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Everlasting Shelters: Life cycle energy assessment for heritage buildings

Usha Iyer-Raniga and James P. C. Wong

Abstract

A total of twelve existing residential buildings (ten with heritage significance) were surveyed and modelled for their operational and embodied energy performance and their associated CO_2 emissions in Australia and New Zealand. This paper presents an integrated life cycle framework, including energy flows associated with embodied energy, replacement of materials, construction processes and heating and cooling loads by combining life cycle modelling with residential building energy rating software.

The research found that overall, lower heating and cooling energy consumption does not necessarily lead to lower carbon emissions as carbon reduction depends on a number of factors including fuel mix profile and efficiency of the conventional grid. Buildings with ceiling insulation generally perform better in terms of energy usage especially in a colder climate and buildings made with heavy construction materials and with high thermal mass might work against the expected building fabric performance in a cold climatic condition with minimum solar gain. While the common perception is that old buildings often perform badly in terms of energy conservation, the higher rating for some of the buildings studied in this research shows that this is not always the case. The implications of this research apply not just to heritage buildings, but also to other existing buildings.

Introduction

The building sector plays a critical role in low-cost climate change mitigation worldwide (IEA 2006; IPCC 2007; UNEP 2007). This sector is the second largest emitter of global carbon dioxide after the manufacturing industry, representing approximately 33 *per cent* of the global total emissions (Price et al. 2006). This is also significant because, across OECD countries including Australia, buildings consume up to half of available raw materials and account for up to a third of final energy consumption (OECD 2002).

The Australian government has adopted a proactive approach in conserving heritage buildings to maintain a sense of community identity. From a socio-economic standpoint, heritage conservation has the potential to nurture the cultural character of a community, provide opportunities for education and interpretation, and even increase the economic value of property (Heritage Council of Western Australia 2009). Smith (2005) explains that heritage conservation extends beyond conservation efforts to not only protect the heritage property but includes increasing community enjoyment of the heritage property without further deterioration to its existing condition.

Rehabilitation of existing buildings provides many environmental and community benefits, including maintenance of historical and architectural integrity, revitalising urban areas and avoiding negative environmental impacts and unnecessary consumption of materials and energy. Opportunities include creating a valuable community resource, reducing construction cost and use of natural resources including associated environmental impact, reducing sprawl and extending the life of the building (Bullen 2007; DEWHA 2004). Adaptive reuse of historic buildings typically tends to have minimum impact on the heritage significance and value of the building and adds a contemporary layer that provides value for the future. When buildings can no longer function in their original use, a new use through adaptation may be the only way to preserve their heritage significance (Mofidi, Moradi & Akhtarkavan 2008).

Whole life cycle assessment for existing buildings

While there is no one accepted method for energy assessment of existing buildings, a key theme driving this research is determining the ‘total energy’ use during the life cycle of a building (Thormark 2002: 429) so as to provide a holistic view of the energy impacts of buildings. Thormark calculated the embodied and operational energy of a low energy housing development in Sweden by assessing the ‘recycling potential’ of the dwellings. The study found that in a life span of 50 years, embodied energy accounted for 40 per cent to 45 per cent of the total energy used and that between 37 per cent and 42 per cent of the embodied energy may be recovered through recycling materials upon the end of the building’s lifespan.

Mithraratne and Vale (2004) developed a method for detailed life cycle analysis of an individual house in New Zealand based on the embodied and operational energy requirements and life cycle cost over the useful life of the building. They found that operational energy is a significant component of the life cycle energy of the building for the common construction types used in New Zealand houses, and improving the insulation of New Zealand houses would be the first step to lessen their environmental impact.

Boardman (2007) described strategies for significantly reducing the CO_2 emissions of the current UK housing stock by 2050, where emissions of the building stock could be reduced by 60 per cent. Lowe (2007) on the other hand, proposed that a 60 per cent emission reduction could be achieved with just 20 per cent cut in total delivered energy. A very high demolition rate yielded a further 4 per cent reduction in emissions. Kohler and Yang (2007) supported Lowe’s view by examining the stock management approach using a holistic sustainability framework which includes the environmental, social and economic perspectives – of particular relevance to heritage buildings – as they provide more than the potential to reduce embodied energy through their adaptation.

