USE OF A LIGHTWEIGHT STEEL FLY ROOF FOR AN 'AUTONOMOUS' RURAL HOUSE IN NSW AUSTRALIA - LIFE CYCLE, ENERGY AND THERMAL IMPLICATIONS

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Abstract

This paper is a report on the design and construction of a house with a lightweight steel framed 'fly' roof in New South Wales (NSW), Australia. The aim is to appraise the environmental performance of this house by monitoring its thermal performance and auditing the embodied energy associated with its construction and the energy consumed in its use, and to produce a Life Cycle Analysis for comparative purposes.

This is an "autonomous" house, in the sense that it has no mains utilities, constructed on a remote bushfire prone site on the northern slopes of a State Forest in the Hunter Valley[1]. The house has no mains utilities, relies on electrical power produced on site, uses roof collected rain water and manages effluent disposal to utilise grey water to irrigate a vegetable garden. Primary design strategies for thermal comfort include the use of a lightweight steel framed 'fly roof' and 'reverse veneer' wall construction.

This paper reviews the design , construction and in-use experiences of this house under the following headings :- site conditions, design strategies, services, communications, transportation, water consumption, effluent disposal, bushfire protection, economics, thermal performance, embodied energy, energy in use and life cycle analysis[2].

Summary of Results to date

(1) Thermal Performance. The house performs very well thermally in summer, maintaining an ambient interior temperature up to 10˚C cooler than external temperatures on a hot day. In winter, it maintains an unheated interior temperature up to 9˚C warmer than external temperatures on a cold night.
(2) Embodied Energy. The house is not an extremely low embodied energy structure, largely due to the high amount of concrete in floors and walls designed to provide thermal mass and the separate steel 'fly' roof. It does, however, compare favourably with standard project homes. Overall embodied energy of the house (excluding outbuildings and external works) is 572 GJ, which is 1.70 GJ/m^2 of roof area, or 2.65

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[1] Johnston, Lindsay. 1998, "The Four Horizons Project", *Houses*, Royal Australian Institute of Architects/Architecture Media Australia, Melbourne, No. 15, May 1998, p.66-69.
[2] Edwartds, Prof. Brian. 1998. "It comes from a land down under - review of Four Horizons", *Steel Design - Supplement to the Architects' Journal*, London, Summer (July) 1998, p.14.

GJ/m^2 of useable floor space, which can be compared with two standard project homes of brick veneer and tiled roof homes at 2.5 and 2.7 GJ/m^2. The dwelling areas without the independent ‘fly’ roof would be 1.52 GJ/m^2. Contentious components in the design, such as the use of aluminium windows, represent a very small proportion of the total.

(3) Energy in Use. The house is very energy efficient with an annual consumption of 48.39 GJ/year compared to the NSW average for a single dwelling of 89.4 GJ, just over one half of the NSW average. If the “free” solar contribution and the forest debris firewood contribution are deducted from this figure the nett energy consumption is 33.14 GJ/year about one third of the NSW average.

(4) Embodied Energy related to Energy in-use. Taking a 40 year life cycle, and amortising the embodied energy of 934 GJ for the house, outbuildings and external works over 40 years, the annual energy consumption derived from embodied energy is 23.35 GJ. The current energy in-use is 48.39GJ/year. Together these total 71.74 GJ/year. The embodied energy represents 33% of the total. The embodied energy of the house by itself, excluding outbuildings and external works, is 572 GJ, representing 14.3 GJ/year over 40 years. This combined with the in-use energy of 48.39 GJ/year, totals 62.69 GJ/year. In this case the embodied energy represents 23% of the total.

(5) Energy in Transportation. This has been audited in order to put in context discussion of energy use in the house. Energy used in the form of petrol for cars to travel to work and shopping is estimated at 84.1 GJ/year. This is 170% of the current in-use energy of the house of 48.39 GJ/year; 588% of the amortised embodied energy of 14.3 GJ/year for the house alone; 360 % of the embodied energy in the house, outbuildings and external works of 23.35 GJ/year; and 118% of the combined in-use and amortised embodied energy for the whole project of 71.74 GJ/year. This is influenced by the remote location of the house, but it emphasises the relative impact of lifestyle decisions.

(6)The embodied energy in the aluminium windows in the house, amortised over a 40 year life cycle, accounts for 0.7 GJ/year. The embodied energy in all the steel in the house and outbuildings, amortised over 40 years, accounts for 12.95 GJ/year. The decision by the owner to drive a small 2 cylinder 650cc car in preference to a V8 sports car represents an energy saving of 70 GJ/year.

Introduction

The house under examination in the study is known as the ‘Four Horizons Project’ because of its elevated location and spectacular prospect. Its designer admits that it was largely designed by informed intuition and prior practical experience and based on a crude understanding of the principles of ESD[3] [4]. The subsequent post-construction, post-occupancy evaluation of its performance, and the associated translation of this into a Life Cycle Analysis, is intended to assess and evaluate these intuitive design decisions. This study begins to highlight new ways of looking at the

[3] Ballinger, J., Prasad, D., Rudder, D. 1992, *Energy Efficient Australian Housing*, Australian Government Publication Service, Canberra.

[4] Cole, Gareth. 1994, “Ecologically Sustainable Passive Solar Architecture”, in *Towards an Ecologically Sustainable Architecture*, ‘The Architecture Show’ Seminar, Projects and Systems, Sydney.

issues of ecological sustainability in house design when viewed in an all of life context.

Site Context

The site is located on the eastern seaboard of Australia, at latitude 33˚S at elevation 430m above sea level facing NE on the crest of a ridge and at the top of a steep 60m escarpment, and is part of a 45 hectare holding in State Forest located 65 km west inland of Newcastle at the north end of the Watagan Mountains overlooking the lower Hunter Valley.

Climatic Conditions

The temperature range for 1996/7 was in winter 4˚C - 24˚C, and in summer 14˚C - 37˚C. Prevailing winds and storms are from S to SE, and in summer there are cool NE breezes. Original design rainfall was based on record for Cessnock at 750mm per annum. Actual rainfall for 1996 was 1125mm and 840mm for 1997.

Design Strategies

The stated objectives were to design and construct a house that would cope with these conditions, that would minimise embodied energy as appropriate to the context, that would require as little energy as possible to sustain its use and that would do as little damage as possible to the environment. There were a number of basic premises on which the house was developed - it had to be cheap, it would be minimalist in form, appointment and finishes, and it would be simple to construct. It would have a big roof for shade and to collect water; use non-combustible materials; have a capability of closing up in a bushfire; use slab on ground for fire reasons and for thermal mass; have masonry or rammed earth construction of some kind for thermal mass; be a low structure to minimise visual impact in its very visible location; have sun penetration from the north-east and north in winter, shading from the sun at all other times. A ‘settlement’ was planned as a group of buildings consisting of the house, a garage, a stable and a walled vegetable garden, the latter to keep out the local fauna. A plan of the house and outbuildings is shown in **Figure 1**, and a cross section of the house and ‘fly’ roof is shown in **Figure 2**.

The main feature of the house is the use of a 'shade' or 'fly' roof completely independent of two separate dwelling modules beneath, each with their own sub-roof. A reasoned debate with the planning officer at Cessnock City Council, who understood the bloodlines of the design from traditional rural Australian farm buildings, and the thermal advantages of a silver roof compared with often favoured dark colours, resulted in the use of standard BHP ‘Zincalume’ corrugated iron for roofing.

An existing chimney breast has been retained and now forms the centrepiece of a central breezeway between the two dwelling modules - a covered space for open air living appropriate to a relatively benign climate - orientated to 33˚ east of solar north, the winter sunrise spills into this area. The two dwelling modules consist of one with living areas and one with bedroom areas. Eaves heights and overhangs have been designed to eliminate direct sun in summer on the main windows, and to allow winter sun penetration into the thermal mass of the concrete floors and walls in winter. This double roof arrangement effectively means that the dwelling units are in permanent shadow in summer while enjoying clear cross flow of air under the ‘fly’ roof above. Other primary design strategies for thermal comfort are the introduction of high thermal mass through the use of concrete on-ground floor slab, concrete blockwork for all external and internal walls[5]; external insulation of the external walls keeping the thermal mass on the inside[6]; and orientation of all major windows to the NE to capture winter morning sun and location of water tanks and vegetation to the west to eliminate hot summer afternoon and evening sun.

