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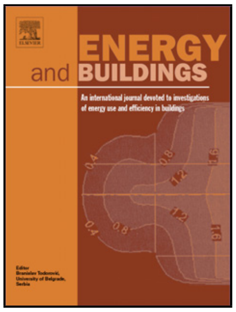

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A New House Wall System for Residential Buildings

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ABSTRACT

The residential housing sector consumes a significant amount of fossil fuel energy and thereby produces a large percentage of greenhouse gas emissions that contribute to global warming and climate change. At present, approximately 40% of the total household energy used is required for space heating/cooling and a substantial amount of that energy is lost through the house walls. Despite the importance of house walls for energy efficiency, most published literature focuses mainly on thermal comfort, environmental impact and economic costs of residential buildings. Little information is available on energy efficient house wall systems that can be used and adapted for varied climate conditions with minimal design change and associated cost. Therefore, the primary objective of this paper was to undertake a thermal performance study of two house wall systems with single and double glazed windows under variable climate conditions. The study was undertaken using thermal performance simulation software AccuRate®. The findings indicate that a significant energy saving can be achieved using the new house wall system compared to currently used brick veneer house wall system.

Keywords: New house wall, brick veneer house, thermal performance, greenhouse, star energy rating, thermal mass, insulation material.

1. Introduction

Rapid urbanisation and population growth necessitate the expansion of cities and towns with new buildings and associated energy needs. The residential sector is a great contributor to greenhouse gas emissions (~ 30%) due to the use of primarily fossil fuel energy (~35-40%) [1]. According to a recently published Australian government report, the energy consumption in the residential housing sector will be around 467 PJ in 2020 compared to 299 PJ in 1990 which means the energy demand will increase by over 50% [1]. The number of residential houses in Australia is expected to be around 10 million in 2020 compared to 6 million in 1990 [2]. The floor space area and volumetric dimension of modern residential houses are increasing at a constant rate in most developed countries including Australia (Fig.1). Therefore, the energy consumption for heating and cooling is also increasing. Figure 2 illustrates a continuous upward energy consumption trend in Australian housing sector for coming years [3, 4]. The increasing energy consumption leads to greater greenhouse gas emissions.

Fig. 1. Average living space in residential houses in Australia [1]

Fig. 2. Energy consumption in Australian housing sector [2]

Figure 3 shows the top 3 countries (Australia, United States and Canada) generate over 18 tonnes CO_2 emission per capita which is significantly higher than India and China [5]. The Australian per capita CO_2 emission has been contributed largely by the coal based power generation and inefficient use of energy in the housing sector. Among household consumption, around 40% of the total energy is used for space heating and cooling (Fig. 4). Hence, the reduction of energy use for space heating and cooling not only enhances energy conservation, it also reduces greenhouse gas emissions and can enhance energy security [6]. A substantial amount of energy required for heating and cooling is lost through the house wall systems [7].

Fig. 3. Greenhouse gas emission per capita from fossil fuel use for selected countries in 2011 [5]

Fig. 4. Australian household energy usages in 2007[6]

Despite the importance of house wall systems for energy efficiency, most published literature focuses mainly on thermal comfort, environmental impact and economic cost of residential buildings [8-14]. Gregory et al. [15], Zhu et al. [16], Wakefield and Dowling [17] reported the importance of thermal comfort and thermal masses on energy performance of various building types (brick veneer, double brick and weatherboard walls). Haapio and Viitaniemi [18], Tommerup et al. [19], Borjesson and Gustavsson [20], Damineli et al. [21], Dodoo et al. [22], Van den Heede and De Belie [23] investigated the environmental impact of various house wall systems (e.g., brick veneer, concrete and weatherboard). The importance of various house insulation materials has been reported by Ozel [24] and Ekici et al. [25], Ballarini and Corrado [26], Budaiwi and Abdou [27], Jelle [28], and Al-Homoud [29].

However, little information is available in the open literature on energy efficient house wall systems made of combined thermal masses and insulation materials that can be used and adapted for variable climate conditions with minimal design changes and cost. Hence, the main objective of this paper is to undertake the thermal performance study of two house wall systems (one conventional and other new design) with single and double glazed windows for variable climate conditions.

2. Description of House Wall Systems

There are two types of house wall systems commonly used in Australia: brick veneer and weatherboard house walls. However, the brick veneer house wall system (here on a conventional house wall system) is the most widely used. In this study, we have selected a 3 bedroom house with a conventional house wall system and a new house wall system. The average floor area is 100.2 m² and the total physical volume is approximately 460 m^3. The house consists of a living or dining area, kitchen, three bedrooms, two bathrooms and an alfresco. The roof slope angle is kept at 20° as per Building Code of Australia (BCA) [30]. Figure 5 illustrates a plan view of the house floor area. The breakdown of house flooring area is shown in Table 1.

Fig. 5. A plan view of 3 bedrooms house

Table 1
House area details

The orientation of the house is north facing due to Australia's geographical location in the southern hemisphere. The bedrooms and living/dining areas need ongoing heating and cooling. The floor foundation is selected "H class" reinforced concrete slab for reactive clay. The thickness of the concrete slab is 100 mm. Figure 6 illustrates a typical reinforced concrete floor foundation and a conventional house under construction in Melbourne, Australia. The roof structure is made of timber with terracotta/concrete tiles. The house has two outer doors (front and rear). The main front door is made of solid wood while the interior doors are made of hollow wood panels. The dimension of the main door is 2040 mm high × 820 mm wide × 0.035 mm thick.

Fig. 6. A typical reinforced concrete floor foundation and house wall system used in Australia

2.2 Wall configurations

As mentioned previously, two house wall systems were selected for this study: a) brick veneer house wall system as standard and b) the new house wall system. Both house wall systems (conventional and new house) consist of external and internal walls. The standard height of house walls is 2.5 m as per the Building Code of Australia (BCA) [30].

2.2.1 Configuration of conventional house wall

The external wall of the conventional house consists of 110 mm brick veneer, 50 mm air gap, 90 mm timber frame structure with 2.5 mm thick insulation foil, and 10 mm plaster (Gypsum) board on the inside [31]. The schematic of the brick veneer house wall used in this study is shown in Fig. 7.

Fig. 7. Conventional house wall construction and materials' sequence

2.2.2 Configurations of new house wall

The new house wall system consists of reinforced concrete with double sided insulation panels. The wall is a made of 10 mm render, 118 mm (59 mm and 59 mm) polystyrene as insulation materials, 150 mm reinforced concrete panel, and 10 mm plaster board on the inside. The schematic of the new wall system is shown in Fig. 8. Additional details for wall materials and their thicknesses for both house wall systems are given in Table 2.

Fig. 8. New house wall construction and materials' sequence

Table 2
Conventional and new house wall components and their thicknesses

2.3 Windows and shading

Two types of standard windows were used in this study as outlined in the Building Code of Australia (BCA). These windows are single glazed and double glazed. The base frame for windows is made of aluminium. The standard size of the window is 1800 mm × 1200 mm and 3mm thickness (single glazed) and 12 mm thickness (double glazed). Figure 9 illustrates typical single and double glazed windows used in this study. The overall heat transfer coefficients (U) of single and double glazed windows are 6.35 $W/m^2.°C$ and 4.95 $W/m^2.°C$ respectively. The double glazed windows have a 6 mm thick air gap. No shading effect due to trees and other surrounding buildings is included in this study. Table 3 shows window opening types and sizes used in this study.

Fig. 9. Schematic of single and double glazed windows

Table 3
Types and dimension of windows used in this study

2.4. Australian climate conditions

The climate in Australia varies significantly including arid, middle, tropical, subtropical and temperate zones. Australian climate is classified into seven main zones based on weather patterns and conditions, meteorological data, and solar radiation. In order to distinguish microclimates throughout Australia, the entire Australian continent has been subdivided into 69 micro climate zones with a certain amount of energy required for ongoing heating and cooling. As mentioned earlier, major Australian cities are located in varied climate conditions. Twelve major cities and towns representing all major climate zones have been selected for this study. These cities/towns are Melbourne, Brisbane, Darwin, Hobart, Adelaide, Sydney, Canberra, Rockhampton, Perth, Alice Springs, Broome, and Cairns. For example, the city of Melbourne experiences mostly cool temperature whereas Brisbane - warm humid summers and mild winters, Darwin - high humid summers and warm winters, and Adelaide - warm temperature. The average overall ambient temperature in the Melbourne metropolitan area ranges between 0°C to 16°C in winter and 18°C to 30°C in summer [32-34]. Table 4 shows climate conditions for selected major cities.

Table 4
Climate conditions for selected cities

2.5. Household heating and cooling energy load in Australian climate conditions

According to Australian state and territory government regulations since 2008, all new houses must comply with certain minimum energy requirements on a scale of 0 to 10 stars for heating and cooling [1]. For example, houses in Melbourne are to be rated for 6 stars, so they should not consume energy more than 114 MJ/m^2 per year for ongoing space heating and cooling. A higher star rating indicates more efficient energy consumption for heating and cooling. Figure 10 illustrates the star energy rating and energy consumption for ongoing heating and cooling for houses located in major Australian cities and towns.

Fig. 10. Star energy ratings vs. energy consumption for selected Australian cities and towns

2.6. Importance of thermal masses

Materials such as concrete and bricks have higher thermal masses as they have higher specific density. A large amount of heat energy can be stored by high density materials. High thermal mass materials also take a longer time to release the heat content once the heat source is removed. On the other hand, lightweight materials such as timber have low thermal mass requiring a lower time to release the heat content [15, 30]. Figure 11 illustrates the time taken to release the heat through different house thermal masses. Materials with high thermal mass such as double brick layer can absorb and keep heat during day or night and release it gradually in 6-8 hours. However, materials with lightweight and low thermal mass such as timber or weatherboard takes less time to store or release heat in 2-3 hours which will also lose heat faster [35-37]. Therefore, the optimal use of thermal masses for the house wall systems can provide a comfortable house environment and reduce energy consumption for the heating and cooling. In order to understand the volumetric heat capacity of various thermal masses of conventional and new design house wall systems, we have estimated the total volumetric heat capacity of materials used in this study. The volumetric heat capacity of the conventional wall system and new house wall system is shown in Tables 5 and 6. The tables show that the new house wall system has higher volumetric heat capacity (17%) compared to the conventional house wall system. This higher heat capacity enables the new wall system to store heat for longer periods as it has higher thermal mass (reinforced concrete).

Fig. 11. Heat flow-delay through different thermal mass house wall systems

Table 5
Volumetric heat capacity of conventional wall system

Table 6
Volumetric heat capacity of new wall system

3. Approach and Methods

In this study, computational modelling is used to investigate the thermal performance of house wall systems. An analytical method is also used to validate and benchmark the computational modelling. The inside air temperature is kept constant for a certain time and the outside air temperature is considered variable based on the daytime mean and night time mean temperature for a given location to estimate the total heat loss/gain through conventional and new wall systems [38, 39].