Gustavsson and Joelsson (2010) highlighted the importance of considering both the embodied and operational life cycle stages of the building. With installation of highly efficient heating system in a passive-design low energy building, the embodied energy contributed to 60 per cent of the life cycle primary energy consumption. Pullen et al. (2006) studied residential dwellings in twelve locations in Sydney (Australia) and the study reported the life cycle energy consumption of two storey houses to be higher than residential apartments in suburban areas and single storey detached houses.

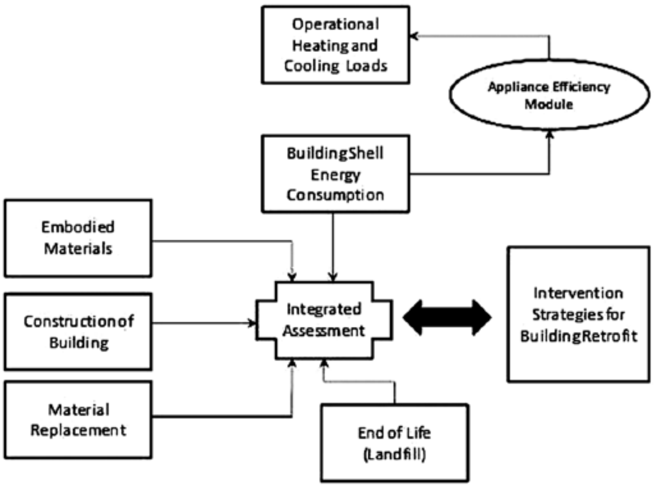

Figure 1. *Life cycle framework of the heritage building model (intervention strategies and analysis are not reported in this paper) (Source: Wong & Sivaraman 2011)*

The research project

The aim of this project was to provide empirical evidence in the form of a comparison between life cycle energy, greenhouse gas emissions, water and other environmental impacts of a range of heritage building designs compared to 'improved' retrofitted designs where heritage values are preserved. Underlying the research was the need to ascertain, purely from an environmental perspective whether (1) heritage buildings should be retained; and if so, then (2) identify the best options available to ensure the ongoing operational performance of heritage buildings in the near future; and (3) understand the role climate and geographical location play in the net energy performance of heritage buildings.

This paper addresses the first point fully and partly, the third point. The second question is beyond the scope of this paper and will be addressed subsequently in appropriate contextual papers. There are many important aspects that influence residential energy efficiency, but due to the specific scope of the project in relation to available funding and timeframe constraints, this research project focuses mainly on the comparative life cycle assessment of heating and cooling, embodied, replacement and construction energy for a limited number of representative archetype buildings with heritage values (Figure 1). In this paper, only the life cycle primary energy assessment, life cycle CO_2 emissions, and the analysis of operational heating and cooling energy of the twelve buildings are compared and reported.

