Anatomy of a Sub-tropical Positive Energy Home (PEH)

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ABSTRACT

Zero energy buildings (ZEB) and zero energy homes (ZEH) are a current hot topic globally for policy makers (what are the benefits and costs), designers (how do we design them), the construction industry (can we build them), marketing (will consumers buy them) and researchers (do they work and what are the implications). This paper presents initial findings from actual measured data from a 9 star (as built), off-ground detached family home constructed in south-east Queensland in 2008. The integrated systems approach to the design of the house is analysed in each of its three main goals: maximising the thermal performance of the building envelope, minimising energy demand whilst maintaining energy service levels, and implementing a multi-pronged low carbon approach to energy supply. The performance outcomes of each of these stages are evaluated against definitions of Net Zero Carbon / Net Zero Emissions (Site and Source) and Net Zero Energy (onsite generation vs primary energy imports). The paper will conclude with a summary of the multiple benefits of combining very high efficiency building envelopes with diverse energy management strategies: a robustness, resilience, affordability and autonomy not generally seen in housing.

Keywords – energy autonomy, house design, zero carbon, zero energy buildings, ZEB

1. INTRODUCTION

Energy consumption and greenhouse gas emissions attributable to the built environment globally are significant and growing [1]. Accounting for roughly half of the building sector's energy impacts, Australia's 8.4 million dwellings (2006 census) are responsible for 10% of the nation's total energy consumption and 13% of greenhouse gas emissions. Total energy demand and greenhouse gas emissions from housing are rising due to growth in the building stock and to lifestyle choices [2]. Queensland (QLD) is Australia's most energy intensive state, heavily reliant on fossil fuels, and the residential sector (1.66 million dwellings) accounts for 4.5% of the State's total energy use, or 7.7% of total electricity consumption [3]. Residential dwellings in Australia, predominantly detached houses, have not historically been constructed with energy efficiency or thermal comfort in mind. For example, despite the relatively benign climate of south-east Queensland, the region has more than 1.6 million refrigerative air-conditioners servicing 1.2 million dwellings[4]. The strong growth in reliance on air-conditioning is a major contributor to increases in household energy consumption and greenhouse gas emissions. Average annual energy use per household in Qld is estimated at 7210 kWh (19.75kWh/hh/day) and greenhouse emissions at 7292kg CO_2e, accounting for 20% of the national residential emissions [5].

The buildings sector has the best potential for dramatic emissions reductions, with an iterative integrated design process offering greater benefits than the incremental energy efficiency improvements resulting from an individual device / design solution approach. Estimates of 30-50% reductions in greenhouse emissions, using currently available technologies, have been made [6]. In comparison with programs aimed at low energy buildings or green buildings, the zero energy or zero carbon building approach is thought to have the greatest potential for energy and carbon reduction in the building sector [7]. In the United States, the Zero Energy Home (ZEH) concept is expected to "begin to diffuse into the market as early as 2012" and "has the potential to reverse the upward trend in new home energy consumption and begins to decrease the energy consumption of the entire U.S. housing stock even as the cumulative number of homes continues to rise" [8]. Australia's National Building Energy Standard-Setting Assessment and Rating Framework currently being formulated for the period 2011 – 2020, will continue to set increasingly stringent minimum performance standards over time and will incorporate the building envelope, the energy efficiency of key building services and a consideration of how building performance can be maintained through commissioning, operation and maintenance. This may or may not include adopting a 'zero energy' target [9].

1.1 What is a zero energy building (ZEB)?

The common definitions of zero energy buildings essentially reflect accounting variations in what is being measured (energy, electricity, carbon emissions or dollars), what energy services and forms are included in the demand (e.g. all electric and gas services) and types and boundaries of the energy supply (e.g. primary or end use energy). All definitions assume significant energy efficiency as a first step [10-12]. Common terminology includes

- *Net zero energy home*: energy consumption vs energy generation (onsite/source)
- *Net energy solar home:* onsite generation is solar
- *Net zero energy costs* ($ earned from exports vs $ spent on imports)
- *Net zero energy emissions / zero carbon home*

The purpose of this paper is to report on initial analysis of a triple bottom line (TBL) sustainability strategy utilized for this zero emissions sub-tropical house and its performance outcomes in its first full year of occupancy. Immediate household and environmental benefits will be quantified, followed by a discussion of key learnings and implications for various industry sectors.

2. METHOD

This paper represents part of a broader research program that utilises quantitative and qualitative approaches to better understand both the process of designing and constructing a sustainable house, and the actual performance of such houses, from the perspectives of the end client (the household). This specific case study adopts a qualitative and quantitative approach to identify and analyse the strategies utilised by one family to achieve an energy positive, zero emissions house, and the performance outcomes of each of the steps incorporated in that strategy.

2.1 Housing context

The physical context of the case study is a residential Ecovillage in sub-tropical Queensland, Australia (latitude 28^{o} south). The housing estate consists of detached housing of 1, 2 or 3+ bedrooms, for either single family housing or co-housing. An extensive Architectural and Landscape Code '*premised on the interconnectedness of all things*' and embracing '*both local and global concerns'*, governs the design and construction of housing in the estate. The elements encompassed by this Code can be broadly categorised into three areas: environment protection, resource management and social cohesion, reflecting the triple bottom line of sustainability. The building codes of the Ecovillage were analysed to understand the context in which this house was designed and constructed: all houses are constructed off-ground (i.e. on stumps or stilts) and incorporate a hybrid approach to the building envelope (mixed use of thermal mass and light-weight materials). Passive solar design, gas boosted solar water heaters (SWH) and a minimum 1kWp photovoltaic (PV) system are all mandatory, whilst high energy use appliances such as air conditioners and clothes driers are not permitted. The housing estate provides reticulated liquid petroleum gas (LPG) to each house lot - i.e. the gas infrastructure is a private network that connects a large LPG tank to each home in the housing estate.

