THE IMPACT OF PASSIVE DESIGN AND SOLAR ENERGY USE IN A HOUSING DEVELOPMENT ON THE ELECTRICAL GRID

W. Saman, E. Halawa
Institute for Sustainable Systems and Technologies
University of South Australia, Mawson Lakes SA 5095
Mawson Lakes, Australia

Abstract

Passive design combined with energy efficient appliances and active solar systems have been implemented in many new house designs. However their impact on the electrical grid has not been sufficiently documented. A new housing development at Lochiel Park, Adelaide, Australia, is being constructed using a number of passive, active and demand side management features. To evaluate the impact of these green features on the electrical grid, the thermal performance of three dwellings having identical form, building structure and orientation but different fabric and appliances, are compared. The first is a house with typical conventional Australian design features while the second represents a newly built house satisfying Australia's current minimum energy rating requirements. The third home represents state of the art solar housing which is the type of house being built at the Lochiel Park Green Village. With the use of energy efficient electrical appliances, solar hot water and grid connected electricity, the study shows that the introduction of the above green features can lead to energy self reliance and the easing of peak demand problems often faced by energy utilities.

1. INTRODUCTION

Extreme heat waves that hit southern Australia in recent years have resulted in a dramatic increase of use of air conditioners and a consequent rise in the state peak electricity demand. The load shedding that occurred on the 30 January 2009 at 1.30 pm – 4.00 pm resulted in a power shortfall of 90 MW affecting 17,000 customers in 83 suburbs in Adelaide (NEMMCO, 2009a; ETSA Utilities, 2009). The recorded peak demand during this shedding period was 3 295 MW (NEMMCO, 2009b) compared to average demand of around 1600 – 1880 MW in normal summer weather. This is a drastic increase that only last for a number of hours during the year. According to a news reports, up to 80 sudden deaths were reported in Adelaide as a result of this heatwave. On the day of the peak heatwave (Friday, 30 January 2009) with record temperature in Adelaide of 45.3°C, 23 sudden deaths were recorded, a 10-fold increase from the Friday before. And the toll on Sunday (2 February) was 25 sudden deaths, according to police records (www.news.com.au, 2009).

The recently escalating phenomenon of high power factors and consequent power blackouts occurring during this extreme heat wave is a logical consequence of total reliance of dwellings on air conditioners powered by conventional centralised electricity generation. Passive design and distributed energy generation is a potential solution which can have a significant impact on easing peak demand by reducing the need for air conditioning and shaving off some of the load from the conventional grid. The effect of this alternative, however, has not been thoroughly investigated and understood. A number of distributed energy systems have been installed in many parts of the world. However, an extensive literature search has not found published information on the impacts of interaction between the distributed energy in a housing development and the grid. In order to understand the reasons cited for installation of distributed energy connected to the grid, Poore et al. (2002) surveyed a number of distributed energy plants across the United States and presented 4 case studies of plants interconnected with the grid namely: (1) Narrow Coastal Island, (2) Magic Valley Foods Cogeneration Plant, (3) Brookfield Zoo Cogeneration and Standby, and (4) Vanderbilt University Power System. The survey noted that the cited reasons for installing distributed plans are: cogeneration, technology demonstration, improved reliability, reduced costs, reduced peak demand, rate structure, price protection, burning of waste product, increased capacity, fuel flexibility, reduced emissions, reduced transmission constraints, market speculation, production of green power and elimination of chlorofluorocarbons (CFCs).

This paper aims to show how the new generation of energy efficient homes together with the widespread introduction of distributed energy generation using solar energy will ease the electricity peak demand problem as well as reducing the electricity cost and consequent greenhouse gas emission from the housing sector. This study is part of a three year project on the investigation of the impact of intelligent grid in a housing development at Lochiel Park, Adelaide, South Australia.

