Passive design
Thermal mass

Thermal mass

Thermal mass is the ability of a material to absorb and store heat energy. A lot of heat energy is required to change the temperature of high density materials like concrete, bricks and tiles. They are therefore said to have high thermal mass. Lightweight materials such as timber have low thermal mass. Appropriate use of thermal mass throughout your home can make a big difference to comfort and heating and cooling bills.

Thermal mass can store solar energy during the day and re-radiate it at night.

Thermal mass, correctly used, moderates internal temperatures by averaging out diurnal (day–night) extremes. This increases comfort and reduces energy costs.

Poor use of thermal mass can exacerbate the worst extremes of the climate and can be a huge energy and comfort liability. It can radiate heat to you all night as you attempt to sleep during a summer heatwave or absorb all the heat you produce on a winter night.

To be effective, thermal mass must be integrated with sound passive design techniques. This means having appropriate areas of glazing facing appropriate directions with appropriate levels of shading, ventilation, insulation and thermal mass.

How thermal mass works

Thermal mass acts as a thermal battery. During summer it absorbs heat during the day and releases it by night to cooling breezes or clear night skies, keeping the house comfortable. In winter the same thermal mass can store the heat from the sun or heaters to release it at night, helping the home stay warm.

Thermal mass is not a substitute for insulation. Thermal mass stores and re-releases heat; insulation stops heat flowing into or out of the building. A high thermal mass material is not generally a good thermal insulator (see Rammed earth).

Thermal mass is particularly beneficial where there is a big difference between day and night outdoor temperatures.

Daily temperature fluctuations for different construction methods.
Correct use of thermal mass can delay heat flow through the building envelope by as much as 10–12 hours, producing a warmer house at night in winter and a cooler house during the day in summer (Wilson 1998). (see ‘Thermal lag’ below)

A high mass building needs to gain or lose a large amount of energy to change its internal temperature, whereas a lightweight building requires only a small energy gain or loss to change the air temperature. This is an important factor to consider when choosing construction systems and assessing climate change adaptation.

**Winter**
Allow thermal mass to absorb heat during the day from direct sunlight or from radiant heaters. It re-radiates this warmth back into the home throughout the night.

**Summer**
Allow cool night breezes and/or convection currents to pass over the thermal mass, drawing out all the stored energy. During the day protect the thermal mass from excess summer sun with shading and insulation if required.

**Using thermal mass effectively**
Thermal mass is most appropriate in climates with a large diurnal temperature range. As a rule of thumb, diurnal ranges of less than 6°C are insufficient; 7°–10°C can be useful depending on climate; where they exceed 10°C, high thermal mass construction is desirable. Exceptions to the rule occur in more extreme climates.

In cool or cold climates where supplementary heating is often used, houses benefit from high mass construction regardless of diurnal range (e.g. Hobart 8.5°C). In tropical climates with diurnal ranges of 7°–8°C (e.g. Cairns 8.2°C) high mass construction can cause thermal discomfort unless carefully designed, well shaded and insulated.

Always use thermal mass in conjunction with sound climate-appropriate passive design.

**Glass to mass ratios for different climates**
Glass to mass ratios compare the area of solar exposed, passively shaded, north-facing glazing to the area of exposed, insulated internal mass (walls and floor), to avoid overheating passive solar houses. The graph below shows recommended glass to mass ratios for Australian capital cities.

**Rule-of-thumb glass to mass ratios for different climates**
- **Cold and alpine climates**: double glazed areas of 20–25% of floor area (snug drapes and pelmets should also be used)
- **Cool temperate**: double glazed windows with drapes and pelmets 15–20% of floor area
- **Temperate climates**: glass area 12–15% of floor area (17% if double glazed)
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- **Cooling dominated climates**: the ratio of solar exposed north-facing glass should be at least 6% but up to 10% can be useful depending on design.
- **Cooling only climates**: solar exposed glass should be avoided; low mass construction with high level ventilation is usually best. Earth coupled slabs can add useful ‘heat wicking’ properties to thermal mass where mass covered ground temperatures at 1.5m depth remain below 19°C in summer, i.e. not Darwin! (for ground temperature map see Baggs et al. 1991)

These ratios should be varied according to:

- solar availability (access and incidence)
- diurnal temperature ranges
- type and orientation of glazing and shading (ambient and diffuse gains).

