made upon the climate and ozone through the reduction of emitted greenhouse gases. Since May 1st 2008, the 5 star energy rating for renovations and relocated homes has complied with the national standard in the Building Code of Australia (Building Commission, 2008).

6.2 Recommendations

The main aims of making any home greener involve reducing energy, waste, water, and cost as well as improving health. In this regard the recommendations made must accommodate all these factors. The development of standards should be carried through for water reuse, recycling construction and debris and indoor environmental quality while passive design in residential buildings will provide massive energy savings.

Incentives should be put in place to further promote the benefits of Green buildings with the drive for more 5 star rated houses to be developed around Melbourne. The focus on better air, water, and energy efficiency must be kept at a high priority so it is important to place standards for them. Along with these standards, further education must be taken in regards to energy efficiency and building design capacity to be able to fully integrate Green buildings into society (Australian Green Building Mission, 2003).

7. CONCLUSION AND RECOMMENDATIONS

Many basic and cost effective passive design techniques, as discussed are currently being implemented into new residential buildings to help reduce energy during the usage phase of the building. These include, but are not limited to, house orientation, shading, double glazing, insulation, thermal mass and passive illumination. A combination of these design parameters are required to help keep the interior warm in winter and cooler in summer to acceptable comfort levels and may also provide natural light. The upcoming technologies of counter current heat exchange ventilation provides fresh air without loosing too much thermal energy while the implementation of PCMs have the potential to play a major role in regulating interior temperatures in a similar way to thermal masses.

Melbourne's mildly temperate climate requires heating or cooling for a major portion of the year and can benefit from all of the discussed methods of passive design. Currently, some building regulations are in place to encourage the implementation of passive design to reduce energy use through heating, cooling and lighting. It is recommended that the Victorian government and Melbourne councils review the current regulations on a regular basis and look towards implementing the Green Star rating system on the majority of existing dwellings as well as new establishments.

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