2. HOUSING DEVELOPMENT AT LOCHIEL PARK – AN OVERVIEW

The Lochiel Park Green Village has the objective of "building ecologically sustainable homes within a natural bush and parkland settings ..." (Lochiel Park Website, 2009). The Green Village master plan was finalised in 2005 and released to market in November 2006. Upon completion at the end of 2010 it will have 106 houses including social housing. The homes being built in the Green Village have green features which include among others: optimised allotment design for maximum benefits from environmental elements, passive design with high envelope energy rating, mandatory use of best available energy efficient appliances in each home, use of solar electricity (1kW per 100m^2 of floor area), installation of electrical load limiting devices, and gas boosted solar hot water systems. Each dwelling has a smart meter and energy usage display. There is an arrangement with the utility for special bundled tariff incorporating green power. The development has many other sustainability features for water usage, waste management and community development.

3. THE CASE STUDY

3.1 House specification

In this study the energy performance of the three dwellings having identical form, building structure and orientation but different fabric are compared. The three dwellings have 2.5, 5 and 7.5 star energy rating, respectively, according to Nationwide House Energy Rating Scheme (NatHERS) used in Australia and implemented using the AccuRate energy rating software (NatHERS website 2009). NatHERS rates the building envelope of dwellings on a scale of 1 to 10 stars according to their total energy performance (i.e. heat required in winter and extracted in summer without considering appliance performance) in satisfying occupants' thermal comfort. Dwellings with more stars require less heating or cooling to deliver thermal comfort to occupants with a 10 star home requiring no additional heating and cooling. The rating is dictated by the following factors: the layout of the dwelling, the construction of the roof, walls, windows and floor, the orientation of windows, shading and local climate. (NatHERS website, 2009).

Table 1 show the energy star bands for rating houses in Adelaide, Australia. According to the table, a 2.5 star dwelling has an annual (cooling and heating) energy requirement of 270 MJ/m^2, more than twice the consumption of a 5 star dwelling. The 7.5 star dwelling consumes less than 60 MJ/m^2 of energy, less than half the energy requirement of the 5 star dwelling. The 2.5 star house is typical conventional Australian design of the nineties while the 5 star represents a newly built house satisfying Australia's current minimum energy rating requirements. 7.5 stars is the minimum rating required for homes being built at the Lochiel Park Green Village. These houses must also comply with environmental guidelines that set out additional requirements including high energy efficiency appliances solar water heating and electricity.

Table 1: NatHERS Star Band for Adelaide:
Number of stars and corresponding annual Energy Requirement (MJ/m^2)

1 Star	2 Star	3 Star	4 Star	5 Star	6 Star	7 Star	8 Star	9 Star	10 Star
480	325	227	165	125	96	70	46	22	3

Table 2 shows the design and appliance specifications of the house selected for this investigation.
To achieve 2.5 and 5 star ratings for the same house plan, the following changes shown in Table 3 are made in the construction material properties:

Table 2 – Specifications of the 7.5 Star house

Dwelling type	Detached
AccuRate energy star rating	7.5
Area-adjusted heating requirement	15 MJ/m^2-annum
Area-adjusted cooling requirement	37.5 MJ/m^2-annum
Number of floors	2
Habitable floor area, m^2	197.1
Conditioned floor area, m^2	156
Number of bedrooms	4
Number of bathrooms	3
Roof/ceiling insulation	R 4.0
External wall insulation	R 3.5
Roof / ceiling construction	Corrugated colorbond with air gap
External wall	Reverse brick veneer with R 2.5 insulation batts
Floor	Standard concrete with carpet and felt underlay
Windows	Double glazed 4 mm clear with 12 mm argon filled and low E film.
Door	Solid construction
Cooling / heating system	Reverse cycle (6 star)
Hot water system	Solar / gas boost
Hot water tank size	300 L
Installed PV system capacity, kW	2.4

