

Article

Net-Zero Energy Retrofitting in Perth's Residential Sector: Key Features and Strategies for Sustainable Building Transformation

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Abstract

The study aims to identify optimum retrofitting strategies that mitigate climate change and support Australia's net-zero emissions target by 2050. Current heating and cooling demands, as well as the energy performance of three stand-alone houses built before 2003, were evaluated to determine optimal retrofitting measures. Based on a comprehensive literature review and physical building surveys and energy simulations using FirstRate5 of three selected case studies of stand-alone houses in Australia's climate zone 5, the study identifies and proposes effective retrofitting opportunities in Western Australia. Additionally, the outcomes from FirstRate5 illustrate that improving ceiling and exterior wall insulation in living and dining areas, sealing air leaks, reducing overshadowing, and replacing single-glazed windows with double-glazed units while enlarging north-facing windows, following the recommended wall-window ratio significantly improve the energy rating of the selected houses. The average energy rating performance of the three selected stand-alone houses increases from an average below 3.5 stars (211.5 MJ/m²) to above 7.5 stars (46.7 MJ/m²), representing around 76.6% improvement in energy efficiency. Just to contextualise the scale up, such retrofitting of all old stand-alone houses built before 2003 would potentially reduce emissions by 12.73 Mt CO₂-e/year, representing a 3.16% contribution toward Australia's national emission reduction target by 2035. Additionally, installing solar energy systems could reduce an extra 4.5 Mt CO₂-e/year. The study's findings demand robust retrofitting strategies for Australia to achieve its 2050 net-zero emissions targets.

Keywords: retrofitting; energy-efficiency; residential building; net-zero; FirstRate5

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1. Introduction

The building sector accounts for almost 34% of the world's energy consumption [1] and 37% of carbon emissions [2]. According to the Paris Agreement, countries must limit global warming to 1.5 °C to reduce climate risk and impacts, by reaching global net-zero CO₂ emissions by 2050 [3]. Australia and all signatory countries of the Paris Agreement have committed to the global goal of holding the increase in global temperature to well below 2 °C above pre-industrial levels, and to pursuing effort to limit the temperature increase to 1.5 °C. The Australian Government's Net Zero Plan articulated six sectors (Electricity and energy, Transportation, Industry, Agriculture and land, Resources, and Built environment) that capture the full breadth of the economy [4]. In Australia, buildings account for about one-fifth of national emissions (operational plus part of embodied), with residential

buildings contributing a significant share [5]. To tackle climate change and achieve net zero by 2050, the Australian building sector plays a crucial role by incorporating various energy-efficient parameters and a building rating system into its national construction code (NCC) for constructing new buildings.

Meanwhile, globally, approximately 98% of the building stock consists of existing structures [6], and less than 2% of buildings in Australia are replaced each year [7]. With energy efficiency being a key consideration in design, achieving net zero by 2050 is a significant challenge without considering the existing building stock. This sector will consume 50% of Australia's carbon budget by 2050 if the heating and cooling of buildings continue at the present rate. Regarding the carbon budget, 40% is mainly allocated to residential buildings, which is almost 90% of the Australian building stock and is responsible for 10% of national emissions [8]. Most existing residential buildings were constructed before the energy-efficient parameters were included in the National Construction Code (NCC), which started on 1 January 2003 [9]. According to ABS (2021), the number of stand-alone houses in Western Australia is 0.76 million, while the nationwide total is 6.7 million [10]; among them 70% of houses are built before 2003 [11]. Millions of residential buildings in Australia require retrofitting to enhance their energy performance, achieve comfort, reduce costs, and increase resilience. The average NatHERS (Nationwide House Energy Rating Scheme) rating of existing dwellings is estimated to be below 2 stars on a 10-star scale [12,13], while 98.5% of the existing housing stock falls short of achieving optimal economic and energy performance [12,14]. Australian residential buildings account for 24% of overall electricity consumption and 10% of total emissions [15]. A study conducted on detached houses in three Australian states (Victoria, New South Wales, and Western Australia) found that upgrading insulation (floor, wall, and ceiling) can reduce annual energy use by an average of 24% and lower emissions by 13%. Effective appliances such as fridge, dishwasher, and washing machine reduce equipment power density by 55% (W/m^2) and LED lighting reduced light power density by 85% (W/m^2) [16]. Additionally, a solar panel (5 kW, 25 m^2) can produce 7300 kW/year on average. In Australian houses approximately 30% of that amount is used for the house and the rest is stored on the battery or contributed to the national grid [17], which also reduces 8.6 t $\text{CO}_2\text{-e}/\text{year}$ for every house [18]. Retrofits also play a significant role in reducing embodied carbon. A new building accounts for 35–40% of its lifecycle emissions from embodied carbon, whereas retrofitting can reduce almost three-quarters of a building's upfront embodied carbon emissions [19]. Consequently, operational emissions will represent only about 12% of the home's total lifecycle carbon [20]. This article aims to identify optimal energy-efficient design features for retrofitting stand-alone houses in Perth, Western Australia (Australian climate zone 5), using FirstRate5 and evaluating the resulting carbon emissions savings.

2. Literature Review

Retrofit refers to upgrading buildings to respond to climate change [21], including renovating, repairing, refurbishing, and restoring old buildings to increase energy efficiency [7]. The primary objective of retrofitting is to mitigate climate change and enhance building resilience against its impacts. Retrofit can be divided into two types: deep and shallow retrofit. Deep retrofitting is an integrated approach, the most effective way to reduce energy consumption, which is costly, and it reduces up to 70% of heating energy demand. Shallow retrofitting means just changing the appliances, and it is a low-cost option that reduces 30% of heating energy demand [22]. In Australia, well-planned retrofitting can reduce household heating demand by up to 69% and cooling demand by 38% [23]. The NCC (National Construction Code) of Australia 2022 requires new homes to achieve a 7-star NatHERS rating, taking into account major fixed appliances as well as on-site energy

generation and storage. This is an increase from the previous 6-star requirement and also includes provisions for retrofitting existing homes to improve energy efficiency and reduce emissions [24]. Retrofit has many benefits, such as improving health issues, reducing fuel poverty, developing a resilient society, and creating employment opportunities [25]. Numerous studies have demonstrated that retrofitting enhances the energy efficiency of existing buildings. Retrofitting can reduce energy consumption by 80%, requiring high investment and a long payback period [26]. The energy waste depends on the building age; older buildings waste more energy than new buildings [27].

Retrofitting is a common practice for transforming a lower-energy building into an energy-efficient one. It is a complex strategy that involves different stakeholders. Many countries have already implemented retrofitting measures to improve the energy efficiency of their buildings. Studies conducted in South Korea have shown that only exterior wall insulation and window retrofitting reduced the annual energy consumption of low-income residential buildings, which mainly depends on the room location, by 22.61% [28,29]. Replacing windows and achieving airtightness can save 15.5% and 18.5% in South Korean warm and cold climates [30]. A study conducted in 44 cities with different climatic conditions in the US found that retrofitting attics with a switchable insulation system in hot and cold seasons benefits energy savings [31]. In another study in the UK, the most effective retrofit option was wall insulation, compared to window glazing, floor and roof insulation, which cost significantly more and has a payback period of 40 years [32]. This, however, contradicts another study in the UK, where the most cost-effective option was found to be insulating walls with 40 mm EPS (Expanded Polystyrene), floors with 40 mm XPS (Extruded Polystyrene), and roofs with 30 mm XPS (Extruded Polystyrene) [33]. Retrofitting with a Trombe wall is very beneficial in hot and arid climates. Concrete in 2/3 of the external wall with glass in a Trombe wall can reduce about 86% heating load in winter, whereas 5% extra energy is necessary for cooling the interior space in summer [34]. Similarly, in the hot climate region of Saudi Arabia, external wall insulation, roof insulation, and floors exposed to the weather are beneficial for energy retrofitting.

In contrast, landscape around the building reduces cooling energy [35]. Research conducted by the Australian Government identified retrofitting options for houses in Australian Climate Zone 5 (e.g., Adelaide, Perth, and Sydney), providing specific details based on the houses' construction periods. For instance, significant retrofitting options for homes built between 1970 and 2000 are adding a solar panel, improving airtightness, a hot water system upgrade, energy-efficient appliances, LED lighting, roof/ceiling insulation, wall insulation, natural ventilation, and an external shading device, which are not difficult to install but enable high energy savings [7].

Time is a significant concern in retrofitting because traditional retrofitting is a labour-dependent process, where replacing old windows with new ones and installing insulation on the wall, floor, and ceiling takes weeks to months [36]. To overcome this problem, an industrialised solution, such as a prefabricated element, could be an alternative to traditional retrofitting. Retrofitting with concrete sandwich panels provides the required R-value with lower CO₂ emissions [37]. Table 1 shows the key building features to improve energy efficiency based on various studies. Based on the local context in Perth and climate zone 5, only the relevant building features are briefly discussed in the following sections.

Table 1. Literature for the study of key features and parameters of energy-efficient buildings.

Building Features Considerations for Energy-Efficiency	Reference
Solar panel and roof shading	[38–42]
Window orientation and overhang shading	[43–48]
Orientation and Window-wall-ratio	[49–53]
External building facade and insulation	[54–57]
Efficient heat pump and high-efficiency HVAC system	[58–61]
Rain and grey water harvesting, renewable energy	[57,62–64]
Natural ventilation, lighting, and airtightness	[65–69]
Window glass properties	[70–73]
Shading device	[74–77]
Efficient appliances	[78–81]

External Wall:

The external wall is the most impactful element for heating and cooling energy demand and indoor comfort [82]. Proper design and application of the external wall in a residential building reduces electricity consumption for heating, cooling, ventilating, and lighting [83]. It also accounts for almost 50–60% of the heat transfer of buildings [84,85]. Thermal performance of the external wall increased in different ways, such as increased thickness of the materials, adding insulation, and introducing an air cavity [86]. The performance of thermal mass depends on climatic conditions. Hot climatic zones require higher thermal mass compared to cold zones, which require low thermal mass [87].

