5x4: A Case Study in Low Energy Infill Housing

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Abstract: *5x4 is a small infill housing project located in inner-suburban Melbourne, Australia. The main aim of the project is to create a low energy building that minimises the long-term environmental impacts of its occupants using passive and active eco-driven processes, materials and performance considerations. This paper describes the process of assessing and optimising the project's energy performance. This included a quantification of predicted operational energy demand as well as its embodied energy over a 100 year period.*

A range of potential construction materials were analysed and appropriate solutions selected. Embodied energy was calculated using a comprehensive hybrid approach, whilst IES-VE software was used to model the operational energy demands. Transport energy demands were significantly reduced compared to a project located in an outer-suburban development. The project also relies on existing infrastructure minimising the embodied energy demand associated with the construction of new infrastructure, typical of greenfield developments.

Keywords: low energy; infill housing; Australia; life cycle energy analysis

Introduction

The 5x4 project is a new infill housing development under construction in the city of Melbourne, Australia. The project uses a number of innovative systems, materials and construction techniques as well as an optimised building envelope, air tight construction and phase change materials to minimise life cycle energy demand as much as possible.

In order to determine whether design solutions will result in a reduction in energy demand, the energy performance of a building project must be assessed. To ensure a net reduction in life cycle energy demand is achieved the traditionally limited focus on improving building operational energy efficiency must be considered in the context of a building's life cycle energy demand, thus ensuring demands aren't inadvertently shifted from one life cycle stage to another. This is particularly crucial in operationally efficient buildings like 5x4 as the indirect, or embodied, energy requirement is proportionately more significant.

The aim of this study is to demonstrate the extent to which household energy demands can be reduced through appropriate siting, design and material selection. Comprehensive assessment techniques are used to quantify the life cycle energy demand of the 5x4 project which is then compared to the performance of an identical house located in an outer-suburban area.

Background

The world's population is increasing at a rapid rate with most people now living in cities [1]. With this comes the need for new housing. In countries such as Australia, where land is in abundance, the response is often one of low-density urban sprawl. However, many cities are struggling to cope, finding it increasingly difficult to fund the infrastructure needed to support these new developments. They are also increasingly competing with prime agricultural land.

There is a growing understanding of the need to move away from low-density urban sprawl as a solution to the world's housing crisis [2,3]. This helps to retain land for agricultural and recreational purposes and aims to maximise the use of existing infrastructure (essential services, roads, schools, shops, hospitals etc.). A preferred housing model is one where new housing is built within established city and inner-suburban areas as well as surrounding outer-suburban activity centres [4]. This infill or higher density housing suits an increasing number of people (professionals, couples and small families), who prefer reduced commuting times to study and work, close proximity to community activities and low maintenance properties.

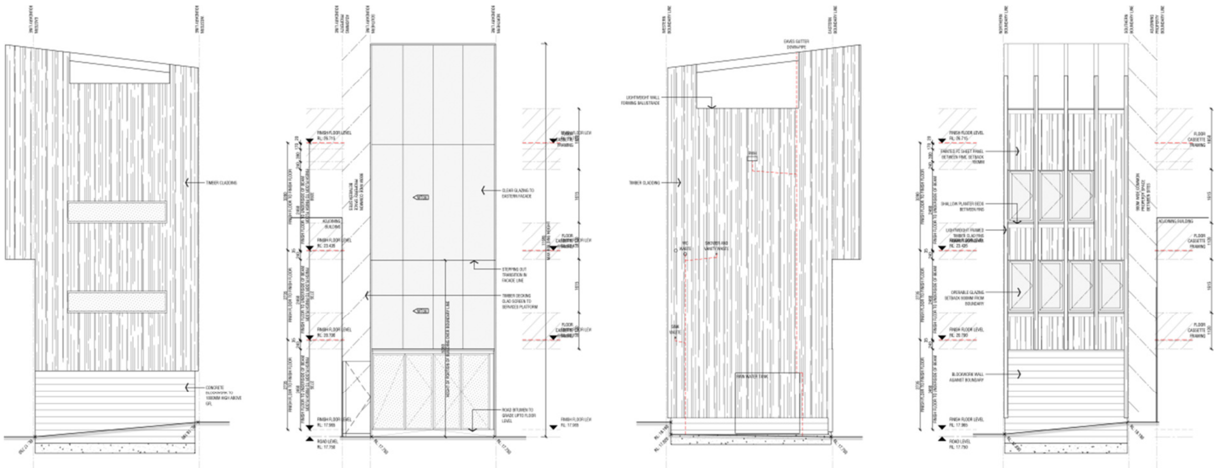
Another aspect that is becoming of increasing importance for future housing is the minimisation of its effect on the environment, especially in terms of the energy used during its production and operation. So important is this that the IPCC identify buildings as being a *critical* component of a low-carbon future [5].

