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Energy Efficient Residential House Wall System

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ABSTRACT

The energy consumption and greenhouse gas emission by the residential housing sector are considered to be one of the largest in economically developed countries. The larger energy consumption and greenhouse gas emission not only put additional pressure on finite fossil fuel resources but also cause global warming and climate change. Additionally, the residential housing sector will be consuming more energy as the house demand and average house floor area are progressively increasing. With currently used residential house wall systems, it is hard to reduce energy consumption for ongoing house space heating and cooling. A smart house wall envelope with optimal thermal masses and insulation materials is vital for reducing our increasing energy consumption. The major aim of this study is to investigate thermal performance and energy saving potential of a new house wall system for variable climate conditions. The thermal performance modelling was carried out using commercially developed software AccuRate®. The findings indicate that a notable energy savings can be accomplished if a smart house wall system is used.

Keywords: Brick veneer house; new house wall; thermal performance; greenhouse gas, thermal mass; insulation material.

1. Introduction

The global population increase, economic prosperity, industrialisation and urbanisation have resulted in millions of new residential house construction annually world wide and ever increasing energy demand [1]. In 2011, the US residential sector's energy consumption was over 21% of the country's total consumption resulted in nearly 25% of national CO_2 emissions [2]. Heating and cooling accounted for 41% of the primary energy requirements and 36% of the CO_2 emissions within the residential sector [2]. In European Union (EU), the residential housing sector is responsible for around 25% of the total energy consumption making it third largest after the transport and industry sectors in terms of energy consumption [3]. Australia's household energy consumption accounts for nearly 40% of the total energy consumed in 2010 [4]. Globally, the housing sector accounts for nearly one-third of global greenhouse gas emissions by consuming over 40% of world's total energy [5]. The International Energy Agency (IEA) and the Organisation for Economic Co-operation and Development (OECD) have projected that by 2050, the energy demand in the housing sector would increase by 60% which is larger than transport or industrial sector's increase [6]. A recent Australian government report depicted a rapid increase of energy demand of over 50% by 2019 (467 PJ) compared to 299 PJ in 1990 [7]. Additionally, the numbers of residential houses in Australia are expected to increase from 6 million in 1990 to 10 million by 2019. Figure 1 illustrates a continuous upward trend of energy demand by the Australian housing sector over the next decade [8, 9]. Majority of modern houses in developed countries especially in Australia, USA and Canada have larger floor space area which requires higher energy for ongoing heating and cooling. Fig. 2 shows the historical trend of Australia's house floor area increase.

Despite having relatively small population, Australia's per capita annual average greenhouse gas emission (CO_2) is one of the highest in the world. Countries like Saudi Arabia and USA have the highest and 2nd highest per capita CO_2 emissions in the world as shown in Fig. 3. The Australia's per capita CO_2 emission is around 16 tonnes due to the use of fossil fuel (e.g. black and brown coals) for most of its power generation [10, 11]. As mentioned earlier, the average energy consumption for residential space heating and cooling in most developed countries is over one-third of the total household energy consumption [12]. The second highest energy consumption component is for hot water systems as shown in Fig. 4.

A significant percentage of energy required for heating and cooling is lost through the house wall systems. Despite the importance of house wall systems for energy efficiency, most published literatures focus on thermal comfort, environmental impact and economic cost of residential buildings [13-18, 49]. Scant information is available on energy efficient house wall systems that can be adapted for varied climate conditions with minimal design changes and cost, except some earlier work [19-22, 48]. Therefore, the primary objective of this paper is to undertake thermal performance study of new house wall systems as well as a current house wall system. The thermal efficiency of house wall systems will be studied for several climate conditions.

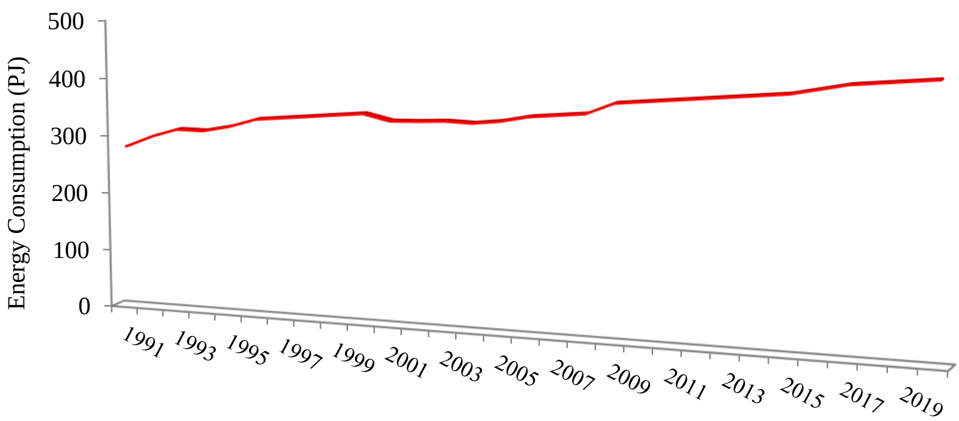


Fig. 1. Energy consumption in Australian housing sector, adapted from [23]

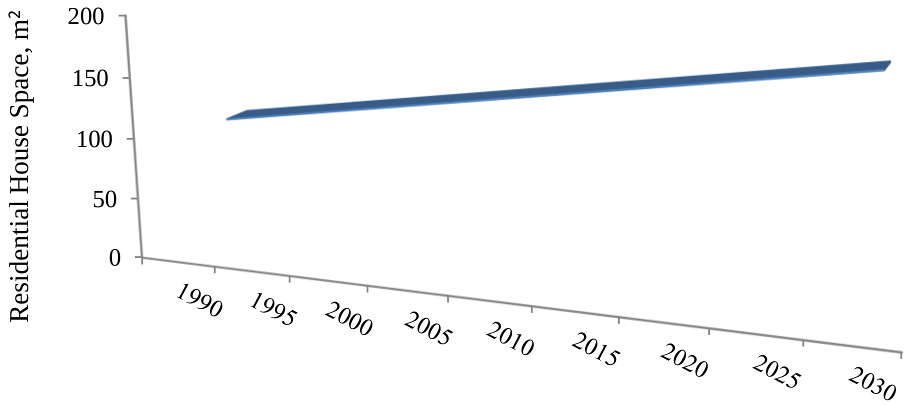


Fig. 2. Average living space in residential houses in Australia, adapted from [23]