NOTE: These rules apply only to predominantly north glazed passive designs with guaranteed solar access. Modelling with energy rating software is the only reliable way to validate them.

Typical applications

In rooms with good access to winter sun it is useful to connect the thermal mass to the earth. The most common example is slab-on-ground construction. Less common examples are brick or earthen floors, earth-covered housing or green roofs. (see Construction systems)

A slab-on-ground is preferable to a suspended slab in most climates because it has greater thermal mass due to direct contact with the ground. This is known as earth coupling. Deeper, more stable ground temperatures rise beneath the house because its insulating properties prevent heat loss. The slab assumes this higher temperature which can range from 16°C to 19°C.

In summer, the earth has the capacity to ‘wick’ away substantial heat loads. It also provides a cool surface for occupants to radiate heat to (or conduct to, with bare feet). This increases both psychological and physiological comfort.

In winter, the slab maintains thermal comfort at a much higher temperature with no heat input. The addition of passive solar or mechanical heating is then more effective due to the lower temperature increase required to achieve comfortable temperatures.

Use surfaces such as quarry tiles or simply polish the concrete slab. Do not cover areas of the slab exposed to winter sun with carpet, cork, wood or other insulating materials: use rugs instead.

The vertical edges of a slab-on-ground are required to be insulated in Zone 8 (cold climate) or when in-slab heating or cooling is installed within the slab (see Clause 3.12.1.5 (c) and (d) of the Building Code of Australia (BCA), Volume Two, for more detail).

Insulate slab edges in cold climates or where in-slab heating or cooling is installed within the slab.

The whole slab must be insulated from earth contact in cold climates and regions with low earth temperatures at 3m depth (e.g. Tasmania) or hot, humid climates with high earth temperatures (e.g. Darwin).

Consider termite proofing when designing slab edge insulation. Take care to ensure that the type of termite management system selected is compatible with the slab edge insulation.

Masonry walls also provide good thermal mass. Recycled materials can be used (e.g. reused bricks). Avoid finishing masonry walls with plasterboard as this insulates the thermal mass from the interior and significantly reduces its capacity to absorb and re-release heat.

Reverse brick veneer is an example of good thermal mass practice for external walls because the mass is on the inside and externally insulated. In traditional brick veneer, the mass of the brick makes no contribution to thermal storage because it is insulated from the inside and not the outside.
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Locate additional thermal mass near the centre of the building, particularly if a heater or cooler is positioned there. Feature brick walls, slabs, water features and large earth or water-filled pots can be used.

Cooling: Protect thermal mass from summer sun with shading and insulation if required. Allow cool night breezes and air currents to pass over the thermal mass, drawing out all the stored energy.

Where not to locate thermal mass

Avoid use in rooms and buildings with poor insulation from external temperature extremes and rooms with minimal exposure to winter sun or cooling summer breezes.

Thermal mass can increase energy use when used in rooms where auxiliary heating or cooling is the only means of adjusting the temperature because it slows the response times.

Careful design is required if locating thermal mass on the upper levels of multi-storey housing in all but cold climates, especially if these are bedroom areas.

Natural convection creates higher upstairs room temperatures and upper level thermal mass absorbs this energy. On hot nights upper level thermal mass can be slow to cool, causing discomfort. The reverse is true in winter.

Specific climate responses

Climatic consideration is critical in the effective use of thermal mass. It is possible to design a high thermal mass building for almost any climate but the more extreme climates require very careful design (see climate-specific glass to mass ratios in 'Thermal mass checklist' below).

Will the current use of thermal mass still be appropriate in 20 or 30 years’ time?

Think about the impact of predicted changes in climate due to global warming. Will the current use of thermal mass still be appropriate in 20 or 30 years’ time if temperatures rise and diurnal ranges are reduced? This is a particularly important issue in tropical climates where temperatures are already close to the upper comfort level. For the main features of these climates see Design for climate.

Hot humid (tropical) climates

Use of high mass construction is generally not recommended in hot humid climates due to their limited diurnal range. Passive cooling in this climate is usually more effective in low mass buildings.
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Thermal comfort during sleeping hours is a primary design consideration in tropical climates. Lightweight construction responds quickly to cooling breezes. High mass can completely negate these benefits by slowly re-releasing heat absorbed during the day.