Building Number	Location	Built Date	Heritage Significant	Building type	Construction	Existing Insulation
1	Bundoora, Melbourne, Victoria	2000	N/A	Free standing 4 bedroom outer suburb house	Brick veneer walls Concrete tiled roof	R3.5 ceiling insulation; R2 wall insulation R1 floor insulation
2	Manifold Heights, Geelong, Victoria	1926-40	Heritage Overlay (HO) and Heritage Precinct	Free standing single-storey house (Victoria Garden Bungalow Design T18)	Timber (weatherboard) walls Metal roof	R2.5 ceiling insulation
3	Newtown, Geelong, Victoria	1932-1933	Interim HO	Free standing double fronted Interwar period house	Timber (weatherboard) walls Terracotta tiled roof	R2.5 ceiling insulation R2 insulation at weatherboard wall only
4	Drumcondra, Geelong, Victoria	1911	HO	Free standing double fronted Edwardian period house	Timber (weatherboard) walls Metal roof	R2.5 ceiling insulation R2 wall insulation
5	Newington, Ballarat, Victoria	1950s	HO	Free standing triple fronted post war house	Brick veneer walls Concrete tiled roof	R2.5 ceiling insulation R2 wall insulation
6	West Melbourne, Victoria	1880s	Victoria Heritage Register (VHR)	Two-storey single fronted mid-late Victorian period terraced house	Solid brick walls Galvanised metal roof	No ceiling/wall insulation
7	Parkville, Melbourne, Victoria	1930s	HO	Apartment in residential block	Brick rendered walls Slate roof	No ceiling/wall insulation
8	Keilor East, Melbourne, Victoria	1972	N/A	Free standing 3 bedroom middle suburb house	Brick veneer walls Concrete tiled roof	R2.5 ceiling insulation
9	Kalbar, Queensland	1912	Queensland Heritage Register	Free standing 5 bedroom pre war house on timber stumps	Single-skin timber walls Corrugated iron hipped roof	R2.5 ceiling insulation
10	Larrakeyah, Northern Territory	1941	Register of the National Estate	Free standing 4 bedroom Type S house on concrete piers	Timber framed walls Corrugated galvanised iron roof	R2.5 ceiling insulation
11	Kingston, Tasmania	1826	Tasmania Heritage Register	Free standing 2-storey house	Sandstone walls with weatherboards extension Corrugated galvanised iron roof	R2.5 ceiling insulation R2 insulation at weatherboard wall only
12	Thorndon, Wellington, New Zealand	1887-1888	Historic Place Category 1, NZ	Free standing double-storey house	Timber framed clad with weatherboards walls Corrugated iron roof	No ceiling/wall insulation

Table 1. *Building archetypes modelled in the project*

The research design

Case studies are the primary method used in this research because they provide practical ways to investigate the amount of operational and embodied energy in existing buildings, identify opportunities to improve the energy performance and meet regulatory requirements. Although there is a need to have a certain number of case studies for the research results to be representative, budgetary constraints limited the number of case studies that could be undertaken.

A total of twelve existing residential buildings (ten with heritage significance) were surveyed and modelled for their operational and embodied energy performance in Australia and New Zealand (Table 1). Most of the buildings selected have heritage overlay controls representing different dominant archetypes ranging from 1820s to 1970s commonly found in Australia and New Zealand. A modern residential building (Building Number 1 in Table 1) was selected as the benchmark building representative of meeting current environmental regulatory standards.

The research primarily uses Life Cycle Assessment (LCA) to evaluate the embodied energy and related potential environmental impacts using the LCA software tool *SimaPro*. While the literature reviewed predominantly uses 50 years, the building lifespan considered in this study is 100 years due to the fact that heritage buildings are being studied. Second generation residential energy rating software *AccuRate* (AccuRate 2006) was used to assess the operational energy of the residential buildings. An advantage of using this software and thereby using its default settings for various zonings, etc. is to provide comparative results for all buildings assessed, regardless of regulatory requirements across state boundaries in Australia.

Research findings and analysis

The operational energy assessment

Building Number 1 is a typical two-storey modern brick veneer building found in most suburban areas of Melbourne. This has been used as the reference building, meeting current regulatory standards of energy efficiency in Victoria. Building Numbers 2 to 7 are existing buildings with heritage overlays ranging from an apartment building (Building Number 7) to a typical single-storey weatherboard clad home with metal roof (Building Number 2). Building Numbers 9 and 10 are timber-framed houses on stilts with metal roofing, typical in tropical Queensland and Northern Territory. These two buildings act as a good comparison with the rest of the traditional heritage buildings found in most developed areas in Australia. Building Number 11 is a unique building type with heavy sandstone walls from Tasmania and Building Number 12 is a typical timber framed house found in New Zealand.