2.2 Case study house

The case study house is the lead author's home, designed in 2007 and constructed in 2008. The floor plan and design and materials specifications of the house are shown in Figure 1 and Table 2. With an overall goal of environmental, social and economic sustainability, four key energy goals were incorporated by the owners and architect into the integrated 'whole-building' design approach: minimizing embodied energy, maximizing the thermal performance of the building envelope, minimizing energy demand and optimizing the performance of energy and water supply systems. Whilst analysis of the embodied energy of the house was not a consideration of this paper, design decisions for low embodied energy had to consider the impact of those decisions on the thermal performance of the building. The design process included reiterative simulations of the thermal performance of the building envelope using BERs Pro 4.1 (www.solarlogic.com.au), an approved thermal simulation software program in the Australian National Home Energy Rating Scheme (NatHERS). NatHERS establishes the thermal performance standards for the building envelope, presented as 'star ratings', indicating the maximum space heating and cooling energy consumption (MJ/m^2) permitted by regulation. Table 1 shows the increasing regulatory standard for houses in this climate zone over the past decade, revealing that regulation of building performance has been slow and incremental, and that the performance standard for the case study house far exceeds current regulatory requirements. (For a full explanation of the energy rating scheme and the simulation software protocols, refer to www.nathers.gov.au).

Tab.1: Star rating bands per climate zone

Climate zone	**Location**	**Star Rating / Maximum annual MJ/m² for space heating and cooling**									
		Star rating	1	3.5	4	5	6	7	8	9	10
10	**Brisbane**	MJ	203	83	71	55	43	34	25	17	10
Regulation standard			Nil: Typical house circa 1990	2003		2006	2011	Australia 2012 – 2020? Case study house 14MJ			

The software simulations utilised in this case study allowed assessment of 'what if' scenarios to assist in the decision making processes relating to design and materials selection (e.g. what is the energy efficiency gain by using low e glass compared with standard float glass.) The house was also rated after construction, to simulate thermal performance ‘as built’. These simulations were carried out in ‘*rating mode*’, under the requirements of the NatHERS rules, i.e. with an assumption that mechanical heating or cooling would be utilised to maintain comfort within specific temperature ranges for different types of rooms at different times of day. Software protocols are required to assume that cooling thermostats are set at 25.5^{o}C for this climate, whilst heating thermostats are set at 18^{o}C (dropping down to 15^{o}C between midnight and 7am). These simulations provided an estimated energy consumption in MJ/m^{2}/yr to maintain comfort if mechanical heating and cooling is used. (Refer to www.nathers.gov.au for more detail on the protocols and assumptions regarding heating and cooling requirements.)

Actual thermal performance data was gathered from temperature sensors in the main living room and main bedroom (refer to EcoVision below). Temperature data was analysed in ‘bins’ to reflect the protocols (thermal comfort bands, occupant interaction with the building and occupancy patterns) that underpin NatHERS protocols for accredited software. This data was compared with the simulation software in ‘*free running mode*’ – i.e. using the software to calculate the internal temperature of each room, assuming that no heating or cooling appliances would be used. This allowed comparison of actual thermal performance with simulated performance of a naturally ventilated, passive solar home.

Figures 1-5 show the floor plan, north (equator) and west elevations, detailed construction section, roof overhangs and sun penetration angles. Site context, design and materials specifications are summarised in Table 2. The impact of these design considerations is shown in section 3.1, and summarized in Table 4.

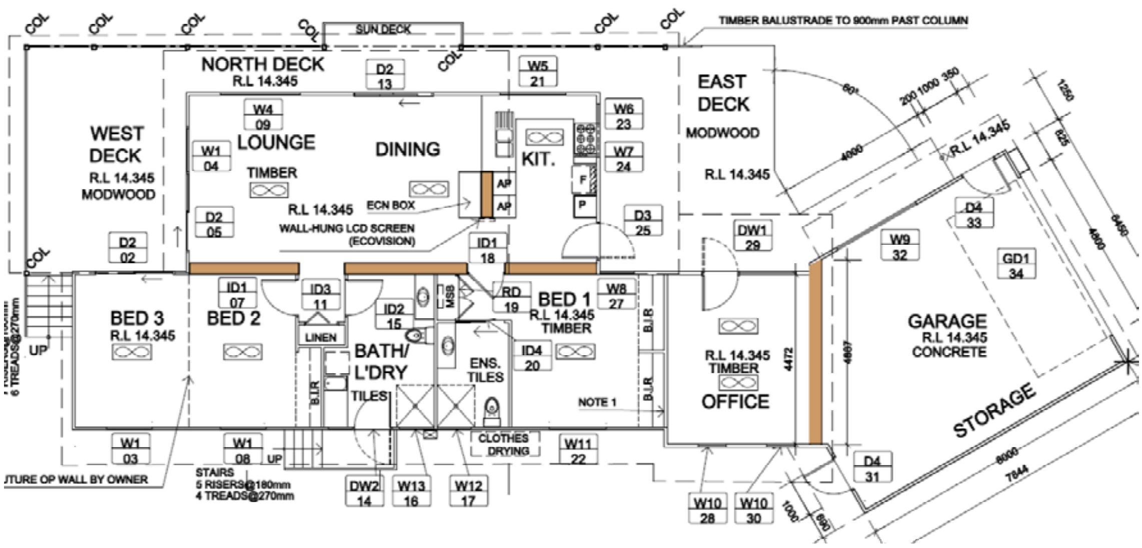

Fig. 1: Floor plan of “*Socrates*”- a small-medium house on stumps

Note: the house is named after the ancient Greek philosopher who espoused the virtues of passive solar design and natural ventilation.