Construction

The concept of a double or ‘fly’ roof was explored from the outset. Initially it was conceived as a fabric or tent roof, but this was discounted once bushfire and cost considerations were examined, due to the high cost per sq.m of non-inflammable fabric. The main ’fly’ roof, and the garage and stable, are constructed using lightweight standard agricultural steel shed frames, consisting of simple lattice columns and roof portals of 50 x 50 x 1.6 RHS and 20mm dia bar. The main roof and the sheds are clad with standard 'BHP Zincalume' corrugated steel. Large curved 'Zincalume' gutters and ridge vents enhance the basic shed aesthetic.

The two 9m x 9m dwelling modules are constructed on concrete slabs with no termite protection except 'Termimesh' collars on pipe penetrations. External and internal walls are of 150mm hollow core off-white concrete blocks exposed on the inside. The outside is clad on the south, east and west with R1.5 recycled polyester wool insulation and ‘BHP Zincalume Mini-orb’ on 22mm steel tophat sections. The north side is clad with 200X38 blue gum planks. Options of mud brick and rammed earth were pursued but discounted on grounds of cost and general difficulty. Pure wool insulation proved too expensive.

The dwelling modules have curved sub-roofs on purpose made lattice steel bow trusses and 'BHP Topspan 61' battens with 'BHP Zincalume Mini-orb', R2.0 polyester wool insulation and plasterboard ceilings. Piped and wired services are distributed in a steel C channel ring/lintel beam on top of the external walls and dropped in the hollow cores of the blockwork. Windows and patio doors are standard single glazed silver anodised aluminium with wire fly screens and fitted with perforated 'Zincalume Mini-orb' fire shutters. There is no timber in the project except doors, external cladding and internal fascias of MDF board.

Services

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[5] Oppenheim, David, and Treloar, Graham. 1994, ‘Towards the Extreme - High Mass Buildings in Temperate Australia’, *Architecture of the Extremes: Proceedings of the Eleventh Passive Low Energy Architecture International Conference*, Dead Sea. p.9.
[6] Wooley, J.C. 1983, *National Energy Research Development and Demonstration Program: Coolwall-Thermal Project Final Report Stage 1*, Department of Architecture, Queensland University of Technology, Brisbane.

The sources of energy for the project are the sun converted into electricity, the sun converted into hot water, LPG, diesel and an unending supply of firewood, debris collected from the forest floor. In essence, the ability to be totally autonomous has been directly related to the capital investment in energy equipment - at this time the house is not autonomous.

Electricity. Electricity consumption in the house is a very small 14 kwh per week, which compares with a NSW average of 80-90 kwh per week. Electricity is produced on site from a recycled second-hand RAPAS (remote area power assistance scheme) installation consisting of 8no. 55w solar panels, a 5kva Lister TR1 one cylinder diesel generator, a BP Solar battery bank consisting of 24 no. 2P566 batteries wired for 48 volt DC then inverted up to 240v AC. An old square wave invertor has been replaced (July 1998) with a new Trace Engineering SW4.01 sine wave invertor. This has dramatically improved the efficiency of the system and reduced diesel consumption for the back-up generator from 15 litres of diesel fuel per week to 4.5 litres. The use of 12v lighting was considered as an option, but 240v compact “warm-white” fluorescent globes have been used, rated mostly at 11w each, using standard wiring and fittings. Thus the house can be fully lit at night on little more than 100 watts.

Water. The large lightweight low cost ‘fly’ roof was a fundamental water strategy as all water is collected from the roofs into 'Aquaplate' steel tanks and an older concrete tank. A calculation was done from the outset which related an estimated daily water requirement of 1000 litres, an average annual rainfall for the area of 750mm, the roof area and the size of the water storage tanks. The combined roof area of house and garage is 450 m^2, yielding 450 litres (100 gallons) for every 1mm of rainfall or 365,000 litres per annum. Actual rainfall for 1996 was 1125mm yielding 500,000 litres, and 840 for 1997 yielding 378,000 litres. Average daily usage is 600 litres per day (including horses and some irrigation). Water use is thus often less than half the water collected. 110,000 litres (23,600gals) of water are stored in tanks for the domestic supply, which would last 6 months at current usage of 600 litres per day. Water saving strategies include dual flush toilets and, importantly, an on/off cock on shower heads. In addition 18,000 litres (4000 gallons) are collected off the stable roof into a separate tank which is used for irrigation of the walled garden and a dedicated fire fighting supply. Water pressure is provided by a 240v ‘Grundfos’ CH-2 pump rated at 600W/50Hz with pressure vessel operating at 1.5-3.0 bar (20-40 psi). Options including a water tower and header tank were considered, but were discounted on the grounds of cost.

Effluent Disposal. There are two separate piped effluent systems - a "blackwater" line and the "greywater" line. There are three toilets which discharge into the "black" line to a traditional non mechanical septic tank and transpiration trench. Composting toilets were considered, but a single unit was equivalent in cost to the whole septic tank system, and there was a problem with rock below the on-ground floor slabs. All other waste water from the bathrooms and laundry discharges into the "grey" line which is piped to a system of land drains as irrigation in the walled garden. The health issues of using greywater for irrigation to a vegetable garden have been studied[7] and,

[7] Jeppesen, Barry. 1993, *Domestic Greywater Reuse: Preliminary Evaluation*, Urban Water Research Asustralia, Melbourne.

although this is not recommended for general application, it may be acceptable for sub-ground irrigation under controlled conditions.

Refrigeration, Cooking, Hot Water. An LPG refrigerator with a small deep-freeze is used and a separate small beer fridge. Cooking is principally by LPG. A solar water heating panel with integral back-up LPG boiler is located on the roof. Over a period of 24 months LPG use is an average of 8.5kg per week currently costing A$10.50.

Wood Burning. There is a slow combustion wood burning stove in each dwelling module for space heating in winter. The 'Nectre' in the living area has a baker's oven and cook-top. The stove in the bedroom is seldom used. There is no other space heating. The open fire in the ‘breezeway’ is mainly aesthetic, but produces intense heat on a cold winter day. It is intended to install a water heating boiler in the open fire in the future. The amount of firewood being used is 10kg per day for approximately 90 days per year. It is almost all Black Wattle debris, collected from the forest floor as part of the bushfire fuel load reduction activity, and dried for at least one season in a large wood shed. Dried Black Wattle is a highly efficient fuel formerly used for bakers’ ovens. The pollution implications of burning this firewood has to be balanced against the fact that it would naturally rot in the forest producing carbon into the atmosphere or be burned in bushfires. The calculated energy component of the wood fires is 13.5 GJ/year.

Communications

No mains telephone service has been available. ‘Telstra’ has installed a solar powered (NA100) dual channel radio link telephone which gives connections to the main telephone network with lines for speech and data. These use normal telephone numbers and incur normal call charges.

Transport

Reference to personal transportation has a relevance to put in context the embodied energy in the construction and the energy in-use of the house. A 650cc 2 cylinder ‘Subaru’ is used for daily travel to work (420 km/week average @ 6.5 litre/100km), and an 1800cc ‘Toyota’ four wheel drive is used for all other purposes including shopping (200 km/week @ 10 litres/100km). Gasoline consumption for the ‘Subaru’ is an average of 27 litres/week costing A$20.00, and the ‘Toyota’ 20 litres/week costing A$15.00. If the use of a V8 vehicle had been continued for travel to work, the weekly fuel consumption for that vehicle would have been 66 litres/week (420 km/week @ 16 litres/100km) costing A$50.00.