Table 2 shows the comparison of total operational heating and cooling energy results assessed using *AccuRate* software for the twelve case studies. The reference building (Building Number 1) has minimum insulation requirements to meet regulatory standards, as set out by the Building Code of Australia (BCA). Insulation is provided to the external walls and the roof. There is no shading to the external windows, except for standard venetian blinds installed to the inside face of the windows. The standard 600mm roof eave is present all around the building. The modelling showed this building has the lowest life cycle primary energy compared to other case study buildings analysed, with embodied energy constituting about 10 per cent of the overall energy consumed over its life.

The operational heating and cooling energy of the case study buildings for Building Numbers 2 to 8, as simulated by the *AccuRate* software, achieved ratings between 0.8 Star to 3.4 Stars. While the common perception is that old buildings perform badly in terms of energy conservation, the higher rating for some buildings shows that this is not always the case. Building Numbers 3 and 4 (located in Geelong, Victoria) use lower heating loads compared to Building Number 2 which is located in a similar area. This may be attributed to these two buildings having standard insulation levels to meet the BCA requirements in the wall space. The weatherboard buildings (Building Numbers 2-4) have lower embodied energy (between 3-5 per cent of the overall energy consumed) as compared to brick veneer buildings (Building Numbers 5 and 8, having 5-8 per cent of the overall energy).

Building Numbers 5 and 8 with similar construction (brick veneer) in Victoria when modelled, perform relatively quite well, with 3.4 and 3.3 Stars respectively. Both buildings have existing insulation in the external walls and roof space. Building Number 5, located in a colder climate (inland location- Ballarat, Victoria) compared to Building Number 8 (near Melbourne city) explains the reason for the modelled higher heating load requirement to maintain acceptable internal comfort for the users. Building Numbers 6 and 7 (located in Melbourne) received ratings of 2.5 and 2.8 Stars respectively in the modelling. Building Number 6 is a terrace house and Building Number 7 is a ground floor apartment with thick masonry external walls. Building Number 6 has roof insulation and shares its walls with other houses leading to lower heat losses. Building Number 7's ceiling is adjacent to the unit above and consequently also has low heat losses through the ceiling. The slightly better performance of these buildings as compared to a typical detached house (e.g. Building Number 2) is attributed to low heat losses through building elements shared with other dwellings (walls, floor).

Building Number 9 is a typical Queensland building, free standing single-skin timber walls on timber piers. The elevated space below the building is enclosed with timber planks and there is minimum insulation on external walls and the ceiling of this building. The results show that this building consumed relatively low total energy (both heating and cooling) per square meter of area compared to Building Numbers 1 to 8, located in cooler regions in Australia. The lightweight building structure provided an appropriate option for energy use in a hot climate.

The building in Northern Territory (Building Number 10) is a free standing timber frame house on concrete piers with open spaces below the building. The building is not insulated either in the external walls or in the ceiling. The design of the building is very 'open' with adjustable louvers located in most of the external walls, and some of the internal walls do not even extend to the ceiling. The building is located in Zone 1, as per the BCA Climate Zone Maps. The modelling showed this building to perform average (3.2 Stars) in terms of its operational energy use. Being in a hot and humid climate, it is expected there would be no heating requirements.

The Tasmanian building (Building Number 11) is a sandstone building with a weatherboard extension. The building, with the insulated weatherboard extension to its South-West side providing extra protection from heat loss, gives a 2.4 Stars *AccuRate* rating. Overall, this building does not perform that well in a cold location even though it has a heavy building mass because the overall insulation levels of the building are low.

