Team UOW solar decathlon house: refurbishment demonstration

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Keywords
demonstration, team, refurbishment, house, decathlon, solar, uow

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Team UOW Solar Decathlon House: Refurbishment Demonstration

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Abstract
This paper describes a practical demonstration of how to refurbish a typical Australian timber framed fibro house to become a net-zero energy, Solar Decathlon (SD) home. The Team UOW Illawarra Flame House was entered in the SD China 2013 competition and was eventually the overall winner of the competition. The house refurbishment method was illustrated initially through architectural changes to the design of the nominal original house in order to improve functionality, daylighting and natural ventilation. Energy simulations for the original house and the house with the architectural refurbishment were then carried out to determine the thermal envelope retrofit targets and investigate the thermal performance enhancement of the house due to its envelope upgrade. An innovative air-conditioning system, which included solar photovoltaic-thermal collectors and a phase change material thermal storage unit, was developed and employed to maintain indoor thermal comfort conditions. The results from both experiments and simulations showed that the thermal and energy performance of the house was significantly improved through the effective implementation of the suite of retrofits. The house demonstrated the potential for existing Australian housing stock to achieve net-zero energy consumption while meeting high indoor thermal comfort standards.

Keywords: refurbishment; net-zero energy; Solar Decathlon; architectural retrofit; envelope upgrading; air-conditioning.

1. Introduction

It has been reported that 23% of Australia's total greenhouse gas emissions are a result of the energy demand in the building sector, 13% arising from residential buildings [1]. Improvement in the energy efficiency of the residential sector is, therefore, essential to achieve a timely reduction in national energy use and progress towards a sustainable built environment.

Many studies have demonstrated that the energy consumption of existing residential buildings can be significantly reduced through proper refurbishment and upgrading [2-15]. Cohen et al. [3] reported that 12% to 21% of normalized annual energy savings in ten single family building retrofit projects were achieved through installation of additional ceiling and wall insulation. Verbeeck and Hens [4] claimed that 50% primary energy savings of small terraced houses in Belgium can be easily achieved through improvement of insulation levels. The study by Silva et al. [5] showed that the total energy usage of a single-family building and a multi-family building can be reduced by 83% and 76%, respectively, through the implementation of an integrated retrofit strategy, a prefabricated retrofit module, and on-site renewable energy sources. Based on a bottom-up modeling technique, Mata et al. [6] reported that final energy demand and CO2 emissions from the Swedish residential sector could be reduced by 53% and 63% respectively, through the effective use of twelve energy conservation measures. Although the benefits due to building refurbishment are significant and promising, the decision as to which retrofit measures should be used in a particular project is very complex as there are many factors influencing the decision-making process and building subsystems are highly interactive. The selection of retrofit measures is a trade-off between the capital investment and the benefits that can be achieved [7]. Zavadskas et al. [8] pointed out that optimal retrofit measures for apartment buildings should be selected after consideration of strategic urban development programs, house conditions and their surrounding environment, retrofit cost, energy savings and the expected increment of market values. Gustafsson and Bojic [9] suggested that the selection of the retrofit strategies for building heating systems should consider: uncertainty in future energy prices, building and installation features, and climate conditions.
In order to facilitate the selection and determination of the best retrofit measures for existing buildings, significant efforts have been made in the development of appropriate decision support systems and retrofit methodologies. For instance, Ouyang et al. [10] presented a methodology on how to develop an energy efficient retrofit plan in the early design phase of a building retrofit project, in which energy savings, CO₂ emission reductions and cost reductions were used as the performance indices. Asadi et al. [11] developed a framework to optimize the retrofit cost, energy savings and thermal comfort of a residential building. Dall’O’ et al. [12] described a novel method to evaluate the potential energy savings for retrofitting residential buildings by taking into account the technological and economic constraints of the retrofit implementation. A retrofit-oriented building energy simulator (ROBESim) based on EnergyPlus was introduced by Chuah et al. [13]. ROBESim includes built-in functions for retrofit modules. Booth and Choudhary [14] described a framework for dealing with the uncertainties related to the estimation of energy savings in the retrofit analysis. A review of the development of decision support systems for building refurbishment was provided by Ferreira et al. [15]. These decision support systems and retrofit methodologies are useful to assist in comparing the performance of different retrofit measures and thus, help to determine the best retrofit measures and reduce the risks and uncertainties related to building retrofits. However, each project is unique and there are many constraints influencing the decision making, thus the determination of the best retrofit options is still complex even with the assistance of the decision support system.

