Impact of Distributed Solar Generation in Low Energy Housing on the Electrical Grid

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Abstract

Passive solar design combined with energy efficient appliances and active solar systems have been implemented in many new house designs and housing developments. However their aggregated impact on the electrical grid has not been sufficiently monitored and documented. A new housing development at Lochiel Park, Adelaide, Australia, is a leading example low carbon development; being constructed using a number of passive solar design and demand side management features, and roof mounted photovoltaic systems on all homes. To evaluate the impact of these features on the electrical grid, the performance of all dwellings is being monitored in detail. The paper summarises the overall household energy consumption patterns. It describes the aggregated seasonal energy and power interaction with the local electrical grid. In particular it focuses on the net power imported from the grid and exported to it during peak summer and winter demand periods. The results demonstrate the reduced energy consumption and power demand during peak events in comparison with typical Australian homes. It also shows the seasonal and maximum impacts of aggregation of rooftop solar generation on the energy and power exported to the grid.

Introduction and Background

The energy consumption of Australian commercial and residential buildings has been increasing throughout the last 2 decades. The energy used by Australian buildings accounts for approximately 20 per cent of Australia's greenhouse gas emissions. On average, space heating and cooling represents 41% and domestic water heating about 30% of the energy demand of the 8.5 million Australian homes with heating and cooling of buildings directly responsible for 11% of Australia's national greenhouse gas emissions despite the temperate climate of major Australian cities [1, 2]. The number of residential dwellings will be around 10 million in 2020 compared to 6 million in 1990. The energy consumption of the residential sector was about 402 PJ in 2008 and is projected to increase to 467 PJ by 2020, showing a 56% increase in residential sector energy consumption over the period 1990 to 2020 [3]. Due to the abundance of cheap energy in the past, housing designs and constructions have not considered energy efficiency as a high priority. Aesthetics, larger built area at minimum construction costs have been the key elements in marketing both new and existing dwellings. A typical traditional Australian home is detached, single or double storey, around 200m^2 in area and has 3-4 bedrooms. It is constructed of brick veneer walls with single glazed, mostly unshaded windows. Roof and wall insulation is becoming the normal practice to comply with building regulations. In 2008, 77% of Australian dwellings had one or more space heaters and two thirds had space coolers [1]. This number has witnessed a rapid increase in the last 10 years and has resulted in a substantial impact on the summer peak demand during heat waves which take place for a few days in the year in many of Australia's largest cities. The necessary augmentation to generation and particularly distribution infrastructure has been mainly responsible for large increases in electricity tariffs.

Lochiel Park Green Village

Upon completion in 2012, the Lochiel Park Green Village will have 106 houses including 23 social housing units. The homes being built in the Green Village have a comprehensive list of sustainable features which include optimised allotment design for maximum benefits from environmental elements, passive solar design with high envelope energy rating [4] (a minimum energy rating of 7.5 stars using the Australian Nationwide House Energy Rating Scheme which currently mandates 5-6 stars for new housing), mandatory use of best available energy efficient appliances in each home, use of solar electricity (1kW$_p$ per 100m^2 of floor area), installation of energy management systems, electrical load limiting devices, and gas boosted solar hot water systems [5]. There is also an arrangement with the utility for special bundled tariff. The Green Village performance targets include 66% and 74% reductions in energy and greenhouse gas emissions respectively in comparison with the Adelaide average for 2004.

Each of the 106 houses incorporates a touch screen computer and an in-home display, a programmable logic controller, and an array of intelligent meters and sensors, which comprehensively measure and display general electricity, water and gas usage, in real-time. Furthermore, each property has a fully customisable load management system installed, which allows devices to be deactivated during periods of peak electricity demand. In addition, 9 houses are being monitored in detail. Indoor air temperature/relative humidity and individual appliance electricity usage are also being recorded.

Impact of Solar Systems on Net Electrical Supply and Demand

The impact of the solar energy generation is demonstrated in Figure 1 below, which shows the aggregated monthly average consumed electrical, solar and net energy per household. Note that the numbers adjacent to the months along the x axis in this figure are the number of houses monitored during that month which increased over time. The average Lochiel Park home consumes 5520kWh of electricity per annum (15.1kWh per day) of which 57% is locally generated and only 2340 kWh per year (6.4kWh/day) is supplied by the grid.