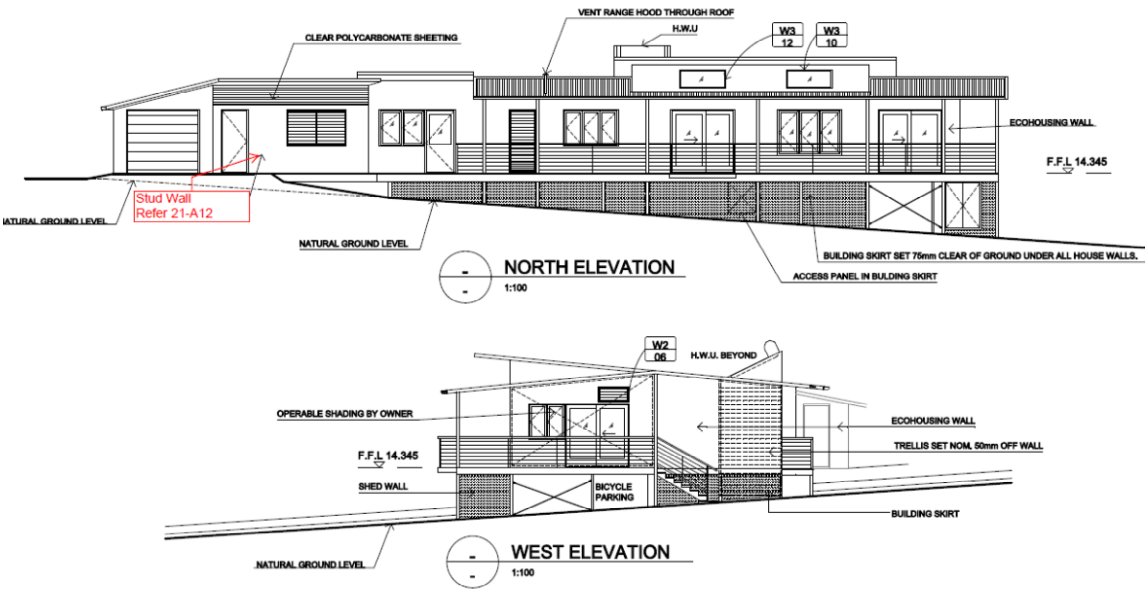

Fig. 2: North and west elevations

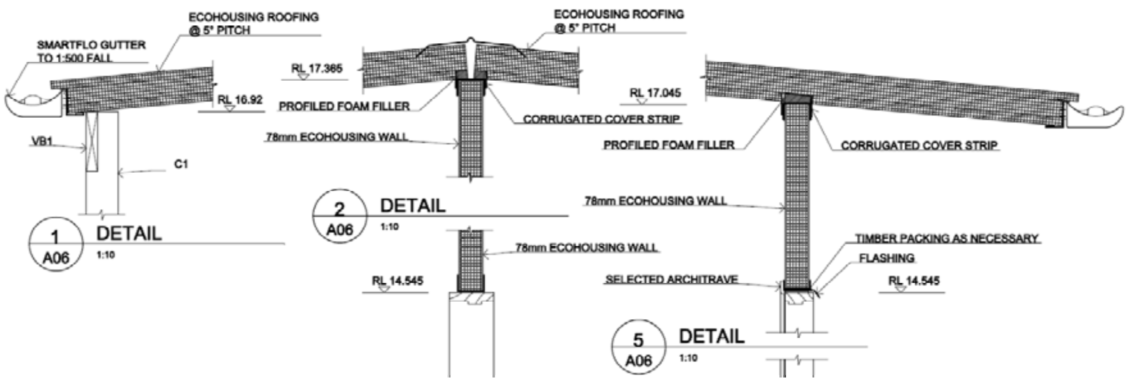

Fig 3: Detailed construction section

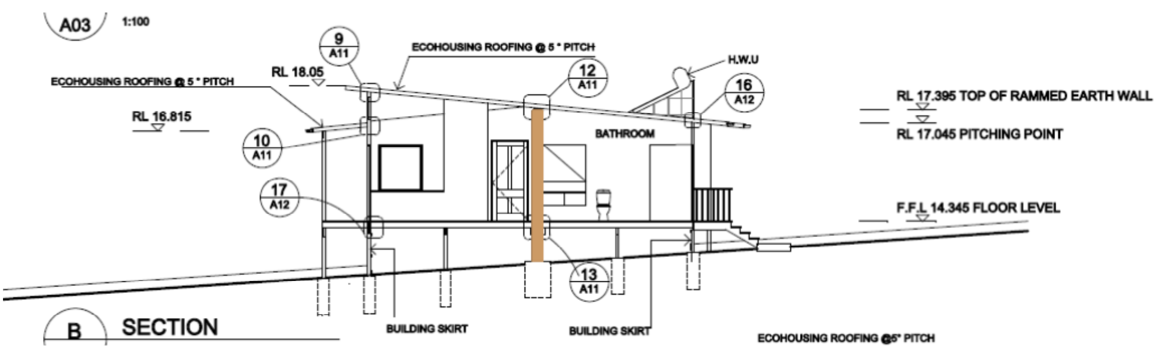

Fig. 4: Detailed section showing roof overhangs

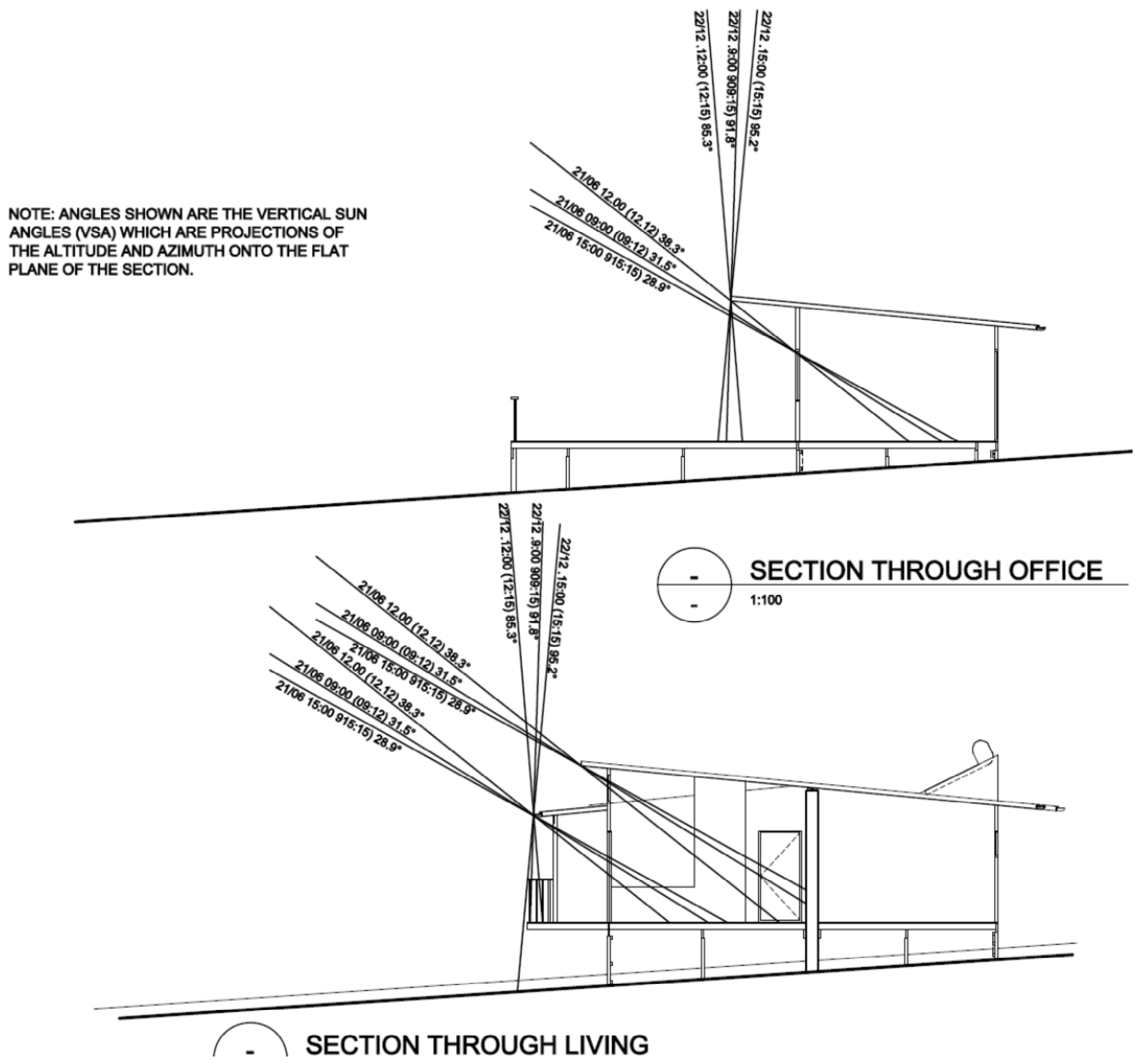

Fig. 5: Sun penetration angles

Tab. 2: House design, materials and construction specifications

"Socrates" specifications	
Orientation / Latitude	North; Latitude 28^{o} south.
Prevailing breezes	N/NE summer; S/SW winter
Daily average global horizontal irradiation	18.1 MJ/m^2 Range from 11.4 MJ/m^2 in June to 24.1 MJ/m^2 in December
Area	184m^2 Enclosed Gross Floor Area (GFA) – including attached garage 115m^2 conditioned space (internal area less bathrooms) 78.3m^2 deck space (deck = veranda / balcony/porch)
Glass to floor area	27.8%
Floor type / materials	Suspended timber floor on timber subfloor / steel posts / screw piers
Footings and garage slab	Cement with high flyash content
Subfloor	600mm off ground; enclosed space; Bearers and joists: 60% reclaimed hardwood; 40% new pine Insulation type: polyester batts + a hybrid insulation blanket consisting of low density closed cell polyethylene foam sandwiched by bimetallic foil. Insulation level R3; floor U-value 0.286.
House frame	The house has no wall or roof framing. The structural insulated panels provide, in one product, the structural integrity, internal and external cladding, and insulation.