The optimization of retrofits of existing residential buildings to generate low energy or net-zero energy buildings is becoming a focus of scientific research. This paper describes the practical demonstration of how to refurbish a typical Australian timber framed fibro house so as to transform it into a net-zero energy, Solar Decathlon house, which participated in the Solar Decathlon (SD) China 2013 competition (See Figure 1).

Figure 1: Solar Decathlon China 2013 competition. The Team UOW Solar Decathlon house is shown in the red rectangle.

2. Description of the ‘original’ house

The design of the original, pre-retrofitted, house was taken to be that of a typical Australian timber framed fibro house. Timber framed ‘fibro’ houses (with fibre-cement cladding) were built in great numbers after the Second World War and can still be found in a large numbers across Australia. Due to the house design philosophy and engineering issues, most timber framed fibro houses constructed during that time did not have a good insulation and had notoriously poor airtightness and low thermal and energy performance.

Figure 2 shows the floor plan and the outlook of the timber framed fibro house taken to be the base-case, or pre-retrofit, house in this study. It should be noted that the practical project did not actually take an original ‘fibro’ home and retrofit it (due to Occupational Health and Safety concerns and logistical difficulties) but rather the Illawarra Flame house was built from scratch in such a way as to demonstrate how such an existing house could be refurbished.
The pre-retrofitted house was assumed to have three bedrooms with a floor area of 84 m². The roof was assumed to have been constructed with terracotta roof tiles and plasterboard ceilings, and the walls clad with plasterboard inside and the fibro-cement outside with a 90 mm air cavity in between. The floor was assumed to be a suspended timber floor. The windows used were single-glazed without any dedicated shading devices. The original house was also assumed to be a passive home, i.e. there was no air-conditioning system present. In order to participate in the SD competition, a ‘pre-retrofitted’ house which mimics the original house design was designed to allow the house to be transported to the competition site and re-assembled in a short time frame.

3. Retrofit design considerations

There are always many factors that influence decision making in the course of a housing retrofit. The key objectives, including decreased energy consumption, enhanced thermal comfort, increased functionality, and improved occupant well-being, were targeted during the retrofit design stage of this project. Figure 3 illustrates the retrofit design procedures used in this project.
The house retrofits started with site visits and survey to understand the house performance and the problems related to the house operation. A number of key thermal and energy related problems were identified at this stage, including lack of insulation, lack of shading, poor airtightness, the use of single glass windows, poor cross ventilation, lack of day-lighting, poor thermal comfort and low energy performance. Based on the results of the initial investigation, the architectural retrofit was first designed to satisfy the retrofitted house functionality requirements, including an increase in the use of day-lighting and natural ventilation. The retrofit targets for the house envelope retrofit were then determined based on energy performance simulations, and appropriate insulation and envelope retrofit technologies were then selected to meet these targets with the assistance of cost-benefit analyses. In order to be competitive in respect of other teams in the SD competition, an innovative air-conditioning system was designed to maintain acceptable indoor thermal comfort conditions.

Based on the architectural retrofit and the house envelope retrofit, the energy consumption of the house can be estimated and the PV panels can then be sized in order to achieve net-zero energy consumption of the house. When the retrofit design is completed, the next step was the house construction, system implementation, and commissioning. The last step was the site test and evaluation. Details on the above key retrofit designs and associated performance analysis are presented in Section 4.