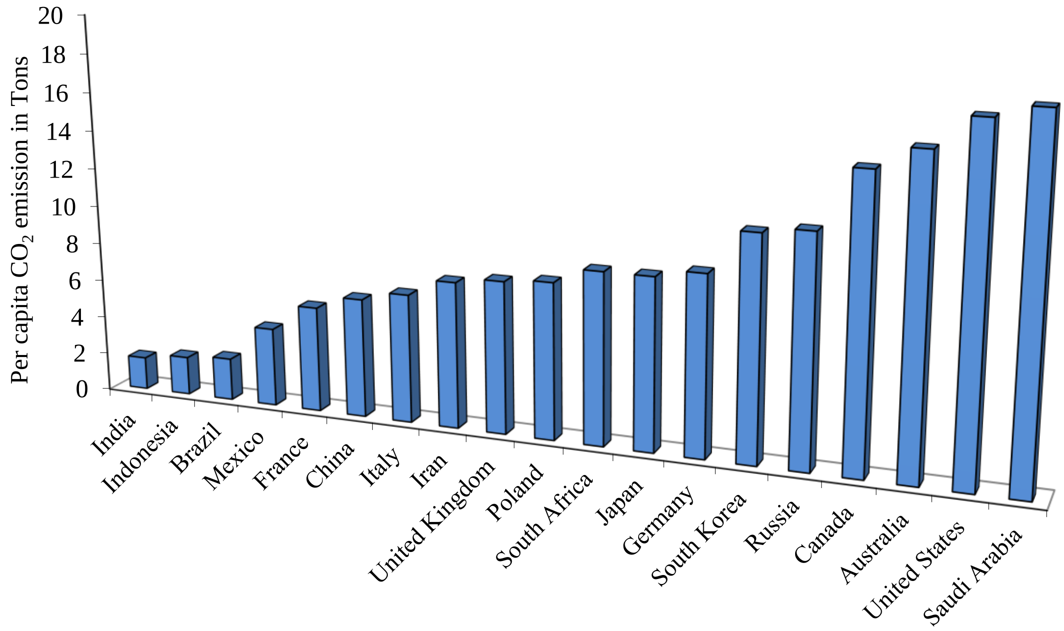


Fig. 3. Per capita greenhouse gas emission for top 19 countries in 2010 adapted from [12]

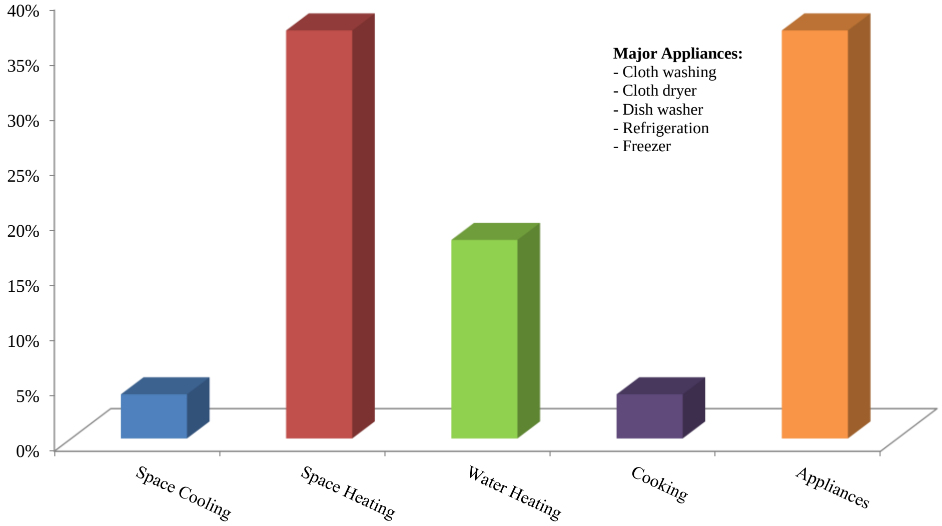


Fig. 4. Australian household energy usages in 2007, adapted from [23]

2. Residential house wall systems in Australia

According to the Australian Bureau of Statistics (ABS), the number of residential buildings in Australia is over 6 million in 2012 [24]. Most of these houses are made of brick veneer and weather board wall systems. However, the brick veneer house wall systems are most widely used. Preliminary estimates show that around 40% of heat is lost through the house wall system [22]. The remaining heat is lost through windows, roof and floor. The thermal performance of the brick veneer house wall system is very low. This study focuses on three new house wall systems and compares their thermal performances with a conventional wall system. For this purpose, a three bedrooms house with a total floor area of 100.2 m^2 and volume of 460 m^3 has been selected. The house possesses a living or dining area, kitchen, three bedrooms, two bathrooms and alfresco. We kept the roof slope angle as 20° as per standard. It was assumed that bedrooms and living/dining areas need ongoing heating or cooling. Hence the thermal performance per unit surface area (per m^2) of the house wall will be investigated. In Fig. 5, a plan view of the house floor area is shown. The orientation of the house is north facing as Australia is geographically located in Southern hemisphere. The north facing orientation allows maximising solar heat gain during winter [25, 26].