Thermal Insulation:

Insulation is used to improve the thermal performance of a building, and optimal insulation thickness can reduce energy consumption by 46.6% [88]. Insulation is used primarily on the roof, ceiling, floor, and walls to prevent heat flow. Effective use of insulation, especially in exterior walls, enhances the energy efficiency of a building, which reduces up to 19.7% of the energy load [89].

Window Glazing:

In a building envelope, the window is the most significant element for energy efficiency. Inefficient windows are responsible for a building's 20–60% energy loss [90]. In Australia, an estimated 1.5% of heat transfer occurs through windows [91]. As a result, window glazing significantly improves the performance of windows in improving a building's energy efficiency [92,93]. Currently, various types of glazing are available; the most commonly used type are single-glazing units, which are almost twice as inefficient as double-glazing units. Triple-glazing units are the most effective in reducing energy consumption among these three options [94]. On the other hand, other high-performance window glazing solutions are also available.

Window–Wall Ratio:

The window-to-wall ratio has a significant impact on a building's energy demand. It refers to the ratio of glazing area with mullions and frames to the gross external wall area [95]. The appropriate window-to-wall ratio according to the site orientation is selected in the design stage to reduce yearly heating and cooling energy [96]. In a hot climate, lowering the window-to-wall ratio by 20% can save 15% of the energy demand of a building [53]. Increasing the window-to-wall ratio by 5–25% compared to the optimal situation is the worst configuration in European climatic conditions [97]. The recommended window-to-wall ratio for southern and eastern facades is 65%, and 95% and 30% for

northern and western facades, respectively, in the Mediterranean climate [98], like the Australian climate zone 5.

Shading Device:

Shading devices protect against the infiltration of solar radiation into the building surface in the summer, while allowing the necessary solar heat gains in the winter to improve thermal performance [99]. Shading can be operable, such as external louvres, pergolas, curtains, blinds and deciduous trees, and fixed, like eaves, fences, and evergreen trees [100]. In the Australian context, horizontal shading above the glass is the solution for a north-facing facade that blocks high-angle sun in summer and allows low-angle sun in winter. On the other hand, vertical shading options are mostly operable and suitable for allowing the winter sun's radiation inside the building [101].

Airtightness:

Energy loss due to air leakage from building openings is a common phenomenon in old buildings and those with poorly installed openings. A heat loss reduction by almost 33% can be attributed to airtight windows [102].

Additional literature suggests that incorporating various building features and parameters can improve energy efficiency in buildings within Perth's climate, with the associated energy savings resulting from their implementation, as presented in Table 2.

Table 2. Building features for retrofitting and their energy saving or reduction for Perth's climatic conditions.

Features	Application	Energy Reduction/Savings	Reference
Insulation (Wall + Roof)	Wall R-value 2.8 and Ceiling R-value	40%	[103]
Window Glazing	Double Glazing	20–33%	[104]
Window-Wall-Ratio	Optimal Window-to-wall ratio (north-facing wall 20–40%, south-facing wall 10–20%, east-facing wall 10–25% and west facing wall 10–25%)	5–25%	[105,106]
Shading	Horizontal fixed with varying depths	5–15%	[107]
Airtightness	Sealed all air leakage	10–15%	[108,109]

3. Materials and Methods

This study was conducted in the suburb of Langford, within the City of Gosnells, Perth, Western Australia. The primary case studies were three NCC Class 1A single-dwelling stand-alone houses, representing Perth's most common housing type (79%) [110]. Yin (1994) [111] defines case study research as an empirical inquiry into a contemporary phenomenon within its real-life context, particularly when the boundaries between them are unclear. He emphasises that the method is the key characteristic of a case study and distinguishes between single- and multiple-case designs. A single-case design addresses the research questions through one case, while a multiple-case design examines two or more cases [111]. This study adopts a single-case design, investigating seven stand-alone houses. Similarly, Stake (1998) identifies three types of case studies: intrinsic, instrumental, and collective [112]. This research adopts an instrumental case study. Selected case study homes were built before 2003, before the introduction of energy standards in the Australian National Construction Code (NCC). While not statistically exhaustive, a sample size of three, which is representative, was chosen to allow for an in-depth and resource-feasible investigation. The selected cases provide a reasonable cross-section of typical pre-2003 homes, which dominate the city's suburban landscape and offer the most significant potential for retrofitting.

The research in this study consists of four parts. Firstly, an intensive literature review was conducted to identify key building features responsible for energy efficiency, mainly in Perth's climate conditions. Secondly, a physical survey of houses with the field survey datasheet (Appendix A) was conducted. During the survey, data were collected through direct observation, photographs, and by obtaining or drawing layout plans of the houses. Thirdly, energy simulations were run on FirstRate5 for each case study building to understand the energy use patterns in every zone of the houses using the data collected from the physical survey. The authors analysed the simulation to identify the optimum zone that plays a significant role in retrofitting. Lastly, another simulation was run for houses that applied for the most effective retrofitting building options, which were gathered from the literature review and applied to the most effective zones identified in the third phase. The data from these simulations were then compared across the case study buildings' star ratings and total energy consumption to determine the emission reduction by retrofitting old houses and their contribution to Australia's net-zero vision.

4. Results

4.1. An Overview of the Case Buildings

All case study buildings surveyed in this research are classified as NCC Class 1A stand-alone single-dwelling houses in the Langford suburb of the City of Gosnells, Perth. A total of three households were investigated. The occupants of Case Studies 1 and 3 are homeowners, whereas the occupants of Case Study 2 are tenants.

4.2. Current Heating and Cooling Energy Use of the Case Study Buildings

Several factors discussed previously influence the heating and cooling energy demand of a building. In this study, FirstRate5, an accredited NatHERS software tool, was employed to calculate the current energy consumption of the case study buildings. Various building-related data were required to perform the simulations, including house type, scaled floor plans, construction material specifications, building features, and location (Table 3). These data were collected during the physical surveys and subsequently input into FirstRate5. In addition to estimating energy use, FirstRate5 provides an Energy Star rating for each house on a scale from 0 to 10, where a lower rating indicates lower energy efficiency and a higher rating reflects greater efficiency.

Table 3. Different features of the case study buildings in Langford.

	Case Study 1	Case Study 2	Case Study 4
Built Year	1982	1970	1981
Land Area	352 m ²	692 m ²	712 m ²
Built Area	103 m ²	60 m ²	93 m ²
Construction Type	Double brick	Brick veneer	Double brick

4.3. Case Study 1

For Case Study 1, Figure 1 (Left) illustrates the architectural plan analysis of the current design features that influence energy efficiency and provides a corresponding photograph (Right).

Table 4 presents the key information required to conduct the energy simulation in FirstRate5 for Case Study 1 house under current conditions.

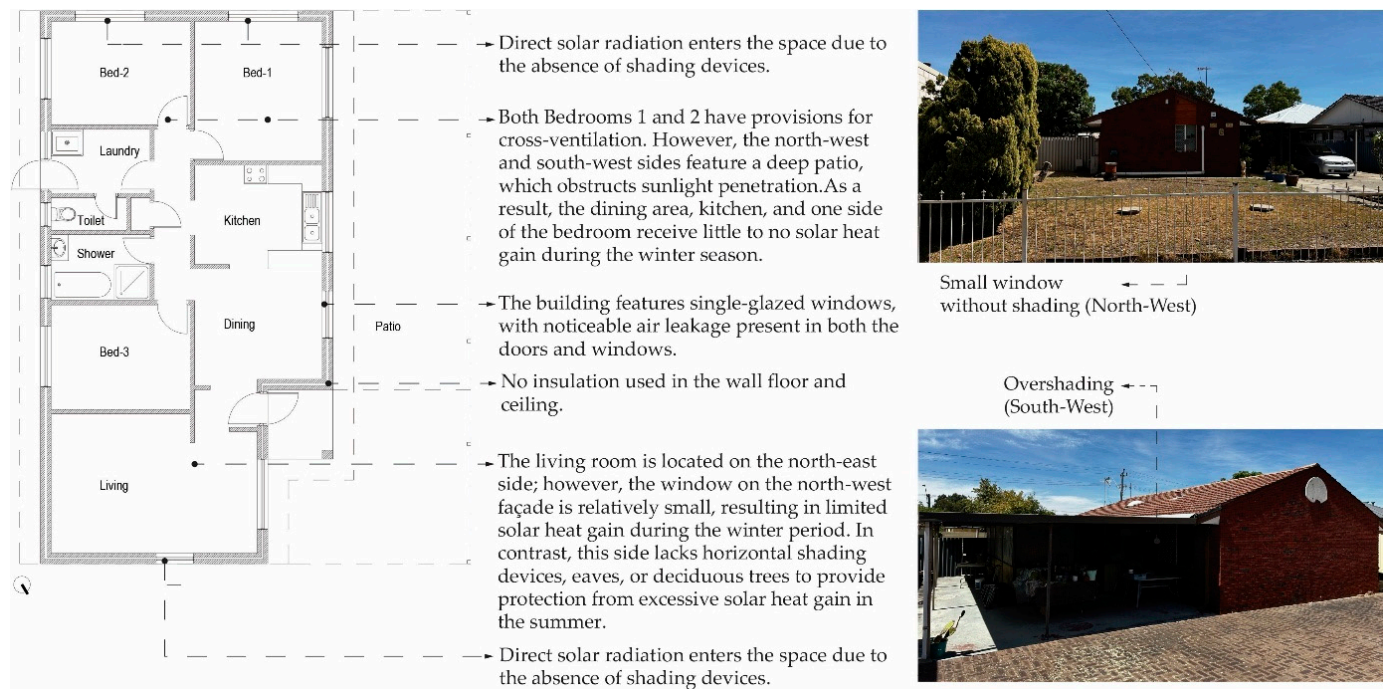


Figure 1. (Left) Plan analysis of Case Study 1 building. (Right) Photographs show Case Study 1 building's southwest small window without shading and overshading at the southwest facade.