External Walls	2700mm height minimum. 78mm structural insulated panel (fibre cement sheeting with polyurethane core). Insulation level R3.5; wall U-value 0.217
Roof	Skillion; 100mm structural insulated panels (.6mm steel sheeting with polyurethane core). Insulation level R4.6; roof U-value 0.215
Eaves (roof overhangs)	Average 900mm all orientations
Interior Spine Wall	3000mm height; Rammed earth 300mm thick.
Interior Walls	Timber frames / plasterboard; Insulated with polyester batts R2; wall U-value 0.439.
Flooring	Timber (reclaimed hardwood tongue and groove) in most areas; Australian made tiles in bathroom/laundry.
Deck Flooring	Wood composite (recycled plastics and sawdust)
Windows Doors Glazing* (single)	Timber frame casement windows (reclaimed) and aluminium frame louvers (reclaimed and new) Reclaimed solid timber doors (hinged) and timber/glass (sliding) Main glazing: Low e clear (U- value 3.67, SHGC 0.71) Western glazing: Low e tint (U- value 3.6, SHGC 0.52)
External balustrades	Reclaimed hardwood
External paving	Reclaimed brick pavers
Kitchen and bathroom fitout	E0 board (i.e. zero VOCs) for cabinetry; reclaimed sink, basins and fixtures Reclaimed timber / steel fittings
Occupancy	2 adults

Explanatory Notes:

Insulation: Insulation in Australia is sold by its R value (the thermal resistance) calculated by dividing its thickness by its thermal conductivity. Depending on the type of insulation, the marketing information may refer to the R value of the material itself, or the Total R value of the material and all other components of a particular building system.