Bushfire Protection

The buildings are located in a high risk location, at the top of a hill and surrounded by forest. Clearing by the former owner established reasonable radiation zones. These have been improved to 50-70 m cleared zones all around the dwelling to comply with requirements of the Department of Bush Fire Services[8]. The walled garden, stables, garage and water tanks give protection to the dwelling from south and west. The dwelling is constructed to meet the requirements of AS. 3959-1991 ‘Construction of buildings in Bushfire-prone Areas’[9] and other guidance advice[10]. Concrete slab on ground construction overcomes potential fire risk from sub-floor areas and timber floors. Sealed ‘Mini-orb’ sub-roofs and steel structure eliminate potential for fire ingress through roof voids. External walls are non-combustible concrete block. The remaining major potential hazard is fire ingress through broken windows. Perforated ’Mini-orb’ fire shutters, combined with wire mesh fly-screens, protect major windows. Thus a safe haven is available within the main dwelling. A dedicated fire fighting water supply is permanently connected to a stand by petrol water pump connected to a permanent 36m fire hosereel.

Economics

The true costs of construction are distorted because the project was constructed by ‘owner builders’. The total cost of construction including all site works, water tanks, septic tank, walled garden, dams, sheds, etc. is A\$270/m^2 of roof area or A\$375/m^2 of enclosed floor area of house and sheds. In these figures are not costed the substantial use of family labour. The estimated new cost of A\$25,000 for the power generation system and solar panels is not included in these figures.

Thermal Performance

An electronic thermal monitoring system was operating in the house in June/July 1996 and December/January 1996/97. Five thermal sensors were located (i) outside north, (ii) outside south, (iii) inside living area, (iv) inside main bedroom, and (v) inside bathroom 2. Thermal readings for inside and outside have been obtained in winter and summer conditions and are shown in **Figures 3, 4, 5, 6, 7 and 8.**

The ‘fly’ roof casts a shadow over the whole house nearly all day in summer. Sun penetrates into the north facing main living area and bedroom on winter mornings. There is free air movement over the sub-roofs of the dwelling modules and a ridge vent in the ‘fly’ roof. The dwelling modules have high level ‘breezeway’ vents on each end to allow cross ventilation of the living area and main bedroom. The sub-roof has thermal insulation. There is substantial thermal mass in the concrete floors and concrete block external and internal walls. The external walls are insulated and clad externally. The living area has an external wall to floor ratio of 1.22:1.0 and the single glazed windows are 38% of the external wall area and 47% of floor area. The main bedroom has an external wall to floor ratio of 1.0:1.0 and the windows are 52% of the external wall or floor area. At the time of this monitoring program there were no curtains on the windows of any rooms

In winter the lowest external temperature recorded was 4˚C and the warmest (not affected by sun) 23˚C. The only space heating was by wood fire in the living area.

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[8] 1991, *Planning for Bush Fire Protection*, Department of Bush Fire Services, Rosehill, NSW.
[9] 1991, *Construction of Buildings in Bushfire-prone Areas*, AS 3959, Standards Australia, Sydney.
[10] Ramsay, G. Caird and Dawkins, Denis. 1993, *Building in Bushfire-prone Areas*, SAA-HB 36, CSIRO/Standards Australia.

The ambient interior temperature in the unheated bedroom on the north side of the house, which enjoys generous morning sun penetration, was in the range 11.5˚C-22˚C, on colder nights maintaining an internal temperature 7.5˚C warmer than outside. In the living area, which also enjoys generous morning sun penetration, with the wood fired stove lit in the evenings up to 10pm, the ambient temperature was in the range 14˚C-24˚C, on colder nights maintaining a temperature up to 10˚C warmer than outside. In the bathroom on the south side of the house, which does not receive any winter sun, the temperature was in the range 10˚C-19˚C, maintaining a temperature 6˚C warmer than outside on cold nights. Addition of curtains to windows should improve the winter thermal performance.

In summer the lowest external temperature recorded was 14˚C and the warmest 37˚C (in the shade). There was no space cooling by air conditioning or fans. The ambient temperature in the main bedroom, which kept external doors and windows closed on hot days, was in the range 18˚C-28˚C on hot days, up to 9-10˚C cooler than outside in the middle of the day, and with night temperatures in the range 18-23˚C. The main living room, which often had the external doors open on hot days, maintained a temperature in the range 19˚C-30˚C, still up to 8˚C cooler than outside. External fire shutters fitted since this monitoring program should enhance the summer thermal performance.

These results appear to fall within the 'comfort zone'[11] in summer without mechanical assistance, and in winter through the limited use of wood fired slow combustion stove heating.

Embodied Construction Energy

An analysis of the embodied energy and greenhouse gas emissions related to the house and outbuildings has been carried out based on post-construction building quantities. The calculated energy consumption and greenhouse gas emissions for the house, fly roof and outbuildings total 934 GJ and 96.4 tCO_2 and are listed in the table **Figure 9**, sorted by materials, building elements and parts of the project. In all cases the energy and greenhouse emissions reported include all significant processes from resources in the ground. The greenhouse emissions are reported in a tonnes of CO_2 equivalent and include a weighting factor for the relative warming effect of gasses such as methane in comparison to CO_2. The breakdown of construction energy and greenhouse gas emissions for the house and fly roof are shown by percentage in the charts **Figures 10, 11 and 12**.

The energy consumption for the house only (excluding outbuildings and external works) is 572 GJ, when calculated on a m^2 basis this is in the range 1.52 - 2.65 GJ/m^2 depending on which way the area is calculated. This is shown in **Figure 13**.

Comparative figures for two A.V.Jenning project homes[12] give them an estimated construction energy content of 2.7 and 2.5 GJ/m^2. Comparative figures published by Lawson[13], for the external envelope only, of six case studies show an estimated

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[11] Greenland, Jack. 1991, *Foundations of Architectural Science*, University of Technology, Sydney. pp.3/25-31.
[12] 1996, BHP Research, Newcastle. Internal Fact Sheets FC 96-01 and FC 96-25.
[13] Lawson, B. 1996, *Building Materials, Energy and the Environment*, Royal Australian Institute of Architects. Canberra., pp.114.

construction energy content in the range 0.361 GJ/m^2, for a wooden beach lodge in Tasmania, to 2.307 GJ/m^2 for a display home in Canberra sponsored by the Energy Research and Development Corporation. A publication by Baird and Chan[14], published in 1983, shows ten case studies for complete houses from Australia, New Zealand, US and UK with a range 1.9GJ/m^2 for a standard UK 'Council' house, 3.6GJ/m^2 for an Australian brick veneer house with slab on ground, 3.2-3.7GJ/m^2 for New Zealand timber frame houses, 7GJ/m^2 for a UK semi-detached house and 8GJ/m^2 for a US home. At the highest figure of 2.65 GJ/m^2, the Four Horizons house can be seen as quite efficient in terms of embodied energy.

The make up of this embodied construction energy shows that the high components are the concrete foundations, floor slabs and concrete blockwork walls totalling 23%, and the steel in roofs at 37%. When expressed in terms of greenhouse gas emissions in tCO2eq, the concrete represents 40% of the whole, and the steel 42%. GJ in aluminium in windows represents only 3% of the total.

Energy in Use

The consumption of delivered energy for the in-use habitation of the house is tabulated in **Figure 14,** and the make-up of the sources of this energy is tabulated in **Figure 15** . The slight difference in totals of 6.55 GJ is due to losses attributable to the operating efficiency of the solar/generator/invertor system.

The house is very energy efficient with an annual consumption of 48.39 GJ/year compared to the NSW average for a single dwelling of 89.4 GJ, just over one half of the NSW average. If the "free" solar contribution and the forest debris firewood contribution are deducted from this figure the nett energy consumption is 33.14 GJ/year about one third of the NSW average. Nevertheless, the analysis of the sources of the energy used shows that the solar contribution is still very small and that there is a long way to go to make the house completely autonomous - ie. a nil producer of greenhouse gas emissions or a nil importer of fuel from off-site.

In addition to the energy consumed in the utilisation of the house, an assessment has been made of the energy requirement, in terms of petrol consumption, for transport to work and shopping. This has been included in order to put in context discussion of energy use in the house. Energy used in the form of petrol for cars is calculated at 84.1 GJ/year. This is 170% of the current in-use energy of the house of 48.39 GJ/year; 588% of the amortised embodied energy of 14.3 GJ/year for the house alone; 360 % of the embodied energy in the house, outbuildings and external works of 23.35 GJ/year; and 118% of the combined in-use and amortised embodied energy for the whole project of 71.74 GJ/year. This is influenced by the remote location of the house, but it emphasises the relative impact of lifestyle decisions.