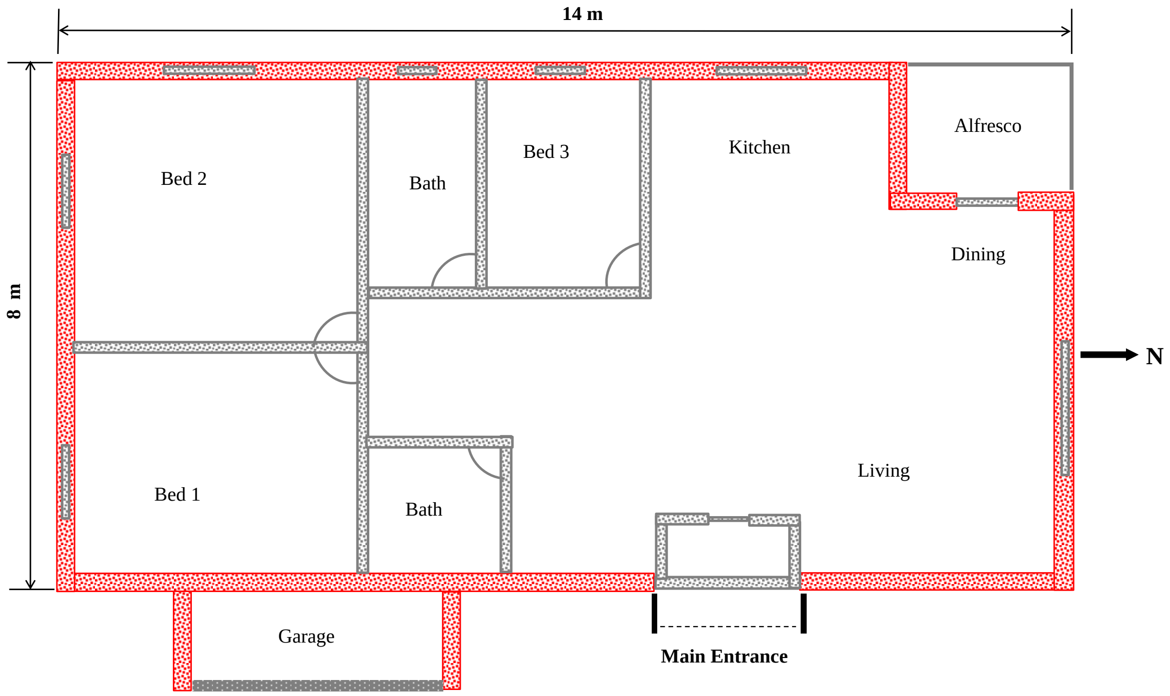
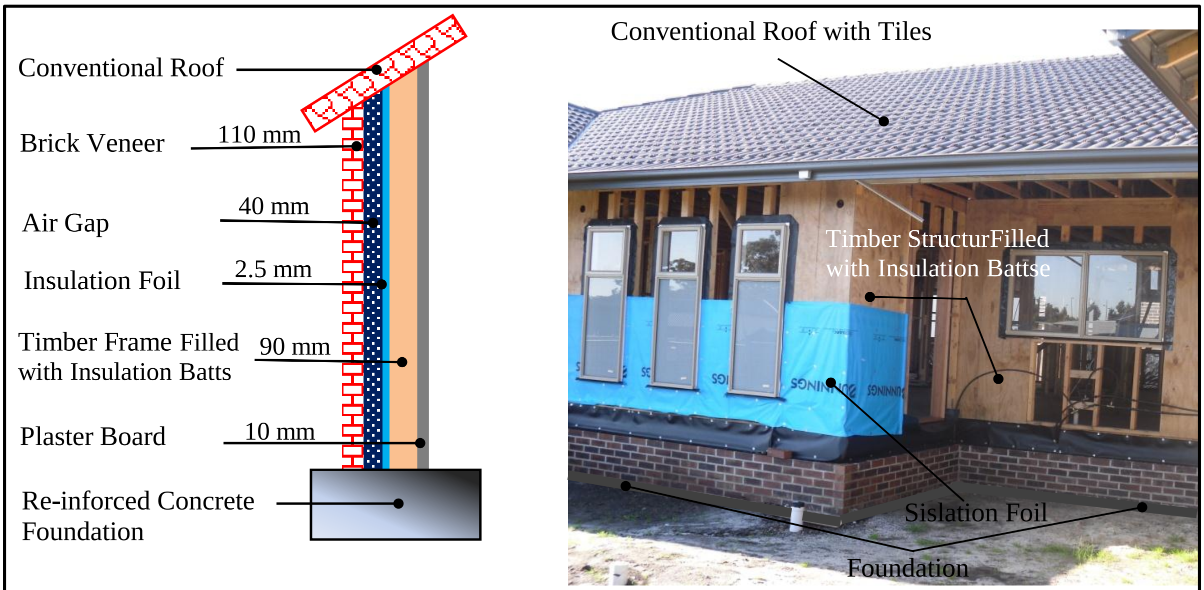


Fig. 5. A plan view of a typical Australian 3 bedrooms house

2.1 Wall configurations

A conventional house wall system and three new house wall systems considered in this study consist of external and internal walls. The wall height of 2.5 m was selected as per the Building Code of Australia (BCA). For the conventional wall system, the external wall is made from 110 mm brick, 50 mm air gap, 90 mm timber frame structure with 2.5 mm insulation foil, and 10 mm plaster (Gypsum) board from inside and the floor foundation is reinforced concrete slab. Furthermore, the roof structure is made of timber with terracotta/concrete tiles with a roof inclination angle of 20°. The exterior wall system of a typical brick veneer house under construction in Melbourne metropolitan area is shown in Fig. 6.



a) Schematic of house wall system b) Typical house wall system under construction, Australia

Fig. 6. A typical conventional house wall construction system (side view)

In this study, we have considered 3 new house wall systems with various sequences of wall materials. These house wall systems are Design 1, Design 2 and Design 3. Each wall system is made of reinforced concrete as structural walls and polystyrenes as insulation material. As shown in Fig. 7, Design 1 consists of 10 mm exterior render, 150 mm reinforced concrete, 59 mm insulated material from outside and another from inside (double layer). Design 2 has same materials used in Design 1 but the insulation material is used from outside only (single layer). Design 3 has also same construction materials used in Design 2, with insulation material installed from the inside only. For all three designs, a 10 mm plaster board is used from the inside. The roof structure is kept the same for all wall systems. Table 1 shows additional details about all 3 designs.