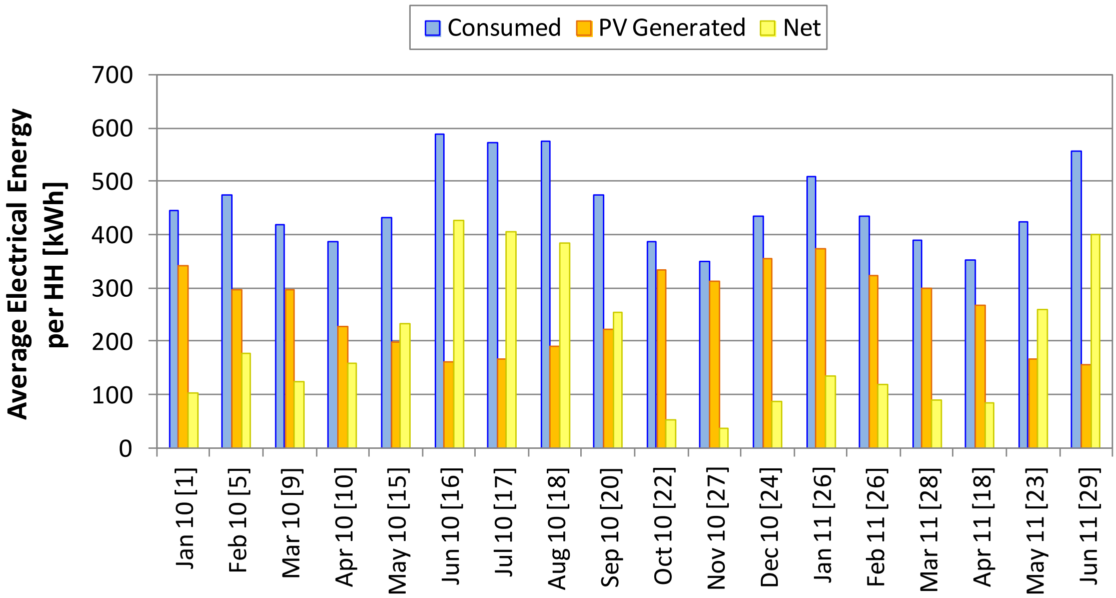

Figure 1 Measured average electrical energy consumed, generated and provided by the grid (Net) per household per month.

Operating under the Adelaide climate, the study [5] has shown that on average, the solar electrical systems installed at Lochiel Park (average size 2.2kWp) generated 2.4kWh/kWp in June and 5.5kWh/kWp in January with an annual average of around 4.0kWh/kWp. As more distributed photovoltaic systems are being installed in Australian dwellings, this result provides direct evidence for estimating the impact of rooftop solar electrical systems on the grid and anticipated emissions reduction.

The gathered data [5] demonstrates the impact of the number of occupants in a household and their behaviour on the electrical grid. In winter (June-August) the range per household varied from feeding the grid 100kWh/month to drawing 1 200kWh/month from it with the average winter demand on the grid being 400kWh/month. The summer period (January-February) shows a maximum input to the grid above 400kWh/month and a maximum demand on the grid of 950kWh/month with the summer demand of all houses averaging around 150kWh/month.

While only one house consistently produced more energy than it consumed and negative emissions, 50% of the monitored dwellings produced more electricity than they consumed and 40% of them produced negative net emissions during the period October to April due to the high performance of the photovoltaic systems during that period [5].

Figure 2 aggregates 15 minute data for the instantaneous solar and net electrical power per house (average of 21 houses), during the coldest period of 2010. The minimum temperature recorded during this period was 3.7°C and the maximum 13.4°C. The figure shows that the average solar power generated is low, as expected for the winter months, and when combined with a high electrical demand for heating, this increases the net electrical power drawn from the grid. The figure shows that throughout this peak period, only a very small portion of the solar generated power exceeds demand and was fed to the grid; with this taking place around noon. However, the peak power drawn from the grid seldom exceeded 2.5kW and took place in the evening (6.00 to 9.00pm).

