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Using Thermal Mass in Timber-framed Buildings

Effective use of thermal mass for increased comfort and energy efficiency

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Introduction

If thermal mass is used correctly within housing it can moderate daily temperature fluctuations – leading to more comfortable interiors – and reduce the energy used for artificial heating or cooling. If thermal mass is used incorrectly, the opposite occurs.

Thermal mass describes the ability of a material to absorb and release thermal energy with little or no change to the temperature of the material itself relative to a large amount of stored thermal energy. This is sometimes described as the thermal mass effect.

High thermal mass means the material can absorb or release large amounts of thermal energy without changing temperature. Low thermal mass, or a 'lightweight' material, describes a material that can only absorb or release a small amount of thermal energy before it changes temperature. Thermal mass can be used to store 'coolth' by acting as a heat sink or 'warmth' by acting as a heat store.

The view that "thermal mass is good and therefore more thermal mass is better" is incorrect

The use of thermal mass to enhance thermal comfort is well documented in design guides and encouraged in legislation, although there is little or no information to help designers understand how much mass is required. The view that "thermal mass is good and therefore more thermal mass is better" is incorrect. Getting the correct amount of thermal mass in a building is important because:

- too much thermal mass can reduce thermal comfort and increase annual energy use; and
- the manufacture of high thermal mass materials often comes with a high environmental cost.

Many rules of thumb have been developed for calculating the amount of thermal mass needed. Unfortunately, in an attempt to provide a simple answer to a complex system, these do not adequately define the climate or design strategies they were developed for, making their useful application to practice impossible.

The thermal behaviour of buildings is dependent on local climatic conditions. Australian climatic conditions can vary considerably, particularly near the coast, where the majority of the population lives.

This Guide was written following an analysis of existing rules of thumb and existing design guidance. It is based on analysis of both real-world and computer simulations of thermal mass in typical project homes and experimental structures in several Australian climates. The project revealed the following surprising results:

- It is possible to have too much thermal mass.
- Thermal mass is more useful in some climates than in others.
- How much thermal mass to use, and whether to use it in the floor, walls or ceiling, depends on the local climate.
- Thermal mass needs to be in one place to aid cooling and a different place to aid heating.
- The size and location of the windows has as large an influence on the thermal efficiency of a space as the quantity of thermal mass.
- Because the manufacture of many materials with high thermal mass results in high carbon dioxide emissions, the inclusion of thermal mass may actually increase rather than reduce the carbon emissions of a building, when viewed across its entire lifecycle.

The energy that is used and the carbon dioxide that is produced during the extraction and manufacturing of products is said to be 'embodied' in the product. Materials commonly used in construction to provide thermal mass also have high embodied energy and high embodied carbon dioxide.

The purpose of this design guide is to help designers understand how to use thermal mass in a building, how to achieve an optimum amount of thermal mass and, as a result, how to reduce the operational energy and embodied energy costs of the buildings.

Related publications are listed under Further Reading at the end of this Guide.

1 Thermal Mass Properties and Materials

Thermal mass is a term used to describe a material's ability to absorb, store and release energy. A material can be said to have good thermal mass if it can absorb a significant amount of heat energy without changing its own temperature. A material needs to be able to absorb and then release heat over a period of several hours to be useful in moderating internal day/night (diurnal) temperature variations. Materials with good thermal mass tend to be heavy, dense and conduct heat sufficiently to be able to absorb heat within their interior.

The two key properties of thermal mass that measure its effectiveness are:

- thermal capacity: heat storage ability; and
- admittance: ability to absorb or release heat.

1.1 Thermal Capacity

Thermal capacity (also called Specific Heat Capacity or Thermal Capacitance) is a measure of the amount of energy needed to raise one kilogram of material by one degree Kelvin. (A temperature difference of one degree Kelvin is the equivalent to one degree Celsius).

- Thermal capacity is expressed in KJ/kg.K

Thermal capacity can also be expressed as a function of the materials volume, i.e. the amount of thermal energy needed to raise one cubic metre of a material one degree Kelvin.

- The volumetric heat capacity is expressed in $KJ/m^3.K$

1.2 Admittance

The term for a material's ability to absorb or release thermal energy is admittance.[1] Admittance is the quantity of energy absorbed by one square metre of a surface in one second given a temperature difference of one degree Kelvin. This measure is useful because it relates to time (1 W = 1 J/s).

- Admittance is measured in $W/m^2.K$.

1.3 Construction Materials and Thermal Mass

Materials that possess thermal properties associated with the thermal mass and are commonly used in construction include:

- concrete
- stone
- bricks.

Water is another material that has excellent thermal mass properties and is readily available. Various architects have used water in clear glass columns or metal tanks.

1.4 Insulation

Thermal insulation is different to thermal mass. The most common form of insulation – bulk insulation – is designed to resist the conduction and convection of thermal energy, rather than the radiation of thermal energy, by using the poor conduction and low thermal capacity properties of air trapped in small pockets as bubbles (foam) or between fibres.

Reflective insulation resists radiation but not conduction or convection. In order to work effectively, the reflective surface must be free from dust or dirt and have a clear air space in front of it. For reflective insulation to keep a space warm, the air space adjacent to the reflective surface must be still.

1.5 Thermal Mass and Insulation

Thermal mass and thermal insulation are both very useful, but do different things for different reasons:

- Thermal mass is intended to absorb and store thermal energy and conduct it away from the source.
- Insulation is designed to resist the passage of thermal energy and prevent it leaving the source.
- Lightweight materials are not good at storing energy – they have a low thermal mass (thermal capacity).

1.6 Phase Change Materials

The use of phase change materials in buildings to regulate internal temperature is an expanding area of research and offers many opportunities.

Phase change materials are often referred to as new, although they have been around since at least the 19th century, when the Victorians used them used them in pistons to open and close windows in their greenhouses.

Phase change materials work by changing state. They absorb thermal energy by changing from a solid to a liquid and release energy by changing back to a solid. When a material changes from one state to another it absorbs or releases huge amounts of energy without changing temperature. This is called latent energy.

There are two types of phase change materials:

- paraffin wax
- phase change salts.

Various manufacturers are looking at how they can be incorporated into building materials, such as plasterboard. Phase change materials can be 'tuned' or designed to change state at a particular temperature. Below and above this temperature, the material does not absorb large amounts of energy and, once all the material has changed state, it cannot absorb or release more energy.

2 Lifetime Environmental Cost

Legislation concentrates on the environmental impact of a building during its operation. The construction and demolition of the building also has a significant environmental impact. In a lifecycle environmental assessment of a building, the environmental cost – including energy – of the extraction, processing and production of the materials used in the construction of the building and the environmental cost of demolition are added to the operational costs of the building to ascertain a lifetime environmental cost.

2.1 Embodied Energy

Materials that possess the properties of thermal mass are dense and usually require large amounts of energy to extract, transport and process them. This energy is said to be 'embodied' in the material and is often expressed as carbon dioxide equivalent (CO_2-equivalent or CO_2-e). This carbon dioxide equivalent value takes into account the energy and other greenhouse gas emissions that are associated with the extraction, processing and manufacturing of a product, from its beginning as a raw material, such as a tree or quarry, to when it leaves the factory gate.[2,3]

2.2 Carbon Dioxide Equivalent

The carbon dioxide equivalent measure converts the energy used into a quantity of CO_2 based on an assessment of the source of the energy. For electricity in Australia, a figure of 1 kg of CO_2 per 1 kWh of electricity is used.[4] In Australia, 96% of electricity is generated from carbon-based fuels.[5]

Different greenhouse gasses (e.g. methane) create more or less powerful greenhouse effects. The carbon dioxide equivalent model converts a quantity of each greenhouse gas into a quantity of CO_2 that has an equivalent greenhouse effect.[3]

AccuRate Sustainability software (AccuRate_Sustainability, 2012)[4] includes a calculation engine for calculating the embodied energy in the building being assessed. The tables that this calculation is based on can be found in the FWPA report *Development of an Embodied CO_2 Emissions Module for AccuRate.*[3]

2.3 Concrete – Chemical Reactions During Manufacture

Some materials are created through a chemical reaction that produces CO_2 or other greenhouse gasses. The most obvious of these in construction is concrete. Concrete is produced by roasting limestone and clay. The chemical reaction that turns limestone into cement emits large quantities of CO_2.

