Positive Energy Homes: Impacts on, and Implications for, Ecologically Sustainable Urban Design

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ABSTRACT

A zero-energy home (ZEH) is a residential dwelling that generates as much energy annually from onsite renewable sources, as it consumes in its operation. A positive energy home (PEH) generates more energy than it consumes. The key design and construction elements, and costs and benefits of such buildings, are the subject of increasing research globally. Approaching this topic from the perspective of the role of such homes in the planning and development 'supply chain', this paper presents the measured outcomes of a PEH and discusses urban design implications. Using twelve months of detailed performance data of an occupied sub-tropical home, the paper analyses the design approach and performance outcomes that enable it to be classified as 'positive energy'. Second, it analyses both the urban design strategies that assisted the house in achieving its positive energy status, and the impacts of such housing on urban design and infrastructure. Third, the triple bottom line implications are discussed from the viewpoint of both the individual household and the broader community. The paper concludes with recommendations for research areas required to further underpin and quantify the role of ZEHs and PEHs in enabling and supporting the economic, social and ecological sustainability of urban developments.

Keywords – energy resilience, positive energy home (PEH), urban design, urban infrastructure, zero energy home (ZEH)

INTRODUCTION

The built environment accounts for about 40% of global energy consumption and is responsible for approximately 1/3 of greenhouse gas emissions (UNEP Sustainable Buildings & Construction Initiative, 2009). 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 (ASBEC, 2008). Total energy demand and greenhouse gas emissions from housing are rising due to growth in the building stock (ASBEC, 2008) and to lifestyle choices (Atkinson, 2010). Being heavily reliant on fossil fuels, Queensland is Australia's most energy intensive state, 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 (Environment and Resources Committee, 2010). Queensland's sub-tropical south-east corner is the fastest growing urban development area in the state and arguably Australia. Household electricity consumption in this region has also been growing by a staggering average of 10% per annum since 2002 (Mills, 2010), predominantly attributable to the increasing reliance on air-conditioners to provide indoor thermal comfort in houses. This growth in electricity consumption is despite a raft of Government energy efficiency programs such as Minimum Energy Performance Standards (MEPS) for appliances, increased thermal performance standards for buildings, financial assistance packages, and information campaigns (www.climatechange.gov.au). This growth in reliance on the electricity network, arguably driven by a combination of poor building forms and social and market pressures and paradigms (Cole *et al*, 2008; Healey, 2008), has significant sustainability implications: economically (in terms of urban infrastructure required for electricity distribution networks as well as household operational costs), ecologically (increased greenhouse gas emissions) and socially (e.g. decreased adaptation responses).

Global research shows that the buildings sector conceivably has the best potential for dramatic emissions reductions, particularly if it adopts an iterative integrated design approach to energy service provision, as opposed to an incremental individual device approach (Levine et al, 2007). Emissions reductions of 30-50% are said to be possible by 2020 through readily available technologies, design, equipment, management systems and alternative generation solutions (UNEP Sustainable Buildings & Construction Initiative, 2009). This potential for dramatic reductions in the energy related emissions of the sector is reflected in policy directions globally that are moving towards zero energy standards for buildings, such as the requirement for all new buildings in the EU to conform to zero-energy and emission standards by 2019 (European Parliament, April 23, 2009). Furthermore, the zero energy (or zero carbon) approach is thought to have the greatest potential for energy and carbon reductions, compared with other ESD approaches such as 'low energy' buildings or 'green' buildings (European Council for an Energy Efficient Economy, 2009). A zero energy home is defined by the U.S. Department of Energy as a 'residential building with greatly reduced needs for energy through efficiency gains, with the balance of energy needs supplied by renewable technologies' (Carlisle *et al*, 2008).

The role of urban design in determining housing sustainability

> *Core to the promotion and uptake of sustainable design, technology and behavior is the need for better thinking about housing and cities, and the need to engage the public imagination* (Crabtree and Hes, 2009).