Table 3 – Specifications of the 7.5, 5 and 2.5 star rated houses

Item	7.5 star Home	5 star home	2 star Home
Floor	Standard concrete with carpet + felt underlay	Standard concrete with carpet + felt underlay	Concrete slab
Roof insulation	R4	R2.5	R2.5
Roof construction	Metal deck	Metal deck	Terracotta tiles
Ceiling	R2 insulation with ceiling fan	R2 insulation with ceiling fan	R1 insulation no ceiling fan
External wall material	Reverse brick veneer with insulation	Brick veneer un-insulated	Brick single skin
Shading devices	Holland blind	Heavy drapes only	Open weave
Windows tightness	Weather-stripped	All windows gap size set to medium	All windows gap size set to large
Door tightness	Weather-stripped	All door gap sizes set to medium	All door gap sizes set to large
Glazing	Low E double glazing	Single glazing	Single glazing

3.2 Appliance specifications

Table 4 shows electrical inputs and assumed number of operating hours per day of appliances used in each of the three houses. It should be noted that it is difficult to select a representative value for each of the items listed in the table and therefore those figure should be regarded as indicative. The choice of these values is somehow influenced by long term monitored consumption results reported in Saman & Mudge (2002), Fung et al. (2003) and Wan & Yik (2004). Other additional information is described below.

Heating and cooling system

It is assumed that the three houses use reverse-cycle air conditioners with the cooling mode energy efficiency ratio (EER) of 2.61, 2.82 and 5.2 and heating coefficient of performance (COP) of 3, 3.47 and 4.8. The systems represent Australia's current 2, 3 and 6 star energy rating for space conditioning appliances (ER, 2009). It was also assumed that the system is correctly sized to satisfy the house energy requirement for cooling and heating. The systems are non-ducted therefore have no delivery losses and they are newly installed so that their performance is unaffected by their age. The annual cooling energy consumption was evaluated using the methodology developed recently (Saman et al., 2009). The heating energy consumption was estimated based on the heating energy requirement calculated with AccuRate with the appropriate COP set above.

Hot water heating system

It is assumed that the water heating for the 2 star home comes from a 300 L electric storage heater (ORER, 2008) and that for the 5 star home from instantaneous gas water heater (AS/NZS 4234-2008). The 7.5 star home has a gas boosted solar hot water system. A 300 L system exposed to Adelaide weather data is used with a RECs value of 35 (ORER, 2008). 1 REC (renewable energy certificate) is 1 MWh electrical energy saved annually by an installed solar energy system.

Cooking, lighting and standby energy

Whenever possible, the information for 7.5 star home is obtained from the house specifications. The figures for 2.5 and 5 star houses are based on typical practice. In the absence of specific data based on monitoring, it is assumed that appliances in the 2.5 and 5 star houses require 30% and 20% more electrical power inputs, respectively, than those used in the 7.5 star house.

Table 4 – Electrical power consumption and hours of use of appliances

House Star rating	2.5		5		7.5	
Appliance	Power, W	Hours	Power, W	Hours	Power, W	Hours
Water heater	3600	4.5	0	0	0	0
Reverse cycle	6700	0.0	3660	0.0	1430	0.0
Fridge	160	5.0	160	5.0	160	5.0
Dishwasher	70	1.0	70	1.0	70	1.0
Microwave	1000	0.8	1000	0.8	1000	0.8
Oven	2000	1.0	2000	1.0	2000	1.0
Other kitchen appliances	1000	1.0	1000	1.0	1000	1.0
Video	45	0.8	45	0.8	45	0.8
Television set	200	5.8	200	5.8	200	5.8
Computer	250	3.5	200	3.5	150	3.5
Washing Machine	600	1.0	600	1.0	600	1.0
Lighting						
Outdoor	100	1.0	40	1.0	20	1.0
Living room	60	4.0	50	4.0	15	4.0
Study Room	60	4.0	50	4.0	15	4.0
Kitchen	60	1.0	50	1.0	15	1.0
Bedrooms	60	2.0	40	2.0	15	2.0
Other rooms	100	1.0	75	1.0	20	1.0
Iron	1000	0.9	1000	0.9	1000	0.9
Vacuum cleaner	250	0.3	250	0.3	250	0.3
Hair dryer	1000	0.3	1000	0.3	1000	0.3

Locally Generated Electrical Energy Source
All houses being built at Lochiel Park Green Village are required to have a minimum of 1 kW solar PV system per 100 m^2 of the roof area. The 7.5 star house being analysed has an installed PV system of 2.4 kW. The assumed PV system coefficient of annual energy production is 0.6 and the system is estimated to operate for 3000 hours annually. The other two houses have no locally generated electrical energy source.