Table 4. Building energy simulation input data for Case Study 1 under current conditions.

Features	Descriptions
Location and Orientation	Langford, Perth, Western Australia. North facing 125.2°.
External Wall	The double brick features 10 mm of cement plaster with a light crème colour finish internally, and face brick externally, without insulation. Total area = 97.7 m ² and R = 0.43.
Internal Wall	Single-brick wall with both sides 10 mm cement plaster with light crème colour finish. Total area = 85.4 m ² and R = 0.30.
Building Height	3 m.
Floor Slab	A concrete slab on the ground, without insulation, is finished with various coloured tiles and vinyl. Total area = 84.7 m ² and R = 0.07.
Roof and Ceiling	Pitch roof with a continuous attic, but without insulation. Dark black cement tiles are used for roofing, and 10 mm plasterboard is used for the ceiling, which is white in colour. Total ceiling area = 84.7 m ² .
Window Frame and Glazing	Aluminium-framed single-clear glazing sliding window with white curtains protecting from the inside; however, the bedroom and kitchen's northwest side windows are of a fixed type. Total area = 18.97 m ² and U = 6.70 and SG = 0.57.
window-wall ratio	South-east = 5.2 m ² , south-west = 4.3 m ² , north-west = 8.3 m ² and north-east = 1.1 m ²
Airtightness	The exterior doors and windows have air leakage.
Shading	Overshading on the northwest side.

The current energy rating of Case Study 1 is 3.3 stars (Figure 2a). The heating and cooling energy requirements of this house are 151.4 MJ/m² and 28.9 MJ/m², respectively, resulting in a total energy demand of 180.3 MJ/m² (Figure 2b). Notably, the demand for space heating is nearly five times greater than that for space cooling.

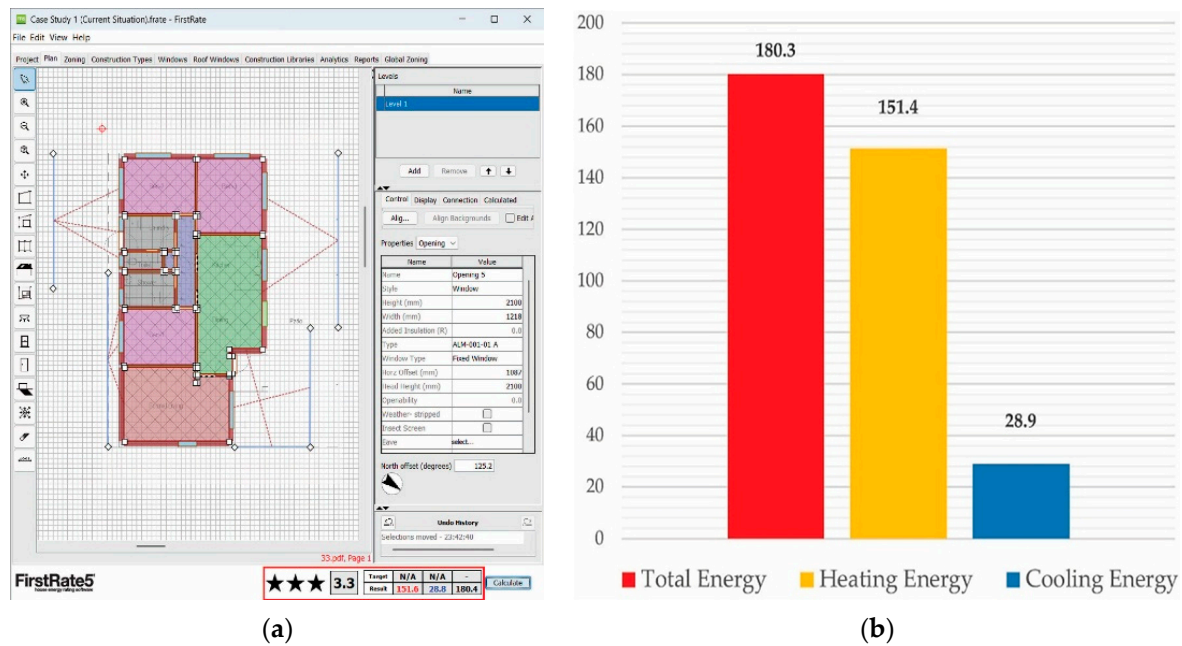


Figure 2. (a) Energy simulation in FirstRate5 using data from Table 4 for Case Study 1. (b) Energy usage of Case Study 1 (MJ/m²).

The living area exhibits the highest space-heating demand (Table 5) due to suboptimal window orientation and shading, with a small northwest-facing window and a larger southwest-facing window heavily shaded by a patio (Figure 1). This results in a relatively low cooling load. The combined living/kitchen area shows the second highest heating demand, remaining largely shaded despite two large windows. Bedroom 2 has the highest heating demand among the bedrooms, followed by Bedrooms 1 and 3. Bedrooms 1 and 2 feature two windows on the southwest and southeast facades without shading devices or extended eaves, and one external wall is permanently shaded by a patio, reducing overall thermal performance.

Table 5. Energy loads by zone in Case Study 1.

Zone	Heating (MJ/m²)	Total Heating (MJ)	Cooling (MJ/m²)	Total Cooling (MJ)
Bedroom 1	40.8	396.7	6.0	58.1
Bedroom 2	95.1	917.6	30.3	292.3
Bedroom 3	72.7	864.2	31.1	369.4
Living	334.1	6128.8	35	641.8
Dining/Kitchen	239.5	4879.6	69.5	1415.2
Service Area	851.7	357.2	1.0	0.4

4.3.1. Case Study 2

For Case Study 2, the architectural plan analysis of the design features impacting energy efficiency is depicted in Figure 3 (Left), and a corresponding photograph is presented in Figure 3 (Right).

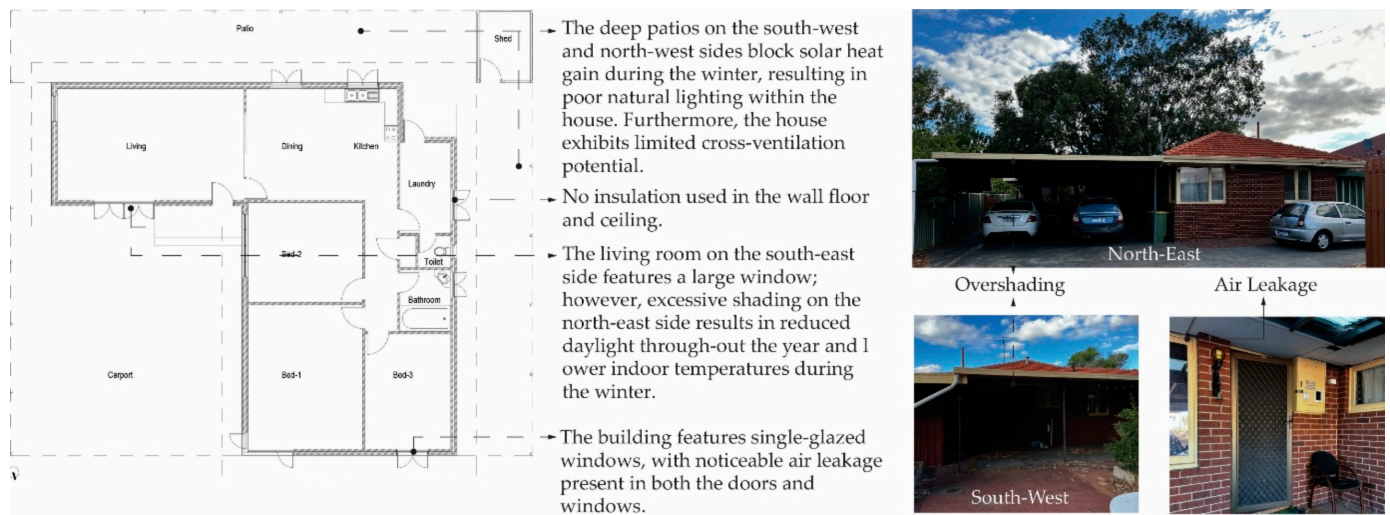


Figure 3. (Left) Plan analysis of Case Study 2 building. (Right) Photographs show Case Study 2 building's north-east and southwest overshadowing and window air leakage.

The information required for the FirstRate5 energy simulation of Case Study 2 house, based on its current conditions, is presented in Table 6.

Table 6. Building energy simulation input data for Case Study 2 under current conditions.

Features	Descriptions
Location and Orientation	Langford, Perth, Western Australia. North facing 145.0°.
External Wall	Brick veneer covers a 10 mm cement plaster with a light crème colour finish internally, and a combination of face brick and 10 mm cement plaster with a light crème colour is used externally, without insulation. Total area = 136.5 m ² and R = 0.40.
Internal Wall	Stud wall with both sides made of 10 mm plasterboard, featuring a light crème colour finish. Total area = 89.5 m ² and R = 0.28.
Building Height	3 m.
Floor Slab	A 125 mm concrete suspended slab without insulation is finished with various colour tiles and vinyl. Total area = 130.3 m ² and R = 0.09.
Roof and Ceiling	Pitch roof with a continuous attic, but without insulation. Dark black cement tiles are used for roofing, and 10 mm plasterboard is used for the ceiling, which is white in colour. Total ceiling area = 130.3 m ² .
Window Frame and Glazing	Wooden-framed single- clear glazing awning window with white curtains protected by inside. Total area = 16.74 m ² and U = 5.40 and SG = 0.56.
Window–Wall Ratio	South–east = 3.6 m ² , south–west = 3.3 m ² , north–west = 2.5 m ² and north–east = 7.3 m ²
Airtightness	The exterior doors and windows have air leakage.
Shading	Every side has overshadowing.