The idea of Zero Energy Housing (ZEH) has been growing over the past decade. ZEH strives to reduce the need for non-renewable energy resources during the operation phase by, firstly, using a variety of approaches to minimise the energy required for heating, cooling, lighting and appliances, such as thermal insulation, thermal mass, appropriate orientation and planning and the use of efficient appliances, and secondly, meeting any remaining energy demands with the use of renewable energy systems (such as wind or solar power).

However, many existing examples of ZEH, such as the Australian Zero Emission House in Melbourne and the Beddington Zero Energy Development in London, do not attempt to offset the energy associated with material manufacture and the construction process, better known as a building's embodied energy. It is no longer acceptable to address only operational energy requirements, as was once commonly the case. It is now more widely understood that a life cycle perspective needs to be used as embodied energy demands across a building's life cycle can often be more significant than operational energy [6,7] and reductions in operational energy can sometimes shift the demand for energy to other stages in the building life cycle.

Description of the 5x4 project

The 5x4 project is currently in the construction phase. When complete, it will occupy a five metre by four metre site at the end of a narrow laneway within a built-up residential area less than three kilometres from the Melbourne CBD (Lat. 37°49´S, Long. 144°58´E), in the suburb of East Melbourne. The project spans across three floors and a total of 87 m^2 and provides an example of how small areas within existing cities can be used to deal with a growing population and provide housing that is supported by existing infrastructure.



North East South West

Figure 1 Elevations of the 5x4 Project, Courtesy: Craig Chatman, Architect

Life cycle energy assessment and optimisation
This section outlines the approach taken to assess and optimise the life cycle energy demand associated with the 5x4 project. A range of construction assemblies were selected based on optimised thermal performance and a selection of standard and low impact materials. Eleven different floor assembly variations and 52 different wall assembly variations were considered. The energy associated with the initial construction, operation, maintenance and refurbishment of the assemblies over a period of 100 years was assessed.

Embodied energy
Optimisation of embodied energy for the 5x4 project was an iterative process. The aim was to select construction assemblies for the building that resulted in minimal life cycle embodied energy requirements (initial and recurrent). A list of floor and wall assemblies was compiled based on currently available materials as well as the design team's knowledge of the types of assemblies that would offer the best opportunities for minimising operational energy demand.

The initial and recurrent embodied energy of each assembly was then assessed, assuming a building life of 100 years. The results of this assessment were analysed by the project team, highlighting reasons for high embodied energy results as well as identifying materials with the highest and lowest life cycle embodied energy demand in order to further refine assembly selection and inform the development of the project's design. Once those assemblies with a comparatively high life cycle embodied energy demand were excluded, the final selection of assemblies was made. This selection was based on a range of environmental and non-environmental factors (i.e. thermal performance, material availability, cost, project suitability etc.). Hence, it is not necessarily the assembly with the lowest life cycle embodied energy that was chosen, but a balance was struck between a number of key factors.

The embodied energy of the assemblies was calculated based on the energy required to manufacture the individual construction materials. For this, a comprehensive hybrid embodied energy assessment approach was used. This approach uses national average statistics that model the financial flows between sectors of the economy, referred to as input–output (I–O) data, to fill the gaps in traditional process-based approaches caused by system boundary incompleteness [inter alia 8,9,10].

Process data were sourced from the SimaPro Australasian database for materials [11], giving quantities of energy required to manufacture a unit of material. The I–O data used was based on Australian I–O tables [12] and national energy accounts for Australia [13]. This data was combined to form hybrid material embodied energy coefficients.

Material quantities were determined for a 1 m^2 area of each assembly. The individual material quantities were multiplied by their respective embodied energy coefficient and summed to determine the initial embodied energy of each assembly. Recurrent embodied energy, accounting for the energy associated with manufacturing replacement materials over the 100-year estimated life of the project, was then determined. Average materials service life figures from a range of previous studies were used to estimate the embodied energy associated with the replacement of materials over the project's life. The estimated service life for some of the main materials used are provided in Crawford [14].