Building Number	Location	Heating Load, MJ/m^2.yr	Cooling Load, MJ/m^2.yr	Total Operational Energy, MJ/m^2.yr	Star Rating	Embodied Energy, MJ/ m^2	Life Cycle Primary Energy, GJ/m^2	CO_2 Emissions, kg/m^2
1	Bundoora, Victoria	117	45	162	5.1	3950	39.1	2900
2	Manifold Heights, Victoria	648	50	698	0.8	4680	183	11500
3	Newtown, Victoria	542	72	614	1.2	5220	104	6950
4	Drumcondra, Victoria	401	18	419	2.3	4890	100	6400
5	Newington, Victoria	365	27	392	3.4	5610	104	6800
6	West Melbourne, Victoria	297	20	317	2.5	4590	80	5100
7	Parkville, Victoria	290	6	296	2.8	4670	79	4850
8	Keilor East, Victoria	264	38	302	3.3	6370	82	5400
9	Kalbar, Queensland	134	103	237	1.9	5220	48	3900
10	Larrakeyah, Northern Territory	0	538	538	3.2	5610	76	4500
11	Kingston, Tasmania	427	5	432	2.4	10200	88	6250
12	Thorndon, New Zealand	464	3	467	2.2	5490	84	5600

***Table 2**. Comparison of modelled operational heating and cooling energy, Star Ratings, embodied energy, life cycle primary energy and CO_2 emissions for the case study buildings*

Building Number 12 is a two-storey weatherboard house, currently used as a museum and has undergone numerous alterations through the years. While the weather files for Wellington (cold climate) are used, the occupant patterns are similar to that used for the *AccuRate* simulation and the modelling here showed 2.2 Stars. A high heating load is required as expected for the building because there is no insulation in the external walls and ceiling.

The life cycle primary energy assessment

The Ecoinvent Cumulative Energy Demand and data from the Intergovernmental Panel on Climate Change were used to evaluate the life cycle primary energy consumption and life cycle carbon emissions from the buildings respectively (Frischknecht & Jungbluth 2007).

Figures 2 and 3 present the variation in total life cycle primary energy due to varying thermal energy losses in space heating appliances with different fuel efficiencies. The primary energy for gas heating loads was evaluated at two different heating appliance efficiencies and for electrical cooling loads was evaluated at a fixed co-efficient of cooling appliance performance factor. The cumulative primary energy associated with embodied, materials replacement and construction ranged from 5 per cent to 20 per cent of the total life cycle primary energy consumption, for all the case study buildings in Victoria when evaluated on a 100-year lifetime. The reference building (Building Number 1) was deemed to consume the lowest total life cycle primary energy amongst all cases analysed (Figure 2). The steel frame roof in the two other brick veneer buildings (Building Numbers 5 and 8) contributed to increased embodied primary energy flows. With a 3.4 and 3.3 star rating for the two brick veneer buildings (Building Numbers 5 and 7), the lifetime heating loads predominantly contributed to the life cycle primary energy consumption (Table 2). These two buildings showed 160 per cent to 200 per cent more than the life cycle primary energy as the reference building (Wong & Sivaraman 2011).

The three weatherboard buildings located in Geelong (Building Numbers 2, 3 and 4) demonstrated significant life cycle primary energy. The energy consumption of their embodied component is predominantly attributed to timber and steel used in the foundation, roof and external walls. The replacement of building materials contributed 20 per cent to 25 per cent of the total embodied primary energy for these buildings. Building Number 2 showed the highest life cycle primary energy among the three buildings in Geelong due to its low operational energy efficiency. With only 0.9 Stars, Building Number 2 was deemed to consume more than 150 per cent the lifetime heating load as the other two buildings.

The primary energy use associated with the two solid brick buildings; Building Numbers 6 and 7 were identical in nature. The use of energy intensive bricks in external walls, and timber in roofs and upper floors led to a cumulative embodied, materials replacement and construction energy contributing to 11 per cent of the total life cycle primary energy in both cases. In addition, heating driven lifetime operational loads led to increased life cycle primary energy use for Building Numbers 6 and 7.