Case Study 2 currently has an energy rating of 2.3 stars (Figure 4a). The house's heating and cooling energy demands are 203.8 MJ/m² and 73.3 MJ/m², respectively, resulting in a total energy requirement of 277.1 MJ/m² (Figure 4b). Notably, the energy demand for space heating is nearly three times higher than that for space cooling. Furthermore, the distribution of energy loads across the main zones of the dwelling is presented in Table 7.

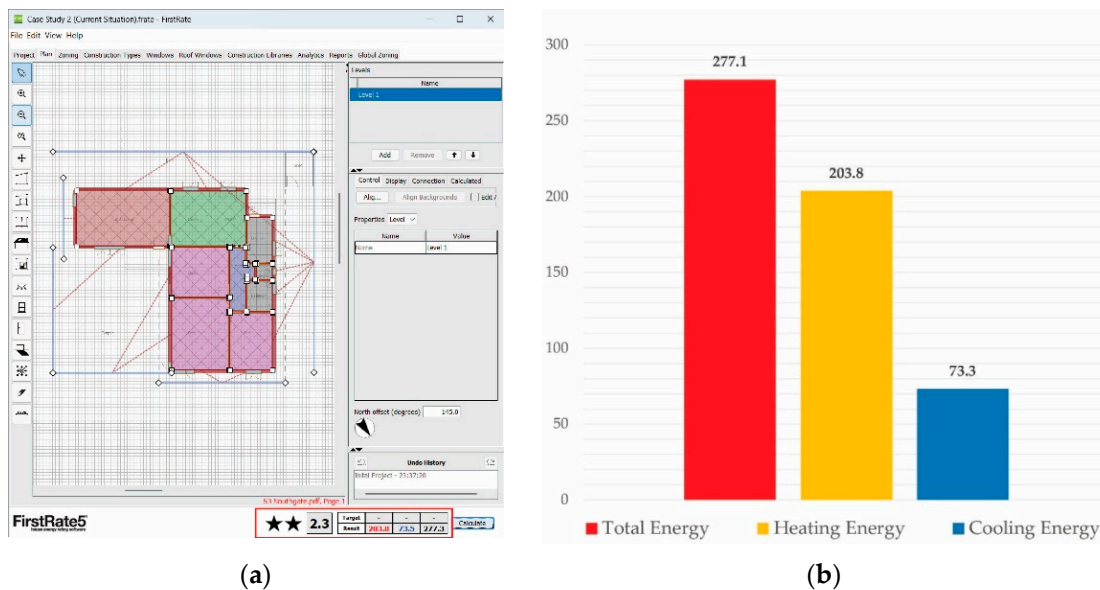


Figure 4. (a) Energy simulation in FirstRate5 using data from Table 6 for Case Study 2. (b) Energy usage of Case Study 2 (MJ/m²).

Table 7. Energy loads by zone in Case Study 2.

Zone	Heating (MJ/m ²)	Total Heating (MJ)	Cooling (MJ/m ²)	Total Cooling (MJ)
Bedroom 1	139.7	3385.4	32.8	795.6
Bedroom 2	113.5	1902.9	24.6	411.9
Bedroom 3	151.3	2199.8	38.5	559.2
Living	348.3	10,634.0	131.2	4006.7
Dining/Kitchen	290.5	7137.4	147.1	3615.4
Service Area	388.1	2610.7	92.0	618.6

The living area records the highest heating energy demand (Table 7) primarily because it is located on the southeast side (Figure 3), where a carport shades a large awning window, and the adjacent facade is further obstructed by a patio (Figure 3). The dining space exhibits the highest cooling demand and the second-highest heating demand, as it is southwest-oriented and partially shaded by a patio. The bedrooms are situated on the northeast and northwest sides; among them, Bedroom 3 shows the most significant combined heating and cooling demand due to a northwest-facing window and additional shading from the patio on the southwest side.

4.3.2. Case Study 3

The architectural plan analysis of design features influencing energy efficiency in Case Study 3 is illustrated in Figure 5(Left), with Figure 5(Right) presenting a photograph of the buildings.

The data required for the FirstRate5 energy simulation of the Case Study 3 house in its current state are shown in Table 8.

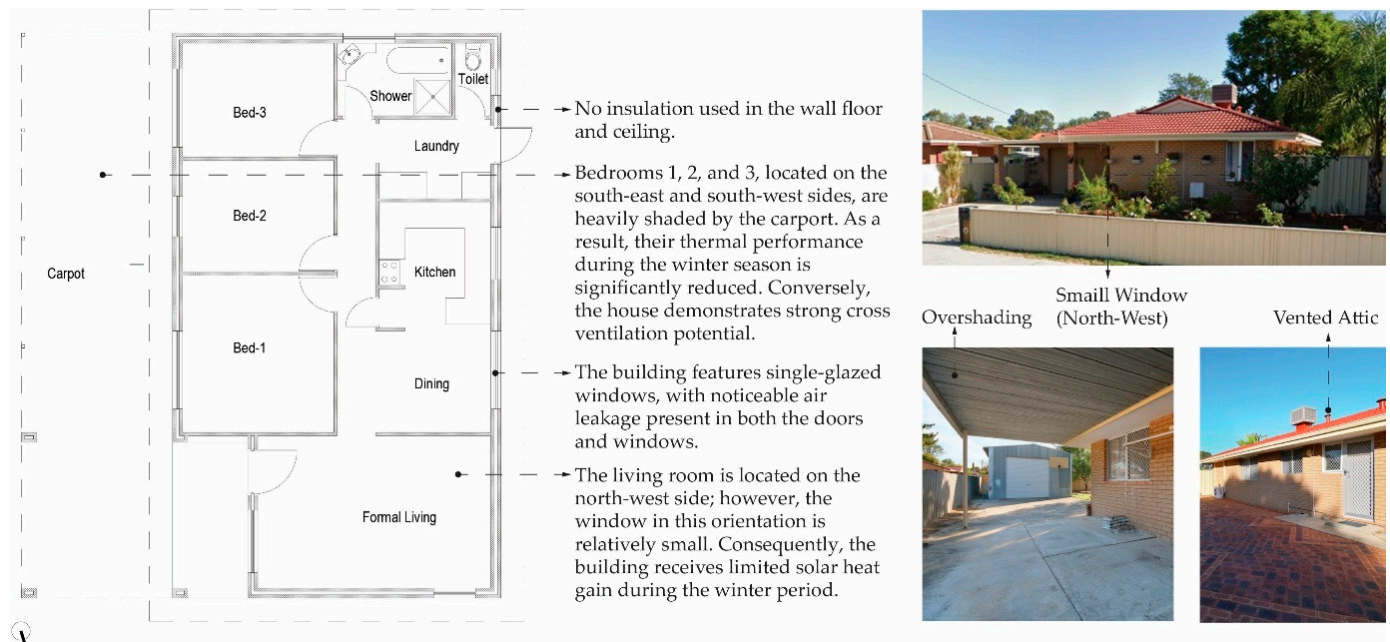


Figure 5. (Left) Plan analysis of Case Study 3 building. (Right) Photograph shows Case Study 3 building's southwest overshading, vented attic, and small window at northwest facade.

Table 8. Building energy simulation input data for Case Study 3 under current conditions.

Features	Descriptions
Location and Orientation	Langford, Perth, Western Australia. North facing 140.2°.
External Wall	The double brick features 10 mm of cement plaster with a light crème colour finish internally, and face brick externally, without insulation. Total area = 93.3 m ² and R = 0.43.
Internal Wall	Single brick wall with both sides 10 mm cement plaster with light crème colour finish. Total area = 82.9 m ² and R = 0.30.
Building Height	3 m.
Floor Slab	A concrete slab on the ground, without insulation, is finished with various coloured tiles and vinyl. Total area = 81.1 m ² and R = 0.07.
Roof and Ceiling	Pitch roof with vented continuous attic without insulation. Dark red cement tiles are used for roofing, and 10 mm plasterboard is used for the ceiling, which is white in colour. Total ceiling area = 81.1 m ² .
Window Frame and Glazing	Aluminium-framed single-clear glazing sliding window with white curtains protected by inside; however. Total area = 15.48 m ² and U = 6.70 and SG = 0.57.
Window–Wall Ratio	South–east = 8.4 m ² , south–west = 0.7 m ² , north–west = 5.1 m ² and north–east = 1.3 m ²
Airtightness	The exterior doors and windows have air leakage.
Shading	Overshading on the northeast side.

Figure 6a shows that Case Study 3 has a current energy rating of 3.3 stars. The house's heating and cooling energy demands are 148.9 MJ/m² and 28.9 MJ/m², respectively, resulting in a total energy requirement of 177.3 MJ/m² (Figure 6b). Notably, the demand for space heating is nearly six times higher than that for space cooling.

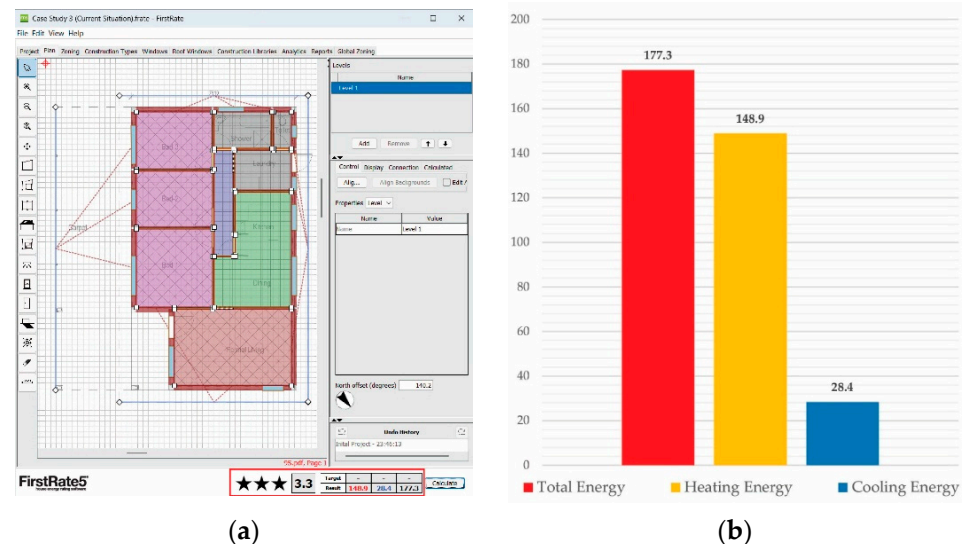


Figure 6. (a) Energy simulation in FirstRate5 using data from Table 8 for Case Study 3. (b) Energy usage of Case Study 3 (MJ/m²).