Housing developments in Australia, at small, medium and large scales, experience challenges and barriers to the implementation of sustainability (Blair *et al*, 2004; Crabtree, 2005). Whilst acknowledging that 'sustainability' is a complex concept that is difficult to both define and measure, it is important that designers understand how 'real life' is impacted by their decisions. Some tools are being developed to assist in this process, such as the Formal Indicators Concept (Porta and Renne, 2005) and Green Star Communities (GBCA, 2010). Planners and developers, key actors in the 'housing system', are responsible, to a large degree, for the forms of human habitation we experience. Historical approaches to urban development processes, as well as different forms of, and approaches to, urban development (e.g. compact cities, eco-cities, neotraditional development and urban containment) and the housing types promoted by these forms, appear to present differing potentials for sustainability (Bramley and Power, 2009; Jabareen, 2006; Morgan and O'Sullivan, 2009). For example, both Transit Oriented Design (TOD) and Urban Village forms incorporate urban density and mixed land uses, with a focus on sustainable mobility (transit hubs or walkability). The compact city also focuses on efficient sustainable transport as well as sustainable use of land, with its compactness supporting social cohesion and cost-effective infrastructure. The Eco-city approach is 'directed to managing urban spaces to achieve sustainability' rather than focusing on the actual urban form itself (Jabareen, 2006). Green Buildings' are not often the concern of planners or urban developers, yet it can be argued that they can 'take a more assertive role in green buildings' as 'sustainable development has emerged as a major paradigm for planning and green buildings have been identified as one tool that can be used to implement sustainable development principles' (Retzlaff, 2009).

Zero energy housing

As reported in 2008 by the International Energy Agency (IEA), Australia's residential building codes have been much less stringent, in energy terms, than those in Central Europe and North America (Laustsen, as reported in European Council for an Energy Efficient Economy, 2009). Australia's first national energy efficiency building regulations were only introduced in 2003 and minimum standards for building envelope thermal performance have been steadily increasing, from 3.5 stars in 2003 to 6 stars (out of a 10 star band) in 2010. The rating bands are logarithmic, with a 10 star house considered to require no additional space heating and cooling (NatHERS). At the same time, the energy efficiency of key building services (lighting and hot water) has also been included in the building codes. The 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. The Framework aims to address market failures such as split incentives and information barriers, acknowledging the complexity of decisions that relate to energy and housing:

> *The inter-relations between greenhouse gas emissions, energy use, peak demand, energy efficiency and human comfort in buildings are complex (National Framework p 6).*

So where do zero energy homes fit into this picture? Despite the plethora of labels and definitions (European Council for an Energy Efficient Economy, 2009; Marszal *et al*, 2011; Torcellini and Crawley, 2006), the implicit goal of zero energy buildings (ZEBs) is two-fold: to eliminate the environmental impacts of the energy required to operate buildings and to dramatically reduce, or eliminate the environmental impacts of the energy required to construct, maintain and deconstruct buildings (the embodied energy or lifecycle energy). Further refinements to this simplistic approach have been proposed (Marszal *et al*, 2011) such as possible restrictions on house size or maximum energy use; the inclusion of other sustainability issues such as indoor air quality (IAQ) that affects the health of inhabitants; and setting requirements for electricity grid-interaction conditions (e.g. effect of building on peak load; onsite energy storage capability, and time the building can 'survive' disconnected from the electricity grid). 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 begin to decrease the energy consumption of the entire U.S. housing stock even as the cumulative number of homes continues to rise" (NAHB Research Centre, 2006).

The purpose of this paper is to qualify and quantify the design strategies and performance outcomes of an Australian sub-tropical positive energy home in its first full year of occupancy, discuss the impact urban planning and development had on the outcomes of the house and derive the impact such housing could have on future urban development and infrastructure planning to deliver positive energy communities.

METHOD

A case study research strategy is adopted which enables the in-depth and longitudinal examination of a bounded phenomenon (e.g. a positive energy house) with a real-world context (i.e. a specific urban development). It allows utilisation of both qualitative and quantitative approaches involving multiple sources of data (Yin, 2009).