The weatherboard buildings in Victoria were modelled to consume 140 per cent to 230 per cent the life cycle primary energy compared to the brick veneer and solid brick buildings, and 340 per cent the life cycle primary energy as compared to the reference building. With more than 94 per cent of electricity derived from brown coal, the Victorian grid has a low primary energy to electricity conversion efficiency. Hence, even with low cooling loads, the grid characteristics lead to primary energy supply for cooling loads contributing to 16 per cent of the life cycle primary energy consumption.

The buildings in both Queensland and Northern Territory (NT) are made of timber. The combination of embodied, replacement and construction stages of the timber house in Queensland (Building Number 9) contributed to 10 per cent of the total life cycle primary energy consumption as modelled. The Queensland electricity grid is marginally more efficient (36.7 per cent) than the Victorian grid (30.3 per cent) thus reducing losses associated with primary energy supply for cooling loads. The cumulative primary energy flows associated with embodied, replacement and construction stages for the timber building in NT (Building Number 10) is comparable to that of the Queensland building. The low operational energy efficiency and significantly high cooling loads required by the NT building, in combination with the 31.3 per cent grid efficiency led to 95 per cent of life cycle primary energy contributed by primary energy supply for cooling loads. The building showed the highest life cycle primary energy (1.23 x 105 MJ/m2) amongst all cases considered (Wong & Sivaraman 2011).

The embodied, replacement and construction primary energy flows contributed to 19 per cent of the total life cycle primary energy consumption for the stone and weatherboard building in Tasmania (Building Number 11). Building Number 11 (sandstone building) has the highest embodied energy value followed by Building Number 5 (brick wall with concrete tile roof building) due the building materials used.

The life cycle CO_2 emissions

Carbon emissions from energy generation are dependent on the type of energy delivered and the resource profile of the energy supply system. In this study, heating is assumed to be provided by gas and cooling is provided by electricity. For the Victorian case studies, gas heating was approximately five times less carbon intensive as electricity powered cooling. Tasmania is a unique case with more than 90 per cent of electricity generation derived from hydropower which has a very low CO_2 emission factor. Hence, overall lower heating and cooling energy consumption does not necessarily lead to lower carbon emissions and sources of power generation plays a critical role. Among the Victorian buildings, the two weatherboard buildings (Building Numbers 2 and 3) showed significantly higher cooling loads than the other buildings and this had contributed high levels of CO_2 emissions (Table 2). Heating energy is dominant for primary energy consumption in colder climates; however, the associated CO_2 emissions are relatively lower (heating is mainly provided by gas). The CO_2 emissions for buildings in hot climates in Australia are predominantly driven by cooling loads (cooling is mainly provided by electricity).

The timber framed building in Queensland showed a higher cooling load than the two weatherboard buildings (Building Numbers 2 and 3) discussed above, but the life cycle CO_2 emissions are lower because of the Queensland grid characteristics. The carbon intensity of the Queensland grid is 30 per cent lower than the Victorian grid. The Tasmanian building presents a contrasting case to NT building, as the very low cooling loads supplied by a low carbon intensive grid explains the lower life cycle CO_2 emissions (Table 2).

Conclusion

This paper reports on a small part of research work currently in progress. Forthcoming papers will address the second research aim, this being the best options available to ensure optimal environmental performance of heritage buildings. The conclusions of this paper can be applied, not just to heritage buildings, but also to other existing buildings of similar construction archetypes. Heritage buildings are a class of existing buildings. As noted through the simulations using *AccuRate* software, the operational heating and cooling energy of the existing heritage buildings was between 0.8 to 3.4 Stars. The buildings selected were modelled under 'as-it-is' conditions. Most of the existing heritage buildings have had some sort of additional works carried out during the course of life