2.4 Sequestered or Stored Carbon Dioxide

Materials that are grown, such as timber, absorb CO_2 from the atmosphere while the trees are growing. When timber is used in buildings, this carbon dioxide is stored in the building fabric. This carbon dioxide is said to be sequestered. When the building is demolished, the carbon dioxide may be released back into the atmosphere either by burning or decomposition, unless the timber is reused. Because the sequestration is not permanent, there is some debate as to whether or not the sequestered carbon should be set against the emitted carbon dioxide over the longer term.[2]

As the global population of trees is in decline, it is important to ensure that the timber used in the construction of a building comes from sustainably managed forests that replace the felled trees.

2.5 Thermal Mass and Saving Energy – Achieving a Balance

Thermal mass materials may require large amounts of energy to produce but, when used appropriately, they also help us save energy and improve comfort in our buildings. So it is important to understand the balance between the energy (or carbon dioxide equivalent) invested in the construction of the building and the energy this will potentially save over the lifetime of the building by making it more efficient. If the building's life is short it is possible that the energy saved during the life of the building is less than the energy invested in the thermal mass used to make it more efficient. In this case, other efficiency strategies should be investigated.

3

Amount of Thermal Mass

You can have too much thermal mass in a space.[7]

The internal temperature of a lightweight building tends to follow the external temperature variation. Adding some thermal mass to the inside of a lightweight building reduces the internal diurnal temperature variation (the difference between the highest and lowest temperature in a calendar day). Increasing the amount of thermal mass in the space further reduces the internal temperature variation until a point is reached when adding further mass has no influence on the diurnal temperature variation.

This may appear to be counterintuitive, because so much design guidance suggests that thermal mass is good and therefore more mass must be better. However, if we consider what thermal mass does, the assertion that it is possible to have too much mass makes sense.

Thermal mass absorbs and stores thermal energy. In any building there will be an average and maximum quantity of thermal energy that enters a particular space and needs to be stored to avoid overheating, or to provide additional warmth in the evening. Therefore, if there is more thermal mass or thermal storage capacity than needed to store the thermal energy, this additional capacity will not be used and will not influence the temperature in the space. In certain circumstances, the additional mass may need to be heated up using the building's heating system so that it does not make the space too cool.

You can have too much thermal mass in a space

The quantity of mass that is useful in a building will depend on the local climate, the size and occupation patterns of the building and the environmental design strategy employed (see Section 4).

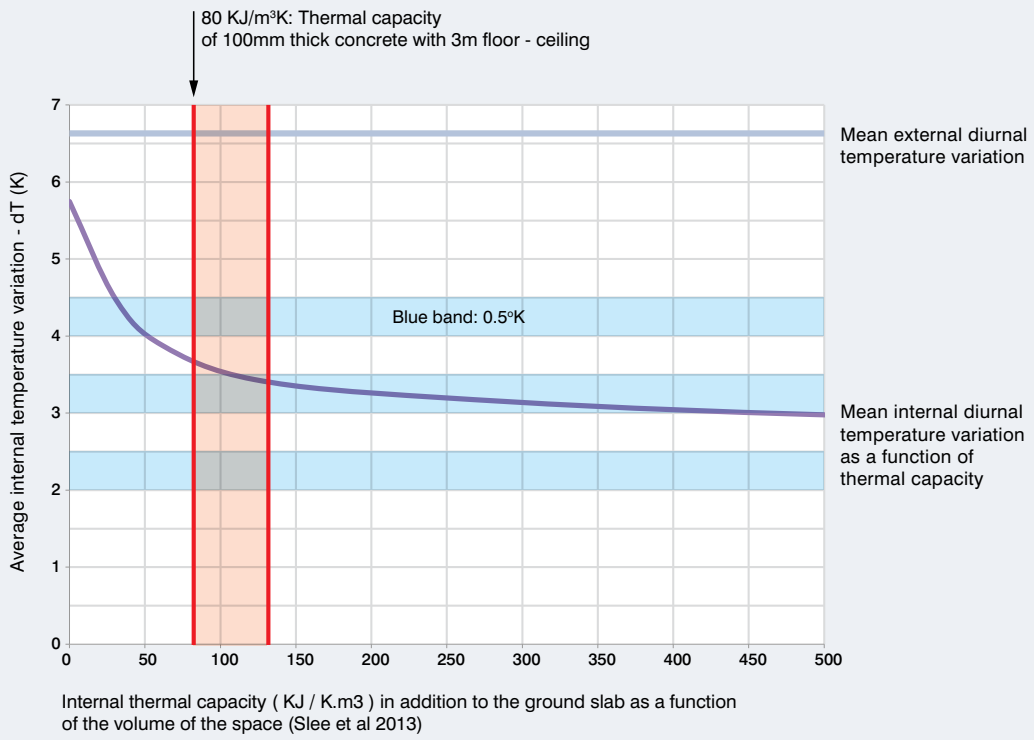

Figure 1: Thermal mass graph. As the thermal mass is increased, the effect on the temperature variation is shown to reduce. (Adapted from Slee et al.)[7,15]

4 Placing of Thermal Mass

4.1 Comfort

Understanding how humans perceive and interact with the thermal environment and how thermal energy is transferred in this environment helps explain how thermal mass, ventilation, shade and sunshine can be used to enhance comfort with the greatest effect.

Appreciation of the thermal environment – thermal comfort – is derived from the rate and direction of the heat energy transfer between the human body and the surrounding environment. Almost half the body's exchange of heat with the surrounding environment occurs through radiation:

- 47.5% through radiation;
- 27.5% though convection and conduction; and
- 25% through other means, including perspiration (evaporation) and respiration (breathing).

The human body continuously produces heat, although the rate of production varies. When lying quietly, the body produces about 83 watts, but it can produce 585 watts when performing heavy work. To maintain a comfortable equilibrium, the body's loss of heat (through radiation, convection, conduction and other means) must equal the amount of heat that it generates.