3.1 Computational modelling

Computational modelling is used to investigate the thermal performance of two house wall systems. Numerous energy simulation software packages are used globally (e.g., Design

Builder, NatHERS, FirstRate, BASIX, BERS Pro, NABERS and AccuRate). However, these software packages cannot be used universally for all climate conditions due to the unavailability of data for local climates, construction materials and house design patterns. Here we have selected the AccuRate software package which is an improved version of the first generation 'Nationwide House Energy Rating Scheme' (NatHERS) developed by the Australian Government's Commonwealth Scientific and Industrial Research Organisation (CSIRO). It is widely used and accepted for the simulation of house energy performances in all Australian states and territories [40]. The software requires detailed information about the house such as orientation, construction type, insulation levels, window size and type, window orientation, shading, overshadowing and ventilation [41]. In AccuRate software, the whole house can be subdivided into a number of zones each of which includes multiple elements, such as floor, roof, ceiling, walls, windows, etc. Each house element is considered to be composed of a series of homogeneous structures [42]. The software has an in-built library of commonly used materials, their thermal properties, and the climate data for Australia (e.g., 69 micro-climate zones). The modeling outcome-report generally shows required heating and cooling energy to maintain conditioned comfort zones within the house. It also provides an energy rating on a scale of 0 to 10. The modelling allows incorporating the effect of natural ventilation caused by the indoor air movement. In this study, the effect of natural ventilation was incorporated in thermal modelling for both house wall systems. However, the variation of thermal energy with and without natural ventilation was found to be negligible. Main data input screens of AccuRate software are shown in Fig. 12.

Fig. 12. Pictorial views of AccuRate thermal modelling software

3.1.1 Thermostat setting and conditioned hours

Only bedrooms and living room are considered to be conditioned (heated or cooled). The rooms have conditioned operating hours regulated by the thermostat setting. Heating is applied if the temperature of the room without heating is below the thermostat setting and the cooling is applied if the temperature rises above the thermostat setting. The thermostat setting depends on local climate condition. In this study, heating or cooling for living rooms was made available from 7:00 to 24:00 hours with the thermostat setting of 22℃. As bedrooms have different conditioned hours for heating and cooling, we have selected a lower temperature (15°C) between 1:00 to 7:00 hours and a higher temperature (18°C) between 8:00 to 9:00 and 16:00 to 24:00 hours. The conditioned temperatures were selected based on recommended temperature settings by the Building Code of Australia (BCA) [30]. The ambient temperatures were selected as per the data of the Bureau of Meteorology, Australia [36].

3.1.2 Household internal heat gains

The house used in this work is an average family house for 2 adults and 2 children. Internal heat gains inside the house slightly contribute to space heating and cooling. The internal heat gain is primarily obtained from household appliances and house occupants. Generally two time zones in a day (day time: 7:00-23:00 and night time: 23:00-7:00) are considered for the internal heat gain. In internal heat gain estimations, 75W per person with 60% availability during daytime and 100% during night time is considered. Equipment gains are generally 16 W/m^2 with 25% available during the day and 5% during the night. Lighting gains are usually 8.5W/m^2 with 15% available during the day and 0% during the night. A constant value for hot water and other systems is also taken into account [43, 44]. In this study, the effect of internal heat gains on heating and cooling performance is not considered due to the computational modelling limitation.

3.2 Theoretical analysis

The analytical study is based on the application of heat transfer theory and equations. The energy performance of the house envelope can be determined by knowing individual building materials, thermal properties and ambient weather conditions. However, the estimated results can differ from the experimental data due to the nonlinear thermal behaviour of materials and the occupant’s energy usage pattern. Three modes of heat transfer (conduction, convection and radiation) are used to determine the overall heat loss or gain. In this study, the one dimensional heat transfer equations are used to estimate the heat flow through the wall as the temperature gradient is significantly greater along the thickness of the house wall compared to the length and height [45, 46]. The maximum conductive heat loss/gain will be predominantly through the wall thickness (X-axis) as illustrated in Fig. 13.

Fig. 13. Schematic of one dimensional heat transfer through house wall system

For the estimation of heat loss or gain through 1 m² of conventional and new house wall systems, various insulations were used. The insulation used for the new house wall system is polystyrene (inner and outer layer of the reinforced concrete panel). On the other hand, for the conventional house wall system, the insulations are air gap and sisalation foil as recommended by the building Codes of Australia (BCA). Equations (1-16) are used for the estimation of heat loss or gain. Schematics of thermal resistance network for heat transfer through conventional and new house wall systems are shown in Figs. 14 and 15.

Fig. 14. Thermal resistance network for heat transfer through conventional house wall system

Fig. 15. Thermal resistance network for heat transfer through new house wall system

$$R_{total} = R_{out} + R_1 + R_2 + R_3 + R_4 + R_5 + R_{in} \qquad (1)$$

Where, $R_{out} = R_{conv,out} = \frac{1}{h_{total}}$, $R_1 = R_{material1} = \frac{x_1}{k_1 A}$, $R_2 = R_{material2} = \frac{x_2}{k_2 A}$, $R_3 = R_{material3} = \frac{x_3}{k_3 A}$, $R_4 = R_{material4} = \frac{x_4}{k_4 A}$, $R_5 = R_{material5} = \frac{x_5}{k_5 A}$, $R_{in} = R_{conv,in} = \frac{1}{h_{total}}$

$R_{out}, R_1, R_2, R_3, R_4, R_5, R_{in}$ are the thermal resistances per unit are of outside convection, brick veneer, air cavity (gap), insulation foil, timber frame, plaster board and inside convection respectively for the conventional wall system. Similarly, $R_{out}, R_1, R_2, R_3, R_4, R_5, R_{in}$ are the thermal resistances of outside convection, render, insulation material (outer layer of the reinforced concrete panel), reinforced concrete, insulation material (inner layer of the reinforced concrete panel); plaster board and inside convection for the new wall system. The thermal conductivity for conventional and new house wall materials is shown in Table 7. As mentioned earlier, equations (1-16) were used to determine the heat gain/loss using one dimensional steady conduction, natural convection and radiation for vertical wall composite materials based on the early work undertaken by Warner and Arpaci [47].

Table 7
Thermal conductivity of materials used in this study

$$Q_{total} = \frac{T_{air.in} - T_{air.out}}{R_{total}} \quad (2)$$

$$T_{film} = \frac{T_{air.in} + T_{air.out}}{2} \quad (3)$$

At this temperature, we read: Pr, k, ν and $\beta = \frac{1}{T_f}$

$$Ra = \frac{g\beta\left(T_{film} - T_{air.in}\right)\delta^3}{\nu^2}\Pr \quad (4)$$

$$Nu = \left[0.825 + \frac{0.387 Ra^{1/6}}{\left[1 + \left(0.492/\Pr^{9/16}\right)\right]^{8/27}}\right]^2 \quad (5)$$

Equations (4) & (5) have been selected for a vertical surface to obtain the heat loss or gain analytically. The convective and conductive heat transfers were based on house wall compositions. Here, Nusselt number (Nu) is used to obtain convective heat transfer coefficient outside and inside the house (h_{out}, h_{in}).

$$h_{total} = \frac{k_{total}}{x_{total}} Nu \quad (6)$$

$$Q_{total} = h_{total} \times A \times (T_{air.in} - T_{wall.in}) \quad (7)$$

$$Q_{total} = h_{total} \times A \times (T_{wall.out} - T_{air.out}) \tag{8}$$

$$h_{in} = \frac{Q_{total}}{A \times (T_{air.in} - T_{wall.in})} \tag{9}$$

$$h_{out} = \frac{Q_{total}}{A \times (T_{air.outt} - T_{wall.out})} \tag{10}$$

$$T_{wall.in} = T_{air.in} - \left(\frac{Q_{loss/gain}}{h_{in} A} \right) \tag{11}$$

$$T_{wall.out} = T_{wall.in} - \left(\frac{Q_{loss/gain}}{k_{total} A} \right) \tag{12}$$

Substituting eq. (11) into eq. (12)

$$T_{wall.out} = T_{air.in} - \left(\frac{Q_{loss/gain}}{h_{in} A} \right) - \left(\frac{Q_{loss/gain}}{k_{total} A} \right) \tag{13}$$

$$Q_{loss/gain} = h_{out} A \left(T_{wall.out} - T_{air.out} \right) \tag{14}$$

Substituting eq. (13) into eq. (14) to find heat gain or loss by conduction & convection

$$Q_{loss/gain} = \frac{h_{in} A (T_{air.in} - T_{air.out})}{\left(1 + \frac{h_{out} A}{h_{in} A} + \frac{h_{out} A}{k_{total} A} \right)} \tag{15}$$

For radiation heat gain or loss through the air inside house to inside wall, eq. (16) is used.

$$Q_{loss/gain} = \varepsilon \times \sigma \times A \times (T_{air.in}{}^{4} - T_{wall.in}{}^{4}) \tag{16}$$

4. Results and Discussion

The thermal performances of conventional and new house wall systems with single glazed and double glazed windows for all 12 major cities/towns were investigated. The findings are discussed in following sub-sections.

4.1 Simulated results for house wall systems with single glazed windows

The energy requirements for ongoing heating and cooling, star energy rating and relative improvement for both house wall systems with single glazed windows are illustrated in Table 8. The total energy requirement for all 12 cities/towns is separately shown in Fig. 16. The conventional system in Darwin and Broome requires the highest energy for heating and cooling while Brisbane and Sydney require the lowest energy for this purpose. Cairns, Alice Springs and Canberra have similar energy requirements for heating and cooling. The energy needs for Melbourne and Rockhampton are in-between. On the other hand, the new house wall system requires less energy for all 12 cities. The highest reduction in energy requirement (44%) is noted for Adelaide and Perth followed by Alice Spring (41%). The cities of Melbourne, Sydney, Darwin, Broome, and Cairns have achieved energy savings between 30-40% while Brisbane, Canberra and Rockhampton 20-30%.

Table 8
Energy requirements for house wall systems with single glazed windows for selected cities

Fig. 16. Total energy required for on-going heating and cooling for selected cities (house walls with single glazed windows)

4.2 Simulated results for house wall systems with double glazed windows

The energy requirements for heating and cooling using double glazed windows for both house wall systems are shown in Fig. 17 and Table 9. The main objective was here to estimate the potential energy savings from the use of double glazed windows. The house wall system shows energy savings compared to a conventional house wall for all cities. The highest energy saving was achieved in Melbourne (37%) followed by Hobart (34%) and Adelaide (31%). The cities of Darwin, Canberra, Perth, Alice Spring, Broome and Cairns have savings from 12 to 30%. All other remaining cities except Brisbane have energy savings around 5%. The city of Brisbane has the lowest energy saving (1%).

Table 9
Energy requirements for house wall systems with double glazed windows for selected cities

Fig. 17. Total energy required for on-going heating and cooling for selected cities (house walls with double glazed windows)

4.3 Comparative analysis of results for single and double glazed windows

The Comparative energy savings for the conventional house wall and new house wall systems with single and double glazed windows is shown in Table 10. A significant energy saving was achieved for the conventional house wall system with double glazed windows for cities/towns that experience warm and tropical climates (e.g., Alice Spring, Perth, Sydney, Adelaide, Broome, Darwin, Rockhampton, Cairns and Brisbane). A moderate gain was achieved for Melbourne, Canberra and Hobart. In contrast, a slightly lower energy savings was obtained for the new house wall system with double glazed windows. The new design with double glazed windows shows better energy savings in cities/towns located in mostly cool climates (e.g., Melbourne). Around 6% energy savings were achieved for cities/towns located in hot/warm humid climates (Darwin, Rockhampton, Sydney, Brisbane, and Broome).