Life Cycle Analysis

To the energy in-use figures tabulated above, have been added the embodied construction energy figures. Taking a 40 year life cycle, and amortising the embodied energy of 934 GJ for the house, outbuildings and external works over 40 years, the

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[14] Baird, George and Chan, Seong Aun. 1983, *Energy Cost of Houses and Light Construction Buildings*, Report No. 76, New Zealand Energy Research Committee, Auckland, p.29.

annual energy consumption derived from embodied energy is 23.35 GJ. The current energy in-use is 48.39 GJ/year. Together these total 71.74 GJ/year. The embodied energy represents 33% of the total. The embodied energy of the house by itself, excluding outbuildings and external works, is 572 GJ, representing 14.3 GJ/year over 40 years. This combined with the in-use energy of 48.39 GJ/year, totals 62.69 GJ/year. In this case the embodied energy represents 23% of the total. The embodied construction energy represents 33% of the total of which 23% is related to the house itself and 10% to the outbuildings and external works - see **Figure 16**.

If the transport fuel consumption is included as part of a total energy analysis for the house, outbuildings and external works, see **Figure 17**, the energy consumption in-use is 31%; the embodied construction energy component amortised annually is 15% - consisting of 9% related to the house and 6% related to outbuildings and external works; and the energy consumption through in-use transportation is a substantial 54%.

These figures indicate that in-use energy heavily outweighs embodied construction energy in an annual analysis, and that transport energy in this case heavily outweighs both.

Conclusions

The main outcomes are set out at the beginning of the paper under the heading ‘Results to Date’.

This is the first case study of a planned series on individual dwellings in various locations. Results of further analyses will broaden the data on which to draw conclusions.

This study appears to indicate the following:-

- the ‘fly’ roof and thermal mass of the house, and its general configuration, are successful in achieving thermal comfort.

- the design and associated energy saving strategies have the potential to achieve substantial reductions in energy use per annum in comparison to ‘average’ patterns of consumption.

- the design and specification options have resulted in a house with reasonably low embodied construction energy even with the use of the ‘fly’ roof and high thermal mass in concrete floors and walls.

- overall energy in-use represents a much higher proportion of a life cycle energy pattern than the component attributed to embodied construction energy.

- personal transportation energy consumption for day to day living can heavily overshadow energy implications of design decisions, and this emphasises the impact of location in strategies for sustainable development.

- the impact of potentially controversial specification decisions, such as the decision to use aluminium windows, appear relatively insignificant in the context this total analysis.

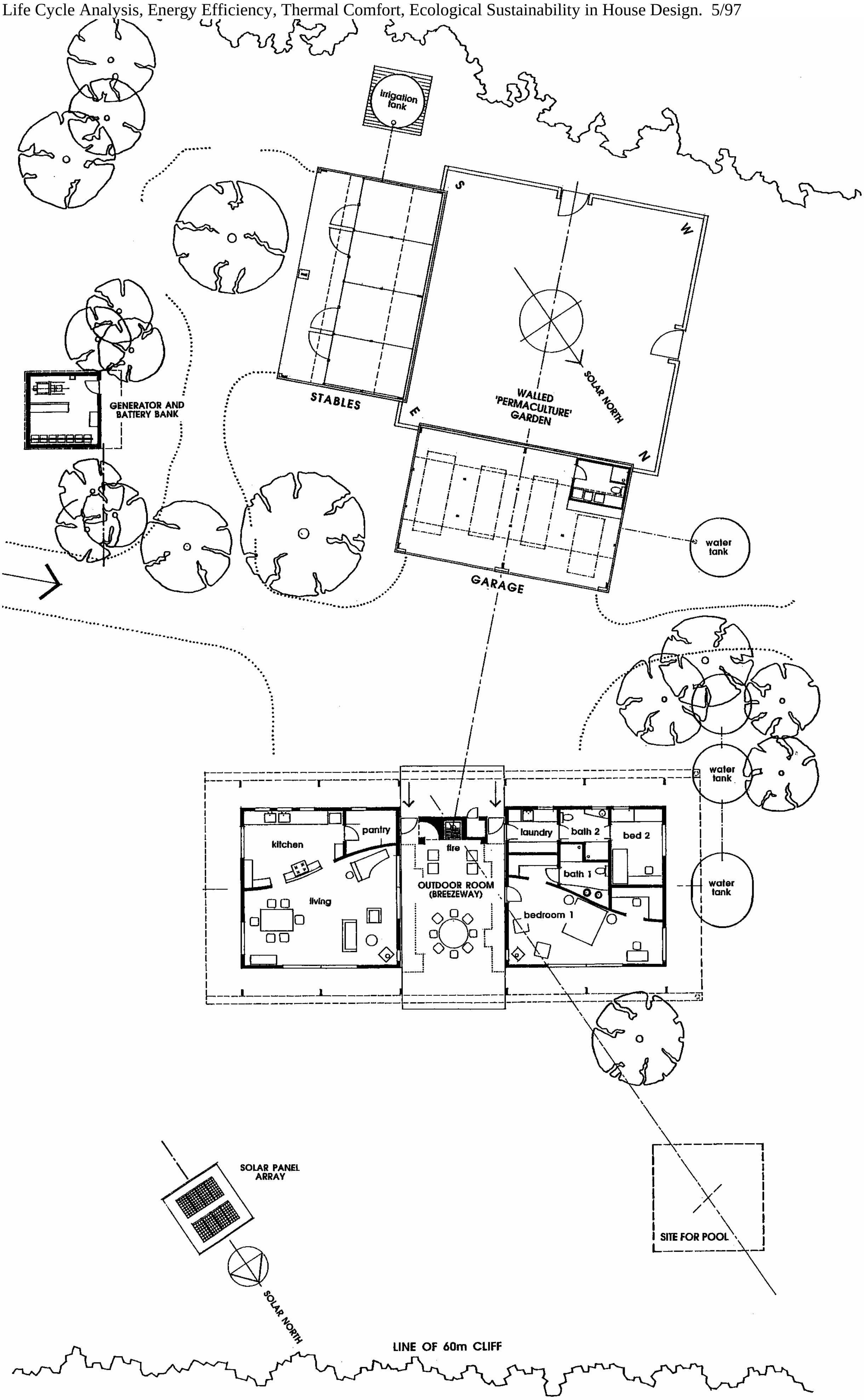

Figure 1 The "Four Horizons" Project. Plan of house and outbuildings

Life Cycle Analysis, Energy Efficiency, Thermal Comfort, Ecological Sustainability in House Design 5/97

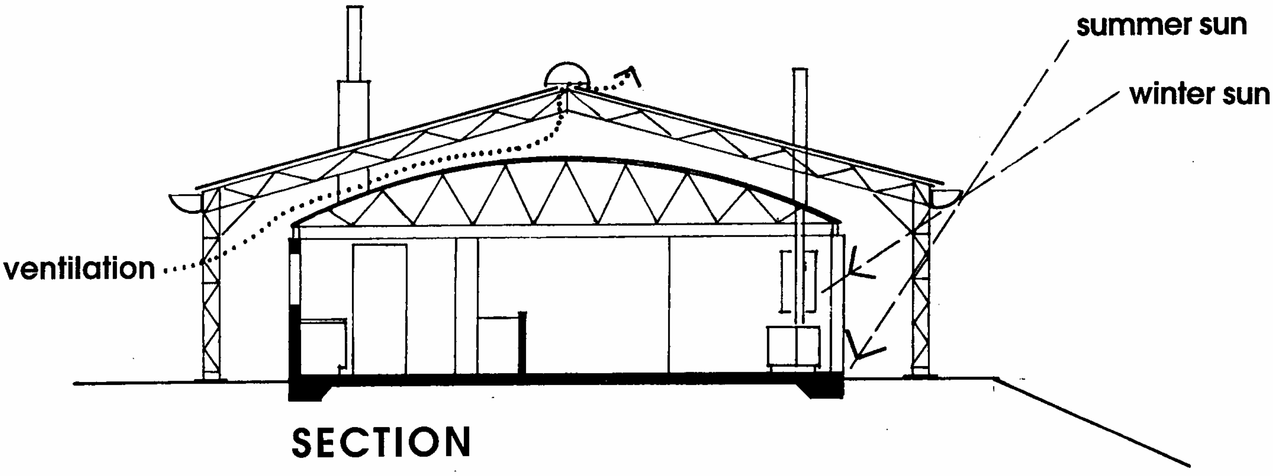

Figure 2 Section of house at "Four Horizons", showing 'fly' roof and dwelling modules beneath, cross ventilation and sun cut-off angles in summer and winter.