Glazing: The U value refers to the insulation properties of the glass. SHGC= Solar Heat Gain Coefficient, a measure of how effectively the glass stops solar heat from entering the building. In each case, the lower the number, the better the performance. Standard 4mm single glazing, the most common glazing used in Australian houses, has a U-value of 5.88 and a SHGC of 0.84.

Window type: sliding aluminium window frames (50% opening) are the most common type of window utilised in Australian housing.

Household performance data was downloaded from the home's integrated water, gas and electricity resource monitoring and control system: EcoVision. This system uses an overarching systems platform to collect and store sensor information, collate the data into predetermined criteria, and display it on an in-house touch screen display:

- Electricity: general power, lighting, refrigeration, PV generation (1 pulse = 0.3125Wh)
- Water consumption: potable (rainwater), recycled, hot water (1 pulse = 1 litre)
- Gas consumption (1 pulse = 10 litres)
- Internal temperature and humidity (temperature only in main bedroom; temperature and humidity in main living area) (5 second sampling)

The raw data from these meters and sensors for the period June 2009 to May 2010 (the first complete 12 months for all sensors and meters) was extracted from the EcoVision database and imported into MatLab and Excel to allow for daily, monthly, seasonal and annual analysis. Internal temperatures were compared with typical mean year (TMY) climate data as incorporated in the simulation software. Building envelope design features, building systems design schematics and behavior analysis were used to provide some insights to explain both thermal performance and energy consumption outcomes.

Greenhouse gas emissions from electricity and gas consumption were calculated using Scope 2 and 3 emissions intensity figures(primary energy plus transmission and distribution losses) for Queensland: electricity 1.01kgCO_2e/kWh; LPG 64.9 kgCO_2e/GJ [13]. Electricity and gas bills were utilised to determine energy costs and revenue.

3. RESULTS

3.1 Thermal comfort

The house 'as constructed' was simulated to achieve 50% better energy efficiency (9 stars – 14.3MJ/m^2 /yr) than 'as designed' (7.5 stars - 31.6MJ/m^2 /yr), reflecting some construction improvements made during construction (e.g. additional insulation), a refinement in details entered into the modeling software, and improvements made in the modeling capacity of national simulation software. The 9 star rating represents the actual building energy rating, not the adjusted rating allowed under national regulations due to the smaller size of the building (under 200m^2). The simulated annual total energy load comprised of a winter heating load of 6MJ/m^2/yr and a summer cooling load of 8.4MJ/m^2/yr.

A histogram (Figure 6) of annual hours within different temperature zones was developed, enabling the comparison of actual room temperature (bedroom and living room) with simulated performance predictions and outdoor temperature (Australian Bureau of Meteorology (BOM) data). (Note: the outdoor temperature data represents a 'typical year' based on a 30 year average, not the data for the specific year 2009-2010. It should be noted that, at the time of this study, local climate data was not available to enable comparison of the local micro-climate with the TMY of the simulation software. Anecdotal evidence suggests that this particular year was not notably different to a 'typical year'.). Examination of this graph reveals several key findings regarding internal temperature compared with external temperature, as shown in Table 3.

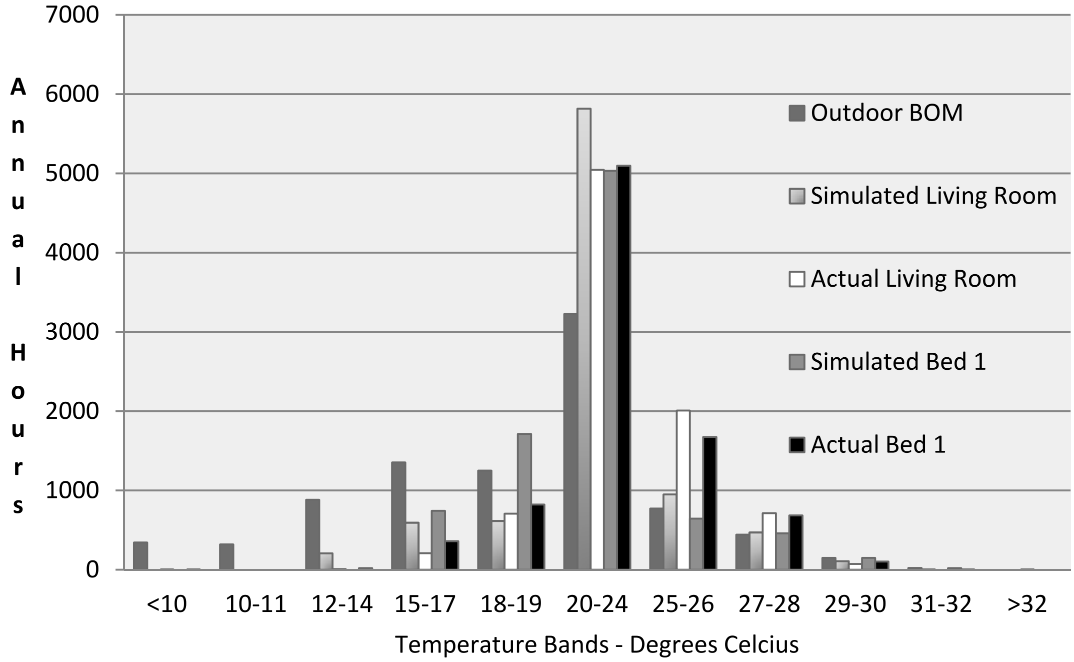

Fig. 6: Comparison of simulated and actual annual thermal performance

Tab. 3: Comparison of internal and external temperatures

Temperature parameter	Internal Ambient Temp.	External (BOM) Ambient Temp.
% of annual hours 20-26^{o} C comfort zone range	80%	45%
% of annual hours in 18-28^{o} C expanded comfort zone range	96%	65%
% of annual hours under 18^{o} C	2-4%	25%
% of annual hours above 28^{o} C	1%	2%
Annual hours above 30^{o} C	1	22

In peak summer, comfort levels were managed on ‘very hot’ days by operating the building as designed, i.e. to exclude incoming heat during daylight hours (closing doors and windows and curtains) when the external temperature was higher than the desired internal temperature, and to open windows to allow for cooling evening breezes when available and allow for night purging. This is consistent with expected behavior assumed by the simulation software, i.e. that occupants will open or close windows and doors if the external climate is hotter or colder than the desired internal temperature. Ceiling fans were utilized on a few occasions where additional cooling effects were required. The table also shows that the house has a significant winter benefit, with annual hours under 18^{o}C being 90% less than external hours in this temperature band. This has removed the need for any space heating. It should be noted that occupants are acclimatized Queenslanders.