3.3 Peak Load Rating
Various studies have shown that the main contributor to the surge of utility peak load in summer is air conditioning (Koomey & Brown (2002), TEPCO (2004), EES (2004), Saman et al. (2009)). In order to evaluate the contribution to each house to the utility electrical peak demand, the peak demand ratio (PDR) of each house is evaluated and compared.

The peak demand ratio can be defined as (Saman & Halawa, 2009):

$$PDR = \frac{PPD}{APD} \qquad (1)$$

where:
PPD = peak power demand, kW
APD = average power demand excluding space conditioning, kW

The peak power demand consists of peak portion of load coming from the use of cooling or heating system and the average power demand. The former is estimated from energy requirement calculated by AccuRate with appropriate EER or COP of the relevant cooling/heating system. The higher this ratio, the larger is the required electricity infrastructure to meet the peak demand. Many technical innovations and pricing mechanisms are being introduced in order to shave the peak and reduce this ratio. Accordingly this is the metric being proposed by the authors as appropriate for ranking residential buildings to determine their impact on their local energy networks.

A methodology for estimating the peak demand for Australian and New Zealand residential buildings has been proposed and reported in Saman & Halawa (2009). From AccuRate energy calculation, the 10 days with greatest seasonal peak demands are identified. These values are then converted into electricity demand using the values of EER and COP given previously. The average value is used in determining the peak demand of that house.

The household average power demand can be estimated from the total energy consumption (Saman & Halawa, 2009). The values given in Table 4 are used to calculate the average power demand of the three houses.

4. RESULTS AND DISCUSSIONS

4.1 Energy consumption and greenhouse gas emissions profiles

Table 5 shows the total energy consumption of the three houses which includes energy for water heating, space heating, space cooling, cooking, lighting, and others including standby energy. The 2.5 star house represents a nearly all electric house with very high electrical energy consumption for water heating and space conditioning. The 5 star house is a mixed (gas and electric) house with much reduced reliance on electricity compared to the former. However, the use of electricity for cooling will increase its summer peak demand ratio.

The space heating and cooling energy consumption for the three homes reflects both the thermal performance of the houses' envelopes and the heating/cooling appliances installed in each home. For space heating, a combined increase of star rating from 2.5 to 5 and from 2.5 to 7.5 and the energy rating of the heating appliance used results in about 33% and 70% reductions in heating energy consumption, respectively. Likewise, for space cooling, an increase of star rating from 2.5 to 5 and from 2.5 to 7.5 results in 30% and 50% reductions in cooling energy consumption, respectively.

Table 5 –Annual Energy (Electricity and Gas) Consumption and greenhouse gas emissions for 2, 5 and 7.5 Star Homes (in MJ)

Star Rating	2.5		5		7.5	
Energy source	E	G	E	G	E	G
Water Heating	21240			22830		8640
Space Heating	4693		3137		1411	
Space Cooling	5172		3608		2567	
Cooking		2527		2246		1872
Lighting	1130		848		269	
Other Appliances	11113		10883		10653	
Standby Energy	2167		924		745	
Total energy consumption	45516	2527	19399	25076	15645	10512
Total energy generated					15552	
Total electricity consumption	45516		19399		93	
Total gas energy consumption		2527		25076		10512
Emissions - electrical, kg-$_{CO2-e}$	13200		5626		27	
Emissions - gas, kg-$_{CO2-e}$		186.5		1850.6		775.8
Total emissions	13386		7476		803	

*) Based on local electrical emission factor of 290 kg-$_{CO2-e}$/GJ and gas emission factor 73.8 kg-$_{CO2-e}$/GJ.