Warm humid and warm/mild temperate climates

Maintaining thermal comfort in these benign climates is relatively easy. Well-designed houses should require little if any supplementary heating or cooling. In fact, 7–8 Nationwide House Energy Rating Scheme (NatHERS) stars can be achieved at relatively low cost.

The predominant requirement for cooling in these climates is often suited to lightweight, low mass construction. High mass construction is also appropriate but requires sound passive design to avoid overheating in summer.

In multi-level design, high mass construction should ideally be used on lower levels to stabilise temperatures. Low mass on the upper levels ensures that as hot air rises (through convective ventilation) it is not stored in the upper level as it leaves the building.

This is particularly important if sleeping spaces are located on upper levels. Ground and first floor spaces should be capable of zoning (closing off) to prevent temperature stratification in winter.

Cool temperate and alpine climates

Winter heating is the main need in these climates although some summer cooling is generally required. Ceiling fans usually provide adequate cooling in these low humidity climates.

High mass construction combined with sound passive solar design and high level insulation is an ideal solution. Good solar access is required in winter to heat the thermal mass. Glass to mass ratios are critical (see ‘Thermal mass checklist’ below).

Insulate slab edges and the underside of suspended slabs in colder climates. It is advisable to insulate the underside of a slab-on-ground in extremely cold climates. (see Insulation installation)

Buildings that receive little or no passive solar gains can still benefit from high mass construction if they are well insulated. However, they respond slowly to heating input and are best suited to homes with high occupation rates.

Auxiliary heating of thermal mass is ideally achieved with efficient or renewable energy sources such as solar, gas or geothermal powered hydronic systems. In-slab electric resistance systems are slow responding and cause higher greenhouse gas emissions. (see Heating and cooling)

Use a solar conservatory in association with thermal mass to increase heat gains. A solar conservatory is a glazed north-facing room that can be closed off from the dwelling at night. Shade the conservatory in summer and provide high level ventilation to minimise overheating. Reflective internal blinds also reduce winter heat loss.

Hot dry climates

Both winter heating and summer cooling are very important in these climates. High mass construction combined with sound passive heating and cooling principles is the most effective and economical means of maintaining thermal comfort.

Diurnal ranges are generally quite significant and can be extreme. High mass construction with high insulation levels is ideal in these conditions. (see Insulation)

Where supplementary heating or cooling is required, locate thermal mass where it is exposed to radiation from heaters or cool air streams from evaporative coolers. The mass moderates temperature variations between high/low or on/off and lowers the level and duration of auxiliary requirements while increasing thermal comfort. With the low humidity in these climates, ceiling fans generally provide adequate cooling comfort in a well-designed home.

Underground or earth covered homes give protection from solar radiation and provide additional thermal mass through earth coupling to stabilise internal air temperatures.

Renovations and additions

When renovating, remove carpet or insulating coverings from concrete slabs that are exposed to winter sun. The slab surface can be tiled or cut and polished to give an attractive and practical finish (see Concrete slab floors). Thermal mass can also be increased by adding brick or stone veneers to existing interior walls.

In some cases it may be necessary to reduce the amount of thermal mass exposed to the building interior where insufficient passive heating or cooling is available to maintain comfort. In such cases, additional auxiliary heating or cooling is required. To isolate existing mass, line the interior wall surface with sheet insulation materials and plasterboard.
If planning an addition, engage a thermal performance assessor to model your whole home to identify strengths and weaknesses in relation to windows (orientation and size) and appropriate levels of thermal mass. This model identifies problem areas that might be able to be overcome by adding (or deleting) new rooms.

**Heating dominated climates**

For heating dominated climates, add thermal mass where winter solar access is already available, such as those buildings with good northerly access. This may be achieved by exposing existing concrete as above or adding thermal mass to walls.

Where the existing floor is slab-on-ground, non-loadbearing walls can be built directly on the concrete slab, after engineering checks are carried out. If the existing building has a raised timber floor it is often practical to combine reverse brick veneer with a retrofitted suspended concrete slab. The underside should be insulated and well ventilated if not earth coupled.