The systematic approach to the design incorporated a number of design and materials strategies contributed, collectively, to this high level of thermal performance, as summarized in Table 4. For example, the re-iterative use of the simulation software, which models air flow, allowed for the optimisation of window placement, size and type to enable cross ventilation into all rooms.

Tab. 4: Effective design and materials strategies

Energy service / Appliance	**Integrated Design Strategies**
Design process	Re-iterative use of simulation software by the architect as a decision support tool, to explore 'what if' scenarios of design and materials selection.
Building Form to enhance natural ventilation (Fig. 1, 2,4)	The long and narrow rectangular form (approximately 2:1 ratio) enhances cross ventilation opportunities for southern rooms. The southern bedrooms extend past the northern living rooms, allowing northern ventilation openings (Fig. 1). High ceilings and skillion roof (2.7 – 4.2m height) allow any hot air to rise above occupants, and be vented through clerestory windows (Fig, 2,4).
Materials selection to control temperature (Fig, 1-4, Tab. 2)	Structural insulated panel walls reduce thermal bridging, infiltration and poor insulation installation. Insulation level is much higher than what can be utilised in a standard 90mm stud framed construction. (Fig. 3) Use of low emissivity glazing throughout + tint on western glazing Mixed window type: louvers were used in areas to capture direct breezes and allow for night purging, whilst casement windows were used to capture and control cross breezes. (Fig. 2) Vertical mass rammed earth wall as central spine, providing thermal mass benefits to all rooms. (Fig. 1, 4) Internal window furnishings (pelmets and thermal-backed heavy curtains).
Sun Control (Tab. 2, Fig. 5)	Light colours for external walls and roof. Eaves (roof overhangs) designed to eliminate sun penetration between spring and autumn equinox. (Fig. 5) Operable western shade.
Decks (Fig. 1; Tab.2)	Eastern and western outdoor living spaces to enable residents to take advantage of the sub-tropical climate.

3.2 Energy efficiency

Electricity consumption in the home provides for the services of lighting, refrigeration and general power (e.g. dishwasher, washing machine, computers, telecommunications, power tools, entertainment equipment etc). Table 5 summarises the strategies used to minimize general power consumption whilst Figure 7 shows how different services account for the average daily electrical load of 3.46 kWh. The daily average gas consumption (for cooking) was 1.5kWh (5.4MJ), which gives a daily average total energy consumption (stationary energy) of 4.96kWh equivalent. This is ¼ of the average Queensland household energy consumption and less than a sixth of the average south-east Queensland household energy consumption.

These figures do not include the energy utilized for potable water pumping (124 litres /day) or ceiling fans. Both of these services are supplied by a 24v DC circuit which is supplied by a battery bank that was charged, until recently, with 'discarded' 25W solar panels. The demand for these services is very low due to building systems design optimization and equipment efficiency as shown in Table 6. The small 135AH 24V DC battery bank (3.24kWh) is now charged by a 300W single axis tracking PV array (second hand monocrystalline PVs) with seasonally adjustable tilt. This will enable additional DC loads, such as communications and monitoring equipment, to be transferred from the ac mains to the DC circuit over time.

Tab. 5: Energy efficiency strategies

Energy service / Appliance	Strategies
Lighting	Lamp choice (T5 fluro tubes; CFLs, LEDs) Placement / luminnaire (wall mounted up-lights; task lighting) Control (1 switch per light)
Refrigeration	Efficiency (5 star; floor and side venting; not close to heat sources)
Appliance efficiency	Water and energy efficiency of dishwasher, washing machine Outdoor clothes line in full sun all year; wet weather drying area included
Other equipment	Laptop computers with high-efficiency LCD desktop monitors Minimise appliance number (e.g. 1 television)
Control	Power points 1 m off floor for easier access / control
Water management	Minimise pipe runs to reduce pumping requirements

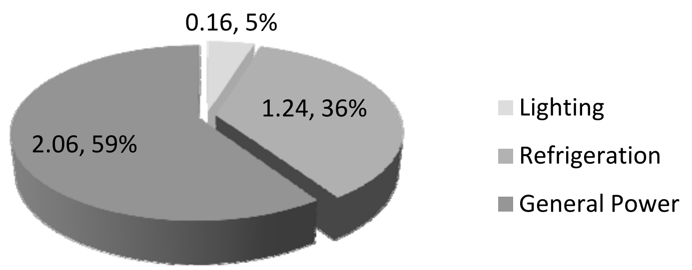

Fig. 7: Average daily electrical demand (kWh) and % per service

Tab. 6: Approaches to services provided on DC power circuit

DC services	Design optimisation	Equipment optimisation
Water pumping	45,000 litre tanks on highest land elevation; adjacent to main water use areas	Variable speed pump 5A at 24V (120W) Water efficient appliances
Ceiling Fans	High insulation and natural ventilation options provide comfort most of year; Fans only required in extreme temperatures	30W max power; 5W normal operation

Recycled water (197 litres/day) is used for toilet flushing and productive food garden. Based on measurement and analysis of the estate's sewage treatment and water reticulation system by the Queensland government, the energy attributable to this household for these services (sewage treatment and reticulation) is 220Wh/day [14].