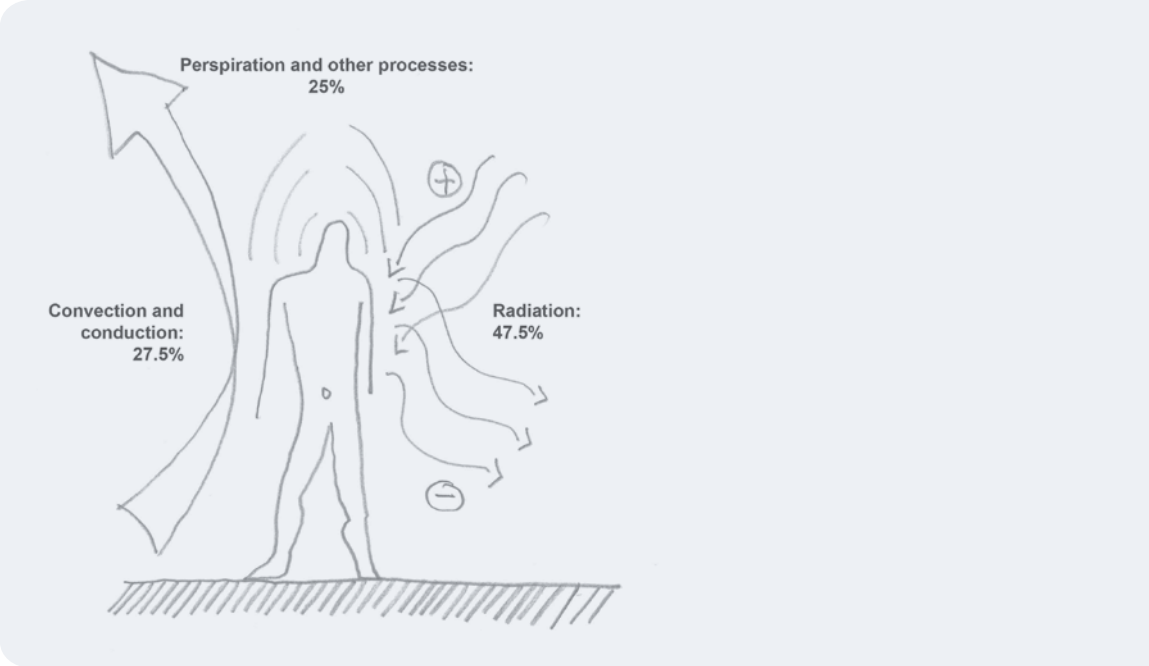

Figure 2: Human Comfort. Thermal perception: Sources of thermal sensation with approximate perceptual weighting.

4.1.1 Radiation

Interior surfaces such as floor, walls, windows and ceilings can radiate heat and absorb heat. These elements exchange thermal energy with people and other surfaces, including the sun, by radiation. If the surface is at a higher temperature than the surface of the body, radiant energy is received from it giving the sensation of warmth. Conversely, if it is at a lower temperature the body will lose radiant energy to it, giving a cool sensation. Since a large part of our perception of comfort is derived from radiation, the relative temperature of those surfaces is important.

4.1.2 Convection and Ventilation

Convection and ventilation are related but slightly different concepts. Convection is the movement of thermal energy by air (or a fluid) as a result of the cooling or heating of the fluid.

Ventilation is the movement and exchange of air in a space involving air from outside that space. Ventilation can result from opening windows (natural ventilation) or be forced through by a mechanical system such as a fan (mechanical ventilation).

Convection

Surfaces that are in contact with the air in the room are constantly exchanging thermal energy with the air through convection. If the air is warmer than the surface of the thermal mass, the thermal mass will absorb thermal energy from the air, cooling the air down. Occupants will experience a lower ambient temperature. If the surface temperature of the mass is higher than the air, for example in the evening, then the mass will warm the air, which will circulate via convection air currents and so the ambient temperature will be increased.

Ventilation

Air movement has a significant influence on the human perception of comfort. Ventilation or breezes are important to aid evaporation in the form of perspiration. The stronger the breeze, the greater the cooling effect, to a point. Indoor breezes stronger than 1.5 metres per second are considered uncomfortable,[8,9] although the same breeze outside would generally be considered comfortable. Natural breezes are considered more comfortable and are more effective at creating a cooling sensation than continuous monotonous mechanical air flow, due to the random variability in the natural breeze.[10,11]

Air Speed	0.6 m/s	0.9 m/s	1.2 m/s
dT_{op} (°C)	1.2	1.8	2.2
dT-op is the change in acceptable Operative Temperature as a result of the air flow. T-op is a good approximation of our perception of temperature. It is normally taken as the mean of the ambient air temperature and the radiant or globe temperature.[9]			

Table 1: Increases in acceptable Operative Temperature (T_{op}) resulting from increasing air speed above 0.3 m/s when T_{op} > 25°C.

4.1.3 Conduction

Conduction occurs through direct contact between materials.

When the human body is in contact with a surface that is cooler than the body's skin, thermal energy will be conducted away from the skin into the surface, particularly if the material is a good conductor (as dense materials are). This causes the part of the body in contact with the cool surface to feel cool. If the temperature difference is reversed, we will feel warm. However, if the material is a poor conductor – such as timber – heat energy will not be conducted away very effectively, so the material will feel relatively warm. Such materials are often considered 'warm' materials.

4.2 Design Strategies

Thermal mass can be used by designers to achieve two different objectives:

- help keep buildings cool in summer; and
- help keep buildings warm in winter.

How and where the thermal mass needs to be used to achieve these two objectives differs. In both cases, thermal mass is used to absorb and store thermal energy so that it can be released later. The higher the temperature difference between surfaces, the faster the heat transfer. It is important to place the thermal mass in a location where it can absorb the thermal energy most effectively.

4.2.1 Summer Cooling

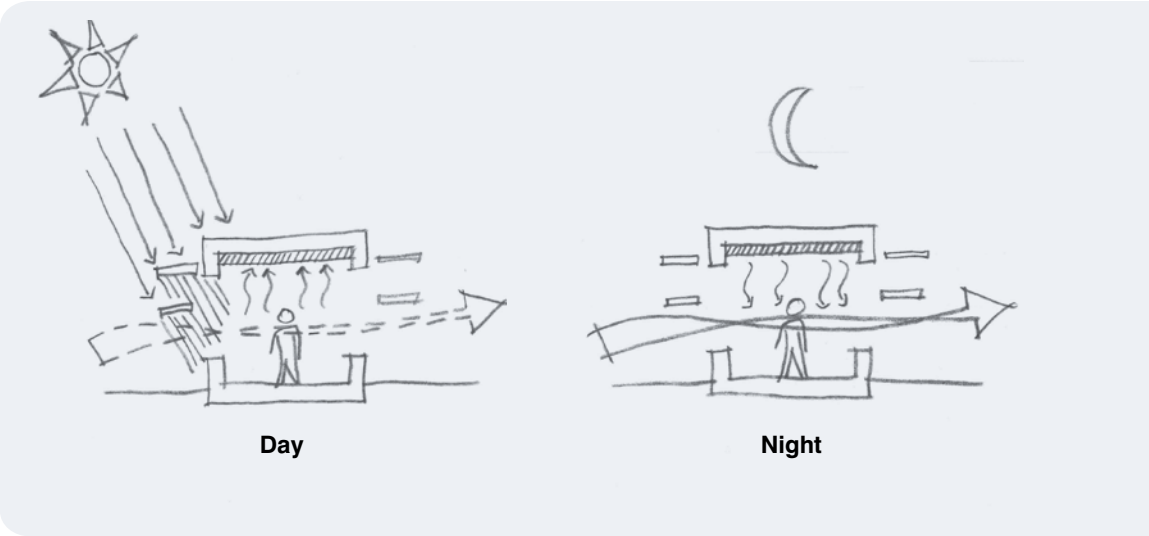

Figure 3: Summer cooling.

When thermal mass is used to keep a space cool in summer, the thermal mass is absorbing thermal energy from the air primarily by conduction. Warm air rises above cooler air (convection) and so the warmest air is always found near the ceiling, the coolest air is near the floor.

The thermal mass should be placed where the warmest air is so it can absorb the most amount of energy most effectively, such as on the ceiling or in the walls. Placing mass on the floor will only help keep the coolest air cool.

When this strategy is employed, the thermal mass is often described as providing or storing 'coolth'.