It may be necessary to consider revising the layout of the house, ‘turning the house around’ to place living areas to the north.

Thermal mass should be located near a heater.

**Cooling dominated climates**

For cooling dominated climates, thermal mass must be protected from summer sun and exposed to cooling night breezes.

Add shading to protect thermal mass from summer sun both internally and externally, particularly outside windows and in uninsulated double brick walls. Thermal mass’s ability to absorb and re-radiate heat over many hours means that in summer or hot climates it can be a source of unwelcome heat long after the sun has set. (see *Shading*)

**Other thermal mass options**

Introduce thermal mass within lightweight structures by using isolated masonry walls, water filled containers, phase change materials (PCMs) or lightweight steel-framed concrete floors.

Internal or enclosed water features such as pools can also provide thermal mass but require good ventilation and must be capable of being isolated, as evaporation can absorb heat in winter and create condensation problems year round.

Air enters this building across the pool (thermal mass) through a semi-enclosed courtyard. It is evaporatively cooled before entering the building. This ‘coolt’ can be stored in thermal mass.

Roof-mounted solar heating of pools is relatively inexpensive and can be used in conjunction with hydronic heating systems or water storage containers to heat thermal mass in winter or (in reverse) supply radiant cooling to night skies in summer. This method can resolve situations where direct solar access for passive heating is unachievable or where conventional thermal mass is inappropriate (e.g. pole homes). (see *Heating and cooling*)

**Thermal mass properties**

The following characteristics determine thermal mass performance.

- **High density**: The more dense the material (i.e. the less trapped air), the higher its thermal mass. For example, concrete has high thermal mass, aerated concrete (AAC) blocks have moderate to low thermal mass, and insulation has almost none.

- **Good thermal conductivity**: To be effective in most climates, thermal mass should have the capacity to absorb and re-emit close to its full heat storage capacity in a single diurnal cycle (see ‘High volumetric heat capacity’ below). If conductivity is too low, passive heating can escape from your home before being absorbed. If conductivity is too high (e.g. steel), stored heat is re-released before it is most needed in the colder part of the night. The same applies to passive cooling only in day−night reverse.

For example, rubber has high density but is a poor conductor of heat. Brick and concrete have high density and are reasonably good conductors.

- **Appropriate thermal lag**: The rate at which heat is absorbed and re-released by uninsulated material
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is referred to as thermal lag. Lag is dependent on conductivity, thickness, insulation levels and temperature differences either side of the wall. Consideration of lag times is important when designing thermal mass, especially with thick uninsulated external wall systems like rammed earth, mud brick or rock.

In moderate climates, a 24 hour lag cycle is ideal. In colder climates subject to long cloudy periods, lags of up to seven days can be useful, providing there is additional solar exposed glazing to 'charge it' in sunny weather (see climate-specific glass to mass ratios in 'Thermal mass checklist'). The table indicates lag times for common materials.

<table>
<thead>
<tr>
<th>Material thickness (mm)</th>
<th>Time lag (hours)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Double brick (220)</td>
<td>6.2</td>
</tr>
<tr>
<td>Concrete (250)</td>
<td>6.9</td>
</tr>
<tr>
<td>Autoclaved aerated concrete (200)</td>
<td>7.0</td>
</tr>
<tr>
<td>Mud brick/adobe (250)</td>
<td>9.2</td>
</tr>
<tr>
<td>Rammed earth (250)</td>
<td>10.3</td>
</tr>
<tr>
<td>Compressed earth blocks (250)</td>
<td>10.5</td>
</tr>
<tr>
<td>Sandy loam (1000)</td>
<td>30 days</td>
</tr>
</tbody>
</table>

Source: Baggs et al. 1991

Thermal lag influences internal–external heat flow through walls.

Thermal lag influences internal–external heat flow through walls. Rammed earth, rock and mud brick have a low insulation value and rely on thicknesses of 300mm or more to increase thermal lag. While this is often adequate in mild climates, these systems require external insulation in cool and cold climates where lag times are reduced by increased internal–external temperature differences (known as delta T or ΔT; see Passive solar heating for an explanation).

Low reflectivity: Dark, matt or textured surfaces absorb and re-radiate more energy than light, smooth, reflective surfaces. (If there is considerable thermal mass in the walls, a more reflective floor will distribute heat to the walls).