3.3 Energy Supply

Daily hot water consumption of 63 litres is provided 99% of the year by a 300 litre close-coupled flat plate solar water heater mounted at 35^o pitch to maximize winter performance when hot water demand is higher and the cold water input temperature is lower. The small amount of boosting required is provided by an instantaneous gas booster, operated manually as required. The high solar fraction is attributable to a combination of system size (essentially oversized for a family of two people with a very low demand) and system optimization for winter performance. The 1.7kW monocrystalline PV system is mounted on a tilt frame ($18 – 40^o$) which is adjusted seasonally to optimize performance. The array is subject to a small amount of shading from an eastern ridge line before 7 am all year round. The average daily output of the array is 7.58kWh, showing a normalized output of 4.41 kWh per kWpeak PV array. The combined cooktop and oven utilizes estate reticulated LPG.

3.4 Energy balance: Net zero energy

On an annualized basis, the house easily meets the *net zero site energy* definition, with a total energy consumption (gas and electric) of 1.8MWh and a total renewable energy electricity generation of 2.77 MWh. This also meets the definition of a *net energy solar home*. Further analysis shows that the house achieved ZEB status each month (June 2009 – Jun 2010), even in winter, as shown in Figure 8.

3.5 Energy balance: beyond net zero emissions to net positive energy

Accounting for primary energy sources and generation and distribution systems losses, the emissions balance from stationary household energy boundaries discussed previously is net positive to the tune of 1396.5 kgCO_2e annually. (Greenhouse gas emissions from electricity and gas consumption were calculated using Scope 2 and 3 emissions intensity figures [13] for Queensland: electricity 1.01kgCO_2e/kWh; LPG 64.9 kgCO_2e/GJ.) Energy use for hot water, potable water pumping and ceiling fans is not included in this calculation, as they are already provided through zero emissions means independent of any centralized network. This means that the house exceeds the parameters implied for *net zero emissions* or *net zero carbon.*

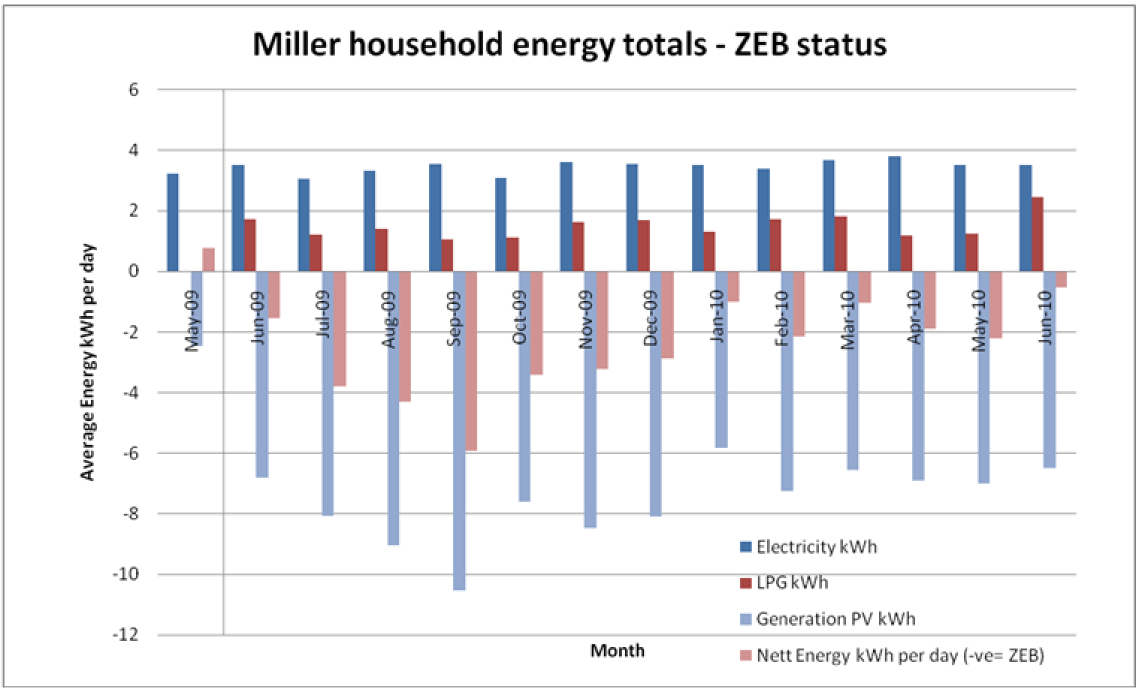

Fig. 8: ZEB status by month

4. DISCUSSION

The specific energy goals for the house could be ascribed to the Triple Bottom Line (TBL) of sustainability: economic (energy and water self-sufficiency; resilience; adaptability), environmental (passive solar design; low embodied energy) and social (thermal comfort; universal design). How has the integrated systems approach to the provision of household energy services, driven by the end user in collaboration with the architect, delivered on the triple bottom line?

4.1 Design for thermal comfort: meeting social need

A house, or indeed any building, exists to serve human needs, yet it is universally acknowledged that buildings do not have a good track record of performing according to design predictions [15]. Designing homes to maximize human thermal comfort whilst minimizing the need for mechanical space heating or cooling technologies is the first major requirement in optimizing design for zero energy buildings [16]. What can we learn from the actual thermal performance of the house in relation to star ratings and thermal simulation software? Firstly, the actual performance (90% within 18 – 28^{o}C) exceeds the predicted performance, providing a sufficient level of certainty in the thermal simulation software to encourage designers to utilise it as one tool in their design process to enhance building performance. On the other hand, the results are disparate enough (refer to Figure 6) to suggest that further analysis is required to understand these discrepancies. The microclimate in this valley is significantly different to the climate at Brisbane airport (open coastal plain) on which the simulation software is based. At this stage, no statistical comparison is possible due to a limited set of local microclimate data. Occupant operation of the house is consistent with simulation software assumptions that people will open and close doors and windows to manage their comfort. The accuracy and placement of the internal temperature sensors was not yet been rigorously tested to determine the accuracy of actual temperature data.