4.2.2 Winter Warming

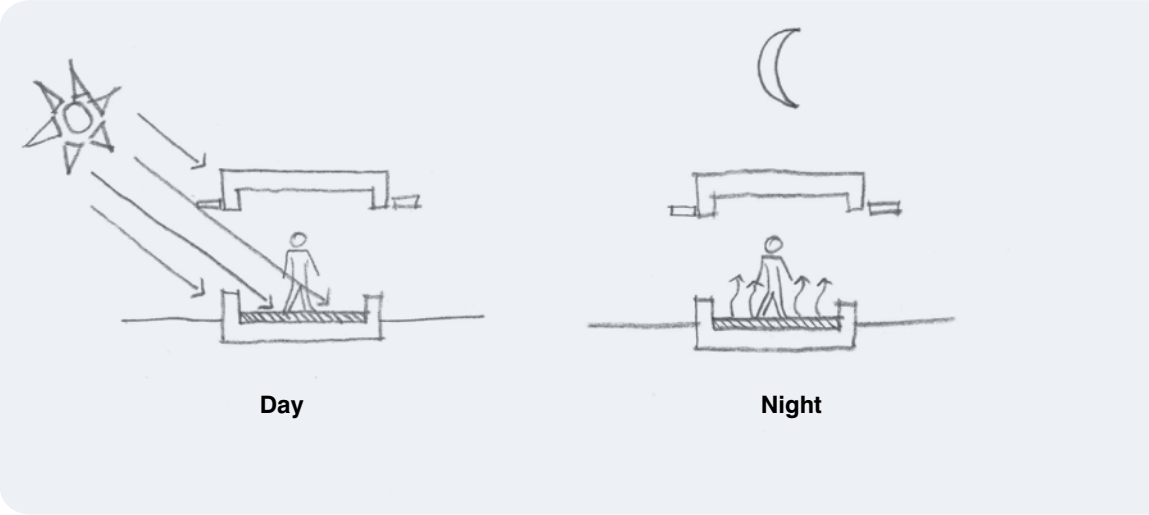

Figure 4: Winter warming.

When thermal mass is used to help keep a space warm in winter, the mass is intended to absorb radiant thermal energy from the sun. The sun shines down and so the thermal mass needs to be on the floor where the sun can shine on it.

This is called a 'direct gain' or 'passive solar' system.

The thermal mass releases the thermal energy slowly through convection (heating the air) and re-radiation, particularly during the cooler part of the afternoon and the evening.

If the climate is cloudy in winter or the days are shorter, there will not be enough sun to make this strategy effective. The thermal mass will need to be kept warm by additional auxiliary heating energy.

When this strategy is employed, the thermal mass is often described as providing or storing warmth.

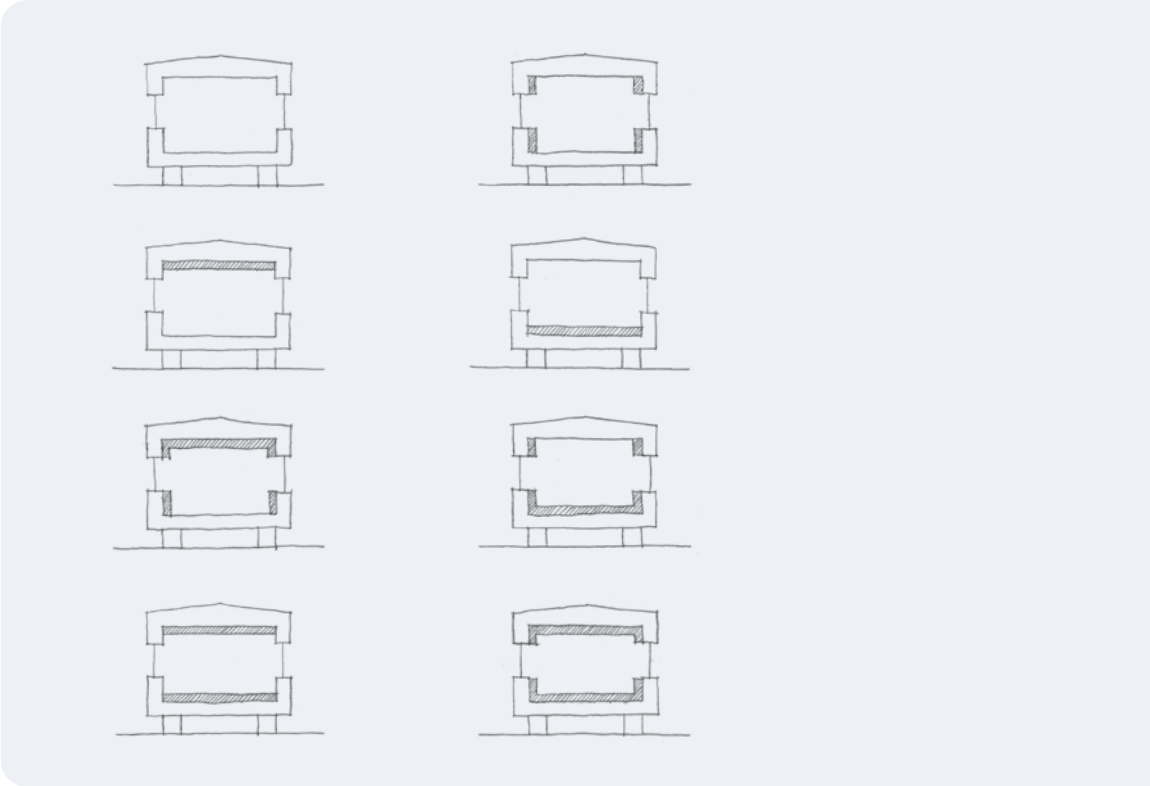

Figure 5: Location of mass within building.

4.2.3 Thermal Mass and Ventilation

When thermal mass is used to absorb excess thermal energy to keep a space cool the mass must be allowed to cool down again so that it has the capacity to absorb more thermal energy the next day. In a passive system this is done by ventilating the space with cool evening and night breezes, occasionally helped by some mechanical ventilation. This strategy is often called night purging.

For the strategy to be effective, there needs to be a difference between the maximum and minimum outside air temperature (diurnal range). There are various opinions on how big this difference needs to be. For instance, Shaviv et al.[12] suggest a minimum of 6°C and Givoni[13] suggests 10°C.

Openings should be on opposite sides of the room to encourage ventilation (cross ventilation), or a roof ventilator can be used. The most effective air speed for cooling a room is between 1.5–2 metres per second.[14] The air transfers less energy above and below these speeds.

4.2.4 Controlled Ventilation

The strategy of night ventilation, sometimes called night flushing, relies on ventilation being controlled – as does our comfort. Control means that the occupant can choose when – and when not – to ventilate. This means minimising uncontrolled infiltration through gaps around windows, etc, so that when the air outside is uncomfortably warm or cool it is prevented from entering the building. The standard 10 mm tolerance gap around a 1 m x 1 m window frame is equivalent to a hole in the wall of 200 mm x 200 mm. (A weather bead is not an air seal).

Airtight construction and controlled ventilation allows the occupant to ventilate when it is useful for improving comfort.

4.2.5 Window Size

In all Australian climates window size has a greater influence on the energy efficiency of a space than the quantity of thermal mass

Window size is important in determining the energy efficiency of a space.

In all Australian climates, window size has a greater influence on the energy efficiency of a space than the quantity of thermal mass

Windows – even double glazed – are relatively poor insulators, and can allow thermal energy to escape from a space and direct sunlight and associated large heat gains to affect the space.

The desired balance between the size of the window and the quantity of thermal mass is dependent on the local climate. Other factors will also influence the size and proportions of the window in a space, such as the orientation to the sun and shading.