High volumetric heat capacity (VHC): The table below compares the thermal mass performance (or VHC) of some common materials. The amount of useful thermal storage is calculated by multiplying the VHC by the total accessible volume of the material, i.e. the volume of material that has its surface exposed to a source of heating or cooling.

Water has the highest VHC of any common material. The table tells us that it takes 4186KJ of energy to raise the temperature of one cubic metre of water by one degree C, whereas it takes only 2060KJ to raise the temperature of an equal volume of concrete by the same amount. In other words, water has around twice the heat storage capacity of concrete. The VHC of rock usually ranges between brick and concrete depending on density.

The VHC of any material is reduced or even eliminated if the material is covered with linings such as carpets, plasterboard, timber.

<table>
<thead>
<tr>
<th>Material</th>
<th>Thermal mass (volumetric heat capacity, KJ/m³.k)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water</td>
<td>4186</td>
</tr>
<tr>
<td>Concrete</td>
<td>2060</td>
</tr>
<tr>
<td>Sandstone</td>
<td>1800</td>
</tr>
<tr>
<td>Compressed earth blocks (compressed)</td>
<td>1740</td>
</tr>
<tr>
<td>Rammed earth</td>
<td>1673</td>
</tr>
<tr>
<td>Fibre cement sheet (compressed)</td>
<td>1530</td>
</tr>
<tr>
<td>Brick</td>
<td>1360</td>
</tr>
<tr>
<td>Earth wall (adobe)</td>
<td>1300</td>
</tr>
<tr>
<td>Autoclaved aerated concrete</td>
<td>550</td>
</tr>
</tbody>
</table>

Some thermal mass materials, such as concrete and brick, have high embodied energy when used in the quantities required. Consider the lifetime energy impact of thermal mass materials: will the savings in heating and cooling energy be greater than the embodied energy content over the life of the building? Can lower embodied materials such as water or recycled brick be used?

In addition, poor design of thermal mass may result in increased heating and cooling energy use on top of the embodied energy content.
Phase change materials

There is growing interest in the use of PCMs as a lightweight thermal mass substitute in construction. All materials require a large energy input to change state (i.e. from a solid to a liquid or a liquid to a gas). This energy does not change their temperature — only their state. For that reason, it is called ‘latent’ (i.e. latent heat of melting or vaporisation). Phase change temperatures vary enormously between materials.

*Phase change materials, or PCMs, may be a useful lightweight substitute for thermal mass.*

Materials that melt between 25° and 35°C are very useful for storing passive solar gains. Any temperature increase over a desired thermal comfort level is absorbed by the PCM as it melts. This energy stays stored until the PCM starts to solidify again as temperatures drop at night. As it solidifies, it releases the stored heat.

Commonly used PCMs include paraffin wax and a variety of benign salts. Many are available in Australia. PCMs are currently expensive compared to conventional thermal mass but can reduce costs through space and structural savings. They are an ideal way to install mass in existing buildings and are particularly useful in lightweight buildings where cost savings are often achieved.

The PCM market is developing rapidly so current suppliers are best found through an internet search. Some PCMs crystallise after many cycles of phase change, which renders them useless. Get a guarantee from your supplier that their product does not do this.

At least one company manufactures building products that integrate phase change microcapsules into their structure, including plasterboard and AAC blocks although this product is currently (in 2012) prohibitively expensive. Gypsum plaster, paints and floor screeds have the potential to contain PCMs and many such applications are likely to appear on the market over the next few years as the technology offers the prospect of lightweight buildings that can behave with characteristics associated with ‘traditional’ thermal mass. For example, the thermal capacity of a 13mm thick plaster layer with 30% microcapsule content is claimed to be equivalent to that of a 150mm thick masonry wall.

Use of PCMs can be very helpful on severely constrained sites where thermal mass would otherwise be difficult to install. (see Challenging sites)

PCMs or water as flexible mass options for climate change

Because the role of thermal mass is primarily one of heat storage in heating climates, it is likely to become less useful as the climate warms within the lifespan of the home. Additionally, it could become a cooling liability as the prevalence of favourable night-time cooling conditions diminishes.