Life Cycle Analysis, Energy Efficiency, Thermal Comfort, Ecological Sustainability in House Design 5/97

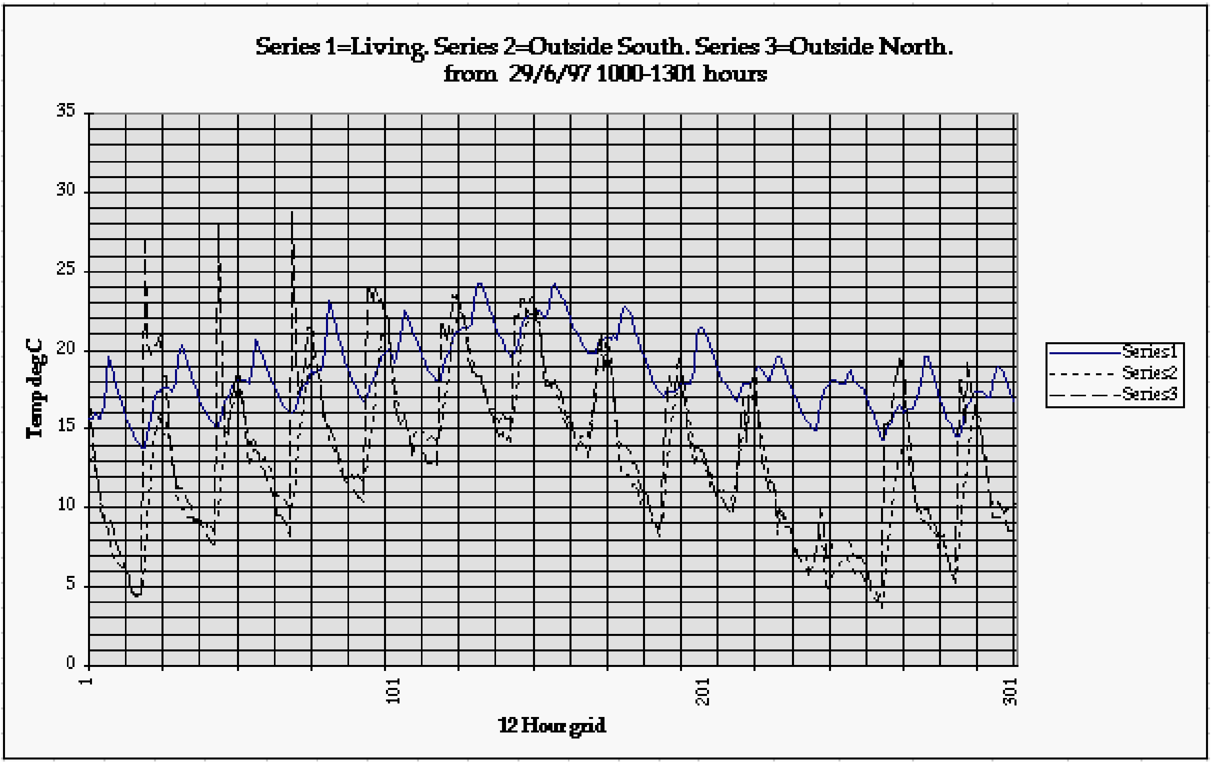

Figure3 Thermal Graph. Winter - Living Area

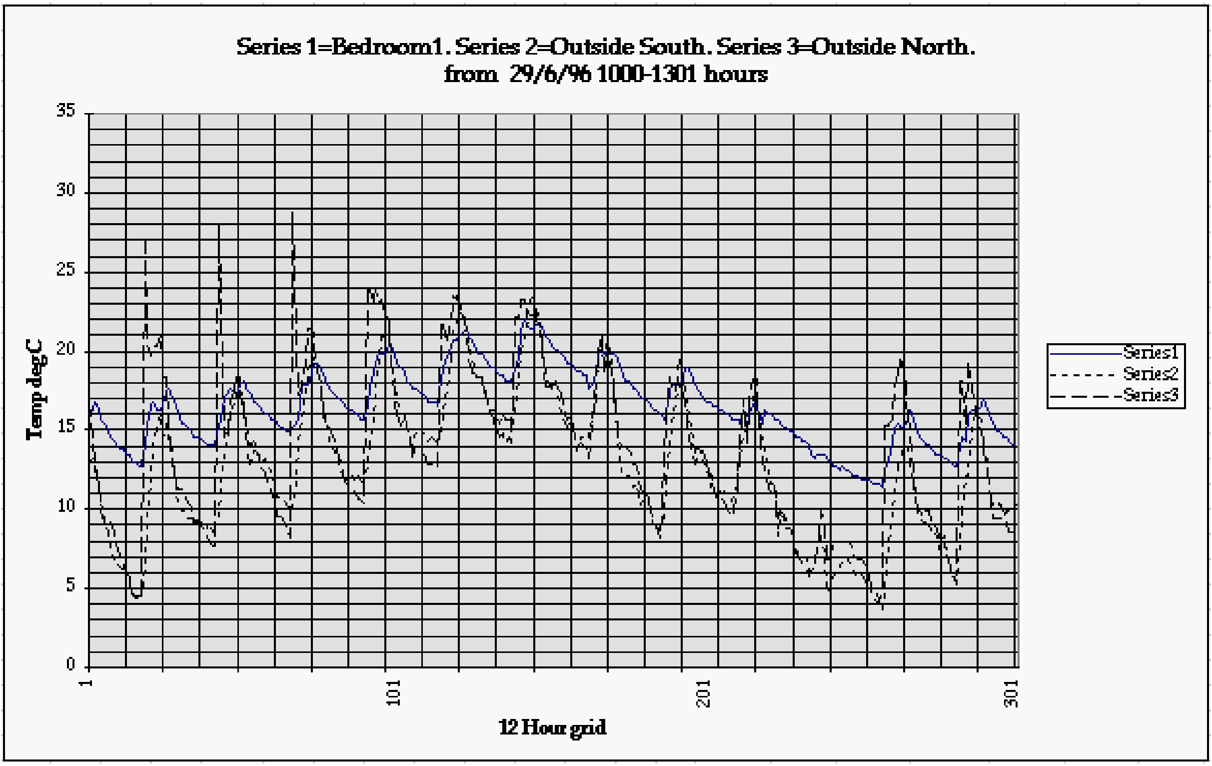

Figure 4 Thermal Graph. Winter - Bedroom 1

Life Cycle Analysis, Energy Efficiency, Thermal Comfort, Ecological Sustainability in House Design 5/97