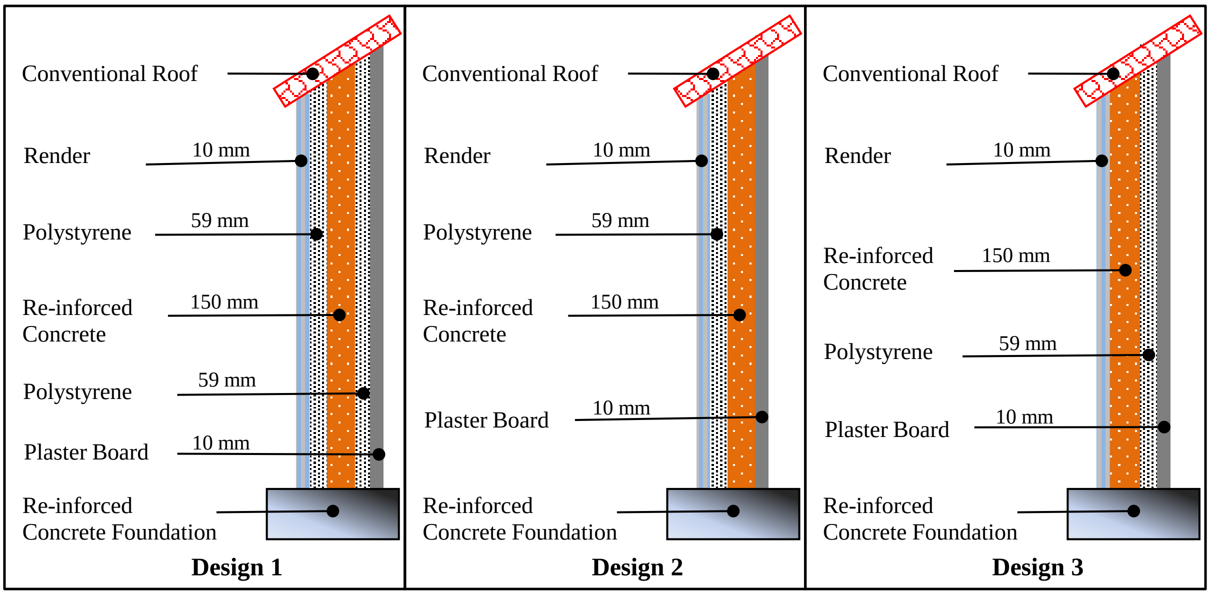


Fig. 7. New house wall construction and materials' sequences

Table 1
Conventional and new house wall components and their thicknesses

No.	Conventional house envelope	Thickness (mm)	New house envelope	Thickness(mm)
1	***External Wall***			
	Brick (single)	110	Render	10
	Air gap	40	Insulation polystyrene	59
	Insulation foil	2.5	Reinforced concrete	150
	Timber structure Filled with Insulation Batts	90	Single glass window	3
	Single glass window	3		
2	***Internal Wall***			
	Plaster board	10	Plaster board	10
3	***Ground/Floor***			
	Reinforced concrete slab	100	Reinforced concrete slab	100
4	***Roof***			
	Timber with concrete tiles (20°)	120	Timber with concrete tiles (20°)	120
	Insulation batts + plaster board	75	Insulation batts + plaster board	75
5	***Internal Door***			
	Timber (mountain ash)	40	Timber (mountain ash)	40

2.2 Windows

Standard windows were selected as per the Building Code of Australia (BCA). The material for the base frame of windows is aluminium. A 3 mm thick single glass window was selected. The external dimension of the window is 1500 mm (height) × 1200 mm (width).

2.3 Doors

Though there are two outer doors in each house, in this study we only considered the main front door which has a dimension of 2040 mm (height) × 820 mm (width) × 0.035 mm (thickness). Furthermore, the main front door is made of solid wood while the interior doors are made of hollow wood panels.

2.4 Floor

For the house floor foundation, the reinforced concrete floor slab was selected, which is classified as “H class concrete slab” with 100 mm depth as per Building Code of Australia. This type of concrete slab is generally used for highly reactive clay soil.

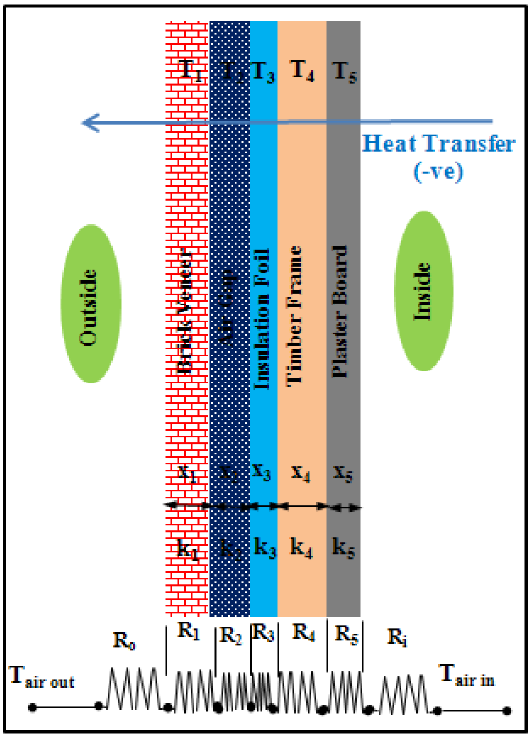
3. Household thermal energy analysis

Generally three approaches (analytical method, experimental method and computational) can be used for the investigation of household energy performance [27-30].

3.1 Analytical method

The energy performance of the house envelope depends on individual building materials, thermal properties and ambient weather conditions. However, the estimated results can differ from the experimentally measured data, mainly due to nonlinear thermal behaviour of materials’ properties and energy usage patterns by the house occupants [31-34].

In this study, we have investigated the thermal performance using computational method. However, a simple theoretical model based on heat transfer equations has also been developed to compare the data with the computational findings. To estimate the total heat loss/gain through conventional and new wall systems following assumptions were made, the performance is estimated for 1 m^2 of house wall system, in order to keep analytical estimation simple, double and single insulations with different sequences were used for the estimation of heat loss or gain. Furthermore, it was assumed that Design 1 used double polystyrene insulations (inner and outer layer), Design 2 used single polystyrene (outer layer) and Design 3 used single polystyrene (inner layer). For the conventional house wall system, the insulations used are glass fibre R1.5, air gap and sisalation foil as recommended by the Building Codes of Australia (BCA). In this analysis, it is assumed that the inside air temperature is constant and the outside air temperature is variable.