Urban development context

The physical context of the case study is a residential Ecovillage in sub-tropical Queensland, Australia. The 110 hectare site is nestled on flat and undulating land on the north face (equatorial facing) of a narrow and relatively short east-west valley. The vision of the developers of this estate was to inspire sustainable living and inform further ecologically sustainable developments (Landmatters Currumbin Valley Pty Ltd, 2006). Fifty percent of the estate is an environmental reserve for the protection of abundant and diverse native flora and fauna, and a further 30% is open space for recreational and horticultural activities (figure 1). The area zoned for housing (20% of estate land) is divided into 144 allotments (lots) of various sizes (450 – 8000 m^2) that are typically organised into small neighbourhoods (ecohamlets). Social interaction is encouraged by the implementation of resident greenways (open space between houses), very limited fencing, productive food gardens on the greenway side of each lot, and cycling and walking paths. Vehicular laneways are on the outside perimeter of the ecohamlets (figure 2). The plan for each house lot stipulates the maximum building footprint and general location of structures on the lot (figure 3). The practical application of the Ecovillage vision, with regards to the design and construction of houses on individually owned residential lots within the estate, is managed through the Architectural and Landscape Code (A&LC), part of the strata title covenant as allowed under the Queensland Body Corporate and Community Management ACT 1997 (BCCM ACT). These estate-level codes also form part of the Development Approval of the estate. The summary of the A&LC is shown in Table 1. The estate has also implemented a building design and construction approval process that encourages and supports an Integrated Design Process (Larsson, 2004) (Larsson, 2004) a reiterative process that encompasses concept, pre-design, design, construction and evaluation.

Figure 1-3 and Table 1 near here

The performance verification loop is closed, to some extent, by the requirement of all homes to install a metering and control system that enables households individually, and the community collectively, to evaluate resource consumption post-occupancy.

Case study house

The case study house is the lead author's home, designed in 2007 and constructed in 2008. The general specifications of the house are shown in 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: (i) minimizing embodied energy; (ii) maximizing the thermal performance of the building envelope; (iii) minimizing energy demand; and (iv) optimizing the performance of energy and water supply systems. Whilst analysis of the embodied energy of the house is not included in this paper, it is important to acknowledge that design decisions for low embodied energy (e.g. size of the house, maximizing reused materials, incorporating rammed earth) also 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, an accredited thermal simulation software program in the Australian National Home Energy Rating Scheme (NatHERS). The house was also rated after construction, to simulate thermal performance 'as built'.

Table 2 near here

Household performance data was downloaded from the home's Integrated Metering and Control System (IMCS) that comprises (i) electrical energy pulse meters for general power, lighting and refrigeration circuits, as well as solar photovoltaic (PV) generation (1 pulse = 0.3125Wh); (ii) pulse meters for potable (rainwater), recycled, and hot water (1 pulse = 1 litre); (iii) gas consumption meter (1 pulse = 10 litres); and (iv) temperature and humidity sensors (5 second sampling of temperature and humidity). 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 imported into MatLab 2009a and Microsoft Office Excel 2007 to allow for daily, monthly, seasonal and annual analysis.

Temperature data was analysed in histogram bins to reflect the protocols (thermal comfort bands, occupant interaction with the building and occupancy patterns) that underpin NatHERS accredited software. Internal temperatures were compared with 30 year average temperatures from the Bureau of Meteorology as well as local temperature data recorded by the estate's weather station. 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.

Electricity load curves, peak demand profiles, and solar power generation curves were developed from the electricity pulse meters and analysed at 1 minute, 5 minute and 10 minute averages. Greenhouse gas emissions from electricity and gas consumption were calculated using Scope 2 and 3 emissions intensity figures (Australian Government, 2010) for Queensland: electricity 1.01kgCO_2e/kWh; LPG 64.9 kgCO_2e/GJ.

To test the possible expansion of the zero energy concept beyond the scope of stationary energy, emissions due to infrastructure services and mobility were also considered. Emissions from private transport use were calculated from the actual distance travelled, the fuel efficiency of the vehicle, and the emissions intensity of the fuel (2.3kgCO_2e/litre). Public transport emissions (train) were calculated using a figure of 138gCO_2e/passenger kilometre. Electricity and gas bills were utilised to determine energy costs and revenue. Energy consumption attributable to sewage treatment, waste water treatment and recycled water reticulation was taken to be 1.1kWh/1Kl , a figure derived from a government study of this estate (Hood *et al*, 2010).