The average energy savings for the conventional house wall system for all selected cities is around 26% while the new house wall system achieved 11%. Nevertheless, the new house wall system with double glazed windows still performs better compared to the conventional house wall system with the same window configurations at around 20% for all cities selected (Table 10).

Table 10
Energy saving and improvement (in percentage) of house wall systems for selected cities

4.4 Analytical results for house wall systems with single glazed windows

In order to compare and validate the simulated findings, a theoretical one-dimensional analysis based on three modes of heat transfer was undertaken for both house wall systems with single glazed windows as mentioned in section 3.2. The analysis included wall areas only. The average monthly house air temperature and climate conditions for the city of Melbourne used in analytical calculations are shown in Tables 11 & 12. The monthly heat gain/loss through 1 m² of conventional and new house wall systems was determined using equations (1-16). The estimated heat gain/loss for both house wall systems are shown in Tables 11 & 12.

The analytical estimation shows that the total heat gain/loss through the conventional house wall system is around 155.14 MJ/m^2/year. In comparison, the total heat gain/loss through the new house wall system is approximately 106.02 MJ/m^2/year. The findings of the computation modelling show that the energy requirement for the conventional and the new house wall systems is 156.2 MJ/m^2/year and 109.0 MJ/m^2/year respectively (Table 8). The findings are in agreement with the computational modelling data for the city of Melbourne. A sample theoretical calculation of heat loss/gain through the conventional house wall system located in Melbourne for the first day of the month of April is shown in Appendix A.

Table 11
Analytically determined data for the conventional house wall system located in Melbourne

Table 12
Analytically determined data for the new house wall system located in Melbourne

5. Economic Analysis for Conventional and New House Wall Systems

Energy savings are directly dependent on patterns of local climate/weather and materials used. The general features of construction materials used here were according to the Building Code of Australia (BCA) [30]. The average retail cost for building materials and labour as on March 2013 are shown in Table 13. The average construction cost for the conventional and new house wall systems is estimated to be A\$106/m^2 and A\$124/m^2. In energy cost estimations, the cost of electricity and gas was taken into account. According to Australian retail gas and electricity companies, the average electricity retail cost is around \$0.069/MJ whereas the cost of gas is \$0.03/MJ for residential uses. The conventional and new houses located in the city of Melbourne consume 156.2 MJ/m^2 and 109.0 MJ/m^2 per annum respectively. Therefore the cost of energy for the conventional house is approximately \$4.68/m^2 per annum if gas is used or \$10.77/m^2 per annum if electricity is used. By contrast, the cost of energy for the new house is around \$3.27/m^2 per annum if gas is used and \$4.68/m^2 per annum if electricity is used. The new house wall construction cost is slightly higher than the conventional house wall by \$18.0/m^2. However, the cost of energy consumed by the new house wall system is lower because of using new construction materials that have better thermal performance. As shown in Table 14, the payback period for the new house wall system is 12.76 years if gas is used and 5.53 years if electricity is used. The payback period is estimated without applying carbon taxes which would shorten the payback period [48].

Table 13
Average retail cost for building materials and labour as on March 2013

Table 14
Payback period for conventional and new house wall systems

The residential building is considered to be complex due to its multiple building components and their different life cycle phases and processes. A building can be considered to have a minimum carbon foot print only if the sum of embedded energy (building material production, transportation, construction) and the energy consumed over its life (operation, maintenance and demolition) is minimum. Usually the choice of building materials and their construction methods affect the primary energy use and the greenhouse gas emissions. Studies on total life cycle energy use of buildings constructed with wood, steel and concrete materials reported that the concrete and steel buildings generally use around 1 to 3% more energy than the wood building [49-51]. However, these studies mainly focused on un-insulated reinforced concrete wall systems which require significantly more energy for ongoing heating and cooling. Additionally, the life of the building was considered to be around 50 years for wood, steel or concrete wall systems. The life span of insulated reinforced concrete wall system is greater than 50 years [52-55]. Therefore, the energy saving from the house operational phase (i.e., ongoing heating and cooling) as well as increasing retail cost of energy and carbon taxes (carbon tax is effective in Australia from 1 July 2012) will make the new house wall system more cost effective and carbon friendly. However, studies are needed to quantify the full environmental impact of the insulated reinforced concrete wall system as insufficient information is currently available in the open literature.

6. Conclusions

The study estimated the total ongoing heating and cooling energy requirement for two house wall systems by computational modelling. The following conclusions were made from the work presented here:

The conventional (brick veneer) house wall system requires more energy for ongoing heating and cooling for all selected Australian cities/towns. However, for a few cities/towns, the system requires slightly less energy than other cities.

The new house wall system with single glazed windows performs significantly better by requiring less heating and cooling energy for most selected cities compared to the conventional house wall system as it possesses combined insulation and thermal mass materials. The energy savings achieved by the new system are between 22% and 44% which would proportionally contribute to the reduction of greenhouse gas emissions. In contrast, the new design with double glazed windows shows energy savings between 1% and 37%.

An average improvement between single and double glazed windows for the conventional and new design is around 26% and 11% respectively. However, compared to the conventional and new design house wall systems with double glazed windows, the average energy saving is around 20%. Therefore, the new design with single and double glazed windows have superior thermal performances (37% & 20%) compared to the conventional house with the same window configurations.

The economic analysis indicates that the conventional house wall system's initial total cost per m^2 is slightly less than the new house wall system. However, the higher cost of the new house wall system will be paid back within 13 years and 6 years if the natural gas or electricity is used for ongoing heating and cooling. The cost was estimated based on current retail price and it did not include the periodic price increase and carbon tax. Should all these be included, the payback period will be much shorter.

In this study the total life cycle assessment of the new house wall system is not considered which is worthwhile for better understanding of full environmental impact. Study is also required to investigate the material composition of the new house wall system to enhance the thermal performance for cities that achieved minimum energy savings.

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Nomenclature

Symbol	Meaning	Unit
h_{in}	Convective heat transfer coefficient inside	$W/m^2.°C$
h_{out}	Convective heat transfer coefficient outside	$W/m^2.°C$
h_{total}	Total convective heat transfer coefficient	$W/m^2.°C$
x	Thickness of wall materials	m
x_{total}	Total wall thickness	m
$T_{wall.in}$	Surface wall temperature inside	°C
$T_{wall.out}$	Surface wall temperature outside	°C
$T_{air.in}$	Air temperature inside	°C
$T_{air.out}$	Air temperature outside	°C
A	Wall surface area	m^2
k	Material thermal conductivity	W/m. °C
K_{total}	Total material thermal conductivity	W/m. °C
Q_{loss}	Heat transfer rate loss	W/m^2
Q_{total}	Total heat transfer rate by convection & conduction	W/m^2
Q_{rad}	Total heat transfer rate by radiation	W/m^2
σ	Stefan-Boltzmann constant = 5.6703×10^{-8}	$W/m^2.K^4$
R	Thermal resistance of material	°C /W
R_{total}	Total thermal resistance of materials	°C /W
β	Coefficient of volume expansion	K^{-1}
g	Gravity acceleration	m/s^2
δ	Characteristic length of wall geometry	m
U	Overall heat transfer coefficient	$W/m^2. °C$
ν	Kinematic viscosity of the air	m/s^2
pr	Prandtl number at certain temperature	-
Ra	Rayleigh number	-
Nu	Nusselt number for vertical plate (wall)	-
ε	Emissivity of the material	-
$A\$$	Australian dollar	A$

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Appendix A: Sample Calculation

A.1 Theoretical analysis for the conventional house wall system: Q $_{loss/gain}$ by (conduction - convection)

Excel tools were used to determine the heat gain/loss for each day of the month. The following example illustrates the calculation procedure for the first day of April month for the city of Melbourne. The sample calculation is based on the area of 1 m^2.

Input data:

$k_{brick} = 1.2\ W/m.K$, $k_{aircavity} = 0.015\ W/m.K$), $k_{sisalation} = 0.15\ W/m.K$, $k_{timber} = 0.18\ W/m.K$, $k_{plasterboard} = 0.21\ W/m.K$

- $\Sigma k = 1.75\ W/m.K$, materials' total thermal conductivity

$x_{brick} = 0.11\ m$, $x_{aircavity} = 0.04\ m$, $x_{sisalation} = 0.0025\ m$, $x_{timber} = 0.09\ m$, $x_{plasterboard} = 0.01\ m$

- $\Sigma x = 0.25\ m$, total materials thickness for brick, air cavity, sisalation foil, timber, and plaster board

    - Area ($A = 1\ m^2$) (we consider $Length = 1\ m$ & $Width = 1 m$ for primary calculation)

Heat loss/gain at maximum temperature (outside house)

$T_{air.in} = 18.0^\circ C$ for human comfort temperature inside the house.

$T_{air.out} = 20.2^\circ C$ for maximum air temperature outside the house (day 1).

Solution:

$$R_{total} = R_{out} + R_1 + R_2 + R_3 + R_4 + R_5 + R_{in} \tag{1}$$

$$Q_{total} = \frac{T_{air.in} - T_{air.out}}{R_{total}} \tag{2}$$

$$T_{film} = \frac{T_{air.in} + T_{air.out}}{2} = \frac{18 + 20.2}{2} = 19.1^\circ C = 19.1^\circ C + 273 K = 292.1 K \tag{3}$$

At this temperature ($292.1K \approx 300K$), based on $T = 300K$ we obtained:

$\Pr = 0.71$, $k = 0.02624\, W/m.^{\circ}C$

$$\nu = 15.69\times10^{-6}\ m^2/s\ \ \&\ \ \beta = \frac{1}{T_f} = \frac{1}{292.1} = 3.42\times10^{-3}\, K^{-1}$$

$$Ra = \frac{g\beta\left(T_{film} - T_{air.in}\right)\delta^3}{\nu^2}\Pr \qquad (4)$$

$$Ra = \frac{9.81\times3.42\times10^{-3}\left(19.1-18.0\right)1^3}{(15.69\times10^{-6})^2}\times0.71 = 1.06\times10^8$$

$$Nu = \left[0.825 + \frac{0.387\ Ra^{1/6}}{\left[1+\left(0.492\ /\ pr^{9/16}\right)\right]^{8/27}}\right]^2 \qquad (5)$$

$$= \left[0.825 + \frac{0.387\ \times 1.06\ \times 10^{8\,1/6}}{\left[1+\left(0.492\ /\ 0.71^{9/16}\right)\right]^{8/27}}\right]^2 = 67.4$$

$$h_{total} = \frac{k_{total}}{x_{total}}Nu \qquad (6)$$

$$h_{total} = \frac{1.75}{0.25}\times67.4 = 471.8\ W/m^2.^{\circ}C$$

$$Q_{total} = \frac{T_{air.in} - T_{air.out}}{R_{total}}$$

$$R_{total} = R_{out} + R_1 + R_2 + R_3 + R_4 + R_5 + R_{in}$$

Where, $R_{out} = R_{conv,out} = \frac{1}{h_{total}} = \frac{1}{471.8} = 0.0021\ ^{\circ}C/W$

$$R_1 = R_{brick} = \frac{x_1}{k_1A} = \frac{0.11}{1.2\times1} = 0.09\ ^{\circ}C/W$$

$$R_2 = R_{aircavity} = 0.16^{\circ}C/W$$

$$R_3 = R_{sisalation} = \frac{x_3}{k_3A} = \frac{0.0025}{0.15\times1} = 0.016\ ^{\circ}C/W$$