The distribution of energy loads across the main zones of the dwelling is presented in Table 9. The dining/kitchen area on the southwest side in Figure 5(Left) exhibits the highest overall energy demand. The living area has a higher heating requirement due to its northwest orientation and the presence of only a small window, which limits solar heat gain. In contrast, the southwest-facing dining/kitchen area features two large windows that allow substantial solar heat gain, resulting in the highest cooling demand among all dwelling zones. The three bedrooms are shaded by a carport in Figure 5(Right), effectively reducing their cooling energy requirements.

Table 9. Energy loads by zone in Case Study 3.

Zone	Heating (MJ/m ²)	Total Heating (MJ)	Cooling (MJ/m ²)	Total Cooling (MJ)
Bedroom 1	78.8	1001.5	5.4	68.8
Bedroom 2	79.2	717.2	4.0	36.5
Bedroom 3	123.0	1133.7	9.9	91.2
Living	348.0	6627.0	40.5	770.4
Dining/Kitchen	170.8	2744.2	102.8	1652.3
Service Area	391.9	1695.8	7.3	31.5

4.4. Overall Findings from Case Study Buildings

The findings from the case study buildings are presented in two parts: data directly collected through the physical survey and results obtained from energy simulations conducted using FirstRate5. The physical survey provided detailed information on building features that improve energy efficiency or increase demand. Additional data required to run the FirstRate5 simulations was also gathered during this survey.

One of the most significant findings concerns building orientation, which in many cases contradicts the climatic requirements of Perth. This issue primarily arises from designers' limited awareness during the design phase. Ideally, living rooms should face north to maximise winter solar heat gain and reduce heating demand. However, this design principle was not effectively implemented in any of the three case study buildings. Instead, all houses exhibited overshadowing issues, which increased heating demand and reduced daylight penetration. Consequently, occupants relied more on artificial lighting during the daytime, further elevating energy consumption. In many instances, these

overshading elements, such as patios, storage rooms, and carports, were added after the original construction of the houses.

All three case study buildings lacked wall and ceiling insulation, significantly contributing to higher energy demand. Among them, one house employed a brick veneer construction system. Its thermal performance was considerably poorer than the two double-brick houses because it lacked insulation between the external brick and the internal plasterboard. Furthermore, all three buildings exhibited air leakage problems, as no weather-stripping was installed on doors or windows.

Following the physical survey, energy simulations were conducted using FirstRate5 to evaluate the overall heating and cooling energy demand of the case study buildings and to determine their current star ratings (Figure 7).

Case Study 1	★★★★☆	3.3
Case Study 2	★★★☆☆	2.3
Case Study 3	★★★★☆	3.3

Figure 7. Current star rating of case study buildings from FirstRate5 simulation.

Detailed zone-level energy consumption data generated from the simulations were also analysed to identify the most energy-intensive spaces and to compare these findings with the existing literature. The results indicate that the living room consistently exhibits the highest energy demand, followed by the dining area in all three case study buildings (Figure 8). These insights are further applied to guide the selection of optimal retrofitting strategies aimed at improving the overall energy performance of each dwelling.

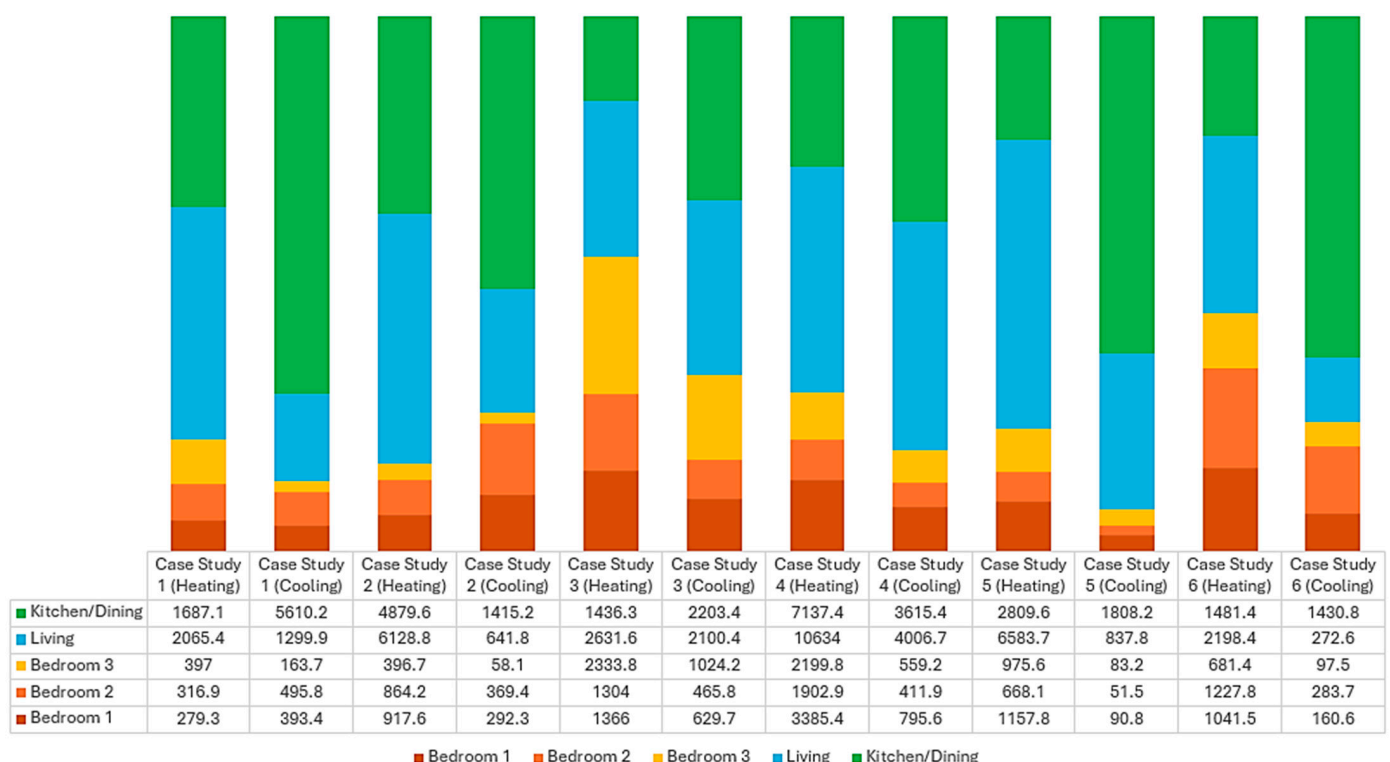


Figure 8. Energy usage by different zones in case study houses (MJ).

4.5. Proposed Optimum Retrofitting Options for Case Study Buildings

Deep or whole-house retrofitting is more beneficial for energy efficiency, while shallow retrofitting offers a more affordable option. Additionally, the main barriers to deep retrofitting are the time required and the disturbance it causes to occupants. Every state in

Australia faces a housing crisis [113], and relocating to another house or taking a long time to complete whole-house retrofitting is often tricky. For these reasons, selecting optimal retrofitting options that require minimal time and do not necessitate relocating occupants during the retrofit work is essential. Modular precast retrofitting options are more suitable for completing the retrofitting work quickly. For instance, a modular low-carbon precast concrete sandwich panel (Figure 9) for the external wall, which could improve the overall thermal quality and energy efficiency of the building's external wall, is a viable option for external wall retrofitting with lower emissions. Retrofitting aims to reduce energy demand, supporting Australia's commitment to achieving net-zero emissions by 2050. The selection of optimal retrofitting options is informed by the literature review, which applied the case study building to compare the overall improvement of energy efficiency of those buildings.

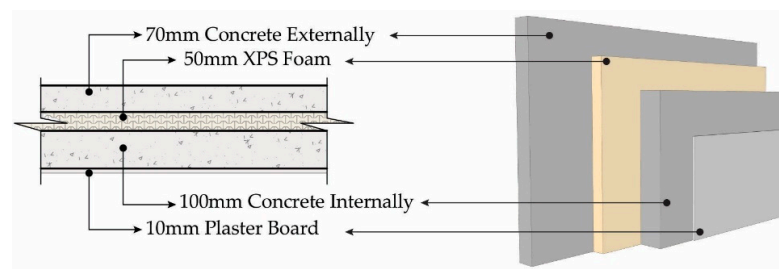


Figure 9. Modular low-carbon precast concrete sandwich panel [114].

Formula for R-value:

$$R = d/k$$

where

R = thermal resistance ($\text{m}^2\text{K}/\text{W}$).

d = thickness of the material (m).

k = thermal conductivity of the material (W/mK).