The recurrent embodied energy of each material was calculated based on its embodied energy coefficient and the quantity requiring replacement. The energy embodied in each material was then multiplied by the number of replacements for that material over the life of the project, and summed to determine the total recurrent embodied energy associated with the assembly. The exact number of replacements required for each material was determined by dividing the service life of the house (100 years), by the average service life of the material, subtracting 1 (representing the material used in initial construction at year zero) and rounding up to the nearest whole number (to reflect the fact that materials cannot be replaced in part).

It is acknowledged that the embodied energy coefficients associated with the replacement materials used over the life of the project will change over time due to factors such as improvements to manufacturing processes. However, for the purpose of this study it was assumed that the embodied energy coefficients would remain constant.

Operational energy

The predicted operational energy demand of the 5x4 project was determined utilising IES-VE software and average climatic data for Melbourne. A complete thermal dynamic model was developed that simulated the operational profile and performance of all the systems in the building. It accounted for the materials used in all the assemblies and the context in which the building is set. Numerous studies were completed to optimise the thermal properties of the building envelope, extent of opening windows and inclusion of phase change material to reduce the annual operational energy consumption.

An energy recovery ventilation system has been incorporated into the building for the periods in the year when the climate necessitates the building to be sealed (approximately 60% of the year). Whilst this consumes energy, the energy recovery in the air streams enables the house to be very well ventilated and maintain comfort conditions without heating or cooling. This results in significant energy savings compared to the current practice of air-conditioning.

Additional energy savings

In addition to the potential embodied and operational energy savings possible through the optimised design of the project, there are additional energy-related benefits associated with the project due to its location in an existing well-serviced area. An estimate of the energy savings due to a reduced reliance on private transport and new infrastructure has been made based on the approach developed by Stephan [15] and compared to the most common form of new housing in Melbourne – low density outer-suburban.

Results and Discussion

This section presents and discusses the results of the life cycle energy assessment and optimisation process for the 5x4 project. It also highlights some of the key findings that may help to inform the design of similar buildings in the future.

Embodied energy

The embodied energy of all 63 different assemblies considered is shown in Figure 2 and 4.

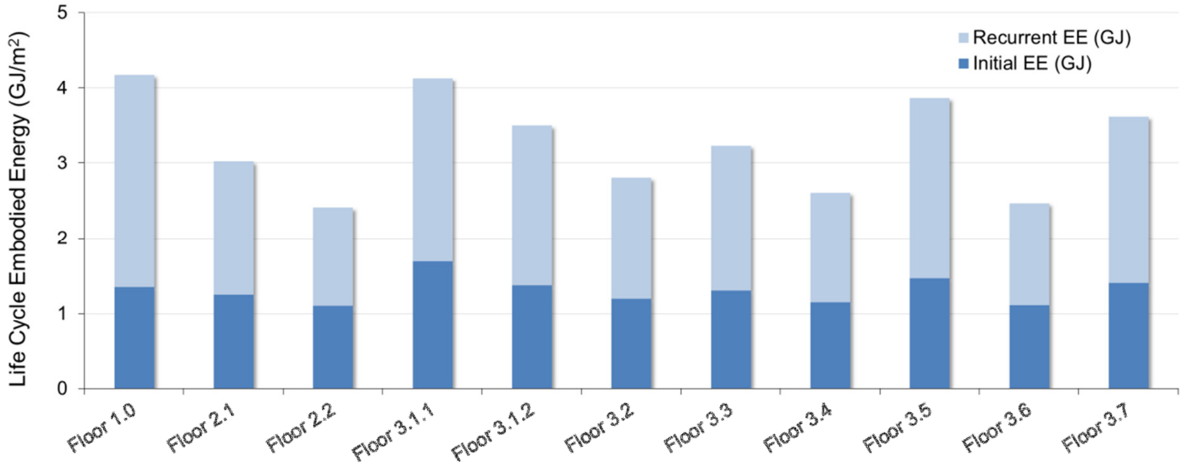


Figure 2 Initial and recurrent embodied energy of 11 floor assemblies

The assemblies with the lowest initial embodied energy tended to also be those with the lowest life cycle embodied energy. The floor assemblies found to have the highest life cycle embodied energy demand were those that used either frequently replaced items, such as carpet, or a more energy-intensive sound insulation material. Conversely, the assemblies with the lowest life cycle embodied energy demand (2.2, 3.4 and 3.6) were those that used less energy-intensive materials, required fewer replacements and included materials with a high recycled content. A breakdown by material for Floor Type 2.2 is shown in Figure 3.