RESULTS

Thermal comfort

The house 'as constructed' achieved a 9 star (out of 10) rating (15.4MJ/m^2), representing the expected thermal efficiency of the building shell. This is a 75% improvement over the 5 star minimum requirement (60MJ/m^2) stipulated by the estate's A&LC and the Queensland building regulations at the time. Figure 4 compares the outside temperature with the simulated and actual temperature of the main living space. It shows that, for the majority of the year (96%) the internal temperature is between 18 – 28^{o}C without the use of mechanical heating or cooling. Occupants managed their comfort by operating the building, for example closing windows and curtains on hot and cold days, and opening windows to capture cooling evening breezes and allow for night purging in summer. Ceiling fans were utilized when additional cooling effects were required, providing a potential cooling effect of up to 7^{o}C (Aynsley, 2007). The house performance and operation are consistent with naturally conditioned spaces as described in the Adaptive Comfort Model (de Dear and Brager, 2001).

Figure 4 near here

Energy efficiency

Household energy and water services are met by a variety of means through regional, estate and household infrastructure. First, electricity, supplied through a standard ac (alternating current) circuit as part of the regional electricity grid, provides for the services of lighting, refrigeration and general power (e.g. dishwasher, washing machine, computers, telecommunications, power tools, entertainment equipment, communications devices etc). Figure 5 shows how different services account for the average daily electrical load of 3.46 kWh (12.36 MJ). Second, estate level reticulated liquid petroleum gas (LPG) is provided to the home for cooking and boosting of solar hot water when required. The daily average gas consumption was 5.4MJ. The provision of reticulated gas in the estate allows for fuel switching to the most greenhouse gas efficient means of meeting heating services within the home. Third, electricity supplied through a ‘stand-alone’ 24 volt dc circuit (direct current) is used for potable (rainwater) water pumping and ceiling fans. The incorporation of a household level limited dc circuit has allowed for the use of more efficient water pumps and ceiling fans compared with ac equipment for these purposes (e.g. the dc ceiling fans utilize 5W under normal operation, with 30W maximum power). Communications and entertainment equipment, well suited to dc operation, have subsequently also been switched over to this circuit for increased household resilience. Fourth, recycled water (197 litres/day) is used for toilet flushing and productive food garden. The recycled water is provided by an estate level wastewater treatment plant. The energy attributable to this household for these services (sewage treatment and reticulation) is 220Wh (0.79MJ) / day (Hood *et al*, 2010).

Figure 5 near here

Energy Supply

The source of energy utilised to provide household services has also been diversified, focusing firstly on optimizing available renewable energy sources at a household level. First, hot water is provided by a solar water heater (SWH: 300 litre close-coupled flat plate solar water heater) with instantaneous gas boosting. Gas-boosted solar water heaters are mandated in the development as they represent the most greenhouse efficient water heaters for this region. The SWH is mounted at 35^o pitch to maximize winter performance when hot water demand is higher and the cold water input temperature is lower. Gas boosting is controlled manually and is required less than 1% of the year. Second, mains power (the ac circuit) is provided through a grid-connected 1.7kW (27.29 MJ) monocrystalline PV system mounted on a tilt frame ($18 – 40^o$) which is adjusted seasonally to optimize performance. The annual average daily output of the photovoltaic array is 7.58kWh, showing a normalized output of 4.41 kWh / kW_{peak} PV. Mains power is drawn from the regional electricity grid whenever the sun is not providing sufficient electricity for household services; conversely when the household is using less electricity than being produced by the sun, the excess electricity is ‘exported’ to the regional grid. A ‘net meter’ accounts for this two way flow of electricity, and Queensland government policy mandates payment to households for net electricity sent back to the network i.e. a net feed-in tariff based on instantaneous flows of electricity. Third, the dc circuit is ‘stand-alone’ or independent of the regional electricity grid. It consists of a small 135Amp Hour 24Volt dc battery bank charged by a 300W single axis tracking PV array with seasonally adjustable tilt.