For Multiple Layers

If you have several materials (e.g., wall layers), the total R-value is the sum of each layer's R-value:

$$R_{\text{total}} = R1 + R2 + R3 + \dots$$

For Pre Low-Carbon Sandwich Panel $R = 2.42$ [114]

$$\text{Thermal Transmittance } U = 1/R$$

$$= 1/2.42$$

$$= 0.41$$

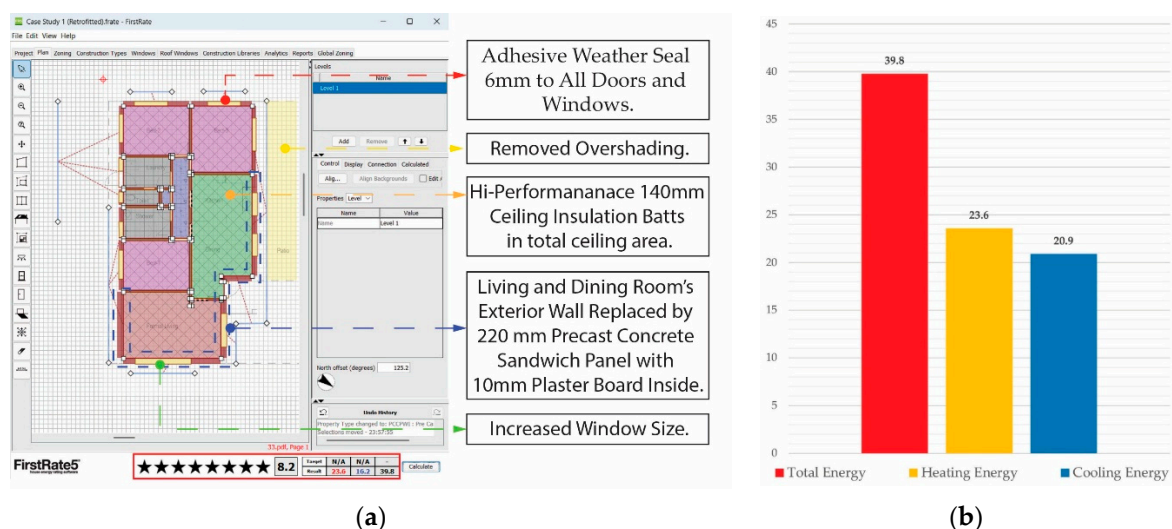
4.5.1. Case Study 1

In Case Study 1, the living and dining areas account for the majority of the energy demand. To enhance performance, a prefabricated modular concrete sandwich panel is proposed for the exterior wall of the living room. Furthermore, the entire house was sealed to minimise air leakage, all windows were replaced with double glazing, and the ceiling was insulated with high-performance insulation batts. Table 10 provides detailed information on the modifications incorporated into the FirstRate5 energy simulation for Case Study 1.

Table 10. Building energy simulation input data for Case Study 1 after retrofitting.

Features	Proposed Retrofitting	Descriptions
Location and Orientation	N/A	Langford, Perth, Western Australia. North facing 125.2°.
External Wall	Yes	At the northeast and northwest sides of the living room, the external wall transitions to a low-carbon concrete sandwich panel (external concrete panel: 70 mm, middle XPS (Extruded Polystyrene Foam) foam: 40 mm, internal concrete panel: 100 mm) with a 10 mm plasterboard finish internally. Total area = 46.3 m ² , R = 2.42, and U = 0.41.
Internal Wall	No	R = 0.30
Building Height	No	3 m.
Floor Slab	No	R = 0.07
Roof and Ceiling	Yes	Total ceiling area (84.7 m ²) insulated with 140 mm high-performance ceiling insulation batts R5.
Window Frame and Glazing	Yes	Aluminium-framed double- clear glazing air-filled sliding window. Total area = 21.21 m ² and U = 4.8 and SG = 0.51.
Window–Wall Ratio	Yes	2.6 m ² window area increased in the north–east orientation, and the current total area is 3.7 m ² .
Airtightness	Yes	The exterior doors and windows are air-leakage sealed.
Shading	Yes	Removed overshading from the northwest side. In addition, a 0.60 m horizontal shading device was added in the same orientation.

After the retrofit modifications, the Case Study 1 house achieved an 8.2-star rating (Figure 10a), with a total energy consumption of 39.8 MJ/m² (Figure 10b). In addition, heating and cooling energy demand decreased by approximately one-sixth and one-third, respectively, compared to the current condition.

**Figure 10.** (a) Energy simulation after retrofitting in FirstRate5 using data from Table 10 for Case Study 1. (b) Energy usage after retrofitting in FirstRate5 of Case Study 1 (MJ/m²).

After retrofitting, the views of the Case Study 1 house are presented in Figure 11 along with details of the low-carbon concrete panel. In addition, the proposed on-site energy production from a solar system is also illustrated.

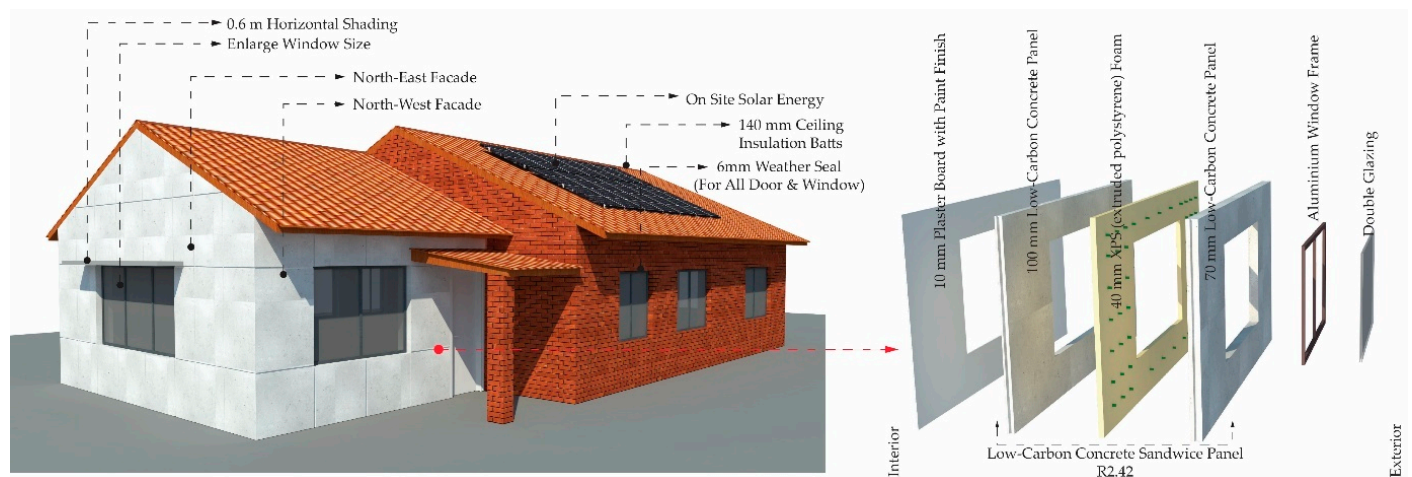


Figure 11. The views show Case Study 1 after retrofitting and prefabricated plugin installation details.

4.5.2. Case Study 2

In Case Study 2, the living, dining, and kitchen areas account for most of the energy demand, similar to Case Study 1. To enhance performance, the external walls of these areas were replaced with low-carbon prefabricated modular concrete sandwich panels. Additionally, all windows were upgraded to double glazing, the ceiling was insulated, and all doors and windows were weather-sealed. Table 11 provides detailed information on the modifications incorporated into the FirstRate5 energy.

Table 11. Building energy simulation input data for Case Study 2 after retrofitting.

Features	Proposed Retrofitting	Descriptions
Location and Orientation	N/A	Langford, Perth, Western Australia. North facing 145.0°.
External Wall	Yes	The external walls of the living, dining, and kitchen areas have been changed to a low-carbon concrete sandwich panel (external concrete panel: 70 mm, middle XPS (Extruded Polystyrene Foam) foam: 50 mm, internal concrete panel: 100 mm) with a 10 mm plasterboard finish internally. Total area = 63.4 m ² , R = 2.42, and U = 0.41.
Internal Wall	No	R = 0.28
Building Height	No	3 m.
Floor Slab	No	R = 0.09
Roof and Ceiling	Yes	Total ceiling area (10.3 m ²) insulated with 140 mm high-performance ceiling insulation batts R5.
Window Frame and Glazing	Yes	Aluminium-framed double clear glazing awning window. Total area = 18.68 m ² and U = 4.8 and SG = 0.51.
Window–Wall Ratio	Yes	The window area in the north–east orientation has increased to 1.9 m ² , and the current total area is 9.2 m ² .
Airtightness	Yes	The exterior doors and windows are air-leakage sealed.
Shading	Yes	Removed all the overshadowing.

The retrofit improved the star rating of Case Study 2 from 2.3 to 8.1 stars (Figure 12a). The total energy demand decreased by approximately one-seventh, with heating and cooling energy demands of 42.1 MJ/m² and 35.1 MJ/m², respectively (Figure 12b).

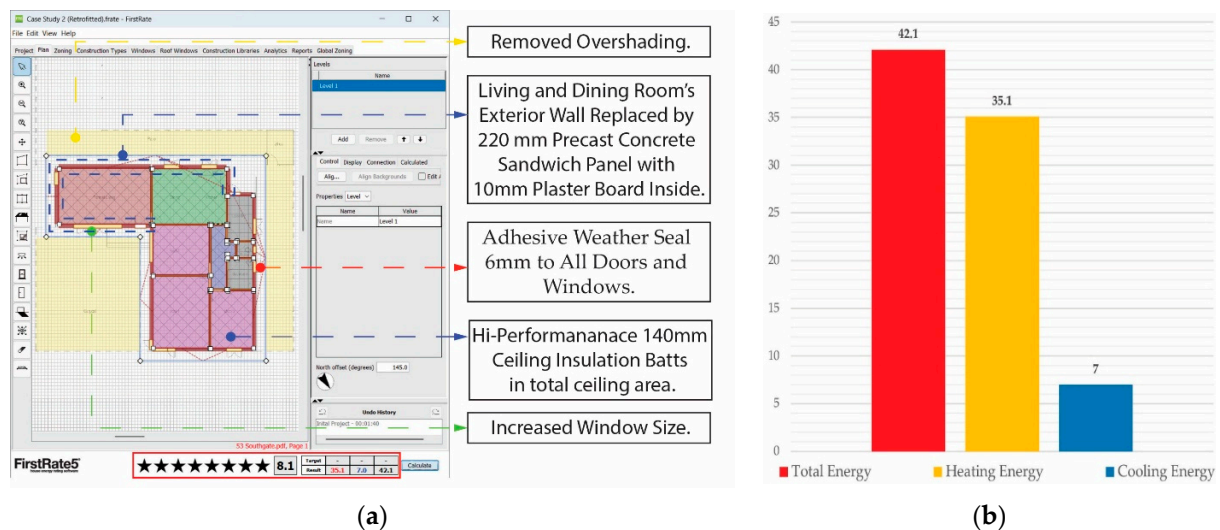


Figure 12. (a) Energy simulation after retrofitting in FirstRate5 using data from Table 11 for Case Study 2. (b) Energy usage after retrofitting in FirstRate5 of Case Study 2 (MJ/m^2).