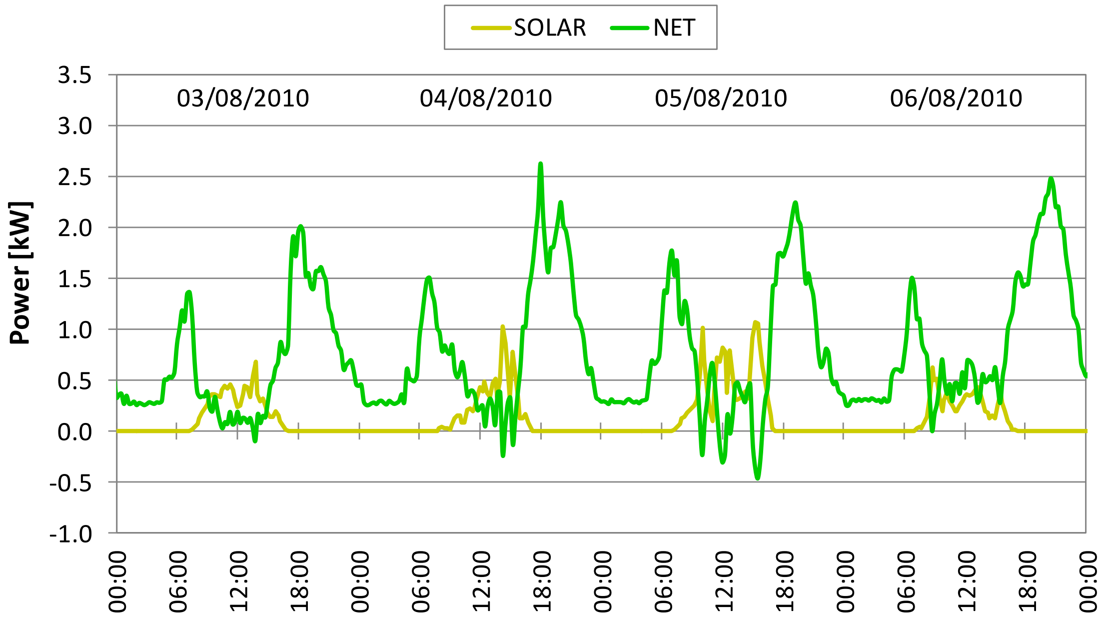

Figure 2 House average measured solar and net electricity power profile, of 21 houses, for the coldest period of the year (3-6/08/2010).

Figure 3 further examines the average electrical power profile during two days of this cold period, by showing the consumed, imported and exported electrical power. The figure indicates that some of the houses were importing energy, whilst others were exporting it at the same time. The average net power is equal to the difference between the average imported and exported values. This shows the net impact of aggregating a number of houses in an estate on the local grid which is to be expected due to the different patterns of energy use/generation in individual homes.