5

Reduction of Lifetime Carbon Dioxide Emissions

Buildings require more energy to construct than they use each year. A masonry building will involve considerably more energy to build than a lightweight building. Over 25, 50 or 100 years the operational energy adds up and may account for an equal or larger proportion of the building's lifetime CO_2 emissions. How the proportions between embodied and total operational energy change over time depends on the construction method and the local climate.

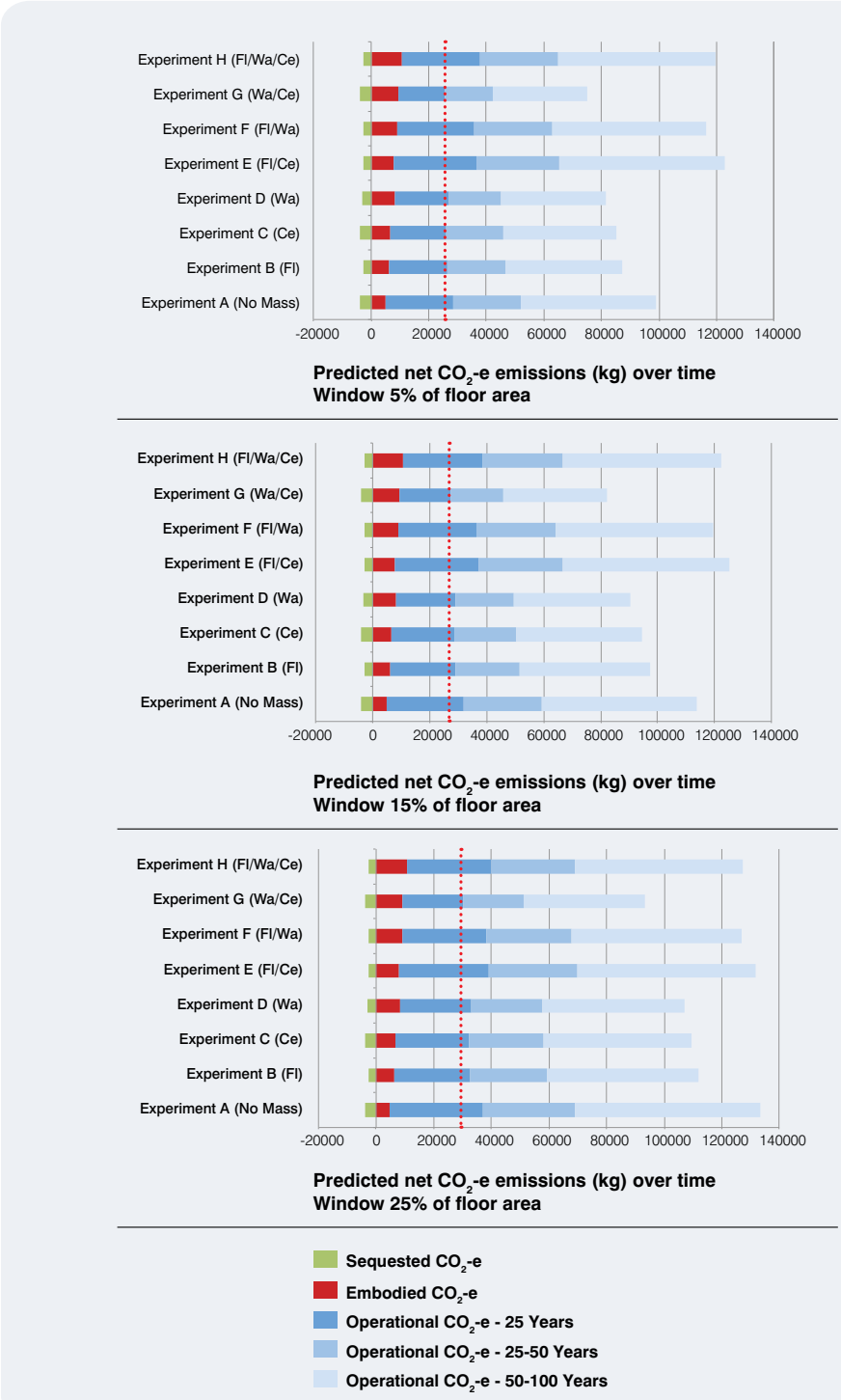

Figure 6: Predicted operational and embodied energy consumption. Shown over 25, 50 and 100 years for Melbourne.

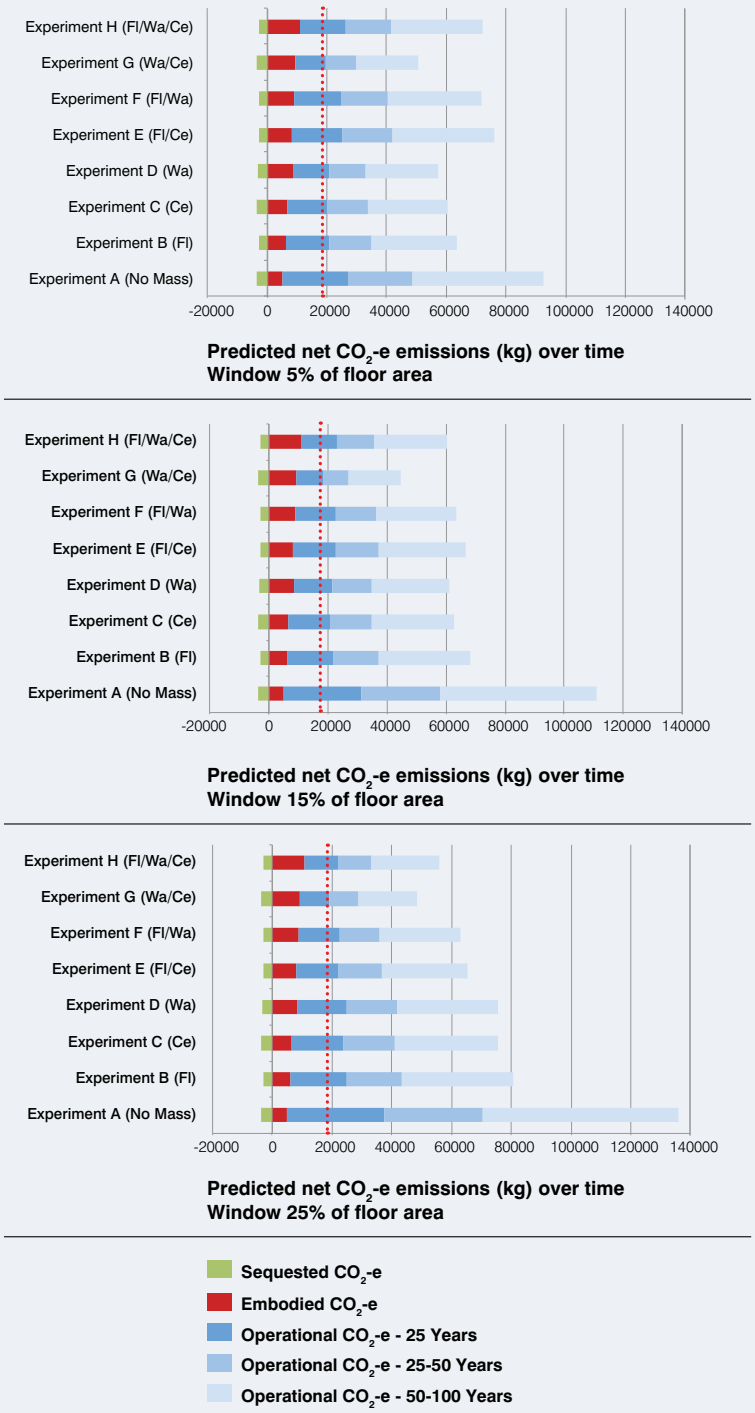

Figure 7: Predicted operational and embodied energy consumption. Shown over 25, 50 and 100 years for Sydney (Penrith).