Figure 13 presents the post-retrofit views of the Case Study 2 house, highlighting the low-carbon concrete panel. It also illustrates the proposed on-site solar energy generation system.



Figure 13. The views show Case Study 2 after retrofitting and prefabricated plugin installation details.

4.5.3. Case Study 3

In Case Study 3, the living, dining, and kitchen areas represent the highest energy demand, consistent with Case Studies 1 and 2 observations. To improve building performance, the external walls of these spaces were upgraded with low-carbon prefabricated modular concrete sandwich panels. In addition, all windows were replaced with double glazing, the ceiling was insulated, and all doors and windows were weather-sealed. Table 12 provides a detailed summary of the modifications implemented in the FirstRate5 energy simulation for Case Study 3.

Table 12. Building energy simulation input data for Case Study 3 after retrofitting.

Features	Proposed Retrofitting	Descriptions
Location and Orientation	N/A	Langford, Perth, Western Australia. North facing 140.2°.
External Wall	Yes	The living, dining, and kitchen external wall is changed to a low-carbon low-concrete sandwich panel (external concrete panel 100 mm, middle XPS (Extruded Polystyrene Foam) foam 40 mm, internal concrete panel 70 mm) with 10 mm plaster board finish internally. Total area = 34.2 m ² , R = 2.42, and U = 0.41.
Internal Wall	No	R = 0.30.
Building Height	No	3 m.
Floor Slab	No	R = 0.07.
Roof and Ceiling	Yes	Total ceiling area (130.3 m ²) insulated with 140 mm high-performance ceiling insulation batts R5.
Window Frame and Glazing	Yes	Aluminium-framed double clear glazing air-filled sliding window. Total area = 18.59 m ² and U = 4.8 and SG = 0.51.
Window–Wall Ratio	Yes	3.1 m ² window area increased in the north–east orientation, and the current total area is 4.4 m ² .
Airtightness	Yes	The exterior doors and windows are air-leakage sealed.
Shading	Yes	Removed overshadowing from the northeast side.

Following the retrofit, the star rating of Case Study 3 rose from 3.3 to 7.7 (Figure 14a). At the same time, total energy demand declined by roughly one-third, with heating and cooling energy consumption of 37.4 MJ/m² and 20.9 MJ/m², respectively, as shown in Figure 14.

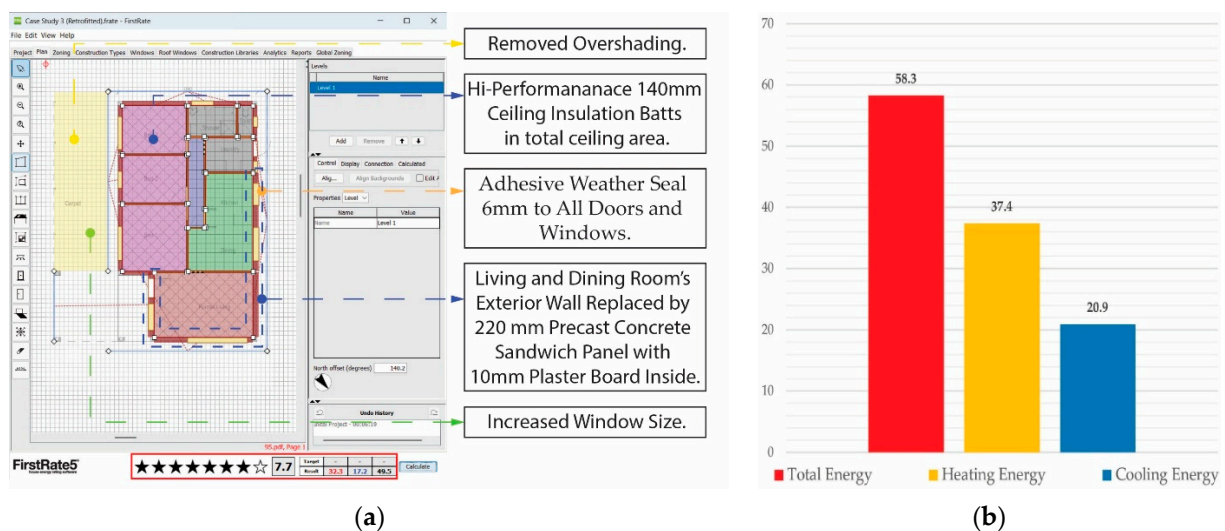
**Figure 14.** (a) Energy simulation after retrofitting in FirstRate5 using data from Table 12 for Case Study 3. (b) Energy usage after retrofitting in FirstRate5 of Case Study 3 (MJ/m²).

Figure 15 shows the Case Study 2 house after retrofitting, featuring the low-carbon concrete panel and the proposed on-site solar energy generation system.

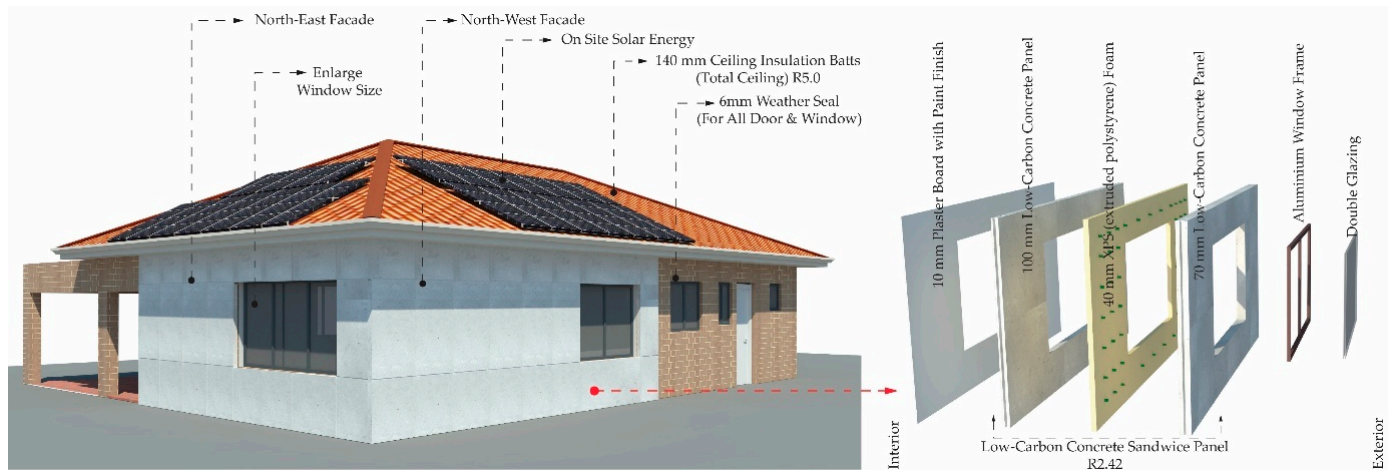


Figure 15. The views show Case Study 2 after retrofitting and prefabricated plugin installation details.

4.6. Comparative Analysis: Before and After Retrofitting of Case Study Buildings

The primary objective of retrofitting is to reduce a building's energy demand. Figure 13 presents the energy consumption of the case study buildings before and after retrofitting. The total energy demand of case study houses 1–3 was initially 180.3 MJ/m², 277.1 MJ/m², and 177.3 MJ/m², respectively, and decreased to 39.8 MJ/m², 42.1 MJ/m², and 58.3 MJ/m² following retrofitting (Figure 13). Consequently, the energy performance ratings of these buildings improved due to the reduction in energy demand. All three case study buildings initially had ratings below 3.5 stars, which increased to over 7.5 stars after retrofitting (Figures 16 and 17).

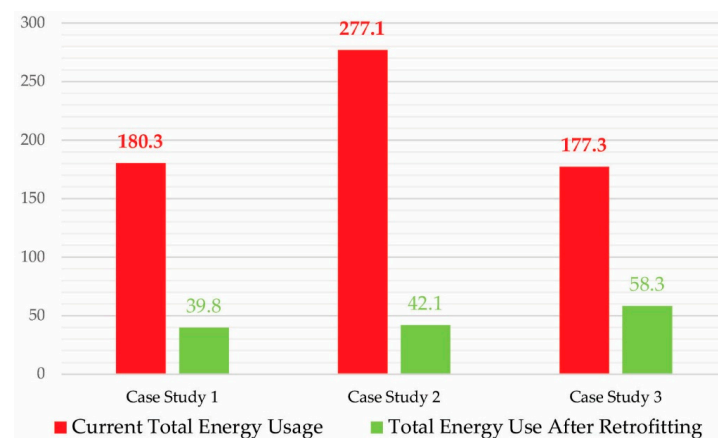


Figure 16. Energy use of case study houses (MJ/m²) (current situation and after optimal retrofitting).

Case Study 1	Current Star Rating	★★★★☆	3.3
	Star Rating After Retrofitting	★★★★★★★★★	8.1
Case Study 2	Current Star Rating	★★★☆☆	2.3
	Star Rating After Retrofitting	★★★★★★★★★	8.1
Case Study 3	Current Star Rating	★★★★☆	3.3
	Star Rating After Retrofitting	★★★★★★★★★	7.7

Figure 17. Star rating of case study houses (current situation and after optimal retrofitting).