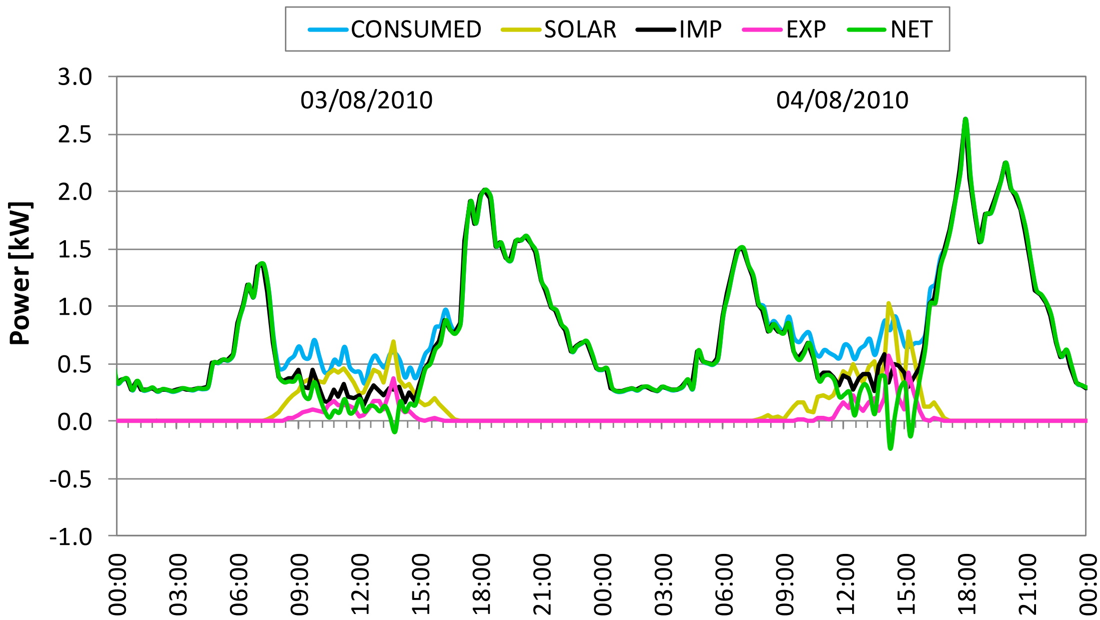

Figure 3 Average monitored consumed, solar, imported, exported, and net electricity power profile, of 21 houses, for the two coldest days of the year.

The figure demonstrates that both days have a small morning and a larger evening electrical peaks, whilst during the day, a steady load of about 500-700W is consumed. This day-time electrical load is well matched by the solar output, and hence the houses do not draw a significant amount of power from the grid. In contrast, both the morning and evening peak electrical demands occur pre and post daylight hours. Despite this, the average peak electrical demand during the coldest period of 2010 is 2.6kW, which is dominated by reverse-cycle heating, but also includes power used for cooking, lighting and other appliances. This power demand highlights the impact of good thermal envelope design and installing highly energy efficient appliances.

Figure 4 shows the 15 minute average solar and net electrical power demand during 2 typical spring days, for 26 houses. Compared to the corresponding data for the coldest 2010 period, the peak net electrical power demand is lower. This is due to the increased average peak solar power generation (higher solar intensities and longer sunlight hour), and the reduction in heating and lighting electrical demand. The figure also shows that on average, the photovoltaic systems are producing a maximum power amounting to 86% of the peak power installed capacity during this period. The consumed and the imported and exported electrical power are also plotted. The consumed power is steady in comparison with winter, as there is no need for heating or cooling during this period. This reduction in consumed energy, together with increased solar power generation, maximises the average net generated energy; as seen for a sunny day (11th). This however, seldom exceeds 1.0kW per home after aggregation. In contrast, the solar power for a partially cloudy day (12th) is lower. Despite this, the solar power approximately matches the average day time electrical demand.