The rest of the energy consumption items listed in Table 3 also reflect the efficiency levels of appliances used in each of the three houses.

The combined effect of high energy performance of the house, high efficiency appliances and the installation of the 2.4 kW PV system on the roof of the 7.5 star house results in very low greenhouse gas emissions. The household can also stake the claim of being a net zero energy and zero emission home.

It is worth comparing some of the results of the above calculations with the results of earlier data reported in Oliphant (2003) for base line energy use in South Australian homes. The data for "all electric homes" in 1989/90 shows that a 3 member family home consumes about 32000 MJ annually whilst a 4 member family home consumes about 35834 MJ annually. The figures for 1997/1999 are: 30304 MJ and 34808 MJ, respectively. Keeping in mind the increased air conditioning and appliance use over the last ten years, these are comparable with the figures for the 2.5 star home listed in Table 5 which represents the homes built in early nineties.

Figures 1 – 3 show the composition of energy consumption in each of the houses. When considering these charts, the energy source type (natural gas for cooking for all houses and for water heating in the 5 and 7.5 star homes and electricity for all other purposes) must be taken into consideration. As shown, the main energy consumer for the 2.5 and 5 star houses is water heating which consumes 44% and 51%, respectively, of the total energy. The installation of a solar hot water heating system in the 7.5 star house reduces the water heating energy consumption (in this case gas) to 33% of the total. In terms of their contribution to total energy consumption, space heating and cooling consumes 21% of the total for the 2.5 star house and 15% for the 5 and 7.5 star houses. Reduced share of space heating and cooling to the total energy consumption for higher star houses is expected due to improved thermal performance of these houses. As the provision of hot water, heating and cooling becomes more energy efficient, the dominant components which assume higher significance are those for cooking and other appliances.