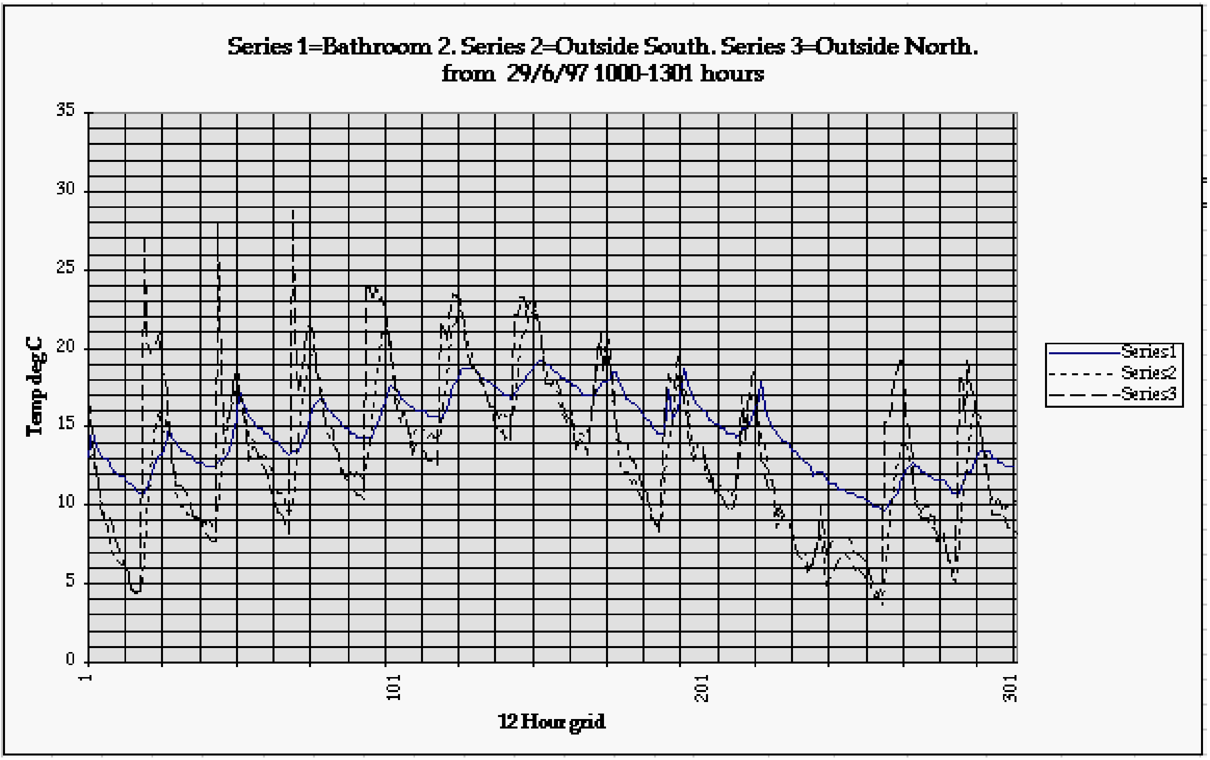

Figure 5. Thermal Graph. Summer - Bathroom 2

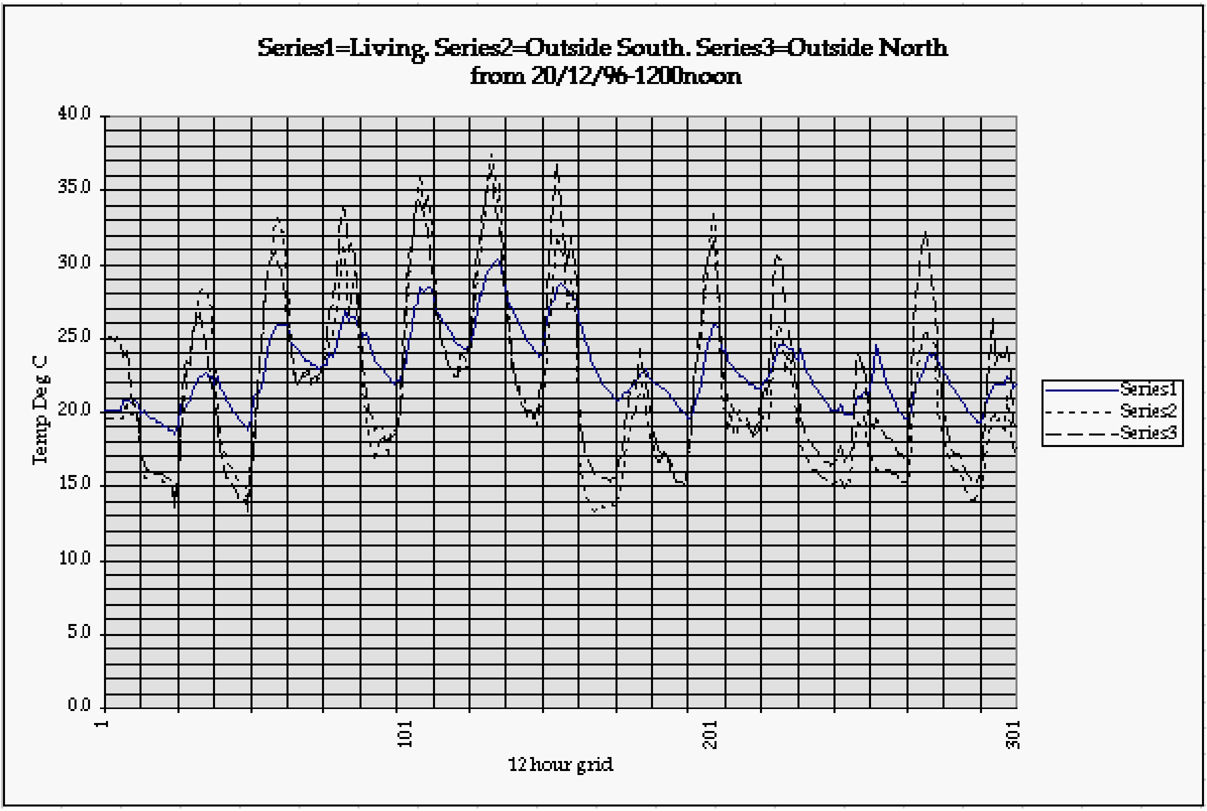

Figure 6. Thermal Graph. Summer - Living

Life Cycle Analysis, Energy Efficiency, Thermal Comfort, Ecological Sustainability in House Design
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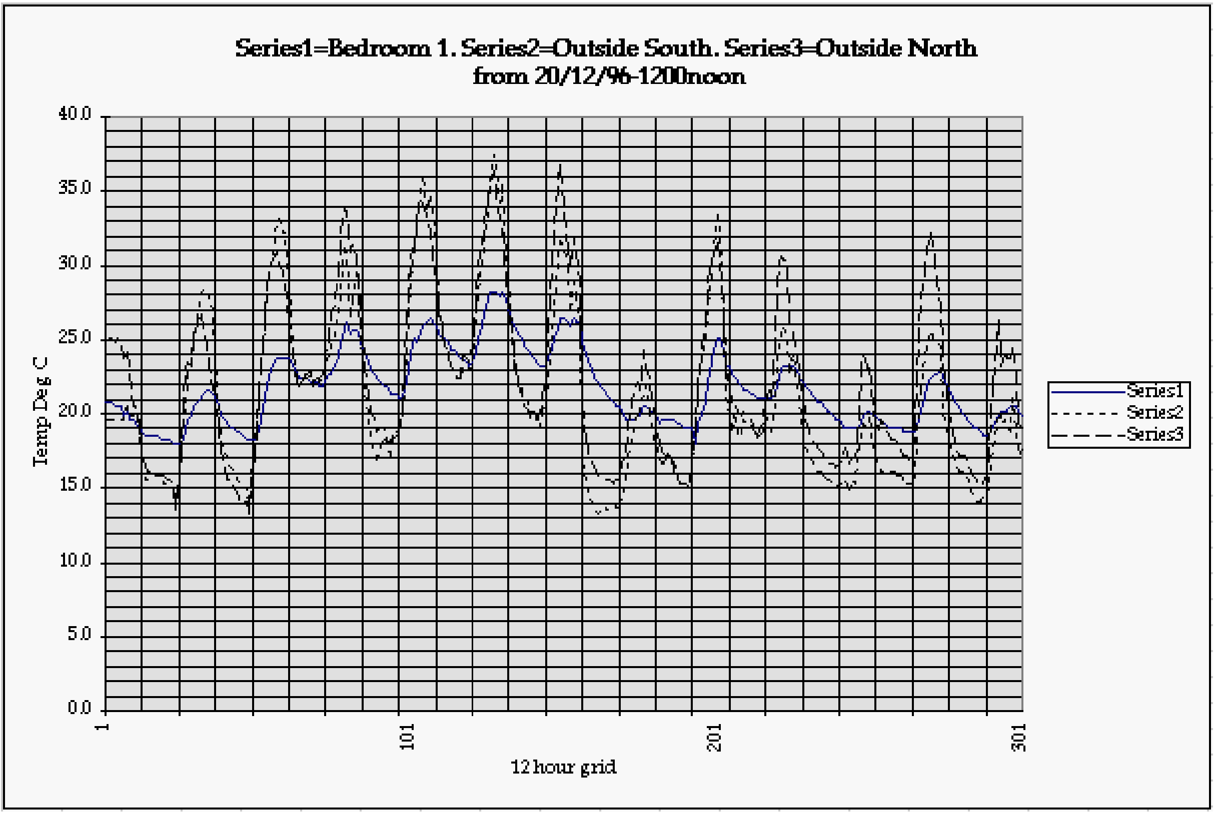