$$R_4 = R_{timber} = \frac{x_4}{k_4A} = \frac{0.09}{0.18\times1} = 0.5\ ^{\circ}C/W$$

$$R_5 = R_{plasterboard} = \frac{x_5}{k_5 A} = \frac{0.01}{0.21\times 1} = 0.04\ ^{\circ}C/W$$

$$R_{in} = R_{conv,in} = \frac{1}{h_{total}} = \frac{1}{471.8} = 0.0021\ ^{\circ}C/W$$

$$R_{total} = R_o + R_1 + R_2 + R_3 + R_4 + R_5 + R_i$$

$$R_{total} = 0.0021 + 0.09 + 0.16 + 0.016 + 0.5 + 0.04 + 0.0021 = 0.81\ ^{\circ}C/W$$

$$Q_{total} = \frac{T_{air.in} - T_{air.out}}{R_{total}} = \frac{18.0 - 20.2}{0.81} = -2.71\ W/m^2$$

$$Q_{total} = h_{total} \times A \times (T_{air.in} - T_{wall.in}) \tag{7}$$

$$-2.71 = 471.8 \times 1 \times (18 - T_{wall.in})$$

$$T_{wall.in} = 18.0057\ ^{\circ}C$$

$$Q_{total} = h_{total} \times A \times (T_{wall.out} - T_{air.out}) \tag{8}$$

$$-2.71 = 471.8 \times 1 \times (T_{wall.out} - 20.2)$$

$$T_{wall.out} = 20.194\ ^{\circ}C$$

$$h_{in} = \frac{Q_{total}}{A \times (T_{air.in} - T_{wall.in})} \tag{9}$$

$$h_{in} = \frac{-2.71}{1 \times (18.0 - 18.0057)} = 475.43\ W/m^2.^{\circ}C$$

$$h_{out} = \frac{Q_{total}}{A \times (T_{air.out} - T_{wall.out})} \tag{10}$$

$$h_{out} = \frac{-2.71}{1 \times (20.2 - 20.194)} = 451.67\ W/m^2.^{\circ}C$$

$$T_{wall.in} = T_{air.in} - \left(\frac{Q_{loss/gain}}{h_{in} A}\right) \tag{11}$$

$$T_{wall.out} = T_{wall.in} - \left(\frac{Q_{loss/gain}}{k_{total} A}\right) \tag{12}$$

Substituting eq. (11) into eq. (12)

$$T_{wall.out} = T_{air.in} - \left(\frac{Q_{loss/gain}}{h_{in} A}\right) - \left(\frac{Q_{loss/gain}}{k_{total} A}\right) \tag{13}$$

$$Q_{loss/gain} = h_{out} A\left(T_{wall.out} - T_{air.out}\right) \tag{14}$$

Substituting eq. (13) into eq. (14)

$$Q_{loss/gain} = \frac{h_{in} A (T_{air.in} - T_{air.out})}{\left(1 + \frac{h_{out} A}{h_{in} A} + \frac{h_{out} A}{k_{total} A}\right)} \tag{15}$$

$$Q_{loss/gain} = \frac{475.43 \times 1 (18 - 20.2)}{\left(1 + \frac{451.67 \times 1}{475.43 \times 1} + \frac{451.67 \times 1}{1.75 \times 1}\right)} = -3.8 W/m^2$$

(Heat loss/gain by conduction and convection)

A.1.1 Theoretical analysis for the conventional house wall system: Q $_{loss/gain}$ by Radiation

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Input data:

$\varepsilon_{plasterboard} = 0.93$, $\sigma = 5.6703 \times 10^{-8}$ (Stefan-Boltzmann constant)

$T_{air.in} = 18.0\ ^\circ C$, $T_{wall.in} = 18.0057\ ^\circ C$, $A = 1\, m^2$

Solution:

$Q_{loss/gain} = \varepsilon \times \sigma \times A \times (T^4_{air.in} - T^4_{wall..in})$ to find heat loss or gain by radiation (16)

$$Q_{loss/gain} = 0.93 \times 5.6703 \times 10^{-8} \times 1 \times (291.0^4 - 291.0057^4) = -0.029 W/m^2$$

Total Q $_{loss/gain}$ by conduction, convection and radiation = -3.8-0.029

= - 3.84 W/m^2

= - 0.166 MJ/m^2/year

A.2 Theoretical analysis for the conventional house wall system: Q $_{loss/gain}$ by (conduction - convection)

Heat loss/gain at minimum temperature (outside house)

$T_{air.in} = 18.0^\circ C$ for human comfort temperature inside the house.

$T_{air.out} = 17.5^\circ C$ for minimum air temperature outside the house (day 1)

Solution:

$$R_{total} = R_{out} + R_1 + R_2 + R_3 + R_4 + R_5 + R_{in} \tag{1}$$

$$Q_{total} = \frac{T_{air.in} - T_{air.out}}{R_{total}} \tag{2}$$

$$T_{film} = \frac{T_{air.in} + T_{air.out}}{2} = \frac{18 + 17.5}{2} = 19.41°C = 17.75°C + 273K = 290.75K \tag{3}$$

At this temperature ($290.75K \approx 300K$), based on $T = 300K$ we obtained:
$\Pr = 0.71$, $k = 0.02624\, W/m.^{\circ}C$

$$\nu = 15.69 \times 10^{-6}\ m^2/s\ \ \&\ \ \beta = \frac{1}{T_f} = \frac{1}{290.75} = 3.44 \times 10^{-3}\, K^{-1}$$

$$Ra = \frac{g\beta\left(T_{film} - T_{air.in}\right)\delta^3}{\nu^2}\Pr \tag{4}$$

$$Ra = \frac{9.81 \times 3.42 \times 10^{-3}\left(18.0 - 17.75\right)1^3}{(15.69 \times 10^{-6})^2} \times 0.71 = 2.42 \times 10^{7}$$

$$Nu = \left[0.825 + \frac{0.387\ Ra^{1/6}}{\left[1 + \left(0.492\ /\ pr^{9/16}\right)\right]^{8/27}}\right]^2 \tag{5}$$

$$= \left[0.825 + \frac{0.387 \times 2.42 \times 10^{7\,1/6}}{\left[1 + \left(0.492\ /\ 0.71^{9/16}\right)\right]^{8/27}}\right]^2 = 42.67$$

$$h_{total} = \frac{k_{total}}{x_{total}} Nu \tag{6}$$

$$h_{total} = \frac{1.75}{0.25} \times 42.67 = 298.7\, W/m^2.^{\circ}C$$

$$Q_{total} = \frac{T_{air.in} - T_{air.out}}{R_{total}}$$

$$R_{total} = R_{out} + R_1 + R_2 + R_3 + R_4 + R_5 + R_{in}$$

Where, $R_{out} = R_{conv,out} = \frac{1}{h_{total}} = \frac{1}{298.7} = 0.0033\, ^{\circ}C/W$

$$R_1 = R_{brick} = \frac{x_1}{k_1 A} = \frac{0.11}{1.2 \times 1} = 0.09\, ^{\circ}C/W$$

$$R_2 = R_{aircavity} = 0.16^{\circ}C/W$$

$$R_3 = R_{sisalation} = \frac{x_3}{k_3 A} = \frac{0.0025}{0.15\times 1} = 0.016\ ^{\circ}C/W$$

$$R_4 = R_{timber} = \frac{x_4}{k_4 A} = \frac{0.09}{0.18\times 1} = 0.5\ ^{\circ}C/W$$

$$R_5 = R_{plasterboard} = \frac{x_5}{k_5 A} = \frac{0.01}{0.21\times 1} = 0.04\ ^{\circ}C/W$$

$$R_{in} = R_{conv,in} = \frac{1}{h_{total}} = \frac{1}{298.7} = 0.0033\ ^{\circ}C/W$$

$$R_{total} = R_o + R_1 + R_2 + R_3 + R_4 + R_5 + R_i$$

$$R_{total} = 0.0033 + 0.09 + 0.16 + 0.016 + 0.5 + 0.04 + 0.0033 = 0.81\ ^{\circ}C/W$$

$$Q_{total} = \frac{T_{air.in} - T_{air.out}}{R_{total}} = \frac{17.5 - 18.0}{0.81} = -0.617\ W/m^2$$

$$Q_{total} = h_{total} \times A \times (T_{air.in} - T_{wall.in}) \tag{7}$$

$$-0.617 = 298.7 \times 1 \times (18 - T_{wall.in})$$

$$T_{wall.in} = 18.00206\ ^{\circ}C$$

$$Q_{total} = h_{total} \times A \times (T_{wall.out} - T_{air.out}) \tag{8}$$

$$-0.617 = 298.7 \times 1 \times (T_{wall.out} - 17.5)$$

$$T_{wall.out} = 17.502\ ^{\circ}C$$

$$h_{in} = \frac{Q_{total}}{A \times (T_{air.in} - T_{wall.in})} \tag{9}$$

$$h_{in} = \frac{-0.617}{1 \times (18.0 - 18.00206)} = 299.51\ W/m^2.^{\circ}C$$

$$h_{out} = \frac{Q_{total}}{A \times (T_{air.out} - T_{wall.out})} \tag{10}$$

$$h_{out} = \frac{-0.617}{1 \times (17.5 - 17.502)} = 308.5 W/m^2.^{\circ}C$$

$$T_{wall.in} = T_{air.in} - \left(\frac{Q_{loss/gain}}{h_{in} A}\right) \tag{11}$$

$$T_{wall.out} = T_{wall.in} - \left(\frac{Q_{loss/gain}}{k_{total} A} \right) \quad (12)$$

Substituting eq. (11) into eq. (12)

$$T_{wall.out} = T_{air.in} - \left(\frac{Q_{loss/gain}}{h_{in} A} \right) - \left(\frac{Q_{loss/gain}}{k_{total} A} \right) \quad (13)$$

$$Q_{loss/gain} = h_{out} A \left(T_{wall.out} - T_{air.out} \right) \quad (14)$$

Substituting eq. (13) into eq. (14)

$$Q_{loss/gain} = \frac{h_{in} A (T_{air.in} - T_{air.out})}{\left(1 + \frac{h_{out} A}{h_{in} A} + \frac{h_{out} A}{k_{total} A} \right)} \quad (15)$$

$$Q_{loss/gain} = \frac{299.51 \times 1 (18.0 - 17.5)}{\left(1 + \frac{308.5 \times 1}{299.51 \times 1} + \frac{308.5 \times 1}{1.75 \times 1} \right)} = 0.84 W/m^2$$

(Heat loss/gain by conduction and convection)

A.2.1 Theoretical analysis for the conventional house wall system: Q $_{loss/gain}$ by Radiation

---

Input data:

$\varepsilon_{plasterboard} = 0.93$, $\sigma = 5.6703 \times 10^{-8}$ (Stefan-Boltzmann constant)

$T_{air.in} = 18.0\ ^\circ C$, $T_{wall.in} = 18.00206\ ^\circ C$, $A = 1\ m^2$

Solution:

$Q_{loss/gain} = \varepsilon \times \sigma \times A \times (T^4_{air.in} - T^4_{wall..in})$ To find heat loss or gain by radiation (16)

$$Q_{loss/gain} = 0.93 \times 5.6703 \times 10^{-8} \times 1 \times (291.0^4 - 291.00206^4) = -0.0107 W/m^2$$