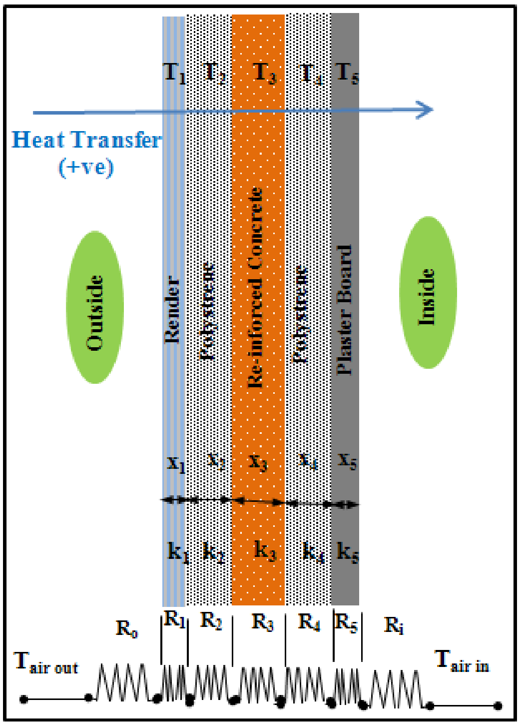


Fig. 8. Brick veneer house wall system

Fig. 9. New house wall system (Design 1)

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

Where, $R_{out} = R_{conv,out} = \dfrac{1}{h_{total}A}$, $R_1 = R_{material1} = \dfrac{x_1}{k_1A}$, $R_2 = R_{material2} = \dfrac{x_2}{k_2A}$, $R_3 = R_{material3} = \dfrac{x_3}{k_3A}$,

$R_4 = R_{material4} = \dfrac{x_4}{k_4A}$, $R_5 = R_{material5} = \dfrac{x_5}{k_5A}$, $R_{in} = R_{conv,in} = \dfrac{1}{h_{total}A}$

As shown in Fig. 8, $R_{out}, R_1, R_2, R_3, R_4, R_5$ & R_{in} are the thermal resistances of outside air, brick, air cavity (gap), insulation foil, timber frame, plaster board and inside air respectively for the conventional wall system. Similarly Fig. 9 shows $R_{out}, R_1, R_2, R_3, R_4, R_5$ & R_{in} are the thermal resistances of outside air, 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 air for the new wall system. Eqs. 1 to 15 were used to estimate the conductive, convective and radiation heat losses or gains through the wall systems.

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

$$T_{film} = \frac{T_{air.in} + T_{air.out}}{2} \tag{3}$$

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

$$h_{total} = \frac{k_{total}}{x_{total}} Nu \tag{4}$$

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

$$Q_{total} = h_{total} \times A \times (T_{air.in} - T_{wall.in}) \tag{6}$$

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

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

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

$$T_{wall.in} = T_{air.in} - \left(\frac{Q_{loss/gain}}{h_{in} A} \right) \tag{10}$$

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

Substituting eq. (10) into eq. (11)

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

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

Substituting eq. (12) into eq. (13)

$$Q_{loss/gain} = \frac{h_{in} A (T_{air.in} - T_{air.out})}{\left(1 + \frac{h_{out} A}{h_{in} A} + \frac{h_{out} A}{kA} \right)} \tag{14}$$

For radiation heat gain or loss through the air inside house to inside wall, eq. (15) is used.

$$Q_{loss/gain} = \varepsilon \times \sigma \times A \times (T_{air.in}{}^4 - T_{wall.in}{}^4) \tag{15}$$

3.2 Computational simulation

Numerous energy simulation software packages are available to estimate the thermal performance of house wall systems. Some widely used commercially developed software packages are: Design Builder, NatHERS, FirstRate, BASIX, BERS Pro, NABERS and AccuRate. However, the application of the software varies with different climate conditions. Furthermore, the application of software depends on the availability of data for local climates, construction materials, complex house design, and occupants' energy uses pattern. The AccuRate software package was selected for this study. The software is an improved version of the first generation energy modeling software known as the Nationwide House Energy Rating Scheme (Nathers) which was developed by the Commonwealth Scientific and Industrial Research Organization (CSIRO), Australia. The software is widely used and accepted for the simulation of house energy performances in all Australian States and Territories. Key feature of this software includes in-built library of thermal properties of commonly used materials, and Australia wide micro climate data. Additionally, it can provide an energy rating on a scale from 0 to 10. The higher the scale rating, the better it is for energy saving as the house requires less energy for ongoing heating and cooling. Another important feature of the software is its ability to incorporate the effects of natural ventilation caused by the indoor air movement. For all house wall systems, the effect of natural ventilation was incorporated in thermal modelling [35].

3.3 Thermostat programming

Thermal conditions and thermostat setting are generally required for living and bedrooms only. Typically, rooms have conditioned operating hours and thermostat setting. In this study, we considered the heating or cooling for living rooms based on local climate conditions and occupants' uses pattern from 0700 to 2400 hours with thermostat setting of 20°C and 18°C from 0000 to 0700 hours. However, Bedrooms have different conditioned hours and thermostat settings for heating and cooling. For better energy savings, the thermostat could be programmed at lower temperature of 15°C between 0000 to 0700 hours and higher temperature (18°C) between 0700 to 0900 hours and 1600 to 2200 hours.

4. Australian climate and household energy loads

The climate condition in Australia varies from arid, middle, tropical, and subtropical to temperate zones. Based on weather patterns and conditions, meteorological data and solar radiation, Australian climate condition is classified into seven major climate zones. In order to distinguish microclimates within these major climate zones, the entire territory of Australia was grouped into 69 micro climate zones. Most Australian cities experience a notably varied climate conditions. For example, the city of Melbourne experiences mostly cool temperature, Brisbane - warm humid summer and mild winter, Darwin - high humid summer and warm winter, and Adelaide - warm temperature in summer and cooler condition in winter. Table 2 shows climate zones for selected major cities of Australia [23, 36, 37].

Table 2
Climate conditions for selected cities

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

All new houses built in Australia's States and Territories must comply with a certain minimum energy requirement for the heating and cooling since 2008 as per government regulations. The energy requirement is rated at a scale of 0 to 10 stars. For example, the ongoing space heating and cooling of a house in Melbourne is to be rated 6 stars if the consumption of energy does not exceed more than 114 MJ/m^2 per year. The higher star rating is the better for energy saving from ongoing heating and cooling. For example, Australian alpine town 'Thredbo' needs the largest amount of energy for ongoing heating and cooling whereas the city of Brisbane needs the minimal energy for the same rating. In the same way, the capital city of Australia 'Canberra' requires the second highest energy for ongoing heating and cooling [38].