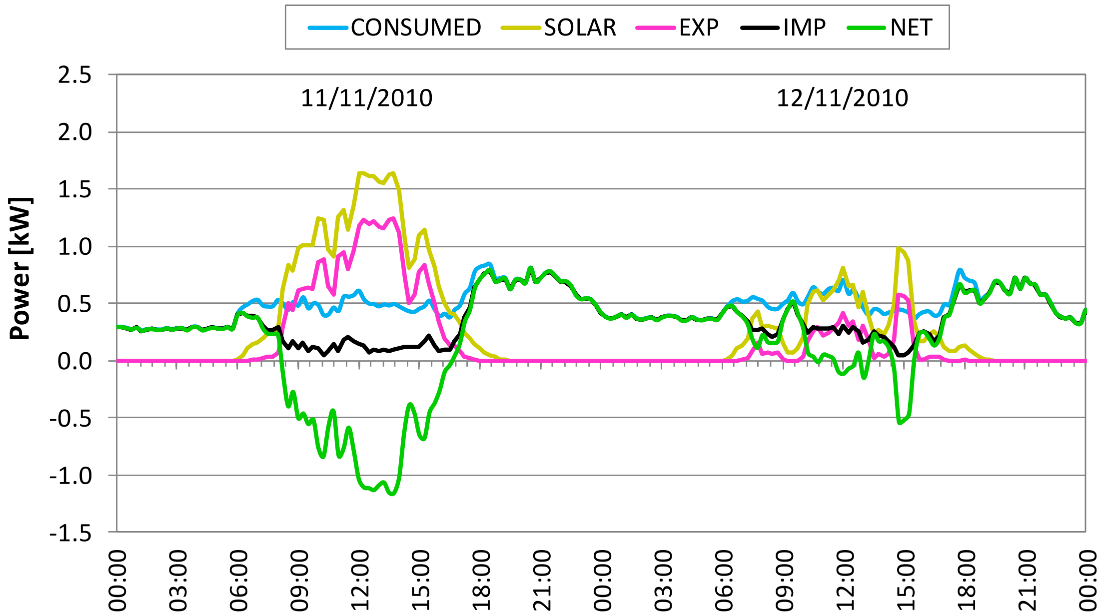

Figure 4 Average measured consumed, solar, imported, exported, and net electricity power profile, of 26 houses, for two typical spring days.

The average 15 minute solar and net electrical power of 27 houses during the two consecutive hottest days of 2011, are shown in Figure 5. The maximum recorded temperatures during this summer peak demand period was 42.5 and 42.9°C respectively with corresponding minima of 25.8 and 28.2°C. The figure illustrate that the net power demand sharply increases at about 18:00 each day. The overnight base load power is also shown to increase. This indicates higher use of air conditioning for cooling. The figure includes the consumed and the imported and exported electrical power. Note that during the daytime period some houses exported power whilst others imported it (as shown by the averages in the figure). The solar systems are shown to provide a significant portion of the consumed power, between the hours of 9:00 and 16:00. The figure also shows that the local generation continues contributing during the house peak demand which takes place around 6.00pm which will reduce and delay the peak demand impact on the grid. Despite this, the peak aggregated consumed power demand is 2.6kW, which takes place after 8.00pm. This is similar in magnitude to the winter peak, and is considered very low in comparison to a typical SA house operating an air conditioner during a similarly hot period.

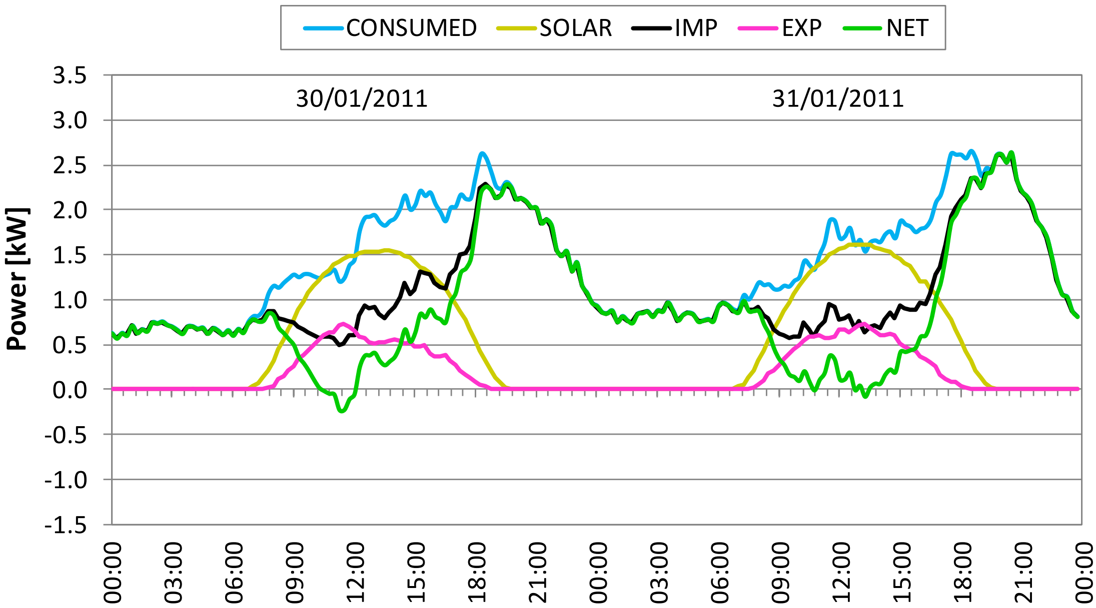

Figure.5 Average measured consumed, solar, imported, exported, and net electricity power profile, of 27 houses, for the two hottest days of the year