4. Retrofit design and performance analysis

4.1 Architectural retrofit design

Due to the often limited nature of building retrofits in Australia, there is generally not a great deal of scope to implement retrofits to the house external shape. Improving the functionality and facilitating day-lighting and natural ventilation are then the key design considerations in architectural retrofits. In order to increase the house functionality the original ‘fibro’ house floor plan was remodelled by converting the third bedroom into a new dining room through removing the walls between the living room and the third bedroom. In this way, the kitchen area was extended and made part of an open-plan space with the dining room and living room.
The second major design modification was the use of two prefabricated pods/modules, which could in principle, be efficiently manufactured off-site and installed on-site so that the retrofitting cost and labour cost can be reduced. One of the pods replaced the laundry and bathroom of the original house, and incorporated many building services systems including the HVAC system, power generation and metering equipment, hot water tank and a small-scale building management system. The second pod provided a wardrobe for the main bedroom and a sofa-bed area for the study/guest room, which significantly increased the functionality and ease use of the house. Another major retrofit of the original house from the architectural aspect was to remove the ceiling above the living room and introduce a clerestory to facilitate daylighting and buoyancy-driven natural ventilation. Together with large bi-fold windows and doors introduced at the front and back of the living-kitchen area, cross ventilation and natural lighting in this area was improved significantly. The open plan living area also enhanced the connection between the interior environment and exterior environment. Figure 4 illustrates the remodelled floor plan after the architectural retrofit design.

![Figure 4: Remodeled floor plan through the architectural retrofit.](image)

### 4.2 Building envelope retrofit

Properly retrofitting a building envelope plays an important role in improving thermal performance and reducing the energy demand of buildings. The choice of retrofit performance target will influence the selection of retrofit measures since different retrofit options provide different benefits with different capital investments. In this project, four building envelope performance parameters, i.e. thermal resistance (R-value), windows U-value, solar heat gain coefficient (SHGC) and infiltration rate, were used to determine the thermal envelope retrofit targets. The targeted values were determined through energy simulations for the house from the architectural retrofits and the point found where improving the envelope performance did result in further significant increases in overall building performance. Table 1 summarizes the thermal performance properties of the original 'fibro' house and the retrofit targets of the post-retrofitted house.

<table>
<thead>
<tr>
<th>Envelope performance properties</th>
<th>Original house</th>
<th>Post-retrofitted house</th>
</tr>
</thead>
<tbody>
<tr>
<td>Envelope thermal resistance R value (m²K/W)</td>
<td>0.5</td>
<td>6.0</td>
</tr>
<tr>
<td>Windows/doors U value (W/m²K)</td>
<td>5.0</td>
<td>1.5</td>
</tr>
<tr>
<td>Windows/doors SHGC</td>
<td>0.8</td>
<td>0.3</td>
</tr>
<tr>
<td>Infiltration rate (ACH)</td>
<td>2</td>
<td>0.2</td>
</tr>
</tbody>
</table>

*Table 1 Summary of the pre- and post-retrofitted envelope thermal performance properties.*
Based on the house envelope retrofit targets determined, the thermal performance of the house before and after the refurbishment without using the air-conditioning system could be evaluated. Figure 5 shows the indoor air temperature of the living room and main bedroom before and after the refurbishment. In this simulation, natural ventilation at 10 air changes per hour (ACH) was assumed to be activated when the indoor air temperature is above the natural ventilation set-point (22°C for the bedrooms and 20°C for the living and dining rooms) providing this temperature is greater than the outdoor air temperature. It was found that variations in the indoor air temperature of the living room and main bedroom after the refurbishment were smaller than that before the refurbishment, and therefore better indoor thermal comfort in the house.

Based on the retrofit targets determined, appropriate insulation materials and products that were cost-effective and could meet the retrofit targets were then selected. In this project, rock wool was chosen for cavity filling to reduce the heat loss of the house envelope due to its low embodied energy and recyclable characteristics. Rigid polyisocyanurate (PIR) board was selected for additional insulation layers and air barriers owing to its low thermal conductivity. Double-glazed, argon-filled windows with a low-E coating were used to replace the original windows. All windows were fitted with blinds in order to adjust the level of incoming light and minimize heat loss and gain from/to the house. In order to achieve net-zero energy and be competitive with other teams in the energy balance sub-contest of the SD competition, a total of 9.4 kWp of solar PV was installed.