Figure 7. Thermal Graph. Summer - Bedroom 1

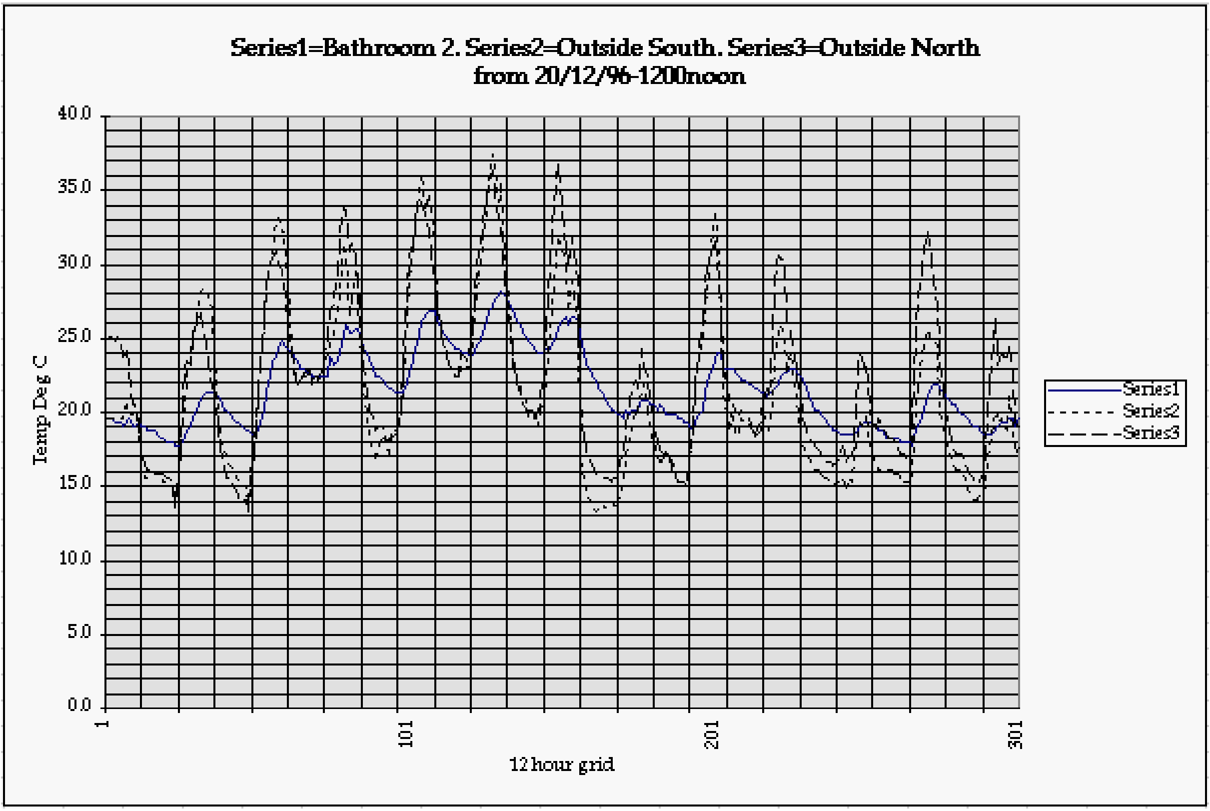

Figure 8. Thermal Graph. Summer - Bedroom 1

Product		**Energy (GJ)**	**Greenhouse (tCO_2 equivalent)**
Material			
Aggregate		15.65	1.10
Aluminium		27.94	2.33
Brick		30.26	1.61
Concrete		219.47	38.04
Copper		2.05	0.12
Glass		12.24	0.77
Gypsum		2.57	0.26
HDPE		4.97	0.08
Mortar		23.19	4.91
Paint		0.29	0.02
PVC		8.02	0.22
Steel		517.91	40.71
Terracotta		1.68	0.12
Timber		6.24	1.13
Other		61.31	4.79
	Total	**934**	**96**
Building Element			
Foundations & slabs		164.79	25.40
External wall		161.74	19.01
Internal wall		29.90	5.41
Floor		6.23	1.08
Sub roof		77.38	5.95
Windows/doors		47.87	4.04
Fittings		24.20	2.10
Flyroof frame		168.90	13.24
Flyroof cladding		105.63	8.22
Water tanks		55.14	5.46
Wiring		3.10	0.15
Piping		11.94	0.27
Solar array		61.31	4.79
Driveway		15.65	1.10
	Total	**934**	**96**
Buildings			
Flyroof		242	22
House		330	39
Outbuildings & externals		362	35
	Total	**934**	**96**

Figure 9 Total energy and greenhouse emissions for the construction of Four Horizons

Figure 9 The total energy and greenhouse emissions for the construction of Four Horizons.

Product	Energy (GJ)	Greenhouse (tCO_2 equivalent)
Living areas		
Frame-dwellings	33.8	2.79
Roof	5.5	0.48
Miscellaneous	9.9	0.82
Trims	2.4	0.2
Bathroom tiles	1.7	0.15
Steel cladding	21.8	1.79
Hardwood cladding	3.6	0.29
Insulation	3.3	0.04
External walls	61.6	12.11
Internal walls	12.9	2.53
Breezeway wall	35.5	2.21
Windows	6.5	0.57
Doors	8.6	0.77
Foundations & slabs	91.8	15.33
Paving	6.3	1.21
sub total	**305**	**41**
Fly roof		
Foundations	33	6.35
Structure and cladding	148.7	12.2
Guttering	4.9	0.4
sub total	**187**	**19**
Outbuildings		
Foundations	16.5	3.17
Frame-sheds	21.4	1.76
Garden wall	17	3.34
Generator shed wall	27.4	1.71
sub total	**82**	**10**
Total	**574**	**70**