Figure 8: Predicted operational and embodied energy consumption. Shown over 25, 50 and 100 years for Brisbane.

For all Australian climates researched by the authors, it appears that a modest amount of thermal mass may help to reduce the total lifetime CO_2 emissions if the building lasts for more than 50 years. However, high mass, high embodied-energy buildings are unlikely to be more efficient overall than lighter-weight buildings – even after 100 years.

Currently, 96% of Australia's energy is produced from non-renewable carbon based sources.[6] How this will change over the next 25, 50 or 100 years is impossible to predict. Regardless of generation, buildings that have a lower embodied and operational environmental cost must be better than buildings that use resources inefficiently.

The research suggests that lightweight timber buildings that incorporate thermal mass strategically, together with controlled ventilation and shading, are better than the status quo.

6

Thermal Mass in Australian Climates

Australia is an enormous country straddling a quarter of the globe, north to south. The country contains a vast range of climates. How thermal mass should be used in a particular building changes, depending on the local climate, and so the building must be designed in response to that climate.

Australia's major cities are located along the coast. The ocean adjacent to each city stays at a fairly constant temperature through the year, which helps moderate the climate on the coast. Maritime climates benefit from cooling sea breezes in summer and warmer winters, compared to inland communities. Inland deserts have the opposite effect, creating extremes of hot and cold in summer and winter.

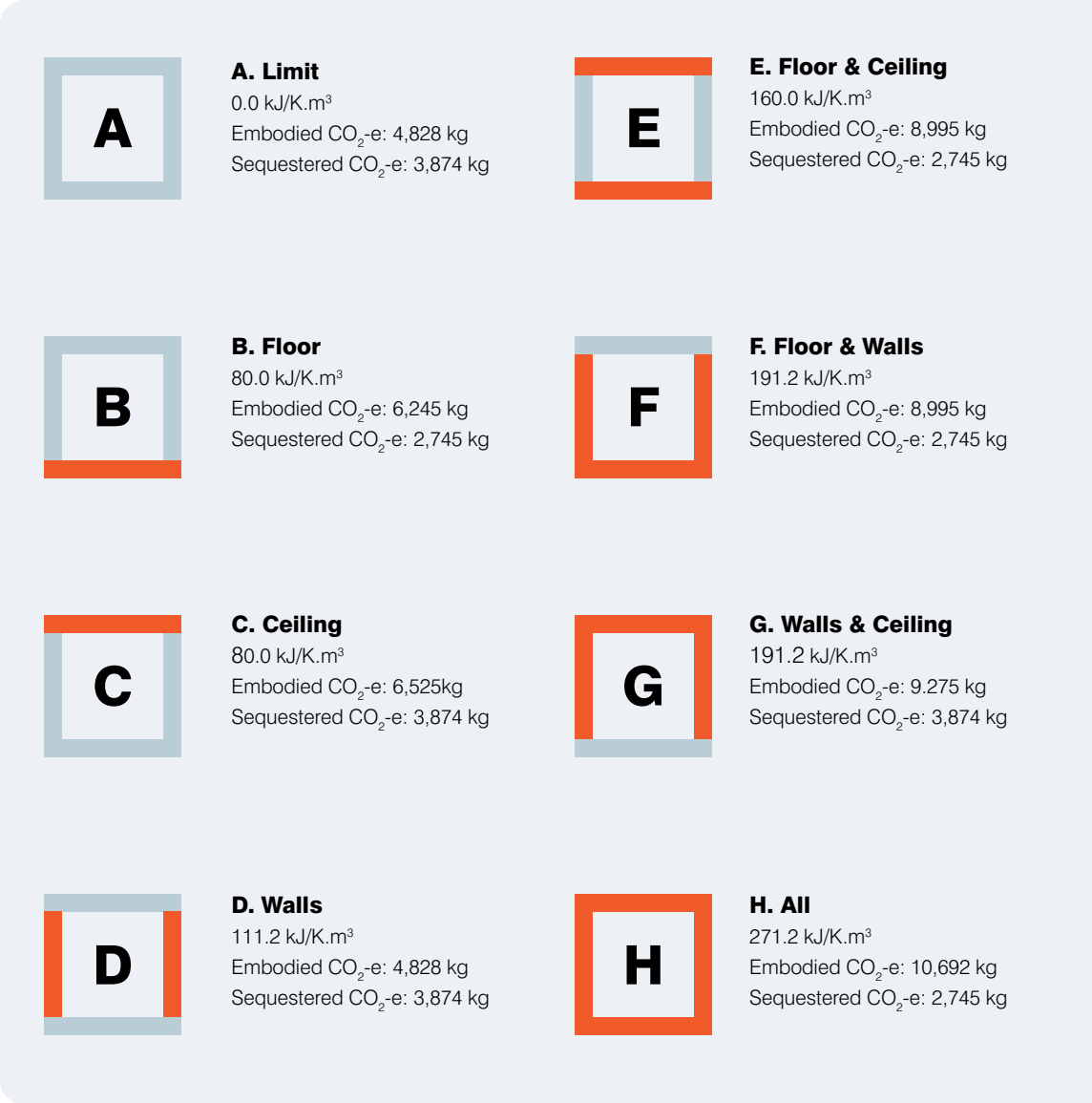

Figure 9: Legend for location of mass in testing.

The above views are diagrammatic sections with the shaded element representing either the ceiling, walls or floors. When shaded, the modelled element has the thermal mass of a 100mm concrete panel. The remaining structure is the equivalent of conventional lightweight, timber-framed construction.

6.1 Colder Climates - Hobart, Melbourne and Canberra

In the cooler climates of Hobart, Melbourne and Canberra, heating is responsible for the majority of the space-conditioning energy consumption. Keeping cool can be a problem but, when considered in the context of a whole year, the cooling energy requirement is for a short period.

Thermal mass can make a useful contribution to improving comfort. However, it is important to understand that thermal mass needs to be heated up whether or not it is hot and sunny outside. For example, an old stone cottage is a high mass house that will be cold, if there is no sun or the weather is cool, unless additional heating is used to warm it up – reducing the energy efficiency of the building. A small amount of mass located where it will maximise its cooling contribution in summer is helpful. More mass either makes no difference or reduces the energy efficiency of a space because it requires extra energy to warm it up when free 'environmental' energy (such as the sun) is not available.

Key observations:

- **Construction** – Lightweight construction improves performance in winter.
- **Winter warmth** – Mass makes little difference to the energy efficiency of the space and can reduce efficiency due to winter heating loads.
- **Summer cool** – Some mass is helpful.
- **Windows** – The size of the north-facing direct-gain window is the primary determinant of energy efficiency. The larger the window, the less efficient the space.
- **Shade** – More shading or smaller windows will improve efficiency.