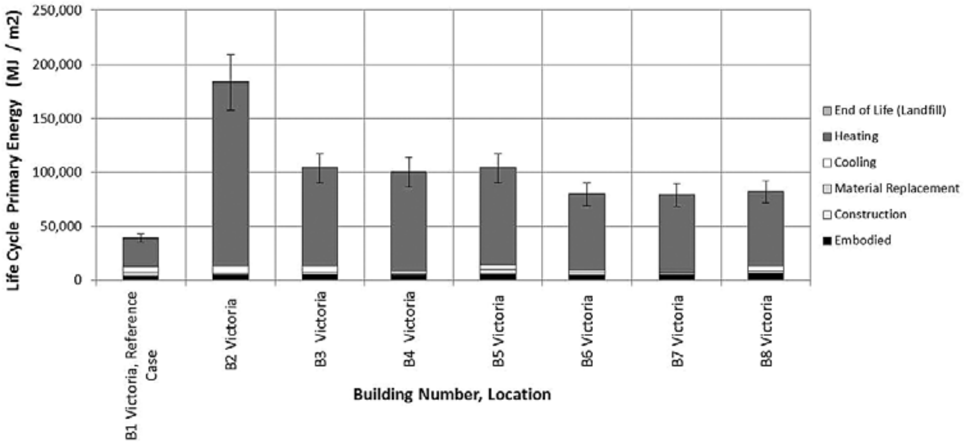

Figure 2. *Life cycle primary energy consumption of the Victorian residential buildings (the variation bar indicated for the heating energy reflect the lower and higher heating appliance efficiencies evaluated) (Source: Wong & Sivaraman 2011)*

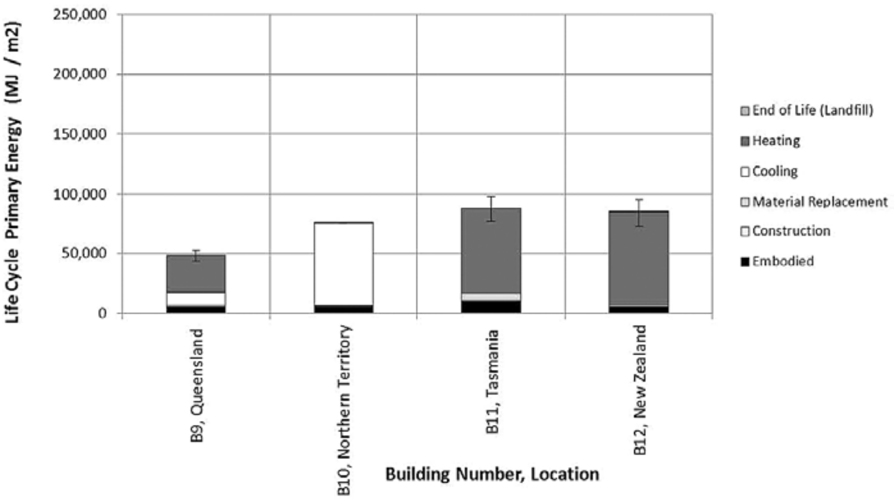

Figure 3. *Life cycle primary energy consumption of the residential buildings in Queensland, Northern Territory, Tasmania and New Zealand (the variation bar indicated for the heating energy reflect the lower and higher heating appliance efficiencies evaluated) (Source: Wong & Sivaraman 2011)*

of the buildings and this was reflected in the 'as-it-is' condition. This would be equally true for contemporary archetypes having varying levels or no insulation, glazing types, poor quality of construction and inappropriate orientation.

There are a number of interesting findings from this research impacting on regulatory frameworks. Buildings with ceiling insulation generally perform better in terms of energy usage especially in a colder climate; heavy construction building with high thermal mass might work against the expected building fabric performance in a cold climatic condition with minimum solar gain; timber framed building on stilts perform well in a hot and humid climate and an enclosed subfloor plays a role in improving the thermal performance of timber framed building in a similar climatic condition; and the Victorian 5-Star building seems to perform better in colder climatic condition.

The concept of whole life cycle assessment is an important approach in assessing the energy consumption of existing buildings in more complete and holistic way. Lower heating and cooling energy consumption does not necessarily lead to lower carbon emissions as found by the research because carbon reduction depends on a combination of primary energy consumption, magnitude of heating and cooling, fuel mix profile and efficiency of the conventional grid. This is a more critical issue for heritage buildings as the preservation of cultural values are equally, if not more important than the environmental performance.