Household stationary energy balance

On an annualized basis, the house meets the *positive energy* definition, that is, annual renewable energy electricity generation of 2.77 MWh (9.97GJ) is greater than annual stationary energy consumption - gas and electricity of 1.8MWh (6.48GJ). The strong focus on energy efficiency (through building design and appliance / service choice) has delivered the most significant benefits, resulting in the annual energy consumption of the household 1/7th of the south-east Queensland average, as shown in Table 3. Further analysis shows that the house achieved zero-energy or positive energy status each month (June 2009 – Jun 2010), even in winter, as shown in Figure 6. Building design, choice of appliances and design of renewable energy systems combined to achieve this result: minimal seasonal variation in both electrical demand and solar generation.

Figure 6 near here

Summary of integrated strategies for Positive Energy Home

Figure 7 provides a pictorial representation of the strategies that were applied to the house, at the conceptual, design, construct and operational phases, in order to achieve its positive energy status in its first full year of occupancy. Features indicated inside the dotted lines represent energy efficiency strategies; boxes within the broader dashed lines represent additional sustainability strategies adopted, and some of the measures outcomes of the energy efficiency strategies. Arrows indicate the general location of the features.

Figure 7 near here

Discussion

This section will explore the implications of the PEH design strategies and performance outcomes, from household, community, sustainability and planning perspectives.

The Triple Bottom Line of Thermal Comfort

Eliminating or dramatically reducing the need for space heating or cooling is the first major design requirement for zero-energy buildings (Charron and Athienitis, 2006), yet buildings don't have a good track record of performing according to design predictions (USGBC, 2008). (US Green Building Council Research Committee, 2008 revised version) The actual thermal performance of this house slightly exceeded the modelled performance, providing a high level of confidence in the thermal simulation software as a design aid. The design of this house allows the occupants to manage their comfort levels through behavioural and psychological adaptations (Roaf *et al*, 2010) such as physically managing the building and using building spaces flexibly. The results indicate a high performance building envelope combined with occupant management of the building can deliver year round comfort in this climate without the need for air-conditioning. Some heating in winter may be required, which can be met through gas appliances. The design has removed the need to externally 'purchase' space heating and cooling which accounts for an average of 38% of Australian household energy use and 20% of household greenhouse gas emissions (Senior Officials Group on Energy Efficiency, 2010). (Senior Officials Group on Energy Efficiency, 2010) This contributes greatly to the economic and environmental sustainability of the household, and adds to their resilience (e.g. from price rises in utility costs) and energy security (e.g. less reliant on network services during extreme weather events). Urban planning decisions contributed to this outcome, first by banning the installation of air conditioners. To assist in meeting comfort levels without the use of air conditioning, the estate's plan optimised the solar aspect of each lot and requires all houses to be oriented towards the equator. This, together with other requirements of the A&LC such as east-west elongation, minimum roof overhangs, minimum ceiling heights of 2700mm and internal thermal mass, combine to maximise the potential of passive solar design outcomes to meet comfort requirements. Additionally, the provision of community 'facilities' by the estate developer has enhanced the adaptive capacity of the household to manage their own comfort. These spaces include a community centre (with shaded picnic tables, community hall, swimming pool, play ground etc), retainment of natural bushland and creek access, and hamlet level green spaces. This highlights the importance of urban design in enabling individual house inhabitants to manage their comfort in a number of ways, adding to household and community resilience.

Demand minimisation: comparison of houses in different developments

Further demand minimisation was shown in the daily average energy consumption of just under 5kWh (18MJ)/day, about ¼ of the average Australian household consumption and less than 1/6 of the average residential electricity customer in south east Queensland. Insufficient research has been undertaken on post-occupancy performance of residential thermal envelopes to enable a comparison of the performance outcomes of this house with other dwellings however the level of savings is at the upper end of savings recorded by low energy *commercial* buildings that had thermal envelopes that exceeded current energy performance codes (Torcellini and Crawley, 2006). Averages however can be misleading, as both total energy use, and the proportions of energy use used by different services, differs with climate, with available fuel sources and with lifestyle choices.