Total Q $_{loss/gain}$ by conduction, convection and radiation = 0.84-0.0107

= 0.83 W/m^2

= 0.036 MJ/m^2/year

- Total heat gain/loss for max. & min. temperature in the first day of April Month =

$-0.166+0.036= -\ 0.130\ \text{MJ/m}^2\text{/year}$

Table A1

Analytically determined data for the conventional house wall (April month)

Table 1
House area details

House description	Area (m^2)	House description	Area (m^2)
External wall bedroom 1	16.0	Total area for externals walls	114.1
External wall bedroom 2	14.2	Total area for windows	33.12
External wall bedroom 3	8.4	Total area for floor/Ceiling	100.2
External wall kitchen	22.4	Total area for roof	124.9
External wall dining/living room	53.1	Total condition floor area	75.0

Table 2
Conventional and new house wall components and their thicknesses

No.	Items	Conventional house envelope	Thickness (mm)	New house envelope	Thickness (mm)
1	External Wall	Brick veneer (single)	110.0	Render	10.0
		Air gap	50.0	Insulation polystyrene	59.0
		Insulation foil	5.0	Reinforced concrete panel	150.0
		Timber structure	90.0	Insulation polystyrene	59.0
		Single glaze window	3.0	Single glaze window	3.0&12.0
2	Internal Wall	Plaster board	10.0	Plaster board	10.0
3	Ground/Floor	Reinforced concrete slab	100.0	Reinforced concrete slab	100.0
	Roof	Timber with concrete tiles (20°)	90.0&20.0	Timber with concrete tiles (20°)	90.0&20.0
		Insulation batts + plaster board	20.0&10.0	Insulation batts + plaster board	20.0&10.0
5	Internal Door	Timber (mountain ash)	30.0	Timber (mountain ash)	30.0
6	External Door	Timber (hard)	50.0	Timber (hard)	50.0

Table 3
Types and dimension of windows used in this study

House description	Window type	Window size (m)	House description	Window type	Window size (m)
Bed 1	Awing	1.8 × 1.2	Living/Dining	Sliding	2.1 × 2.4
Bed 2	Awing	1.8 × 1.2	Living/Dining	Sliding	1.8 × 2.4
Bed 2	Awing	1.8 × 1.2	Living/Dining	Sliding	1.8 × 2.4
Bed 3	Awing	1.8 × 1.2	Living/Dining	Sliding	1.2 × 1.2
Bath	Awing	1.8 × 1.2	Living/Dining	Sliding	2.1 × 2.4
Landry	Awing	1.8 × 1.2			

Table 4

Climate conditions for selected cities

No.	City	Climate/weather types
1	Darwin	High humid summer, warm winter
2	Brisbane	Warm humid summer, mild winter
3	Alice Springs	Hot dry summer, warm winter
4	Hobart	Hot dry summer, cool winter
5	Adelaide, Perth	Warm temperature
6	Sydney	Mild temperature
7	Melbourne	Cool temperature
8	Rockhampton	Hot summer, warm winter

Table 5

Volumetric heat capacity of conventional wall system

Material	Volume / unit area of wall surface	Volumetric heat capacity kJ/m^3.K	Specific heat per layer kJ/m^2.K
Brick veneer	0.110	1400.0	154.000
Air cavity	0.050	0.001	0.00005
Sisalation foil	0.005	10.6	0.053
Timber	0.090	1057.0	95.130
Plaster board	0.010	924.0	9.240
Total	0.265		258.420
Volumetric heat capacity of conventional wall system = 258.420 / 0.265 = 975.17 kJ/m^3.K			

Table 6

Volumetric heat capacity of new wall system

Material	Volume / unit area of wall surface	Volumetric heat capacity kJ/m^3.K	Specific heat per layer kJ/m^2.K
Render	0.010	1200.0	12.00
Polystyrene	0.059	5.5	0.32
Reinforced concrete	0.150	2112.0	316.80
Polystyrene	0.059	5.5	0.32
Plaster board	0.010	924.0	9.24
Total	0.288		338.68
Volumetric heat capacity of new wall system = 338.68 / 0.288 = 1176 kJ/m^3.K			

Table 7

Thermal conductivity of materials used in this study

Material	Thermal conductivity (W/m.K)	Material	Thermal conductivity (W/m.K)
Brick	1.2	Render	0.01
Air cavity	0.015	Polystyrene	0.034
Sisalation foil	0.15	Concrete	1.2
Timber frame	0.18	Plaster board	0.21

Table 8

Energy requirements for house wall systems with single glazed windows for selected cities

No.	City	State	Heating load MJ/m^2. annum		Cooling load MJ/m^2. annum		Total energy required MJ/m^2. annum		Star rating 0-10		Impro- -vement
			Conv.	***New***	***Conv.***	***New***	***Conv.***	***New***	***Conv.***	***New***	***%***
1	Melbourne	VIC	120.7	65.8	35.5	43.2	156.2	109.0	4.8	6.5	**30.2**
2	Brisbane	QLD	7.6	0.9	61.8	52.8	69.4	53.7	4.1	5.1	**22.6**
3	Darwin	NT	0.0	0.0	639.8	395.3	639.8	395.3	2.1	5.3	**38.2**
4	Hobart	TAS	199.5	127.6	4.3	18.7	203.8	146.3	4.9	6.2	**28.2**
5	Adelaide	SA	55.8	23.4	83.5	54.3	139.3	77.7	4.6	6.7	**44.2**
6	Sydney	NSW	13.1	1.9	58.2	46.9	71.3	48.8	3.9	5.1	**31.6**
7	Canberra	ACT	186.8	134.4	37	33.3	223.8	167.7	4.9	5.9	**25.1**
8	Rockhampton	QLD	0.6	0.0	163.5	116.3	164.1	116.3	3.2	4.7	**29.1**
9	Perth	WA	26.4	6.3	89.9	59.7	116.3	66.0	4.1	6.2	**43.3**
10	Alice Springs	NT	16.5	4.6	194.7	119.6	211.2	124.2	3.8	5.7	**41.2**
11	Broome	WA	0.0	0.0	470	302.8	470.0	302.8	2.4	5.1	**35.6**
12	Cairns	QLD	0.0	0.0	233.7	147.6	233.7	147.6	2.4	5.2	**36.8**

Table 9

Energy requirements for house wall systems with double glazed windows for selected cities

No.	City	State	Heating load MJ/m^2. annum		Cooling load MJ/m^2. annum		Total energy required MJ/m^2. annum		Star rating 0-10		Impro- -vemnt
			Conv.	***New***	***Conv.***	***New***	***Conv.***	***New***	***Conv.***	***New***	***%***
1	Melbourne	VIC	115.2	54.8	18.8	29.6	134.0	84.4	5.4	6.9	**37.0**
2	Brisbane	QLD	5.4	0.5	45.3	49.8	50.7	50.3	5.3	5.3	**0.8**
3	Darwin	NT	0.0	0.0	491.4	372.7	491.4	372.7	3.8	5.6	**24.2**
4	Hobart	TAS	190.0	108.4	1.5	18.4	191.5	126.8	5.2	6.7	**33.8**
5	Adelaide	SA	52.0	18.2	46.3	49.5	98.3	67.7	5.9	7.1	**31.1**
6	Sydney	NSW	11.3	1.1	35.6	43.7	46.9	44.8	5.3	5.4	**4.5**
7	Canberra	ACT	181.8	114.4	14	31	195.8	145.4	5.4	6.4	**25.7**
8	Rockhampton	QLD	0.5	0.0	114.2	108.6	114.7	108.6	4.8	5.1	**5.3**
9	Perth	WA	22.3	4.1	46.5	54.4	68.8	58.5	6.1	6.6	**15.0**
10	Alice Springs	NT	13.1	2.6	110.6	105.7	123.7	108.3	5.7	6.2	**12.4**
11	Broome	WA	0.0	0.0	343	276	343.0	276.0	4.1	5.4	**19.5**
12	Cairns	QLD	0.0	0.0	182.1	139	182.1	139	3.9	5.5	**23.7**

Table 10
Energy saving and improvement (in percentage) of house wall systems for selected cities

No.	City	State	Total energy required MJ/m^2. annum		Improve-ment	Total energy required MJ/m^2. annum		Improve-ment	*New- double glazed*
			Conv. single glaze window	***Conv. double glaze window***	***%***	***New- single glaze window***	***New- double glaze window***	***%***	***%***
1	Melbourne	VIC	156.2	134	14.2	109	84.4	22.6	37.0
2	Brisbane	QLD	69.4	50.7	26.9	53.7	50.3	6.3	0.8
3	Darwin	NT	639.8	491.4	23.2	395.3	372.7	5.7	24.2
4	Hobart	TAS	203.8	191.5	6.0	146.3	126.8	13.3	33.8
5	Adelaide	SA	139.3	98.3	29.4	77.7	67.7	12.9	31.1
6	Sydney	NSW	71.3	46.9	34.2	48.8	44.8	8.2	4.5
7	Canberra	ACT	223.8	195.8	12.5	167.7	145.4	13.3	25.7
8	Rockhampton	QLD	164.1	114.7	30.1	116.3	108.6	6.6	5.3
9	Perth	WA	116.3	68.8	40.8	66	58.5	11.4	15.0
10	Alice Springs	NT	211.2	123.7	41.4	124.2	108.3	12.8	12.4
11	Broome	WA	470	343	27.0	302.8	276	8.9	19.5
12	Cairns	QLD	233.7	182.1	22.1	147.6	139	5.8	37.0
Average improvement					**25.7**			**10.6**	**19.4**

Table 11
Analytically determined data for the conventional house wall system located in Melbourne

Month	Avg. Human comfort temp. inside house °C	Avg. of Max. air temp. outside house °C	Q $_{\text{loss/gain}}$ with Max. temp. (cond.-conv.-rad.) MJ/m^2/month	Avg. of Min. air temp. outside house °C	Q $_{\text{loss/gain}}$ with Min. temp. (cond.-conv.-rad.) MJ/m^2/month	**Total** Q $_{\text{loss/gain}}$ (cond.-conv.-rad.) MJ/m^2/month
Jan	22.0	25.80	8.95	20.40	-3.48	5.46
Feb	22.0	20.90	7.04	16.50	-4.85	2.19
Mar	22.0	21.90	-0.05	16.60	-12.39	-12.45
Apr	18.0	20.78	6.34	15.17	-6.33	-0.01
May	18.0	16.03	-4.54	11.80	-14.29	-18.83
Jun	18.0	13.26	-10.65	9.87	-18.30	-28.95
Jul	18.0	13.85	-9.61	9.53	-19.68	-29.29
Aug	18.0	14.00	-9.26	10.18	-18.17	-27.44
Sep	18.0	17.75	-0.50	13.59	-9.89	-10.40
Oct	22.0	19.52	-6.05	14.35	-17.77	-23.83
Nov	22.0	22.82	1.93	17.81	-9.38	-7.45
Dec	22.0	23.55	3.69	18.60	-7.84	-4.14
Total gross heat loss/gain (MJ/m^2/Year)						**-155.14**