Secondly, the design of this house allows the occupants to manage their comfort levels in a variety of ways: through the utilisation of two large outdoor living spaces (to make use of, or avoid, prevailing seasonal breezes), through the capture and control of natural ventilation through louvers (direct breezes) and directional casements (cross winds), and through night purging (windows allowing hot air to escape at night, without posing a security risk). Because of this flexibility, the ceiling fans are only required in extreme circumstances. This indicates that the thermal performance of the building envelope is only one indicator of a house's ability to provide human comfort. Incorporating a range of options within the design allows for a greater level of personalisation to meet individual comfort needs. It also indicates a need for 'operations manuals' to be provided with houses in order for occupants to learn how to 'drive' the house to achieve its designed performance levels. A comparison of the performance of this house, and its occupants, is being made with seven other dwellings in the same estate. This is the subject of another paper.

4.2 Demand minimisation: meeting economic need

Further demand minimisation was shown in the daily average energy consumption of just under 5kWh/day, about ¼ of the 'average' Queensland home. This level of savings is at the upper end of savings recorded by low energy commercial buildings that had thermal envelopes that exceeded current energy codes [10]. The demand minimisation achieved in this house has had three significant economic impacts for the household: firstly, the annual energy bills for the household (gas and electricity purchases plus associated network charges) for this study period (2009-2010) amounted to AUD$310 compared with a regional average of AUD$2100. (Electricity prices at the start of the study period were 16.29c/kWh, rising to 18.84c/kWh for most of the study period. LPG prices were the equivalent of 15.01c/kWh at the commencement of the study period, rising to 16.29c/kWh then17.42c/kWh by halfway through the study.)

Secondly, the household has been able to benefit from the Queensland government's Solar Bonus scheme, which pays 44c/kWh for 'instantaneous net' electricity exported to the grid (www.cleanenergy.qld.gov.au/solar_bonus_scheme.cfm). Earnings from the Solar Bonus scheme, combined with the electricity retailer's additional payment of 6c/kWh for exported solar power, have resulted in household earnings from PV exports of $1139. This level of earnings from a net feed in tariff is due to an optimisation of PV generation output and a minimisation of household load. This means that the net cost for the provision of energy services for the household was a net income of $829, exceeding the definition of a *net zero cost house*. This can be compared with an 'average' annual cost to Queensland households of $1600. Thirdly, the household has been relatively unaffected by the 11.8% and 15.5% increases in the price of electricity and gas respectively, during this study period (12 months to June 2010). Considering that Queensland electricity prices increased almost 50% in the period 2007 – July 2010 and are expected to rise by at least 10% per annum for at least the next five years [5], the economic benefit of energy efficiency and the utilisation of renewable energy will grow over time.

4.3 Energy supply strategy: meeting environmental need

Good design and energy efficiency combined to minimise energy demand, making it much more economical to meet most of the remaining demands from renewable energy sources. Good design enables the solar water heater to meet almost 100% of hot water demand. Utilisation of gas for cooking and the residual water heating enabled maximum energy transformation efficiency, making the achievement of ZEB status easier [10]. Installing the PV system in a manner which allows for seasonal optimisation enables this system to meet its rated performance parameters, maximising economic benefit. The addition of a DC circuit with energy storage, whilst not common, has an added value of energy service security and resilience: neither the water pumps nor the fans are reliant on grid availability, nor do they contribute to grid peak demand.

4.4 Systems approach

The design strategy utilised by this case study house viewed the building as a complex integrated system in order to deliver energy services in a sustainable manner. Whilst this does not appear to be a common strategy in the residential market, it is consistent with high-performance green (commercial) buildings that deliver 20-40% greater energy savings than the mainstream approaches to reducing energy in buildings [17]. This strategy also reflects the process identified for achieving zero energy homes in the US [8, 10]. The integrated systems approach allowed for the optimisation of outcomes that ensured better cost effectiveness, a 'bundling' strategy that has been shown to be successful in the US [8]. This approach represents a significant shift from current practice in the design and construction of single-family dwellings in Australia, arguably enabling a transformation of the building stock that is required [9].

Further analysis and evaluation of this case study data is being undertaken in four areas:

- Correlating thermal performance and BOM data with microclimate data
- Determining the extent to which zero energy boundaries can be extended to include other household energy services and related services such as water supply and sewage treatment;
- Quantifying the impact of the house on the electricity network; and
- Evaluation of the multi-resource monitoring technology.

5. CONCLUSION

Measured performance data for this house has shown that it achieves high levels of thermal comfort, a significantly reduced energy demand and an energy supply strategy that enables the home to be net zero emissions for all stationary energy use. The benefits for the household extend beyond environmental considerations of greenhouse gas emissions. The enhanced comfort levels (e.g. 90% of time between 18 – 28^{o}C; 1% of time >30^{o}C and 2% of time <18^{o}C) means that this family does not rely on either commodity purchases (e.g. electricity, gas) or infrastructure provision in order to achieve comfort. The house also provides a variety of strategies for the family to manage their comfort levels through building operation and space utilisation.
The very low energy consumption for remaining services (one sixth of the regional average consumption) results in energy bills one seventh of the regional average ($310 compared with $2100), without taking account of the earnings from the net feed in tariff. This low consumption means that the family is much less impacted on by rises in energy costs, and will be minimally affected by any future carbon prices. The earnings from the net feed in tariff were more than sufficient to cover the consumption costs and network charges, resulting in a net annual income of $800.

The integrated systems approach to this zero energy home, encompassing building design, materials selection, energy demand management, optimisation of solar technology performance, and fuel diversification, have enhanced the social, economic and environmental sustainability of this family in their subtropical climate.

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