5. Thermal storage in house wall systems

Thermal mass depends on the specific density of the material. Materials such as concrete and bricks have higher thermal masses thanks to their higher specific densities. High density materials stores large amount of heat energy and also takes longer time to release the heat content once the heat source is removed. However, lightweight materials such as timbers have low thermal mass requiring shorter time to release the heat content. For this reason, double brick layer having high thermal mass, can absorb and keep the heat during day or night and release it gradually in 6-8 hours. On the other hand, materials with light weight and low thermal mass such as timber or weatherboard takes less time (2-3 hours) to store or release the heat and they also lose heat at a faster rate [19, 39, 40]. Therefore, the appropriate use of high thermal masses for house wall systems can provide a comfortable indoor house environment and reduce energy consumption for heating and cooling. The new house wall system that we used in this study has higher thermal mass than the conventional house wall as it uses the reinforced concrete. Table 3 shows thermal properties of building materials used in this study.

Table 3
Building materials properties

Materials	Thermal conductivity (W/m.K)	Density kg/m^3	Specific heat capacity (J/kg.K)
Walls			
Brick	0.80	1700	800
Re-inforced concrete	0.50	1400	1000
Timber	0.15	650	1200
Single glass window	0.65	2500	840
Surface Finish			
External rendering	0.25	1300	1000
Roofs			
Tile concrete	0.84	1900	800
Floors			
Cast concrete slab	1.13	2200	1000
Timber flooring	0.14	650	1200
Insulation			
Expanded polystyrene	0.034	24	1400
Sisalation foil	0.035	25	840
Plasterboard	0.25	950	840

Generally higher the thermal mass, it is larger the volumetric heat capacity. In order to assess the volumetric heat capacity of two categories of thermal masses (conventional and Design 2 house wall system), an analytical model was developed. The total volumetric heat capacity of the conventional wall system is estimated to be 975.17 kJ/m^{3}K. In contrast, the total volumetric heat capacity of the new wall system is approximately 1176 kJ/m^3.K which is shown in Table 5. The new wall system reduces the thermal conductivity of the wall at the same time increases the volumetric heat capacity of the wall by 20%. This higher heat capacity enables the new wall system to store heat for longer periods [14, 41].

Table 4
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	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 5
Volumetric heat capacity of new wall system (Design 2)

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
Re-inforced concrete	0.150	2112.0	316.80
Plaster board	0.010	924.0	9.24
Total	0.229		338.36
Volumetric heat capacity of new wall system = 338.36 / 0.229 = 1477.55 $kJ/m^3.K$			

6. Results and discussion

6.1 Simulated results for conventional and new house wall systems

Using AccuRate thermal modelling software, the thermal performances for all house wall systems (conventional and new) were investigated. The modelling results show the energy requirement for ongoing heating and cooling as well as star energy rating of all house wall systems. In Table 6, we have presented the total energy requirement for conventional and new house wall systems in all major cities located in different States and Territories of Australia. The conventional house wall system for Darwin and Broome requires the highest energy for heating and cooling ($MJ/m^2/year$) while Brisbane and Sydney require the lowest energy for the same. A similar energy requirement for heating and cooling is also noted for Cairns, Alice Springs, Hobart and Canberra (data for Hobart and Canberra not shown here). The energy needs for Melbourne and Rockhampton are in-between. However, our study indicates that the new house wall system requires less energy for most cities. Designs 1 & 2 have displayed higher energy savings compared to Design 3. This is primarily due to the use of double-thickness insulation material in Design 1 and outer insulation material for Design 2. The highest reduction in energy needs (over 35%) for ongoing heating and cooling is noted for Adelaide, Perth and Alice Springs using Design 2. Additionally, Darwin and Broom have also shown a significant improvement by reducing the energy need around 30% for Design 1. Sydney, Cairns and Rockhampton showed the energy reduction for the new house wall system approximately 20%. A notable improvement is noted for Melbourne and Brisbane using Designs 1 & 2.

A summary of heating and cooling load improvements in percentage for all three new house wall systems (Design 1, Design 2 & Design 3) compared to the conventional house wall system based on computational modelling is shown in Table 7. The external insulation provides opportunity for the reinforced concrete to absorb some heat from the indoor air which it releases back as soon as the indoor air temperature drops below the surface temperature of the concrete wall. If the insulation is installed from the inside, the reinforced concrete thermal mass cannot store any heat from the heated indoor air. This heat would be lost through ceiling via the natural convection of the air especially for houses located in cooler climate. However, the insulation from inside is better for the house located in the warmer climate. The insulation does not allow releasing heat from the reinforced concrete thermal mass to the indoor air thereby reducing the energy loss. The double insulation minimise the effect of both conditions and provides an average effect.

Table 6
Energy required for conventional & new house wall systems for selected cities

No.	City	State	Total energy required (MJ/m^2)/year			
			Conventional house	Design 1	Design 2	Design 3
1	Melbourne	VIC	135.5	114.4	111.1	129.2
2	Brisbane	QLD	60.4	54.5	50.1	57.3
3	Darwin	NT	622.0	424.6	461.0	440.0
4	Adelaide	SA	131.0	91	84.0	103.6
5	Sydney	NSW	67.0	52.1	48.5	56.5
6	Rockhampton	QLD	158.7	115.4	116.8	121
7	Perth	WA	117.0	74.2	61.7	83.2
8	Alice Springs	NT	224.0	143.8	131.0	157.1
9	Broome	WA	498.6	345.7	374.4	357.2
10	Cairns	QLD	209.0	157.4	165.5	161.8

Table 7
New house wall systems improvement percentage comparing to conventional house wall for selected cities

No.	City	Improvement (%)		
		Design 1	Design 2	Design 3
1	Melbourne	15.57	18.0	4.64
2	Brisbane	9.76	17.05	5.13
3	Darwin	31.73	25.88	29.26
4	Adelaide	30.53	35.87	20.91
5	Sydney	22.23	27.61	15.67
6	Rockhampton	27.28	26.40	23.75
7	Perth	36.58	47.26	28.88
8	Alice Springs	35.80	41.51	29.86
9	Broome	30.66	24.90	28.35
10	Cairns	24.68	20.81	22.58