The wall assemblies with highest life cycle embodied energy demand (Wall 4.0 – 6.8.3) are those consisting of double and triple glazing. Wall type 6 is a double-glazed spandrel panel with variations to internal lining and insulation types. For these assemblies, glazing represents at least 70% of their life cycle embodied energy demand. Avoiding the use of glazing in spandrel panels, where there are less energy-intensive alternatives for the equivalent function, can significantly reduce a building's embodied energy.

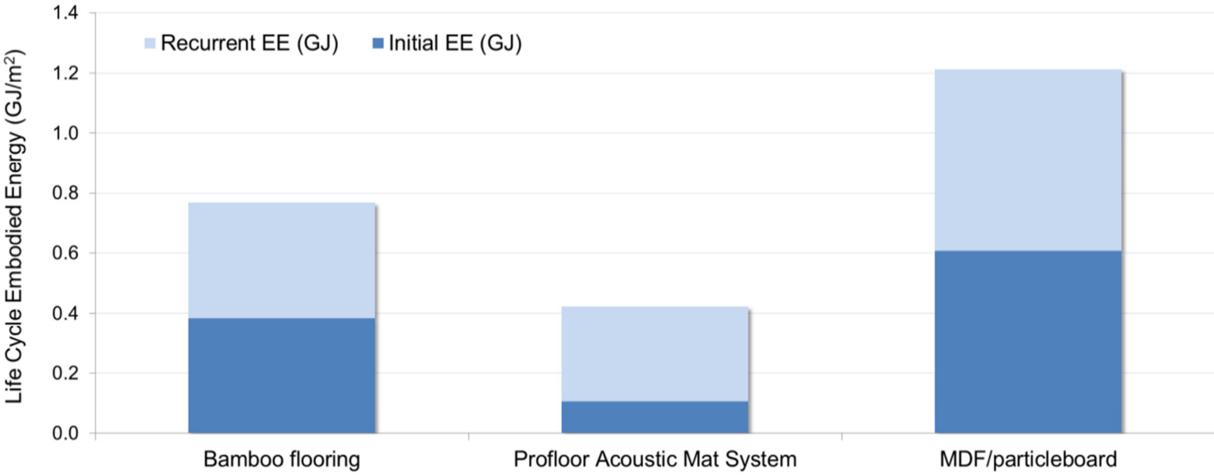


Figure 3 Initial and recurrent embodied energy of Floor Type 2.2, by material

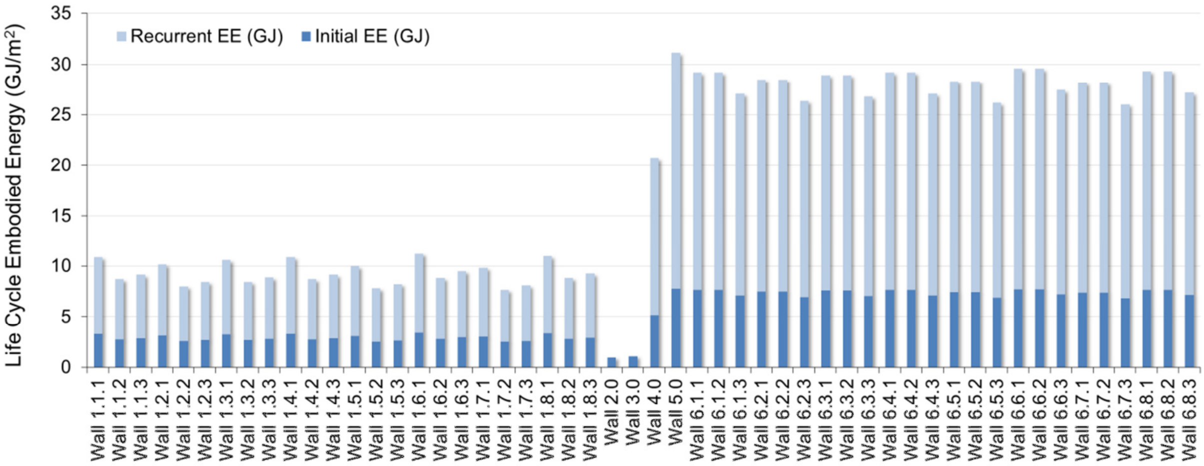


Figure 4 Initial and recurrent embodied energy of 52 wall assemblies

Fluctuations in embodied energy for Wall Type 1 relate to variations in internal and external linings and insulation types. Of the materials assessed, wool-based insulation, high recycled content internal linings and panellised timber external linings result in the lowest embodied energy demand. Wall Type 2 (concrete blockwork) and 3 (precast concrete) have no recurrent embodied energy due to an expected service life of at least 100 years. Operational energy demand is expected to be higher for these wall types due to a lack of additional insulation.