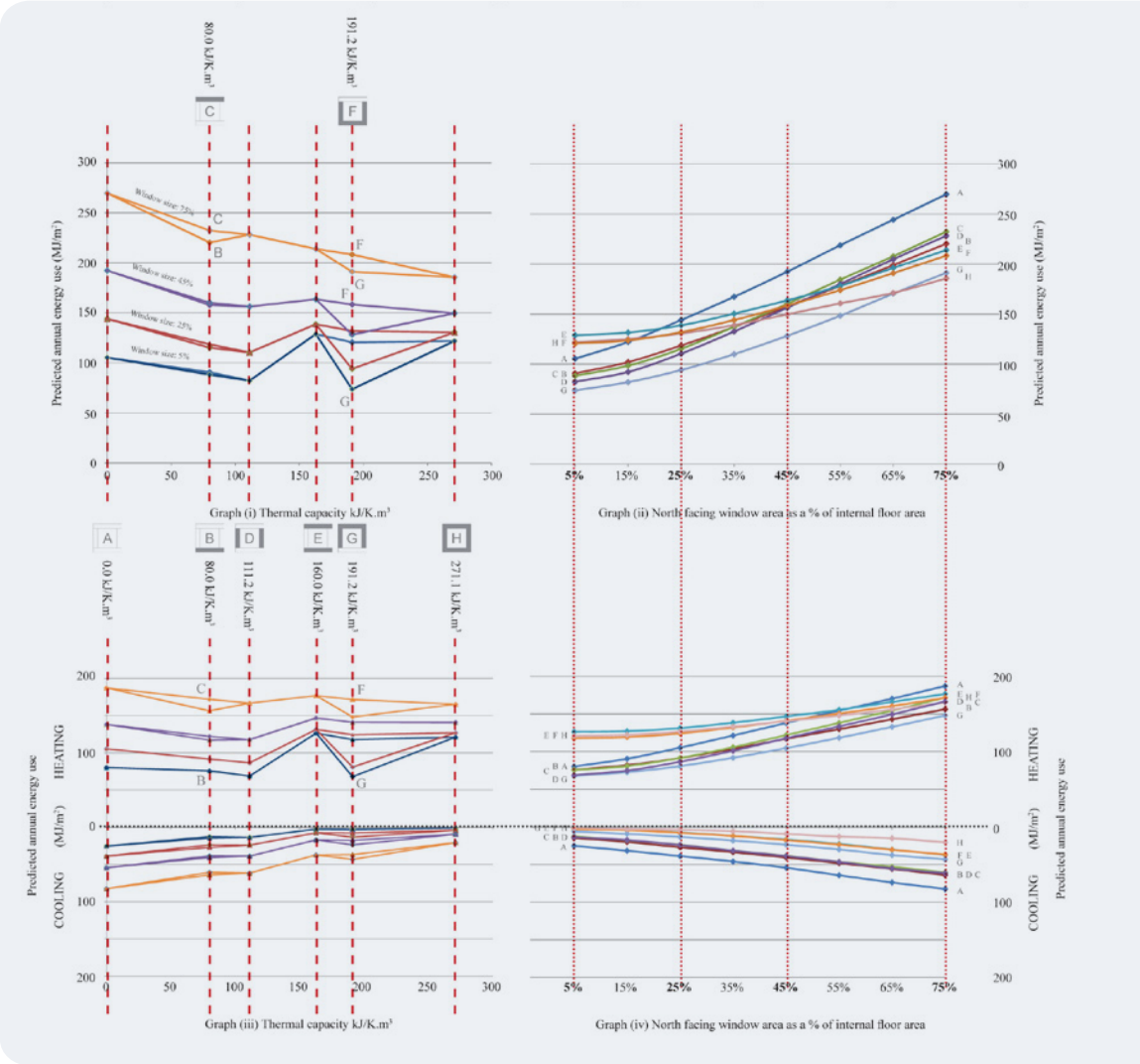

Figure 10: Predicted annual operational energy consumption for Melbourne.

6.2 Warm Temperate Climates - Sydney and Perth

The climate of Sydney becomes more extreme as it moves inland from the coast to the edge of the mountains to its west. The opportunities to save energy and the benefits of modifications to a design increase proportionately.

The climate in Perth has similarities to both the eastern and western Sydney climates.

In these warm temperate climates, some mass helps moderate the extreme climates. High levels of mass can help to keep a building cool during a heat wave. However, the same mass can then take several days to cool down – creating discomfort when the heat wave passes and the air temperature returns to something more pleasant. The same problem can happen on a daily cycle where the house stays warmer than desired in the evening because there is too much heat stored in the mass.

In winter, the mass must then be heated, and more mass means more heating to achieve the desired temperature. Given the right site and careful design, the sun can be used in winter to heat the mass. Beware of warmer winter days when it is easy to overheat the space.

Key observations:

- **Construction** – A lightweight structure that avoids direct solar gain can be efficient
- **Position of mass** – A ground slab plus mass in the walls or the ceiling is very helpful.
- **Amount of mass** – Lots of mass is no more efficient than some mass. The limit of useful thermal capacity is 160KJ/K.m^3 (including ground slab).
- **Direct sun** – If there is no direct gain, higher mass reduces efficiency. Passive solar design (direct gain) can be helpful in this climate provided the window is not too large and the mass is on the floor.
- **Windows** – The size of the windows facing the northern sun is important. Windows larger than 30% of floor area receiving direct sun, and which are fully shaded between the spring and autumn equinoxes, reduce efficiency.
- **Design iteration** – Using a simulation tool such as AccuRate or BERS to model slightly different versions of the building will help find the best balance between window size and thermal capacity and will improve the performance of the building.