Table 12

Analytically determined data for the new house wall system located in Melbourne

Month	Avg. Human comfort temp. inside house °C	Avg. of Max. air temp. outside house °C	$Q_{loss/gain}$ with Max. temp. (cond.-conv.-rad.) MJ/m^2/month	Avg. of Min. air temp. outside house °C	$Q_{loss/gain}$ with Min. temp. (cond.-conv.-rad.) MJ/m^2/month	**Total** $Q_{loss/gain}$ (cond.-conv.-rad.) MJ/m^2/month
Jan	22.0	25.80	7.00	20.40	-2.77	4.23
Feb	22.0	20.90	1.17	16.50	-0.73	0.44
Mar	22.0	21.90	-0.07	16.60	-9.78	-9.85
Apr	18.0	20.78	4.82	15.17	-5.00	-0.18
May	18.0	16.03	-3.60	11.80	-11.30	-14.90
Jun	18.0	13.26	-8.42	9.87	-14.46	-22.89
Jul	18.0	13.85	-7.60	9.53	-15.56	-23.16
Aug	18.0	14.00	-1.83	10.18	-8.84	-10.67
Sep	18.0	17.75	-0.43	13.59	-7.83	-8.26
Oct	22.0	19.52	-1.13	14.35	-10.37	-11.50
Nov	22.0	22.82	1.49	17.81	-7.43	-5.94
Dec	22.0	23.55	2.88	18.60	-6.21	-3.33
Total gross heat loss/gain (MJ/m^2/Year)						**106.02**

Table 13

Average retail cost for building materials and labour as on March 2013

Conv. Material	Cost ($/m^2)	New Material	Cost ($/m^2)
Brick	56.0	Reinforced concrete	86.0
Sisalation foil	4.0	Plaster board	15.0
Timber frame and board	31.0	Polystyrene	7.0×2
Plaster board	15.0	Render	9.0
Total	106.0	Total	124.0

Table 14

Payback period for conventional and new house wall systems

Parameter	Total energy required MJ/m^2.annum	Gas power cost $/MJ	Electricity power cost $/MJ	Construction cost $/m^2
New house wall system	109.0	109.0×0.03 = 3.27	109.0×0.069 = 7.52	124.0
Conv. house wall system	156.2	156.2×0.03= 4.68	156.2×0.069 = 10.77	106.0
Saving expenses = New – Conv.	47.2	- 1.41	- 3.25	18.0
Payback period (Year)	-	18/1.41 = 12.76 yrs.	18/3.25 = 5.53 yrs.	-

Table A1

Analytically determined data for the conventional house wall (April month)

Day	Human comfort temp. inside house °C	Max. air temp. outside house 3.00 PM °C	$Q_{\text{loss/gain}}$ with Max. temp. (cond.-conv.-rad) MJ/m^2/day	Min. air temp. outside house 9.00 AM °C	$Q_{\text{loss/gain}}$ with Min. temp. (cond.-conv.-rad.) MJ/m^2/day	Total $Q_{\text{loss/gain}}$ (cond.-conv.-rad.) MJ/m^2/day
1	18.0	20.2	-0.166	17.5	0.036	-0.130
2	18.0	24.7	-0.508	15.4	0.1942	-0.314
3	18.0	24.7	-0.508	22.9	-0.3716	-0.880
4	18.0	24.7	-0.508	17.3	0.0519	-0.456
5	18.0	27.1	-0.690	17	0.0743	-0.616
6	18.0	27.7	-0.736	22.6	-0.3488	-1.084
7	18.0	17.7	0.022	14.4	0.2693	0.291
8	18.0	19.3	-0.099	13.3	0.352	0.253
9	18.0	14.3	0.277	13.3	0.352	0.629
10	18.0	15.3	0.202	10.8	0.54	0.742
11	18.0	18.8	-0.061	15.6	0.1792	0.119
12	18.0	22.2	-0.319	11.9	0.4573	0.139
13	18.0	24	-0.455	13.5	0.337	-0.118
14	18.0	24.3	-0.478	16.9	0.0818	-0.396
15	18.0	26.5	-0.645	19.6	-0.1213	-0.766
16	18.0	20.7	-0.205	16.9	0.0818	-0.123
17	18.0	22.7	-0.356	14.5	0.2618	-0.095
18	18.0	24.4	-0.485	15.4	0.1942	-0.291
19	18.0	23.9	-0.447	18.7	-0.0531	-0.501
20	18.0	21.4	-0.258	15.9	0.1567	-0.101
21	18.0	23.4	-0.410	13.9	0.3069	-0.103
22	18.0	22.8	-0.364	17.4	0.0445	-0.320
23	18.0	14.5	0.262	16.8	0.0893	0.351
24	18.0	12	0.450	9.4	0.6454	1.095
25	18.0	15.5	0.187	11.2	0.5099	0.697
26	18.0	17.1	0.067	13.6	0.3294	0.396
27	18.0	18.5	-0.038	14.2	0.2844	0.246
28	18.0	20.6	-0.197	13.6	0.3294	0.132
29	18.0	16.6	0.104	13.6	0.3294	0.434
30	18.0	17.8	0.015	8.2	0.7357	0.750
Avg.	18.0	20.78	-	15.17	-	-
Total		-	-6.34	-	6.33	-
Total gross heat loss/gain (MJ/m^2/month)						**-0.01**

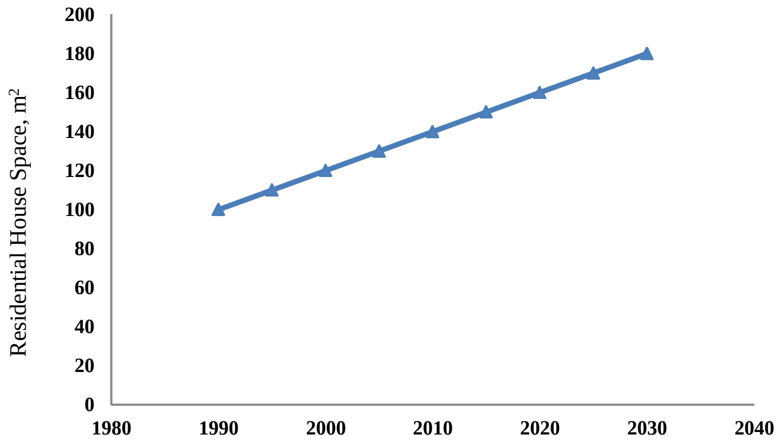


Fig. 1.

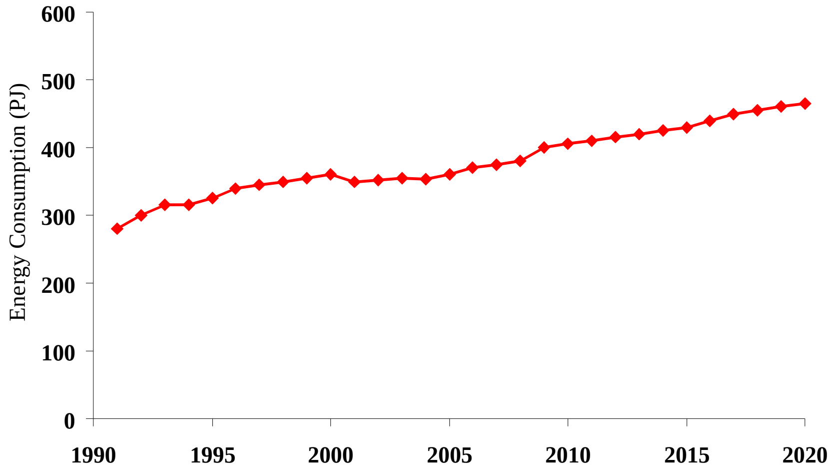


Fig. 2.

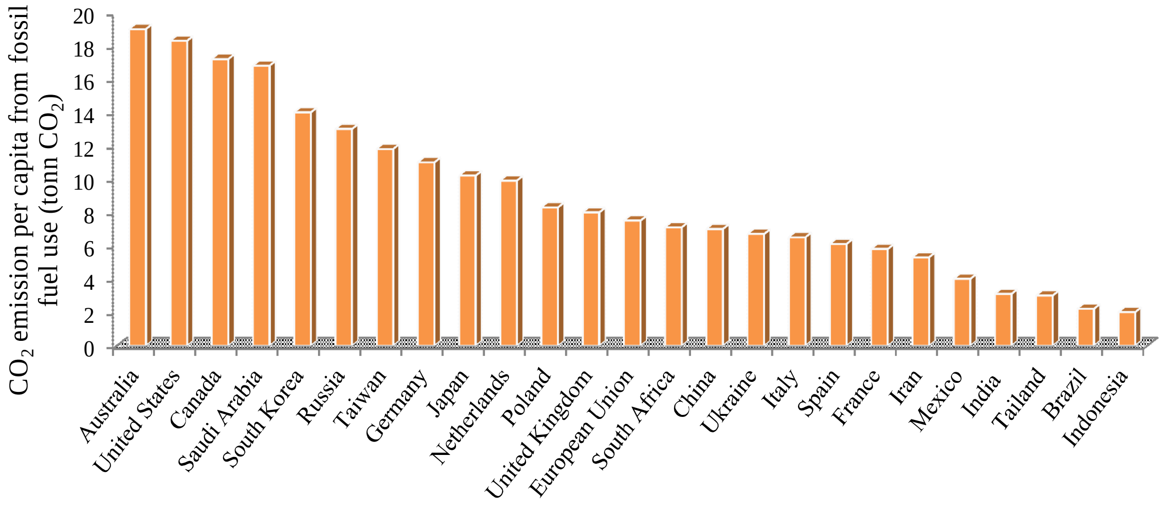


Fig. 3.

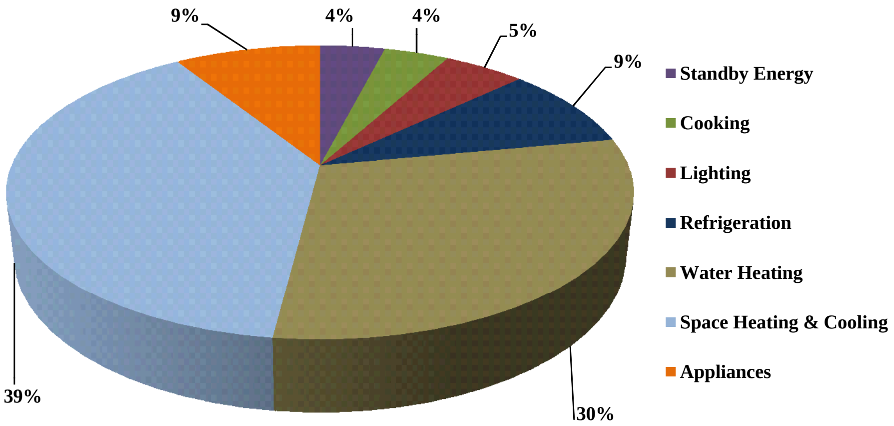

9%
4%
4%
5%
9%
39%
30%
Standby Energy
Cooking
Lighting
Refrigeration
Water Heating
Space Heating & Cooling
Appliances

Fig. 4.