6.2 Results from theoretical analysis for conventional and new house wall systems

As mentioned in Section 3.1, in order to compare the findings obtained through modelling by commercial software, a theoretical one dimensional analysis based on three modes of heat transfer was undertaken for both house wall systems. Using eqs. (1) to (15), the monthly heat gain/loss through 1 m² of conventional and new house wall systems was determined. Melbourne city's ambient air temperature and climate conditions are used for analytical calculations for each of 12 months as shown in Tables 8, 9 and 10. The analytical estimation shows that the total heat gain/loss through the conventional house wall system is around 114.67 MJ/m^2/year, whereas, the total heat gain/loss through the new house wall system is approximately 94.4 MJ/m^2/year for Design 1 and 92.03 MJ/m^2/year for Designs 2 & 3. The improvement of new house wall system based on analytical finding is around 17.6% for Design 1, 19.7% for Designs 2 & 3 located in Melbourne City respectively. However, the variation between computational and analytical finding for conventional house wall system located in Melbourne is around 15.3% and 17.3% for Designs 2 & 3. A sample of analytically obtained heat gain/loss through conventional house wall system for the month of January is shown in Table 11.

Table 8

Analytically determined data for the conventional house wall system in Melbourne

Month	Human comfort temp. inside °C	Max. air temp. outside °C	$Q_{loss/gain}$ with Max. temp. (cond.-conv.-rad.) MJ/m^2/month	Min air temp. outside °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	20	38.20	15.37	14.30	1.29	16.67
Feb	20	35.80	12.88	15.50	-0.59	12.28
Mar	20	30.30	5.18	11.20	-8.81	-3.62
Apr	18	27.70	7.13	8.20	-7.21	-0.08
May	18	21.80	-5.18	7.70	-16.26	-21.45
Jun	18	16.50	-12.12	5.20	-20.81	-32.93
Jul	18	17.10	-10.94	4.60	-22.38	-33.33
Aug	18	20.40	-10.55	4.80	-20.67	-31.23
Sep	18	27.60	-0.62	8.20	-11.26	-11.88
Oct	20	29.10	-1.63	9.70	-14.92	-16.56
Nov	20	33.90	7.26	14.10	-5.57	1.69
Dec	20	34.00	9.42	14.60	-3.64	5.77
Total gross heat loss/gain (MJ/m^2/Year)						**-114.67**

Table 9

Analytically determined data for the new house wall system (Design 1) in Melbourne

Month	Human comfort temp. inside °C	Max. air temp. outside °C	$Q_{loss/gain}$ with Max. temp. (cond.-conv.-rad.) MJ/m^2/month	Min. air temp. outside °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	20	38.20	12.64	14.30	1.06	13.70
Feb	20	35.80	10.59	15.50	-0.48	10.10
Mar	20	30.30	4.26	11.20	-7.24	-2.98
Apr	18	27.70	5.71	8.20	-5.93	-0.22
May	18	21.80	-4.26	7.70	-13.37	-17.63
Jun	18	16.50	-9.96	5.20	-17.10	-27.07
Jul	18	17.10	-8.99	4.60	-18.40	-27.39
Aug	18	20.40	-8.67	4.80	-16.99	-25.67
Sep	18	27.60	-0.51	8.20	-9.25	-9.77
Oct	20	29.10	-1.34	9.70	-12.27	-13.61
Nov	20	33.90	5.97	14.10	-4.58	1.39
Dec	20	34.00	7.75	14.60	-2.99	4.75
Total gross heat loss/gain (MJ/m^2/Year)						**-94.4**

Table 10

Analytically determined data for the new house wall system (Designs 2 & 3)

Month	Human comfort temp. inside °C	Max. air temp. outside °C	$Q_{loss/gain}$ with Max. temp. (cond.-conv.-rad.) MJ/m^2/month	Min. air temp. outside °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	20	38.2	12.50	14.30	1.22	13.73
Feb	20	35.8	10.38	15.50	-0.47	9.91
Mar	20	30.3	4.17	11.20	-7.09	-2.91
Apr	18	27.7	5.75	8.20	-5.81	-0.06
May	18	21.8	-4.17	7.70	-13.10	-17.28
Jun	18	16.5	-9.76	5.20	-16.76	-26.53
Jul	18	17.1	-8.81	4.60	-18.03	-26.85
Aug	18	20.4	-8.50	4.80	-16.65	-25.16
Sep	18	27.6	-0.49	8.20	-9.07	-9.57
Oct	20	29.1	-1.31	9.70	-12.02	-13.33
Nov	20	33.9	5.85	14.10	-4.48	1.36
Dec	20	34.0	7.60	14.60	-2.93	4.66
Total gross heat loss/gain (MJ/m^2/Year)						**-92.03**

Table 11
Analytically determined data for the conventional house wall (January month)