![Figure 5: Simulation results for the indoor air temperature of the living room and main bedroom before and after the refurbishment.](image)

4.3 Development of an innovative air-conditioning system

Fibro homes in south eastern Australia would generally not have been fitted originally with mechanical heating or cooling systems to maintain the acceptable indoor thermal conditions. In order to provide the required thermal energy to satisfy the indoor comfort requirements and successfully compete in the thermal comfort sub-contest of the Solar Decathlon China competition, an innovative air-conditioning system was developed, as shown in Figure 6. The HVAC system consisted of three key components: a photovoltaic thermal (PVT) air collector system; a phase change material (PCM) thermal storage unit; and an air handling unit coupled to a conventional reverse-cycle air-to-air heat pump.
This system was designed to operate in four different modes: i) PCM charging with PVT, ii) PVT system direct supply, iii) supply air preconditioned through the PCM storage unit and iv) conventional air-conditioning. If the supply of warm (or cool) air from the PVT system and the heating (or cooling) demand of the house occur at the same time, the warm (or cool) air from the PVT system could be directly supplied to the house for space heating (or cooling). Otherwise, the warm (or cool) air was discharged to the ambient or directed into the PCM thermal storage unit. In the supply air preconditioned mode, the system could operate in two different ways: i) outdoor air first mixed with the return air and was then heated (or cooled) by the PCM storage unit and supplied to the house; ii) outdoor air was first pre-heated (or pre-cooled) by the PCM storage unit and then mixed with the return air and supplied to the air-handling unit for further processing. If there was no PVT thermal generation available and no significant energy stored in the PCM storage unit, the conventional air-handling mode was used. A hybrid model-based predictive controller was also developed to control the operation of this air-conditioning system, as described in [16]. Figure 7 shows some experimental results from February 2015, by way of example. The test started with the average indoor temperature of the house outside the comfort band. It can be seen that the controller could appropriately control the operation of the air-conditioning system and could maintain the indoor temperature within the thermal comfort band.
4.4 In-situ performance testing during the SD China competition

Figure 8 illustrates the outlook of the house after the refurbishment and re-built in Datong, the competition site of the SD China 2013 competition. The house competed with the other 18 teams from over 30 universities. Over 35,000 people visited the house during the competition period from 2nd August to 10th August 2013.

Figure 8: Views of the Team UOW 'Illawarra Flame House' retrofit demonstration.

Figure 9 shows the measured room temperature and relative humidity in the house during the ‘scored periods’ during the 10-day SD China competition. As thermal comfort was one of the sub-contests in the SD competition, it was required that the time-averaged interior dry-bulb temperature be maintained between 22°C and 25°C and the relative humidity below 60.0%. Otherwise, point penalties were imposed. It was found that the house was capable of keeping the indoor temperature and relative humidity within the thermal comfort range required during the majority of the scored periods (though the large deadband in the heat pump heating mode was problematic). The student team earned 97.9 out of 100 thermal comfort points and was placed fourth in the thermal comfort competition. It is worthwhile to note that the room temperature and relative humidity during the house public opening hours in the SD China competition are not presented in Figure 9 as there very many people touring through the house (35,000 in ten days, i.e. one every 8 seconds) and it was difficult to maintain room temperature and relative humidity within the required thermal comfort ranges.

Energy balance was another sub-contest in the Solar Decathlon China competition. Figure 10 shows the cumulative electricity generation, consumption and net production of the house during the competition period. It can be seen that the house PV systems generated significantly more electricity than was consumed. The total electricity generation and consumption during the competition period were 243.1 kWh and 116.9 kWh, respectively, with a net production of 126.2 kWh.
5. Conclusions

This paper has described a practical demonstration of how to retrofit both the building envelope and heating/cooling systems of a typical Australian timber framed ‘fibro’ house, to result in a net-zero energy home with excellent architectural aesthetics and livability, and which performed to a very high standard in terms of energy consumption. The experimental results showed that the thermal and energy performance of a lightweight timber framed fibro house can be significantly improved through the implementation of retrofit strategies to improve air tightness, replace windows and install additional insulation in the building envelope. Architectural retrofits are also essential to improve the house functionality and facilitate day-lighting and natural ventilation, to further reduce the energy demand of the house. The results from this retrofit project demonstrate that it is technically feasible to retrofit and transform Australian timber framed fibro houses into energy efficient and sustainable homes.

6. References

[1] CIE, "Capitalising on the building sector’s potential to lessen the costs of a broad based GHG emissions cut", Centre for International Economics (CIE), Canberra & Sydney, Australia, September 2007.