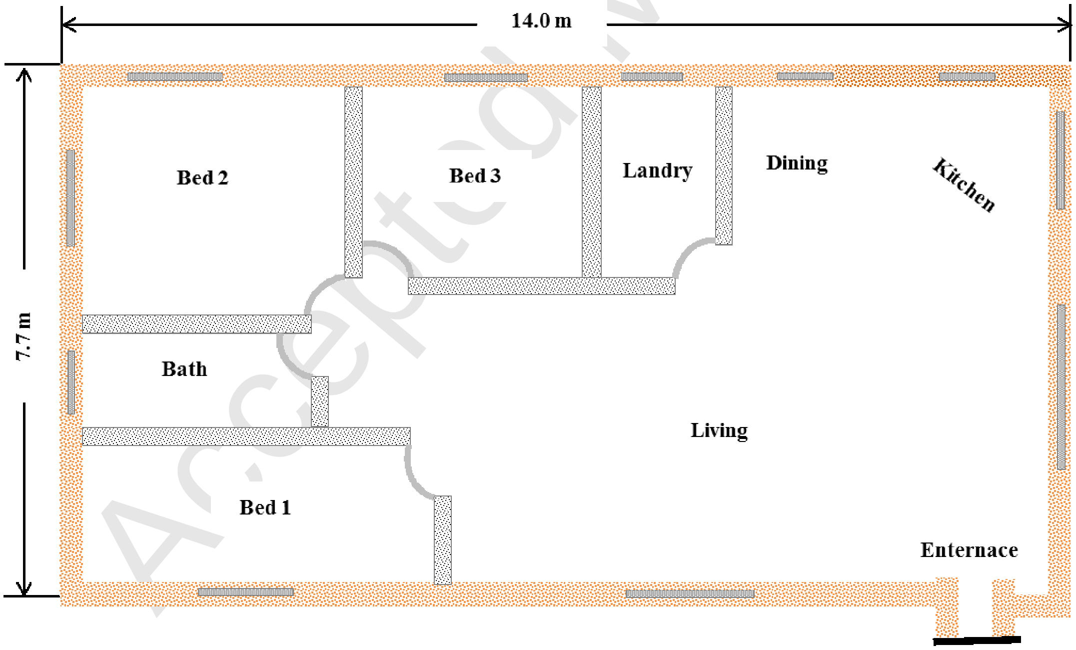
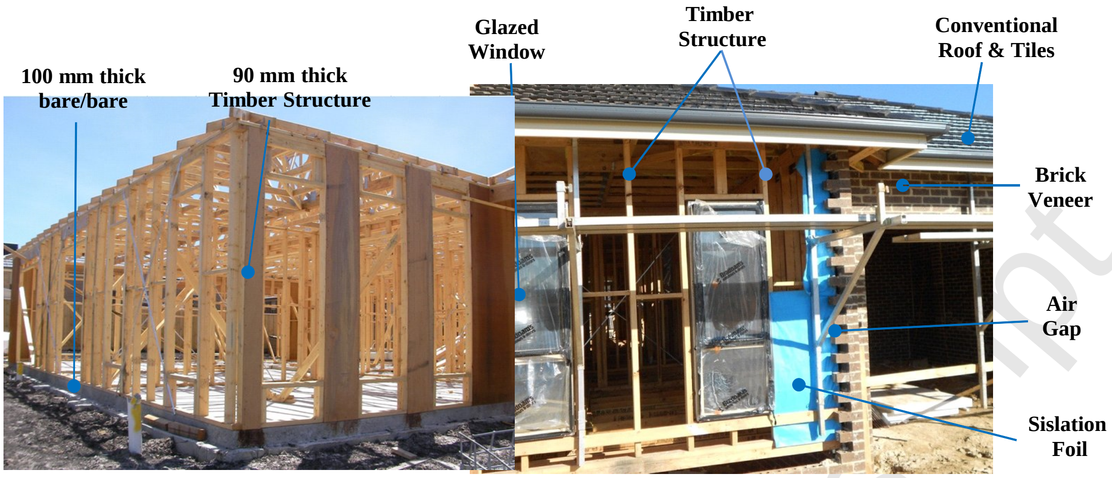

14.0 m
7.7 m
Bed 2
Bed 3
Landry
Dining
Kitchen
Bath
Living
Bed 1
Enternace

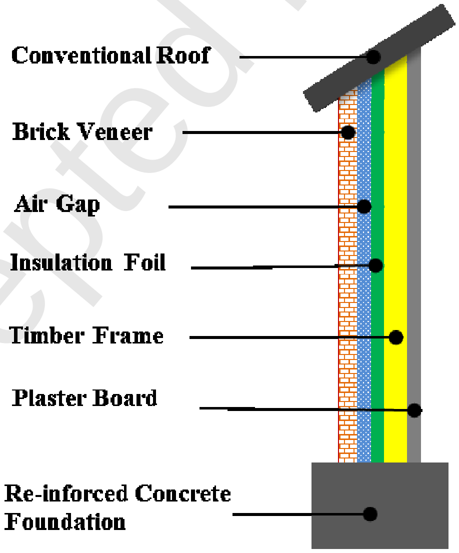
Fig. 5.



a) Reinforced concrete floor foundation and timber structure

b) House wall system under construction

Fig. 6.



a) Schematic of house wall system

Fig. 7.

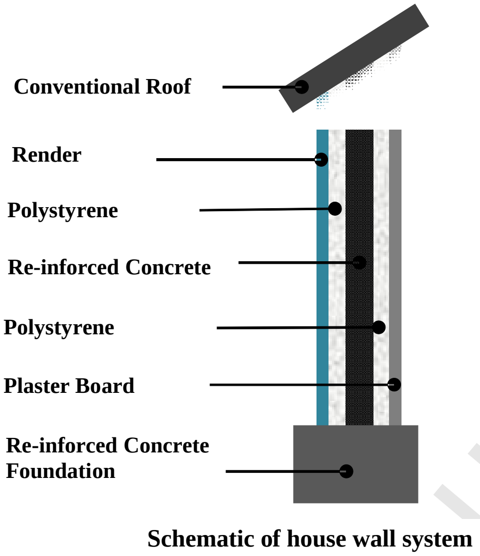

Conventional Roof
Render
Polystyrene
Re-inforced Concrete
Polystyrene
Plaster Board
Re-inforced Concrete Foundation
Schematic of house wall system

Fig. 8.

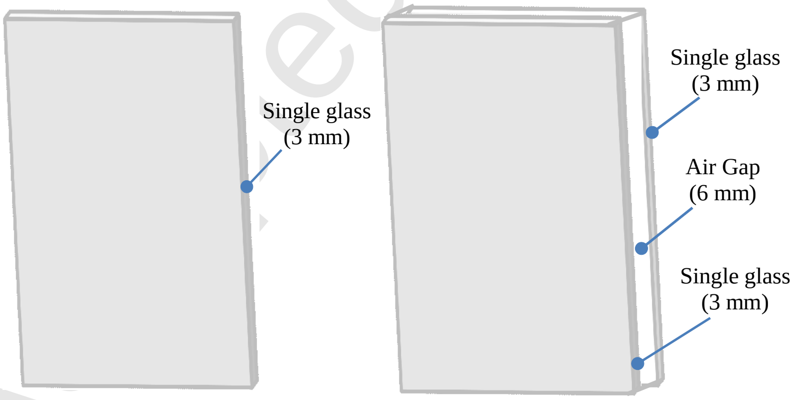

Single glass
(3 mm)
Single glass
(3 mm)
Air Gap
(6 mm)
Single glass
(3 mm)

Fig. 9.

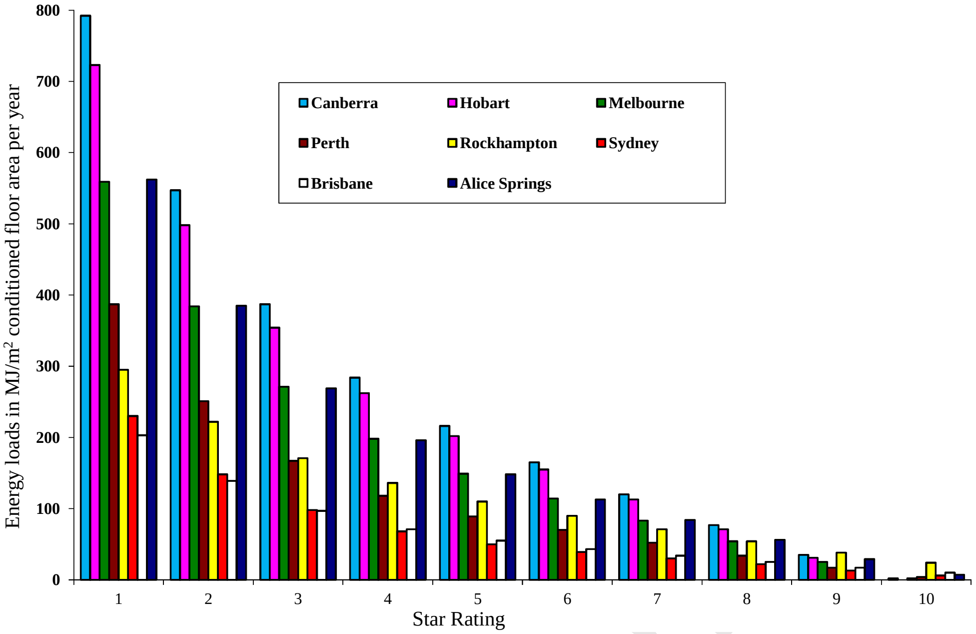

800
700
600
500
400
300
200
100
0
Energy loads in MJ/m^2 conditioned floor area per year
Canberra
Hobart
Melbourne
Perth
Rockhampton
Sydney
Brisbane
Alice Springs
1
2
3
4
5
6
7
8
9
10
Star Rating

Fig. 10.

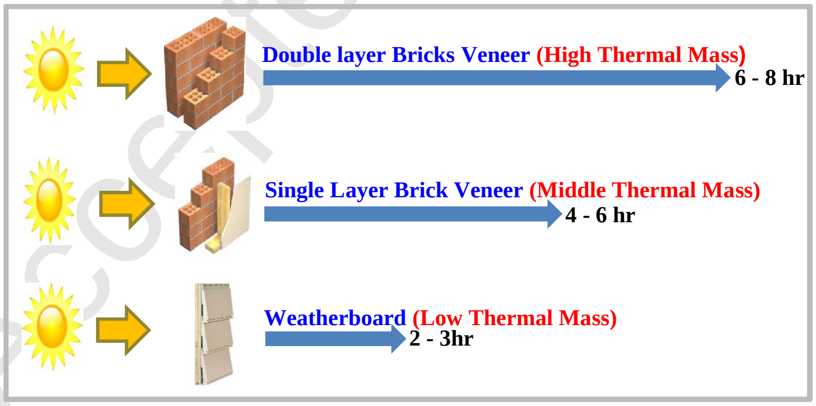
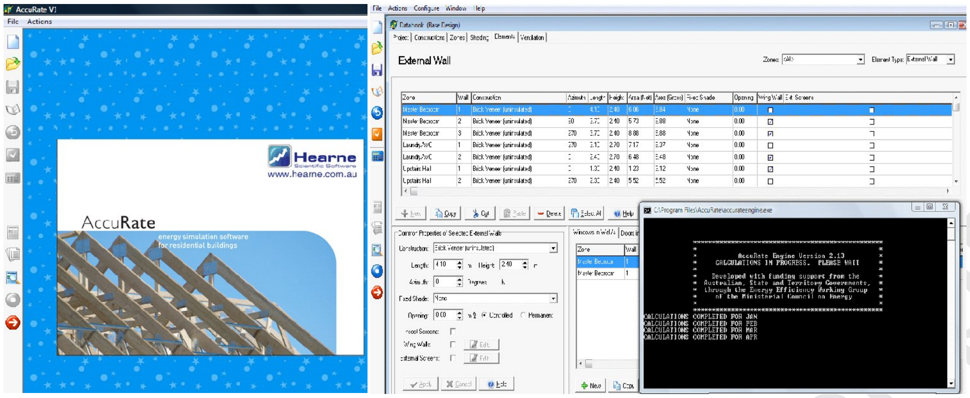

Double layer Bricks Veneer (High Thermal Mass)
6 - 8 hr
Single Layer Brick Veneer (Middle Thermal Mass)
4 - 6 hr
Weatherboard (Low Thermal Mass)
2 - 3hr

Fig. 11.