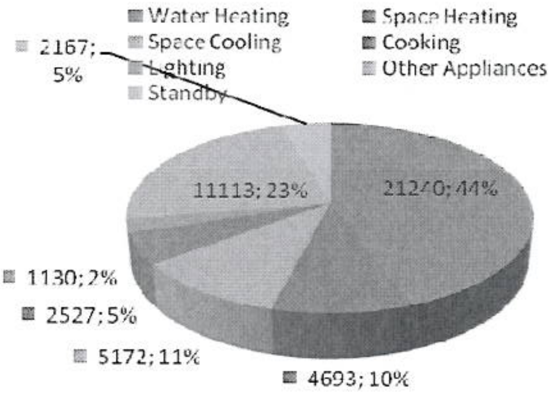

Figure 1 – Composition of energy use in the 2.5 star house

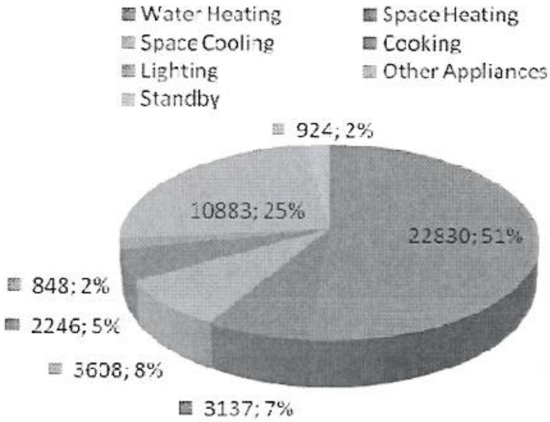

Figure 2 – Composition of energy use in the 5 star house

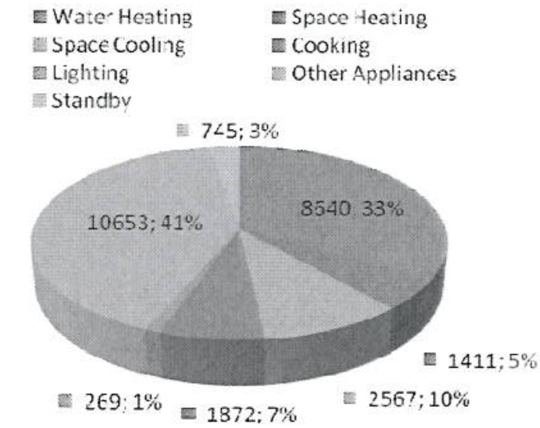

Figure 3 – Composition of energy use in the 7.5 star house

4.2 Peak Demand Ratio

Based on the information given in Table 4 and the method described in Section 3.3, the average power demand, the peak portion of load due to space conditioning and the peak demand ratios of the three houses are presented in Table 6.

It is worth nothing that in estimating the impacts of passive design and solar energy use on the improved performance of the 7.5 house in terms of its contribution to the utility peak load, most of the electrical appliances used in the three houses are assumed to have the same operating hours. The main impacts are due to energy efficient lighting, solar hot water and the space heating and cooling.

Table 6 – Peak Load Performance of the 2.5, 5 and 7.5 star houses

House Star Rating	2.5	5	7.5
Average Power Demand, W	1062	372	349
Load contribution from air conditioning, W	6700	3660	1430
Locally Generated Power during peak period, W	0	0	600
Peak Power Demand without LGP*), W	7762	4032	1779
Peak Power Demand with LGP, W	7762	4032	1179
Peak Demand Ratio without LGP	7.3	10.8	5.1
Peak Demand Ratio with LGP	7.3	10.8	3.4

*) LGP = Locally generated electrical power

Based on the method mentioned in Section 3.3, the peak cooling requirements for the three houses are: 17.5 kW, 10.33 kW and 7.44 kW, respectively. For an EER of 2.61, 2.82 and 5.2 the electrical input power of cooling systems are: 6.7 kW, 3.66 kW, 1.43 kW. These values significantly impact on the peak load.

As discussed previously, the installation of the 2.4 kW PV system on the roof of the 7.5 star house helps to reduce the annual energy consumption of the 7.5 star house. The same system also contributes to reducing the electrical peak demand of the house despite its diminished power generation capacity during the peak demand period. For an equator facing PV system, the peak power of 2.4 kW_p is attained at noon when solar radiation reaches its maximum intensity. The peak electricity demand in South Australia, on the other hand, occurs at about 16.00 – 16.30 hrs in the afternoon (ESCOSA (2007 & 2008), Saman & Halawa (2009)). Based on daily performance monitoring results, a conservative estimate of 25% of the peak power output of 2.4 kW is deemed appropriate as the PV system contribution to reducing the peak demand (Table 6).

The reduced peak power demand and peak demand ratio for the 7.5 star house comes from the combined effect of much improved thermal performance of the house, the use of more efficient appliances and the installation of PV system and gas boosted solar hot water system.

5. CONCLUSIONS AND RECOMMENDATIONS

The study demonstrates the effectiveness of combined passive design, energy efficient appliances and solar energy use in realising self-sufficient energy homes and consequent reduction of greenhouse gas emissions and in reducing the peak load of dwellings. Widespread construction/renovation of dwellings approaching the specifications similar to those of the 7.5 star home described in this paper will lead to a considerable reduction of the greenhouse gas emissions from the housing sector and will help reverse the recent trend of increasing load factors due to domestic air conditioning use.

Compared with the 2.5 star rated home, the 5 star home has reduced energy consumption, reduced peak load but higher peak demand ratio. This demonstrates that in designing houses and selecting their appliances, both the total energy and peak demand aspects must be considered. In order to reduce the peak demand ratio, houses need to have low heating and cooling requirement, efficient heating and cooling appliances as well as local energy generation. The previous trends in some Australian housing development in reducing heating and cooling requirements and switching to gas powered hot water provision has resulted in reductions of their overall greenhouse gas emission but has raised their peak demand ratio. This paper has demonstrated the causes of this trend and offered some solutions in reversing the trend and thus reducing the need for upgrading the electricity supply and distribution infrastructure.