Day	Human comfort temp. inside house °C	Max. air temp. outside house 3.00 PM °C	$Q_{loss/gain}$ with Max. temp. (cond.-conv.-rad) MJ/m^2/day	Min. air temp. outside house 9.00 AM °C	$Q_{loss/gain}$ with Min. temp. (cond.-conv.-rad.) MJ/m^2/day	Total $Q_{loss/gain}$ (cond.-conv.-rad.) MJ/m^2/day
1	20	32.8	1.0952	22.3	0.1961	1.2913
2	20	38.2	1.5580	29.1	0.7782	2.3362
3	20	26.4	0.5469	26.4	0.5469	1.0939
4	20	22.1	0.1790	19.2	-0.0677	0.1112
5	20	20.1	0.0084	16.5	-0.2980	-0.2896
6	20	23.7	0.3159	17.7	-0.19563	0.1202
7	20	29.9	0.8467	22.2	0.18761	1.0343
8	20	27	0.5983	21.9	0.1619	0.7603
9	20	22.5	0.2132	18.5	-0.1274	0.0858
10	20	19.6	-0.0337	16.7	-0.2809	-0.3147
11	20	18.1	-0.1615	14.5	-0.4689	-0.6304
12	20	20.5	0.0424	14.3	-0.4860	-0.4436
13	20	19.4	-0.0507	15.4	-0.3920	-0.4428
14	20	19.1	-0.0762	15.4	-0.3920	-0.4683
15	20	22.2	0.1876	16.8	-0.2724	-0.0848
16	20	31.3	0.9666	23.7	0.3159	1.2825
17	20	32.8	1.095	26.1	0.5213	1.6165
18	20	24.1	0.3501	22.7	0.2303	0.5804
19	20	23.1	0.2645	18.6	-0.1188	0.1456
20	20	19.9	-0.0083	17.6	-0.2041	-0.2125
21	20	24.6	0.3929	19.9	-0.0083	0.3845
22	20	32.2	1.0437	21	0.0851	1.1288
23	20	33.4	1.1466	24.1	0.3501	1.4967
24	20	33.7	1.1723	24.4	0.3757	1.5481
25	20	23.8	0.3244	20.8	0.0680	0.3924
26	20	23.7	0.3159	18.9	-0.0933	0.2225
27	20	26.3	0.5384	20.5	0.0424	0.5808
28	20	27.4	0.6326	24.1	0.3501	0.9827
29	20	34	1.1980	24.6	0.3929	1.5909
30	20	29.5	0.8124	23.7	0.3159	1.1283
31	20	18.4	-0.1359	17.4	-0.2212	-0.3571
Total gross heat loss/gain (MJ/m^2/month)						**16.67**

6.3 Economic analysis for conventional and new house wall systems

Energy savings depend on climate zone/weather pattern, building materials and occupants' energy uses pattern. The general features of construction materials used in this study were according to the Building Code of Australia (BCA) [42]. Table 12 shows the average retail cost for building materials and labour as on March 2012. The estimated average construction cost for the conventional and new house wall systems is approximately A\$102/m^2 and A\$112/m^2 respectively. The cost of electricity and gas was included in energy cost estimation. The average electricity cost is around \$0.069/MJ whereas the cost of gas is \$0.03/MJ for residential uses according to Australian retail gas and electricity companies. The conventional and new houses located in Melbourne city consume 135.5 MJ/m^2 and 111.1 MJ/m^2 energy each year respectively. A cost analysis was undertaken based on criteria described in [43]. If gas is used for heating and cooling, the cost of energy for the conventional house wall system will be around \$4.06/m^2 per annum. Similarly, if electricity is used for heating and cooling, the cost will be \$9.35/m^2 per annum. On the other hand, the cost of energy for the new house (Design 2) will be around \$3.33/m^2 per annum if gas is used and \$7.66/m^2 per annum if electricity is used. However, the new house wall construction cost is slightly higher than the conventional house wall by \$10/m^2. The cost of energy consumed by the new house wall system is lower due to less energy consumption. The payback period for the new house wall system is 13.69 years if gas is used and 5.95 years if electricity is used, as shown in Table 13. However, the carbon tax has not been included in this estimation, which will reduce the payback period.

Table 12
Costs of building materials in Australia

Conventional house wall		New house wall	
Material	Cost (\$/m^2)	Material	Cost (\$/m^2)
Brick	54.0	Render	9.0
Timber structure & insulation batts	30.0	Reinforced concrete	74.0
Sisalation foil	3.0	Polystyrene	7.0
Plaster board	15.0	Plaster board	15.0

Table 13
Payback period

Parameter	Conventional house wall system	Design (2) house wall system	Saving expenses
Total energy required (MJ/m^2.Year)	135.5	111.1	-
Construction cost (\$/m^2)	108	120	112 – 102 = 10
Gas power cost (\$/MJ)	0.03	0.03	-
Electricity power cost (\$/MJ)	0.069	0.069	-
Total cost with gas (\$/MJ)	135.5 × 0.03 = 4.06	111.1 × 0.03 = 3.33	4.06 – 3.33 = 0.73
Total cost with electricity (\$/MJ)	135.5 × 0.069 = 9.35	111.1 × 0.069 = 7.66	9.35 – 7.66 = 1.68
Payback period if gas is used (Year)			10 / 0.73 = 13.69
Payback period if electricity is used (Year)			10 / 1.68 = 5.95

6.4 Environmental Impact

Due to multiple building components and different life cycle phases and processes, the residential building is generally considered to be complex. Minimum carbon foot print of a building is estimated based on the embedded energy (building material production, transportation, construction) and the energy consumed over its life (operation, maintenance and demolition phases). It is obvious that the choice of building materials and their construction methods can affect the primary energy use and the greenhouse gas emission. Several studies have reported that the concrete and steel buildings generally use around 1 to 3% more energy than the wood building [44-47]. The main constrain of these studies is that they mainly focused on un-insulated reinforced concrete wall system which requires higher energy for ongoing heating and cooling. Furthermore, the life of a building was considered in those studies around 50 years for wood, steel or concrete wall systems. In reality, the life span of an insulated reinforced concrete wall system is much higher than 50 years. Therefore, the energy saving from house operational phase (e.g., ongoing heating and cooling) as well as increased 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. At present, insufficient information is available in the open literature about environmental impact of insulated reinforced concrete house wall system over its life span.

7. Conclusion and recommendation

This research estimated the total ongoing heating and cooling energy requirements for four house wall systems: 1 conventional and 3 newly designed.

The new house wall systems (Designs 1, 2 & 3) have shown significantly higher energy efficiency in comparison with the conventional house wall system for all Australian climate conditions.

The Design 2 house wall system possesses highest energy savings (over 47%) compared to the conventional house wall system for cooler climate zones in Southern regions of Australia.

For the humid and warmer climate zones of Australia (e.g., northern regions), the Design 3 displays significantly higher energy savings for ongoing heating and cooling.

The average construction cost per m^2 of the new house wall system is slightly higher than that of the conventional house wall system. Nevertheless, the higher cost of the new house wall system will be paid back within 6 to 14 years depending on types of heating and cooling system used. The new house wall systems will be more economically viable in future with the increase of energy cost and the introduction of carbon tax.

The complete Life Cycle Assessment (LCA) of new house wall systems is important for better understanding of new house wall systems' full environmental impact and sustainability.

The simulated findings of new house wall systems should also be validated with the long term experimental thermal performance data for the wider acceptance and mainstream housing application.

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Nomenclature

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

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