Impact of Air Conditioners on the Peak Electrical Demand

Extreme heat waves that hit southern Australia in recent years have resulted in a dramatic increase of the use of domestic air conditioners and a consequent rise in the peak electricity demand [6]. Furthermore, Australia has to adapt to increasing frequency of heat wavesas a consequence of climate change. As examples, the number of days over 35°C will increase to 19-25 by 2030 and to 20-32 by2050 from a current value of 17 for Adelaide. The corresponding figures for Perth are 29-38 and 31-48 from 27 respectively [7]

Figure 6 shows the average instantaneous power consumption of the air conditioner, the house total load, the solar system generation and the resulting electricity imported from the grid during South Australia's peak demand day for 2011. Note that the data shown is averaged for periods of 15 minutes, for five houses. The figure indicates that the average peak Lochiel Park air conditioner power usage occurs between 17:15 and 22:30, which is after the state's peak demand, which occurred at 16:30. At the time of the state peak, the figure also demonstrates that the houses aggregated average air conditioner load is matched by the power generated by their solar systems. On average, the houses are only demanding an additional power of about 500W during the peak event, which is imported from the grid. This demand on the grid power is very low in comparison with typical demand of similar houses when air conditioning is used and do not have a solar system installed. The average air conditioner power is shown to increase after 17:30, as this is when the Lochiel Park residents arrive home. The average power increases with time, as the solar generation drops, hence increasing the imported power. The average grid power demand peaks at 20:15, after the end of the solar power generation

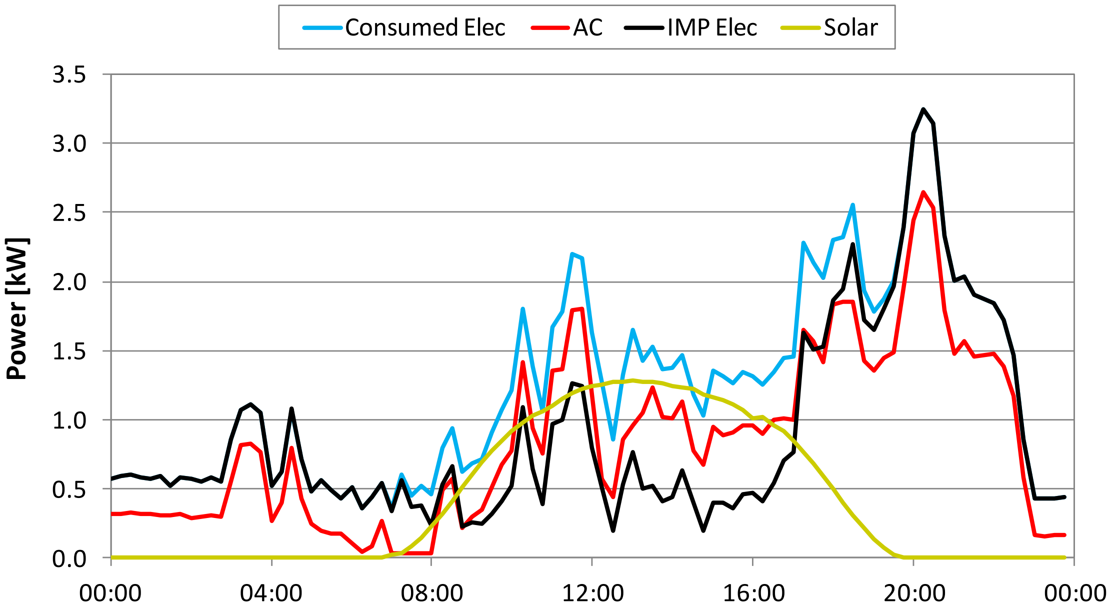

Figure 6 Measured 15 minute average instantaneous consumed electrical (Consumed Elec), air conditioner (AC), imported (IMP Elec) and solar power, of five houses, during the 2011 South Australian peak electrical demand.