REFERENCES

AS/NZS 4234-2008 - Heated water systems - Calculation of energy consumption.

EES, 2004: Electrical Peak Load Analysis – Victoria 1999 – 2003, Energy Efficient Strategies, prepared for VENCORP.

ER, 2009: The Energy Rating website: www.energyrating.gov.au – accessed 30 July 2009.

ESCOSA, 2007: ETSA Utilities Demand Management Program – Progress Report, June. The Essential Services Commission of South Australia.

ESCOSA, 2008: ETSA Utilities Demand Management Program – Progress Report, October. The Essential Services Commission of South Australia.

ETSA Utilities, 2009: Load Shedding Hits 83 Suburbs, ETSA Utilities Media Release, 30 January 2009 - http://www.etsautilities.com.au/centric/news_information/media_releases/load_shedding_hits_83_suburbs.jsp

Fung, A.S., Aulenback, A., Ferguson, A. & Ugursal, V.I., 2003: Standby power requirements of household appliances in Canada, Energy and Buildings, vol. 35, pp. 217 – 228.

Koomey, J. & Brown, R.E., 2002: *The role of building technologies in reducing and controlling peak electricity demand*, Energy Analysis Dept. – Environmental Energy. Technologies Division – Ernest Orlando Lawrence Berkeley National Laboratory – University of California – Berkeley, CA 94720, September – http://enduse.lbl.gov/Info/LBNL-49947.pdf.

NatHERS Website, 2009: www.nathers.com.au – accesses 15 July 2009.

NEMMCO, 2009a: NEMMCO Media Release, Friday 30 January 2009.

NEMMCO, 2009b: *Pricing Event Reports - January 2009*, http://www.nemmco.com.au/opreports/pricing_jan.html

News.com.au, 2009 - *Increase in sudden deaths of elderly in Adelaide appear to be due to the heatwave* – 7 February:

http://www.theaustralian.news.com.au/story/0,25197,25019866-5006787,00.html

ORER, 2008: REC calculation methodology for solar water heaters and heat pump water heaters with a volumetric capacity of up to and including 700 liters – Version 13, The Office of Renewable Energy Regulator (ORER), January 2008.

Poore, W.P., Stovall, T.K., Kirby, B.J., Rizy, D.T., Kueck, J.D., Sotavl, J.P., *Connecting distributed energy resources to the grid: their benefits to the DER owner/customer, the utility, and society*, Oak Ridge National Laboratory, ORNL/TM-2001/290

TEPCO, 2004: Electricity Market in Japan – Tokyo Electric Power Company website:

http://www.tepco.co.jp/en/news/presen/pdf-1/0406-e.pdf - accessed 27 March 2009

Saman, W. & Mudge, L., 2002: Development, implementation and promotion of a scoresheet for household greenhouse gas reduction in South Australia, Submitted to Partnerships Group, Australian Greenhouse Office, Canberra.

Saman, W., Mudge, L., Cheng, T.Y., Halawa, E., Bruno, F., 2009: ANZHERS - Space Cooling Rating Tool - Final Report, submitted to Residential Building Efficiency Team, Department of the Environment, Water, Heritage And the Arts, Canberra.

Saman, W., Halawa, E., 2009: NATHERS – Peak Load Performance Module Research – Final Report, submitted Residential Building Efficiency Team, Department of the Environment, Water, Heritage And the Arts, Canberra.

Wan, K.S.Y. & Yik, F.W.H., 2004: Building design and energy use characteristics of high-rise buildings in Hong Kong, Applied Energy, vol. 78, pp. 19 – 36.

ACKNOWLEDGEMENT
This study is part of a CSIRO funded three year project on the investigation of the impact of the intelligent grid in a new housing development. The authors acknowledge the financial support from CSIRO Energy Transformed Flagship and Land Management Corporation, South Australia.