5. Discussion

From the literature review, energy savings achieved through the implementation of energy-efficient building features for retrofitting in Perth's climatic conditions can be roughly estimated by summing the lower-bound values of the features listed in Table 2,

resulting in a total energy savings of approximately 80% (40% + 20% + 5% + 5% + 10%). In this study, case studies 1–3 achieved reductions in energy consumption of 77.9%, 84.8%, and 67.1%, respectively, with an average decrease of 76.6%, closely aligning with the findings reported in the literature. In Australia, 70% of stand-alone houses were constructed before 2003 [11], i.e., before implementing energy-efficiency requirements in the National Construction Code (NCC). Based on this proportion, people built 538,326 stand-alone households in Western Australia and 4,697,407 stand-alone households nationwide before 2003 [10]. The Australian Government has recently set a 2035 target of reducing emissions by 62–70% below 2005 levels, focusing on retrofitting existing housing to enhance energy efficiency and expand on-site renewable energy generation as part of its Scope 2 emission reduction strategy [115]. If the Government takes initiatives for retrofitting those houses within the next five years by 2030, it will contribute to a 3.16% reduction in its national target by 2035, equivalent to 12.73 Mt CO₂-e. At the same time, it will contribute to a 9.2% reduction in emissions in the built environment sector (Appendix B for detailed calculation). This amount will contribute to the national target of 40.3 Mt CO₂-e abatement from existing houses by 2050 [116].

Western Australia's Sectoral Emissions Reduction Strategy (SERS) outlines that the building sector should achieve near-zero emissions by 2050, prioritising improvements in efficiency, electrification, greater use of distributed solar and storage, and more substantial upgrades as reliance on gas decreases and to comply with the Paris Agreement, the target for the building sector is a 41% reduction in emissions by 2030 and 70% by 2040 compared to 2005 levels [117]. In Western Australia, this retrofitting reduces 1.3 Mt CO₂-e carbon emissions yearly (Appendix B for detailed calculation), which will help the state achieve its emissions reduction targets for 2030 and 2040. Additionally, the provision of solar energy for stand-alone houses built before 2003 reduces carbon emissions by 4.6 Mt CO₂-e per year by using 5 kW (25 m²) solar panel to their roof top [18].

6. Conclusions

This study contextualises the key building features significantly improving energy efficiency in Australia's Climate Zone 5, specifically in Perth, Western Australia. In Perth's climate, the most effective retrofitting measures include improving the insulation of the building envelope, optimising the window-to-wall ratio with upgraded glazing, achieving airtightness, implementing appropriate shading, and removing overshadowing. Additional features relevant to Perth's residential buildings include orienting the longitudinal axis of the house north–south, providing a north-facing living room with large windows; prefabricated plugin solutions are promising due to their time-efficiency and the ability to avoid occupant relocation.

The research also highlights that pre-retrofitting assessments are essential for identifying optimal interventions, which can deliver more effective outcomes than whole-house retrofitting. FirstRate5 simulations evaluated current energy demand and the reductions achievable through retrofitting. The results indicated that lowering energy demand translates into reduced energy bills and decreased emissions from the residential sector. Although FirstRate5 has certain limitations, the simulation outcomes are broadly consistent with findings reported in the literature. Retrofitting measures can improve the energy rating of case houses from below 2.3–3.3 stars to above 7.7–8.2 stars. These interventions could contribute approximately 3.16% of the carbon emission reductions required to meet Australia's national target by 2035, equivalent to 12.73 Mt CO₂-e/year. In Western Australia, such retrofitting would reduce emissions by approximately 1.3 Mt of CO₂-e annually.

Furthermore, integrating 5 kW solar energy systems (25 m²) of the targeted stand-alone houses could provide an additional reduction of 4.5 Mt CO₂-e/year, contributing further

to the national net zero target by 2050. The main limitation of this study is the exclusion of occupants' perspectives on retrofitting, along with the methodological constraints of FirstRate5, which relies on standardised assumptions and may not fully capture real-world conditions. Future research should consider occupants' perspectives, use complementary modelling to capture real-world situations, and validate outcomes through longitudinal and post-occupancy studies.

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Conflicts of Interest: The authors declare no conflicts of interest.

Appendix A

PART 1: Building information.

1. Size of the land

Ans:

2. Built area of the land

Ans:

3. Front façade orientation of the house?

North	☐	South	☐
Northeast	☐	Southwest	☐
East	☐	West	☐
Southeast	☐	Northwest	☐

4. Type of construction of the house?

Steel frame (low thermal mass)	☐	Timber frame (low thermal mass)	☐
Cavity Wall (medium thermal mass)	☐	Solid wall (high thermal mass)	☐
Modern method of construction	☐	Other ☐ specify	

5. Type of floor construction of the house?

Concrete slab on ground	☐	Timber	☐
Waffle Pod	☐	Unclassified ☐ specify	

6. Type of floor insulation (floor covering) of the house?

Carpet	☐	Tiles	☐
Timber	☐	Vinyl	☐
Mixed	☐	None	☐
Unclassified	☐	specify	

7. Type of external wall construction of the house?

Brick Veneer	☐	Clad ACC	☐
Clad insulated panel system	☐	Clad Metal	☐
Clad timber	☐	Clad weather board	☐
Clad others ☐ specify		Concrete Block	☐
Concrete Panel	☐	Concrete Other ☐ specify	
Rammed earth	☐	Insulated concrete framework	☐
Masonry cavity	☐	Masonry single brick	☐
Masonry other ☐ specify		Party wall	☐
Retaining wall	☐	Reverse brick veneer	☐
Structural insulated panel system	☐	Unclassified ☐ specify	

8. Type of roof cladding of the house?

Concrete	☐	Tiles	☐
Metal		Mixed	☐
Unclassified	☐	specify	

9. Roof colour of the house?

Light	☐	Medium	☐
Dark	☐		

10. Number of Rooms in this house.

Bedroom	☐	Living room	☐
Toilet	☐	Dining	☐
Bathroom	☐	Kitchen	☐
Laundry room	☐	Study room	☐

11. Electric appliances list:

Types	Bed 1	Bed 2	Bed 3	Living 1	Living 2	Dining	Bathroom 1	Bathroom 2	Study Room	Kitchen	Laundry room	Storeroom	Outdoor
Halogen Light													
CFL Light													
LED Light													
Ceiling fan													
Stand fan													
Exhaust fan													
Split Type AC													
Window Type AC													
Ducted Air Conditioning													
Portable Room Heater													
Dish Washer													
Electric burner													
Gas burner													
Washing machine													
Microwave													

12. Major building materials

Location	Name	Thickness
Interior wall		
Floor slab		
Roof		
Window glass		
Window glass frame		
External Doors		
Internal doors		

13. Insulation materials.

Location	Name	Thickness
Interior wall insulation		
Floor insulation		
Ceiling insulation		
Weather stripping of windows		
External doors weather stripping		
Internal doors weather stripping		

14. Is there any water-efficient fixture used in this house?

Yes ☐ No ☐

15. Cooking system used in this house.

Gas stove ☐ Induction cooker ☐
Electric stove ☐

16. Which Passive solar design features are used in the house?

Orientation ☐ Eaves ☐ Shading Device ☐
Sky light ☐ Window ☐ Not Used ☐
Other ☐ Specify

END OF SURVEY

Thanks for your participation. If you have any queries or other comments, please email Chief Investigator, Prof. Dr. Peter Newman, via email: p.newman@curtin.edu.au, to learn more about the research.

The project partner can be contacted at 21073313@student.curtin.edu.au / taqirarch@gmail.com or via mobile at +610449228431.

Appendix B

ELECTRICITY CONSUMPTION AND CARBON EMISSION CALCULATION

Current Condition (Case Study Houses): From Simulation

Average Household Size (Case Study) = 94 m²

Average Electricity Consumption (Case Study house) = 211.57 MJ/m²

Total Electricity Consumption Case Study House = 211.57 × 94 = 19,887.58 MJ = 5524.68 kWh

After Retrofitting: From Simulation

Average Household Size (Case Study) = 94 m²

Average Electricity Consumption (Case Study house) = 46.73 MJ/m²

Total Electricity Consumption Case Study House = 46.73 × 94 = 4392.62 MJ = 1220.28 kWh

Energy Savings Per House = (5524.68 – 1220.28) kWh = 4304.4 kWh

(Electricity Savings by Retrofitting = 76.6% from simulation, which is close to the literature review Table 2)

Western Australia Scenario:

Australia's carbon emission factor for electricity = 0.56 kg CO₂-e/kWh [118]

Number of stand-alone houses in WA = 769,038 nos [10]

(70% Household Built Before 2003 [11]) Stand-alone House Built Before 2003 in Western Australia = 769,038 × 70% = 538,326 nos

Total emissions avoided/reduction for Western Australia = 4304.3 kWh × 0.56 = 2410.41 = 2.4 t CO₂-e/household = 2.4 × 538,326 nos = 1.3 Mt CO₂-e

Australia Scenario:

Australia's carbon emission factor for electricity = 0.63 kg CO₂-e/kWh [118]

Number of stand-alone houses in Australia = 6710,582 nos [10]

(70% Household Built Before 2003) Stand-alone House Built Before 2003 in Australia = 6,710,582 × 70% = 4,697,407 nos.

Total emissions avoided/reduction for Western Australia = 4304.3 kWh × 0.63 = 2711.71 kg CO₂-e = 2.71 t CO₂-e/household = 2.71 × 4,697,407 nos = 12,729,974.97 t CO₂-e = 12.73 Mt CO₂-e

Emission Target For Australia:

Total net carbon emissions in 2005 = 610.6 Mt CO₂-e [119,120]

Total net carbon emissions target by 2035 = 62–70% [115] = 402.97 Mt CO₂-e from 2005 base level (66% average).

Emission Reduction Achieved by Retrofitting:

Retrofitting contributes to achieving the emission target for Australia by 2035 = (12.73/402.97 × 100) % = 3.16%

Reduction contributes to the built environment sector by 2035 = 402.97 × 0.34 (34% emission caused by the built environment [115]) = (137 Mt CO₂-e = 12.73/137 × 100) = 9.2%

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