The peak demand behavior in 2010 is demonstrated in figure 7 which provides the data for two of the houses during the hottest February day in 2010.which had more severe heat waves than 2011. The state peak demand on that day was close to the maximum of the year which took place on 31st January. The figure shows that on average, the two houses used air conditioning for the entire 24 hour period corresponding to the hottest February day. This occurred as the previous day experienced a similar maximum ambient temperature, and air conditioners were left operating from the previous night. This stresses the positive impact of aggregation, as one of these households maintains a steady air conditioner power profile, whilst the other switched their cooling on at 14:45 and then it cycled on and off on an hourly basis between 18:00 and 22:00. The figure also demonstrates the significant contribution of the PV system during the first peak demand period. However, solar generation stops before the evening peak demand period.

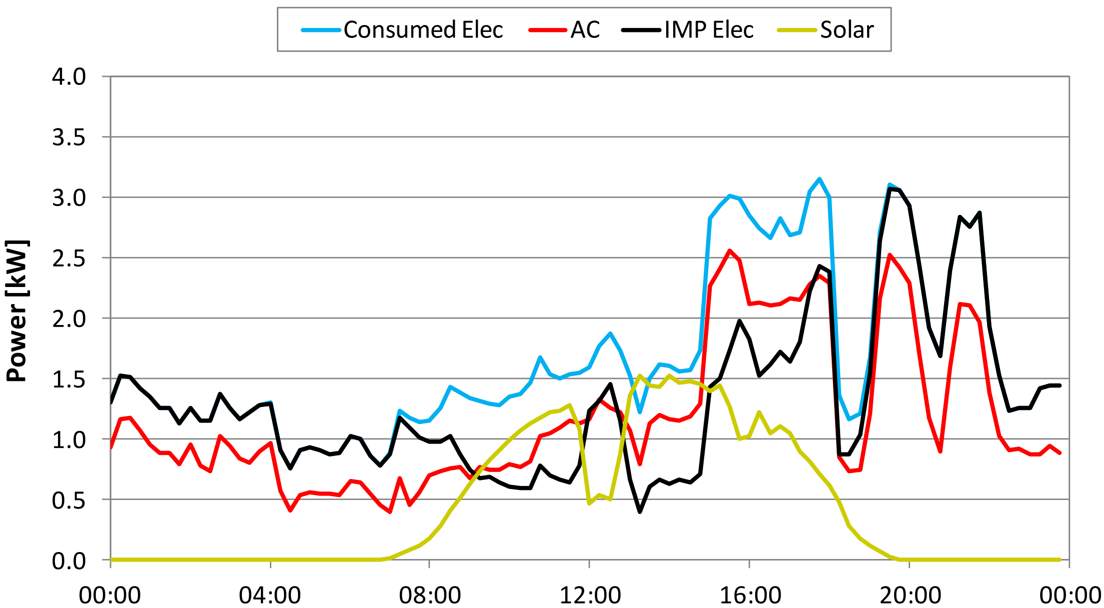

Figure 7 Monitored consumed electrical (Consumed Elec), air conditioner (AC), imported (IMP Elec) and solar power, of two houses during the hottest February day in 2010.

By way of comparison to demand profiles for air conditioning in typical Adelaide homes, the total electrical and air conditioner power consumption profiles, averaged for five homes of smaller conditioned area built in 2002 during a peak electrical demand day, are shown in Figure 8 [8].