Zone	Wall	Construction	Azimuth	Length	Height	Area (Net)	Area (Gross)	Fixed Shade	Opening	Wing Wall	Ext Screens
Master Bedroom	1	Brick Veneer (uninsulated)	[illegible]	4.10	2.40	6.06	[illegible]	None	0.00	☐	☐
Master Bedroom	2	Brick Veneer (uninsulated)	[illegible]	[illegible]	2.40	5.73	[illegible]	None	0.00	☑	☐
Master Bedroom	3	Brick Veneer (uninsulated)	270	[illegible]	2.40	8.88	[illegible]	None	0.00	☑	☐
Laundry/WC	1	Brick Veneer (uninsulated)	270	[illegible]	2.70	7.17	[illegible]	None	0.00	☐	☐
Laundry/WC	2	Brick Veneer (uninsulated)	[illegible]	[illegible]	2.70	6.48	[illegible]	None	0.00	☑	☐
Upstairs Hall	1	Brick Veneer (uninsulated)	[illegible]	[illegible]	2.40	1.23	[illegible]	None	0.00	☑	☐
Upstairs Hall	2	Brick Veneer (uninsulated)	270	[illegible]	2.40	5.52	[illegible]	None	0.00	☐	☐

Construction: Brick Veneer (uninsulated)

Length: 4.10 m Height: 2.40 m

Azimuth: 0 Degrees

Fixed Shade: None

Opening: 0.00

Zone	Wall
Master Bedroom	1
Master Bedroom	1

```
***************************************************
*                                                 *
*        AccuRate Engine Version 2.13             *
*     CALCULATIONS IN PROGRESS.  PLEASE WAIT      *
*                                                 *
*    Developed with funding support from the      *
*  Australian, State and Territory Governments,   *
*  through the Energy Efficiency Working Group    *
*     of the Ministerial Council on Energy        *
*                                                 *
***************************************************
CALCULATIONS COMPLETED FOR JAN
CALCULATIONS COMPLETED FOR FEB
CALCULATIONS COMPLETED FOR MAR
CALCULATIONS COMPLETED FOR APR
```

a) Main screen b) Data input screen

Fig. 12

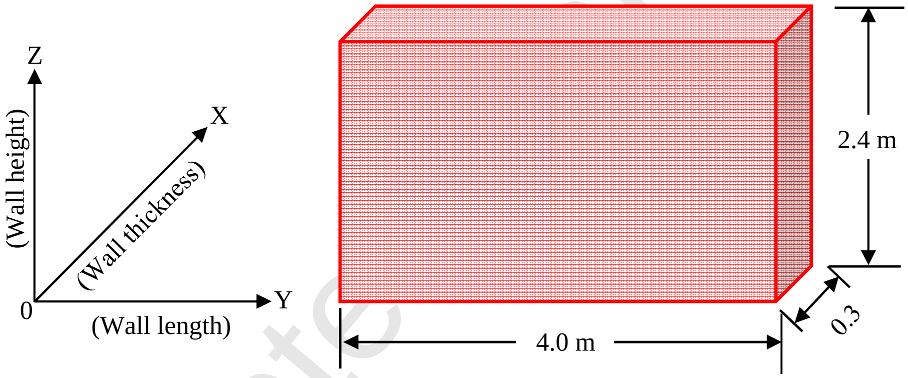


Fig. 13.

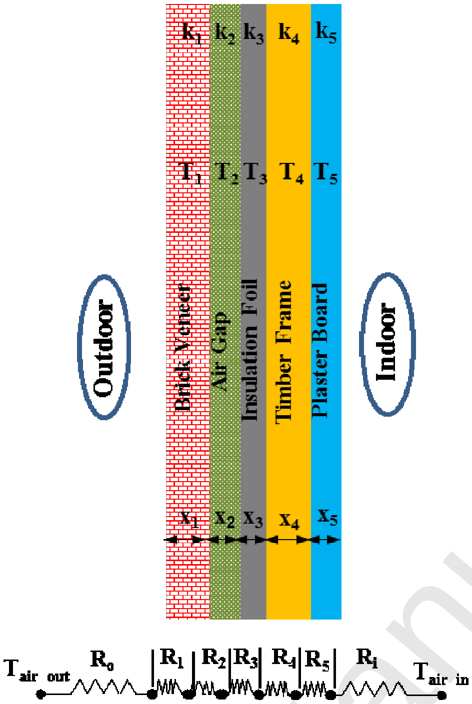

Outdoor
k1 k2 k3 k4 k5
T1 T2 T3 T4 T5
Brick Veneer
Air Gap
Insulation Foil
Timber Frame
Plaster Board
x1 x2 x3 x4 x5
Indoor
T air out
R0
R1 R2 R3 R4 R5
Ri
T air in

Fig. 14.

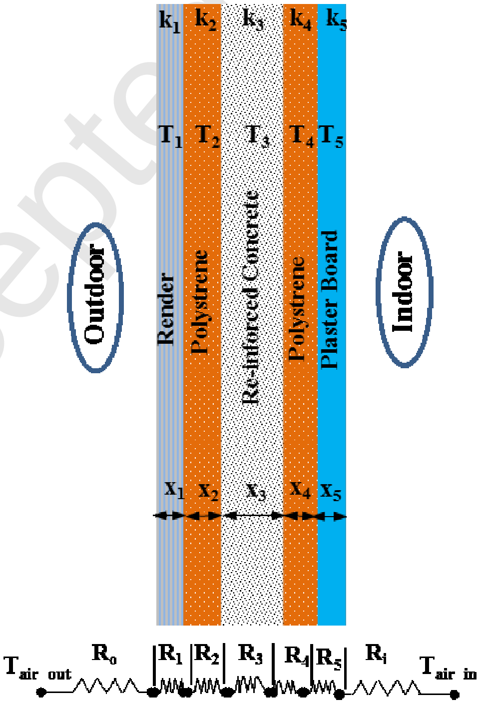

Outdoor
k1 k2 k3 k4 k5
T1 T2 T3 T4 T5
Render
Polystrene
Re-inforced Concrete
Polystrene
Plaster Board
x1 x2 x3 x4 x5
Indoor
T air out
R0
R1 R2 R3 R4 R5
Ri
T air in

Fig. 15.

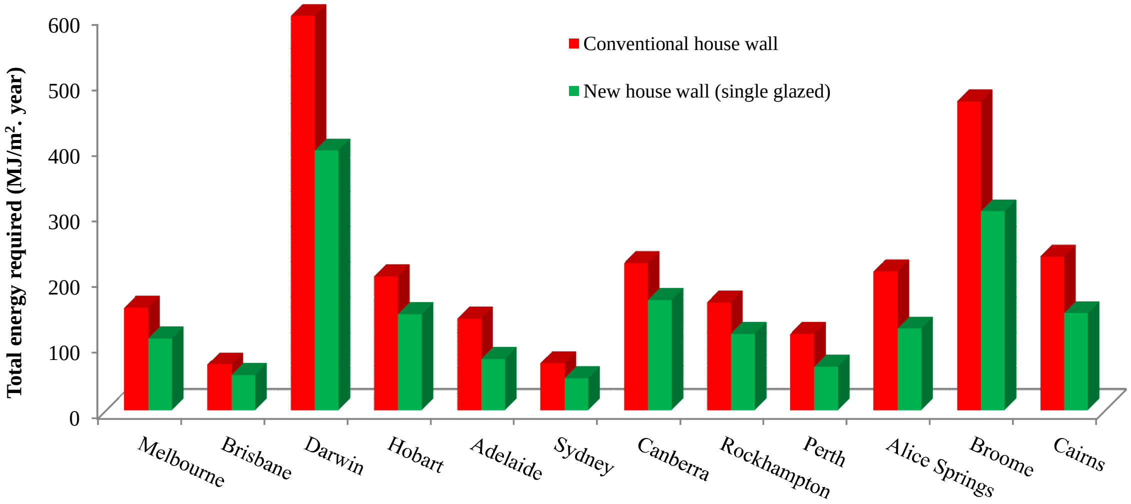

Total energy required (MJ/m^2. year)
600
500
400
300
200
100
0
🟥 Conventional house wall
🟩 New house wall (single glazed)
Melbourne
Brisbane
Darwin
Hobart
Adelaide
Sydney
Canberra
Rockhampton
Perth
Alice Springs
Broome
Cairns

Fig. 16.

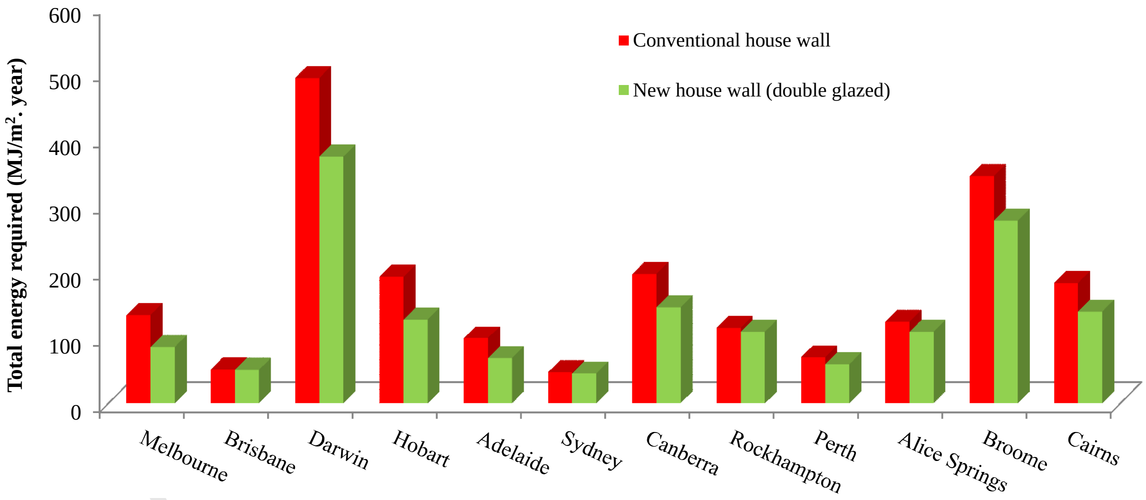

Total energy required (MJ/m^2. year)
600
500
400
300
200
100
0
🟥 Conventional house wall
🟩 New house wall (double glazed)
Melbourne
Brisbane
Darwin
Hobart
Adelaide
Sydney
Canberra
Rockhampton
Perth
Alice Springs
Broome
Cairns

Fig. 17.

Smart house wall system

Thermal performance modelling

Star energy rating

Energy savings for heating & cooling

Low energy house