Replacement of conventional masonry with PCMs could present a solution to the challenge of designing for current and future climates. PCM thermal mass could easily be removed from the building, initially perhaps on a seasonal basis as the climate changes and ultimately become permanent should peak predicted levels of warming occur.

Low cost mass options for upper storeys

PCMs or water filled containers have much greater thermal storage capacity than masonry and can be used as a mass substitute. PCMs are much lighter than masonry. Water has double the storage capacity of concrete and because of convection within the container, penetration rates are substantially higher. Thus water can supply similar storage capacity to masonry with significantly less mass and bulk. Accordingly, both can be cost effective mass options for upper storeys because they require no (or less) additional structural support.

Photo: Mike Cleaver, Clever Design

Water filled balustrades provide abundant thermal mass as part of this mezzanine balcony.
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Mobile thermal mass
An added benefit arising from water or PCM substitutes for masonry in upper levels is their potential for mobility. Water containers could be drained and PCM containers moved outside should they become a thermal comfort liability in any season or lifestyle pattern.

Mobile PCMs and water can be placed in ideal solar gain positions by day and moved to convenient heating locations at night. Similarly, they can be placed in breeze paths or outside night sky radiation positions to cool at night and moved to warmer rooms during the day to even out diurnal fluctuations.

Thermal mass checklist
The simple rules of thumb set out here help determine appropriate thermal mass levels in different climate zones — heating dominated temperate and cold climates, cooling dominated temperate climates, and heating dominated climates with no northerly solar access. Mass levels vary according to:

- solar access (glazing type, orientation, area and shading)
- cool breeze and cool night air access (including mechanical)
- diffuse and ambient heat gains in summer
- night-time sleeping comfort
- occupation patterns and heating/cooling system use
- seasonal extremes (climate zone).

The average diurnal range is a useful indicator of appropriate thermal mass levels in a house:

- Low mass construction generally performs best where diurnal ranges are consistently 6°C or less (coastal, temperate climates).
- Moderate mass is best for a 6°–10°C diurnal range (slab-on-ground, lightweight walls such as brick veneer).
- High mass construction is desirable for a diurnal range over 10°C (slab-on-ground and some or all high mass walls).

However, simulation modelling with house energy rating software is the only way to validate these guidelines for a specific house design and climate zone.

Heating dominated temperate and cold climates

- In the quantities present in most standard construction (e.g. brick veneer with exposed, uncarpeted concrete slab-on-ground), thermal mass is useful for evening out diurnal temperature ranges.
- Greater quantities of both thermal mass and passive heating and cooling are required to moderate temperature cycles up to one week (e.g. slab-on-ground with masonry walls or earth bermed).
- Very high levels of thermal mass (e.g. earth covered buildings) can even out summer–winter ranges if well-designed.
Cooling dominated temperate climates

Where cooling loads are equal to or greater than heating loads, low to moderate levels of mass are often preferable.

- Earth coupled slabs can moderate diurnal cycles by absorbing summer heat loads, providing a radiant cooling source, and storing winter solar gains for limited periods.
- Non earth coupled mass can overheat during summer days, leaving an undesirable radiant heat source at night — particularly in upper level bedrooms.
- Well-designed or located thermal mass walls backing onto conditioned spaces in hybrid designs (i.e. using both passive and active cooling) can create a source of radiant cooling (you radiate to the mass). This improves sleeping comfort and allows cooling to be turned off or down. It is ideal when combined with ceiling fans in open ventilated south-facing or ground floor sleeping areas.

Heating dominated climates with no northerly solar access

In heating dominated climates where northerly solar access is unavailable, westerly sun (if available) is desirable providing:

- glazing is adequately actively shaded in summer (see Shading)
- double glazing and drapes with pelmets are used to compensate for reduced heat gain or higher heat loss (3 heat gain hours versus 21 heat loss hours) (see Glazing)
- thermal mass is reduced where limited solar heat gains necessitate additional heating.

Actively shaded, double glazed west-facing windows with solar access are particularly useful for meeting variable heating and cooling needs in spring and autumn. Easterly sun can be less effective for heating in some cooler climates due to morning fog.

References and additional reading

Contact your state, territory or local government for further information on passive design considerations for your climate. www.gov.au


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