The outcomes reported in this paper help in recommending strategies to improve the energy efficiency of heritage buildings to today's and future regulatory standards particularly from an environmental perspective by focusing not just on the thermal performance of the fabric of the building, but also the operational, including the upstream primary energy fuel source to service the building over its lifetime.

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References

Boardman, B. 2007, 'Examining the carbon agenda via the 40 per cent House scenario', *Building Research and Information*, vol. 35, no. 4, pp. 363 – 378.

Bullen, P. 2007, 'Adaptive reuse and sustainability of commercial buildings', *Facilities,* vol. 25, no. 1-2, pp. 20 – 31.

Department of the Environment, Water, Heritage and the Arts (DEWHA). 2004, *Adaptive reuse*, Commonwealth of Australia, Canberra.

Frischknecht, R. & Jungbluth, N. 2007, *Eco-invent centre: implementation of life cycle impact assessment methods*, viewed 19 Sept. 2011, <http://www.ecoinvent.org/fileadmin/documents/en/03_LCIA-Implementation.pdf>.

Gustavsson, L. & Joelsson, A. 2010, 'Life cycle primary energy analysis of residential buildings', *Energy and Buildings*, vol. 42, no. 2, pp. 210 – 220.

Heritage Council of Western Australia. 2009, *Heritage: a future for our past*, viewed 26 Oct. 2010, <http://www.heritage.wa.gov.au/>.

International Energy Agency (IEA). 2006, *Energy technology perspectives*, OECD/IEA, Paris.

IPCC. 2007, *Climate change 2007: mitigation of climate change*, Contribution of Working Group III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, B. Metz, O.R. Davidson, P.R. Bosch, R. Dave and L.A. Meyer (eds), Cambridge University Press, Cambridge and New York.

Kohler, N. & Yang, W. 2007, 'Long-term management of building stocks', *Building Research and Information*, vol. 35, no. 4, pp. 351 – 362.

Lowe, R. 2007, 'Technical options and strategies for decarbonising UK housing'. *Building Research and Information*, vol. 35, no. 4, pp. 412 – 425.

Mithraratne, N. & Vale, B. 2004. 'Life cycle analysis model for New Zealand houses', *Building and Environment*, vol. 39, pp. 483 – 492.

Mofidi, S.M., Moradi, A.M., & Akhtarkavan, M. 2008, 'Assessing sustainable adaptation of historical buildings to climate changes of Iran', *3rd IASME/WSEAS International Conference on Energy & Environment,* University of Cambridge, UK, pp. 145 – 150.

Organisation for Economic Co-operation and Development (OECD). 2002, *Design of sustainable building policies: scope for improvement and barriers*, OECD, Paris.

Price, L., De la Rue du Can, S., Sinton, J. & Worrell, E. 2006, *Sectoral trends in global energy use and GHG emissions*, Lawrence Berkeley National Laboratory, Berkeley, CA.

Pullen, S.F., Holloway, D., Randolph, B. & Troy, P. 2006, 'Energy profiles of selected residential developments in Sydney with special reference to embodied energy', *Proceedings in Australia and New Zealand Architectural Science Association*, Adelaide, Australia, November 22–25, 2006.

Smith, J. 2005, 'Cost budgeting in conservation management plans for heritage buildings', *Structural Survey*, vol. 23, no. 2, pp. 101 – 110.

Thormark, C. 2002. 'A low energy building in a life cycle – its embodied energy, energy need for operational and recycling potential', *Building and Environment*, vol. 37, pp. 429 – 435.

United Nations Environmental Programme (UNEP). 2007, *Buildings and climate change: status, challenges, and opportunities*, UNEP, Geneva.

Wong, J.P.C. & Sivaraman, D. 2011, HCOANZ *Sustainability and Heritage Project – Residential,* Final Report for Heritage Council of Victoria, Melbourne.