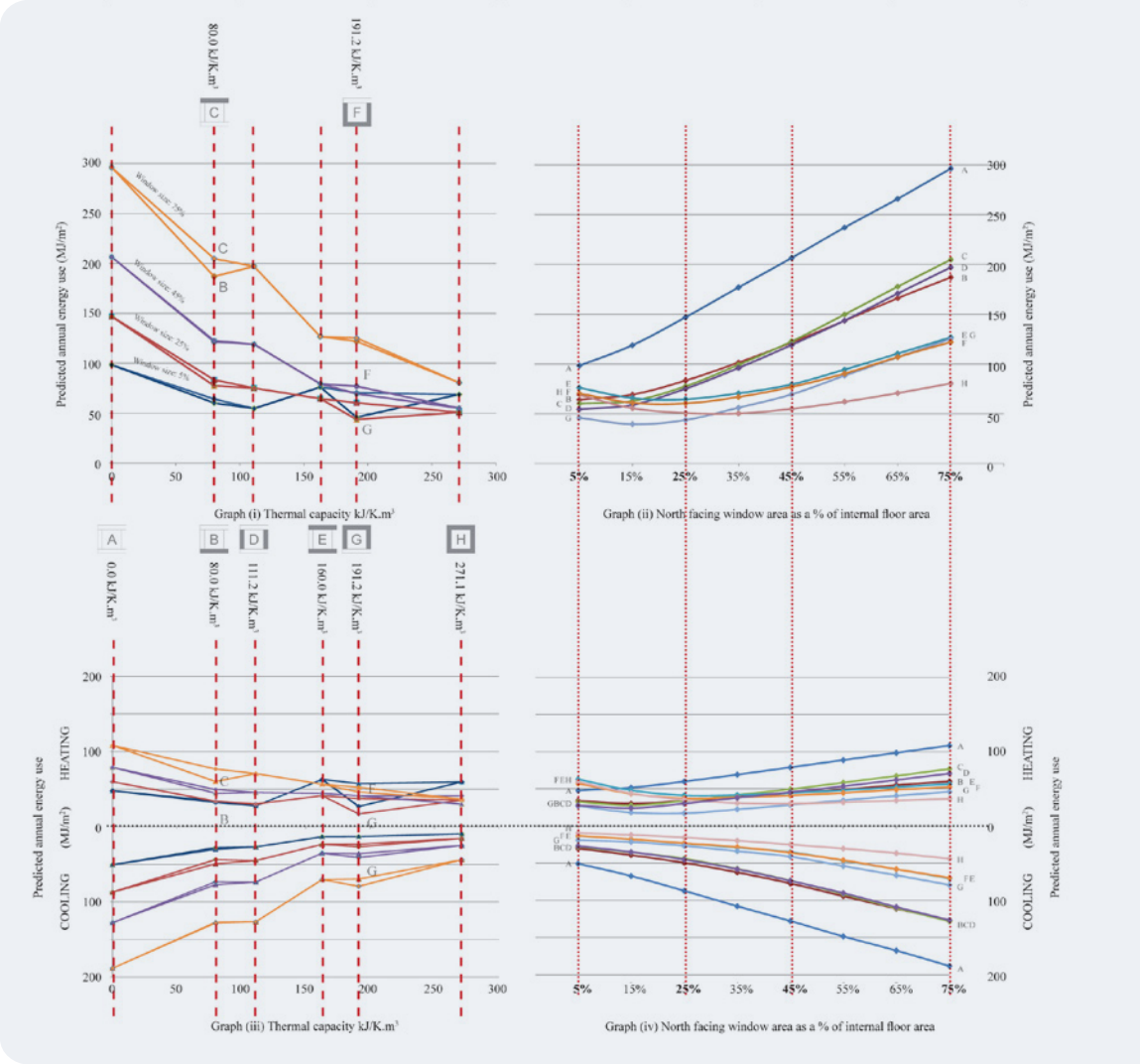

Figure: 11 Predicted annual operational energy consumption for Sydney (Penrith).

6.3 Hot, and Hot and Humid Climates - Brisbane and Darwin

Two distinct design strategies emerge from research looking at these climates:

- the high mass, sealed, conditioned space
- the lightweight, flexible naturally ventilated space.

When the energy embodied in the structure of the building (embodied carbon dioxide equivalent); the physiological factors influencing our perception of comfort; and the desire for a relaxed, free-flowing lifestyle are all taken into account, the well-shaded, lightweight approach appears to be preferable for this climate.

- **Vernacular** – the lightweight construction of 'the Queenslander' is the traditional design and construction system for northern Australia. It uses verandahs and awnings to avoid direct solar gain and lightweight construction with little or no thermal mass.
- **Windows** – to improve thermal comfort, it is important to avoid larger windows that allow direct solar gain.
- **Amount of mass** – Some mass may be helpful in the floor or walls or ceiling.

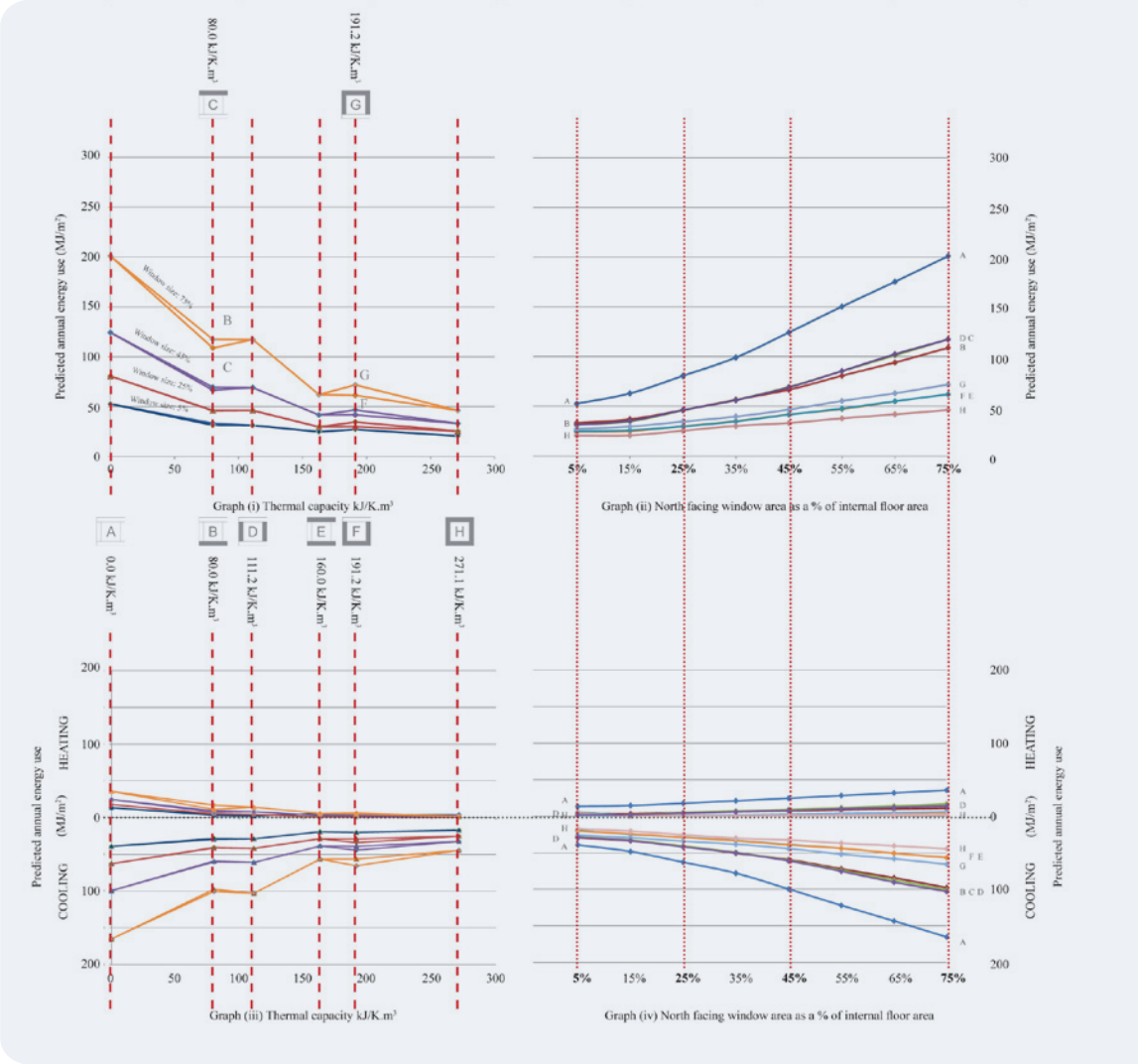

Figure 12: Predicted annual operational energy consumption for Brisbane.

6.4 Five Design Considerations

1. Design for your climate Passive solar design might work in Sydney but not in Darwin, Brisbane or Melbourne.15 Different climates will have different heating or cooling priorities. In some climates, keeping cool in summer is the biggest problem while keeping warm in winter is the bigger problem in other climates. If thermal mass is used to help keep the house warm in winter, the climate needs to provide very consistent clear sunny days. If the thermal mass is to be used to keep the house cool in summer then the evenings need to be consistently cooler than the day, with a diurnal range of about 10°C or more.

2. Orientation Consider the local factors affecting the site including shadows, wind patterns and solar orientation.

3. Natural ventilation Natural ventilation does not mean draughty or leaky buildings. Good natural ventilation should be controllable. A well-sealed building avoids wasting actively heated or cooled air.

4. Thermal mass and insulation Thermal mass is not thermal insulation. Insulation does not provide thermal mass. Both mass and insulation have an important role to play in improving comfort and energy efficiency. They must be used together and in the right place for the particular climate.

5. Window size Large windows can provide wonderful views and light, but they can also significantly reduce the thermal comfort and energy efficiency of a space.

In every climate, larger windows that allow direct solar gain reduce the efficiency of a space. If larger windows are used, direct solar gain should be carefully controlled with solar shading throughout the year.

7

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Further Reading

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