Figure 10 Breakdown of embodied energy

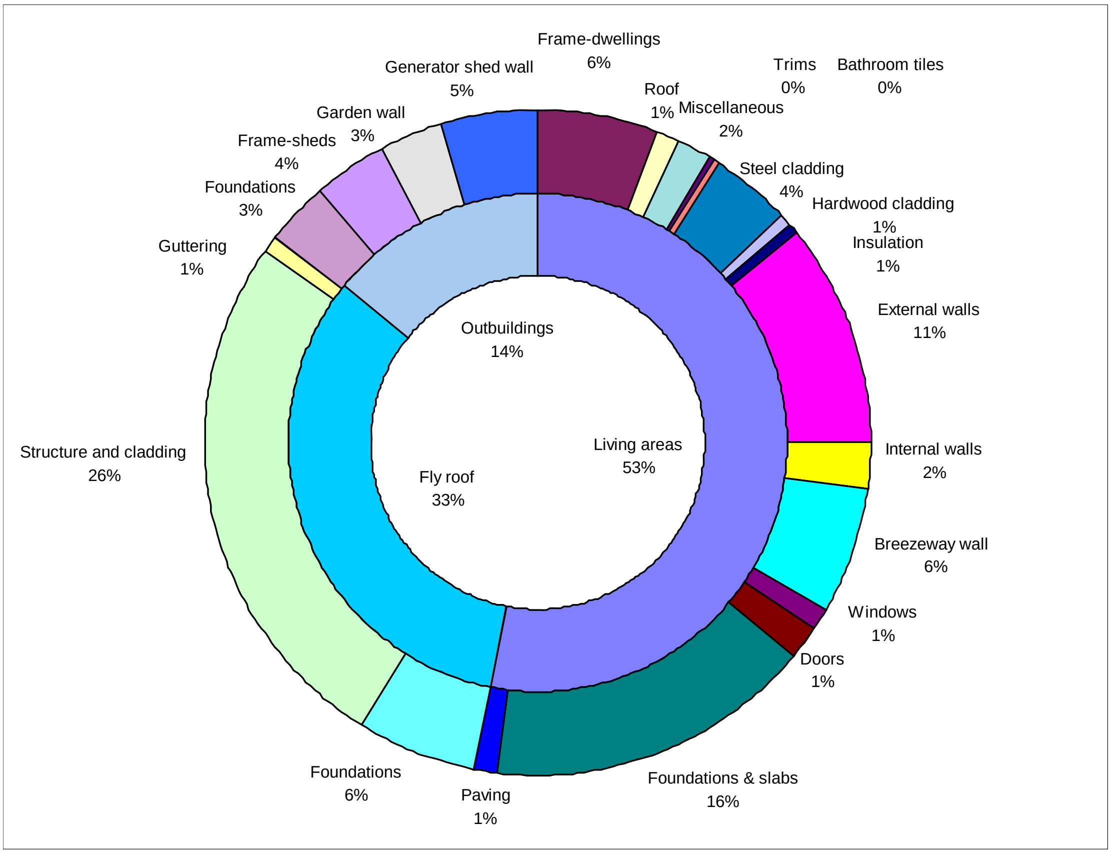

Figure 11 Breakdown of embodied greenhouse emissions.

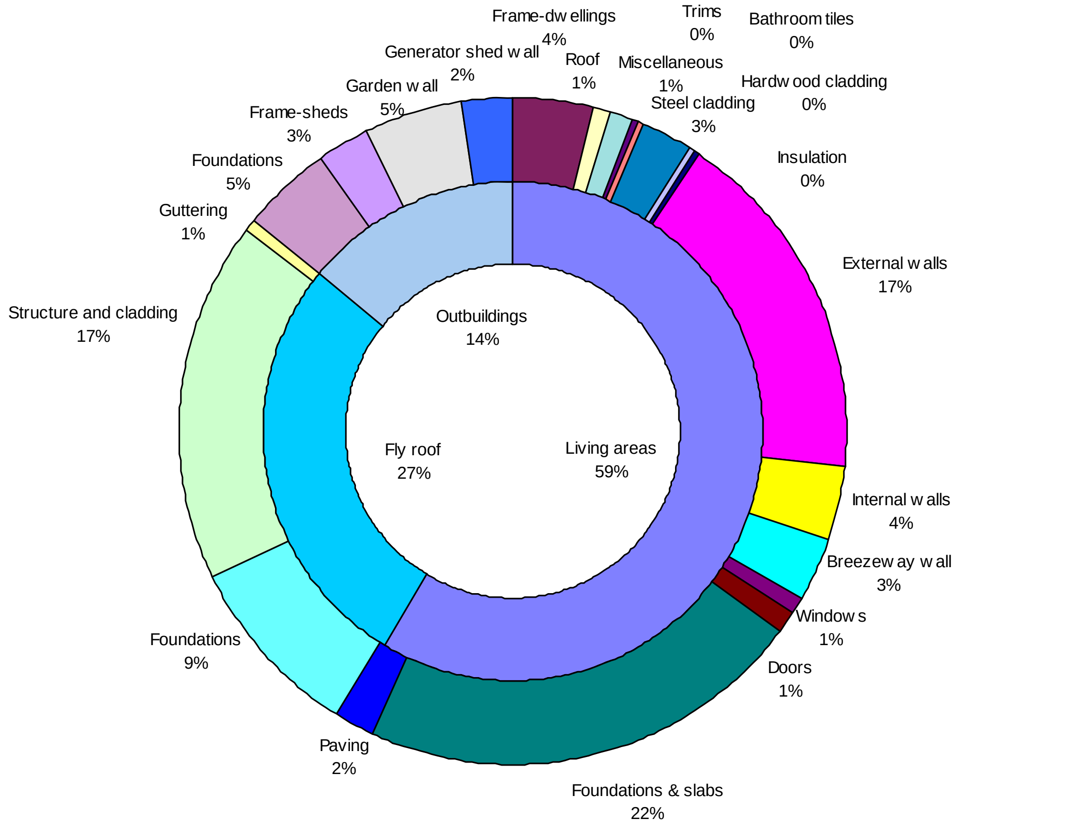

Figure 12 Embodied energy by area.

Area	Embodied energy GJ	Area m2	GJ/m2
House and fly roof	492	336 (roof area)	1.46
		216 (floor area)	2.28
Dwelling modules (excluding fly roof)	305	216 (including breezeway)	1.41
		162 (excluding breezeway)	1.88
Fly roof only	187	336	0.56

Figure 13 Utilisation energy per year and over a 40 year life.

Energy type	Quantity used (per year)	Energy content	Energy (GJ/y)	Energy (GJ/40 y life)
Solar	338 kWh	0.0036 GJ/kWh	1.2	49
Diesel	780 litres	38.3 GJ/kL	30	1195
Timber	468 kg	15 GJ/t	7	281
LPG	442 kg	49.1 GJ/t	22	868
Total			**60**	**2393**

Figure 14 Comparison of embodied energy and utilisation energy over a 40 year life.

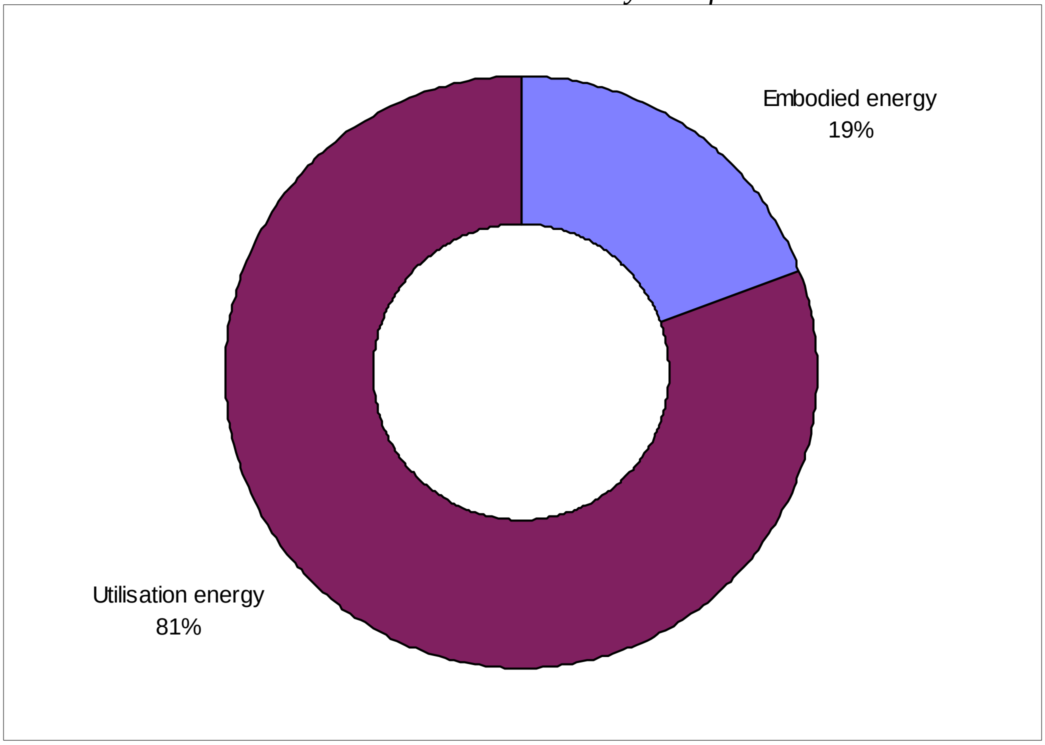

Figure 15 Comparison of embodied energy utilisation energy and travel energy over a 40 year life.