Table 3 near here

To understand the impacts of the case study house's performance, Table 3 compares this case study house with energy demand figures from other studies conducted in south-east Queensland (SEQ). The EMI study of 15 suburban Brisbane homes was conducted by EnSight in late 2009 – early 2010 (Atkinson, 2010). The Ecovillage and south-east Queensland (SEQ) figures come from Hood *et al* (2010) and Mills (2010). Electricity costs in column 5 assume 25% of usage on a controlled tariff at AUD$0.12/kWh and remainder on a standard tariff at AUD$0.20/kWh. Network charges are not included in this column. All other costs are actual costs as indicated in electricity and gas bills. Rows 2-3 compare the total household energy consumption and per person consumption between the case study house, the Ecovillage mean, houses from a Brisbane urban estate and the regional average. Rows 4-5 remove the energy related to water heating, space cooling and pool pump systems (typical loads for non-ecovillage housing in this region). This shows that, even accounting for the lifestyle choices of the Ecovillage houses to NOT have electric water heating, airconditioning and pool pumps, the daily energy consumption is still considerably less. Rows 6-8 explain this difference by disaggregating the electrical load into lighting, refrigeration and general power. The difference in lighting load between Ecovillage houses and houses outside of the Ecovillage is especially interesting. The estate mandates the use of energy efficient lighting (e.g. compact fluorescent lamps and light emitting diodes) and has a 'dark sky' policy (i.e. lights from houses are not to cause light pollution to neighbouring lots or greenways. (This policy also means that there is no street lighting.) Rows 10-11 compare energy costs (income and expenses), showing that the energy costs of the case study house are one seventh of the region's average even without counting for the income earned from the solar power system. The last row compares the greenhouse gas emissions from stationary energy services of the different houses, showing net positive emissions from the case study home, close to net neutral emissions for the Ecovillage homes, and 9-17 tonnes of CO_2e from the other homes. These comparisons are useful for revealing different levels of economic and ecological sustainability.

Differences in energy consumption per person are conceivably attributable to lifestyle choices in terms of numbers and types of appliances and behaviour. These life style choices impact on economic sustainability. The Queensland government study of the Ecovillage noted that

> *useful but incremental gains can be obtained by reducing the numbers of other appliances such as televisions or home entertainment systems. Importantly the lifestyle of the residents does not need to change greatly, as all appliance types are represented with a few exceptions (i.e. air conditioning and clothes dryers)* (Hood *et al*, 2010).

Lifestyle choices to minimise energy use go a long way to minimising the impact of energy price rises (as a % of household income) or even avoiding long term energy price rises through the utilisation of renewable energy. 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 the next five years (Atkinson, 2010) (Atkinson, 2010) the economic benefit of energy efficiency and the utilisation of renewable energy will grow over time. The role of urban design in enabling or restricting the ability of households to be resilient to increases in energy pricing is an important consideration in current climate change policy debates relating to the introduction of carbon pricing mechanisms into the economy.

Supply Optimisation for carbon reduction

Good design and energy efficiency combined in this PEH to minimise energy demand, making it much easier and more economical, to meet most of the remaining demands from renewable energy sources. Good design and installation optimisation enabled the solar water heater to meet almost 100% of hot water demand. Utilisation of gas for cooking and the residual water heating enabled fuel switching to maximise energy transformation efficiency, making the achievement of ZEB status easier (Torcelling and Crawley, 2006). (Torcellini and Crawley, 2006) Installing the PV system in a manner which allows for seasonal optimisation enables this system to meet its rated performance parameters, maximising environment and economic benefit. Meeting user needs and the optimisation of environmental outcomes are the two core functions of environmentally sound technologies (Halls, 2007). The addition of a dc circuit, 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 or greenhouse gas emissions. The cost of this system is covered by energy efficiency savings.

Household resilience

The combination of strategies has also enabled the house to 'survive' for significant periods disconnected from the electricity grid. In the absence of the grid, the home will still provide, in a range of weather conditions, for the occupants' thermal comfort, water supply, hot water supply, cooking, and communications. Refrigeration is the main service that will be lost, but even that service can be temporarily provided by the battery bank for 12 hours. Further research is required to quantify the financial value of such energy autonomy and resilience. Urban planning has contributed to this resilience by diversifying the resources on which households depend. Thermal comfort is provided by the building itself enabled by lot layouts and building covenants; energy infrastructure includes electricity and gas; and water infrastructure includes household level rainwater collection and estate reticulated recycled water.