Operational energy

The breakdown of the predicted operational energy demand for the 5x4 house is shown in Figure 4. The total operational energy demand for the optimised building was found to be 38.5 kWh/m^2/annum. The nature of a building that can operate in both a fully sealed and naturally ventilated mode means that energy consumption is largely determined by occupant behaviour and weather. Predicting the energy demand is thus subject to large variation and significantly influenced by assumptions made in any calculation. For the purposes of benchmarking performances, the building has been simulated as a fully sealed building based on NaTHERS operational profiles and the performance specifications of all the equipment. In reality, we expect the building to never use cooling or heating when the windows and shading systems are used correctly by the occupant.

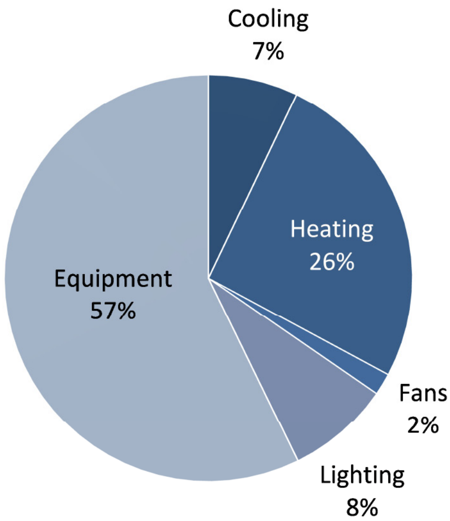


Figure 5 Annual predicted operational energy demand (fully sealed mode)

Additional energy savings

The total transport energy savings for the occupants of the house are estimated to be 9,738 GJ over 100 years. The combined direct (fuel/electricity) and indirect (embodied) transport energy requirement of the occupants of 7,902 GJ is significantly lower than the 17,640 GJ that is estimated to be required by an identical house in the outer-suburban areas of Melbourne. A greater use of public transport is the main reason for this energy saving.

The house's location in an established, well-serviced inner-suburban area is estimated to have saved 2,175 GJ over 100 years due to the avoidance of new infrastructure construction (roads, pipes etc.). The density of housing in this area also means that recurrent embodied energy for infrastructure maintenance is reduced on a per household and capita basis. Excluding the operational and embodied energy demands, as these are assumed to be identical for both locations, the inner-suburban house results in a 60% reduction in life cycle energy demand.

The initial life cycle energy analysis performed at assembly level provides a useful starting point to identify optimal materials and systems and provides useful information for designing similar projects. However, it is the combination of assemblies and systems that represents the basis of the eventual life cycle energy performance of a building. While beyond the scope of this initial study, the next phase will involve an analysis of the complete house. This will provide an opportunity to make any final adjustments to the energy performance of the project and provide a benchmark for future monitoring and performance comparisons.

Conclusion

This analysis and the 5x4 project demonstrate the ability to significantly reduce the energy demand of housing as well as the need for comprehensive assessment techniques and a well-informed design process. The analysis of the results suggests that:

- Materials with a high recycled content are preferred as they tend to have a lower embodied energy compared to virgin material alternatives
- Material life needs to be considered as those with a low embodied energy but frequent replacement can result in higher life cycle embodied energy
- Solid timber products are preferred over manufactured/processed timber products
- The embodied energy of some insulation products can be significant
- The embodied energy of glass can be considerable and the need for double/triple glazing must be balanced with the level of thermal performance they can provide
- Double-glazed spandrel panels should be avoided
- Minimising energy embodied in a building's initial construction is critical as energy expended in the future (for replacement materials and building operation) is likely to be less carbon intensive than the energy presently being used in material production
- Considering the thermal performance of the building envelope in relation to the climatic variation in a year will determine an efficient balance between reducing peak loads and annual energy consumed.

However, the extent of energy savings and level of environmental performance achievable in our buildings are still very much limited by the currently available materials and systems and fuel sources used in material and product manufacture and transportation. They are also highly dependent on our individual living standards, housing expectations and personal preferences and behaviours. Figures presented will vary depending on a number of factors, not least the service life of the building and materials used. Also, the findings of this study assume that energy intensities for various transport modes, energy supply and industrial processes remain constant for the next 100 years, which is highly unlikely.

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