Extending the 'zero-energy' boundaries

Accounting for primary energy sources and generation and distribution systems losses, the emissions balance from stationary household energy discussed previously is net positive to the tune of 1396.5 kgCO_2e annually. Household services, however, also include utility services (e.g. water supply and waste disposal) and mobility services. The energy for potable water supply was met from the house's rainwater tanks with solar powered dc pumps. The energy required to operate the estate's waste water treatment plant and reticulate the treated water throughout the estate is less than that required by the city's centralized water treatment plant (Hood *et al*, 2010). The need for mobility was been dramatically reduced by enabling working from home (home offices were pre-approved for all lots in the estate's Development Approval), modern communications infrastructure (fibre-to-the-home), social infrastructure to support car sharing, and facilities to enable local social, recreational and sporting activities. Table 4 shows that the net emissions can extend the boundaries beyond stationary energy to include household sewage treatment and reticulated recycled water supply, and 34% of the household's land transport emissions.   This highlights that good urban design can combine with good house design to deliver a zero energy community. The five elements of a renewable energy community are a sustainable approach to urban design, zero energy buildings, efficient transport, utility role expansion and the successful integration of these at a community level (Carlisle *et al*, 2008).

PEH design strategy

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, viewed as 'a single durable good' with 'complex component systems', that deliver 20-40% greater energy savings than the mainstream approaches to reducing energy in buildings (National Science and Technology Council Committee on Technology, 2008). This strategy also reflects the process identified for achieving zero energy homes in the US (NAHB Research Centre, 2006; Torcellini and Crawley, 2006) and in a proposed roadmap towards intelligent net zero- and positive-energy buildings (Kolokotsa *et al*, 2010). 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 (NAHB Research Centre, 2006). 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 (Senior Officials Group on Energy Efficiency, 2010).

However, the current positive energy status of the case study house and the potential for the family to further enhance their sustainability, relied, at least in part, on urban design decisions made by the developers of the estate, supported by local and regional planning authorities. These are summarised in Table 5.

Table 5 near here

PEH impact on electricity and water infrastructure

The removal of the need for space heating and cooling, and the use of solar and gas for other heating services, has resulted not only in a significantly lower daily electricity consumption, but also in a significantly lower peak demand profile. Analysis of electricity load, at 5 minutes averages, shows a maximum peak demand of 2.7MJ (750W) (Figure 8). There are two key implications for this. First, the house does not contribute to the peak demand stress that the south east Queensland electricity distribution network has become increasingly subject to. Second, the low peak demand, if maintained, has implications for the design of electricity infrastructure to residential estates. Current electricity infrastructure design practice, in south-east Queensland, is to supply homes with 5kVA capacity, a factor of 7 higher than what is used in this PEH. An estate of PEH homes could potentially save millions of dollars in electricity infrastructure requirements: how these savings could be distributed fairly to all stakeholders is a matter for further research.

Figure 8 near here

Similarly, a combination of water efficiency, rainwater harvesting, estate level waste water treatment and reticulation, and water sensitive urban design enables both the house and the community to be water self-sufficient and resilient. The impacts of the integrated water management plan have not been analysed, however such an analysis has been attempted, at least at a theoretical level, for the city of Perth in Western Australia (Grace, 2007).

From houses to communities: urban planning recommendations

Meeting the sustainability goals of the household required the successful integration of energy, water and materials 'systems' into a 'single entity'. The complexity of each system, and the interactions between systems, needed to be thoroughly understood in order to maximise the performance of each system individually as well as the 'product' as a whole. Design and materials/product selection decisions focused on win-win solutions with multiple benefits, rather than single solutions. Optimisation of the performance of each of the selected technologies was considered in the design of the house structure, and the house and each of its systems needed to be flexible, adaptable and resilient to a range of scenarios. This study highlights that an integrated systems approach, based on interrelationships rather than single elements, could be applied to energy services at a community level (Carlisle et al, 2008), enhancing the triple bottom line sustainability of urban settlements. Further research is needed to enhance understanding of possible pathways towards ecologically sustainable development in urban planning, assisting in the market diffusion of the zero-energy or positive-energy housing agenda into the broader community.

1. **Integration of ZEBs/PEHs into planning and development schemes**: this case study has shown a close symbiotic relationship between buildings and planning and development schemes and practices: arguably neither 'field' can achieve their greatest potential for delivering triple bottom line sustainability outcomes without working cooperatively and knowledgeably with the other. An understanding of how urban planning decisions restrict or promote sustainable

building practices, evidence of the implications of zero-energy and positive-energy homes, and better tools to enable comparative analysis would encourage and enhance the market diffusion of zero-energy and positive-energy homes (Retzlaff, 2009).

2. **Resource monitoring and units of measure:** Analysis of performance outcomes is not possible without a means of monitoring the energy (or resource) flows into and out of the home. In-situ measurements enabling disaggregation of energy loads and performance monitoring of both the building envelope and renewable energy generation are essential (Massuchusetts Zero Net Energy Buildings Task Force, 2009; National Science and Technology Council Committee on Technology, 2008). A complete understanding of these flows, however, requires common units of measure: utilizing MJ as the unit enables comparison of the solar resource, space heating and cooling requirements, and energy consumption (electrical, gas and liquid fuels). At a community level, monitoring and management are equally important in order to be able to manage, control and understand the resource metabolism of the estate as a whole organism, and its interactions within bigger systems. Household and community level monitoring then inform economic and engineering decisions regarding the design of regional infrastructure (Shimoda *et al*, 2004; Yao and Steemers, 2005). Using monitored data to develop electricity demand and generation curves at household and community levels will assist in quantifying the impact of zero or positive energy houses and communities on the electricity network and analysing their potential to contribute to grid reliability (NAHB Research Centre, 2006; Torcellini and Crawley, 2006). Understanding how ZEBs / PEHs

impact on the electricity network in terms of peak demand, load profile and load factors would assist in reducing network barriers to the implementation of ZEB programs and policies, and assist in determining how ZEBs could be diffused into the main stream housing market (Crawley, 2009).

3. **Multiple benefits:** Very high efficiency building envelopes with diverse energy demand and energy supply strategies can achieve more benefits than 'zero emissions'. 'Upgrading' the home to allow some level of independence from the grid (NAHB Research Centre, 2006) provides the household with a level of energy resilience (in terms of supply and costs) that enhances social and economic sustainability. Enhancing that capacity at an urban precinct level, through the design and interconnectivity of microgrids for example, will maximise system efficiencies and provide the community with the benefits of low carbon intensity, energy resilience and security. A neighbourhood of PEHs would require significantly less energy infrastructure, and conceivably lower infrastructure charges for developers. More research is needed in this area to quantify the infrastructure savings and the network benefits of a decentralised network consisting of interconnected microgrids.

4. **Need to focus beyond energy:** Because of the strong inter-relationships between energy and water, and between building design and renewable energy systems performance, there is a strong argument, at a building level, for the convergence of building simulation, solar systems design, and water collection/utilisation design tools, in order to optimise the synergies of these systems (Charron and Athienitis, 2006; Luetzkendorf and Lorenz, 2006). A similar need exists in planning and development. Decentralised energy, water

and sanitation services can be provided at lower environmental and economic costs than the current centralised systems, however identifying and capturing the interdependencies will maximise the community benefits.

CONCLUSION

Analysis of the design strategies and performance outcomes of this sub-tropical home has shown that the home produces more energy from its onsite renewable energy system than it uses for electricity and gas services. The home also meets, from non-grid-connected onsite renewable energy sources, the energy requirements for supply of potable water and water heating. Additionally, the home's net emissions offset the energy required for sanitation and reticulation of recycled water at an estate level and a portion of the household's land transport emissions. The high performance building envelope, combined with fuel diversity, energy efficiency and renewable energy, has enabled the household to meet its triple bottom line sustainability goals and achieve a high level of energy resilience and security. These features also benefit the electricity network in terms of not contributing to peak demand. The integrated design solutions applied to this house can also be applied to ecologically sustainable urban development to enable the formation of zero-energy and positive-energy communities.

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