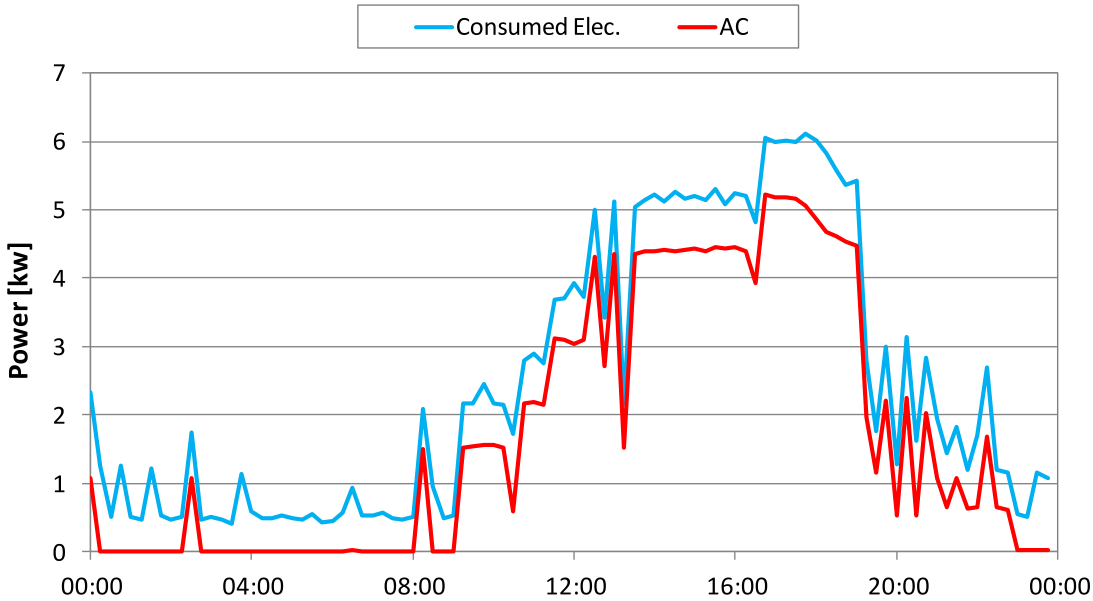

Figure 8 Monitored 15 minute average instantaneous consumed electrical (Consumed Elec), and air conditioner (AC) powers, of five Adelaide houses, during the 2003 peak electrical demand day.

On comparing this figure with Figures 6 and 7, on average, air conditioning is responsible for about 70% of the household power demand during a peak demand day. The significant difference is the marked reduction in air conditioner power demand for the Lochiel Park houses, despite the increased Lochiel Park household conditioned floor area. This reduction in air conditioning demand is due to the superior performance of the building envelope and the use of highly efficient air conditioners. An average peak power demand reduction at Lochiel Park to about half the average power depicted in Figure 8 is observed. While these are initial findings and need considerable more data gathering and analysis, the technical and economic implications of reducing the summer peak power demands of Australian housing to around 3kW are enormous.

Conclusions

The key feature of the work reported is the level of rigour implemented in monitoring the energy use to enable detailed performance evaluation of individual houses as well as specific appliances to enable thorough evaluation of the overall impact on the grid. The aggregated results for some 30 households provide reliable data on the overall impact of low energy housing generating solar power on the electrical grid. Operating under the Adelaide climate, the study has shown that on average, the domestic solar electrical energy generated ranges from 2.4kWh/kW$_p$ in June to 5.5kWh/kW$_p$ in January with an annual average of around 4.0kWh/kW$_p$. While only one house consistently produced excess energy and negative emissions, 50% of the monitored dwellings produced more electricity than they consumed and 40% of them produced negative net emissions during the period October to April due to the high output of the photovoltaic systems during that period.

The significant feature of air conditioning system usage is the relatively low hours when air conditioning was needed in comparison with similar Adelaide homes with the worst of the houses investigated needing a maximum of 3 kW of electrical power with some systems needing below 1kW. This demand is well below typical air conditioning systems previously monitored. The impact on the local and state peak demand during hot spells and cost of associated with transmission/distribution infrastructure is significant.

The data analysis provides real world evidence to support the development of energy regulatory framework and future energy policy directions in the housing and appliance sectors. The monitoring of current and new dwellings, including a number of smaller units will continue for the next three years and beyond. The lessons learnt from this project, while significant along the path towards zero energy housing, demonstrate the need for better design integration to ensure the achievement of low energy dwellings which are also affordable, comfortable and aesthetically acceptable. The project also highlights the need to pay particular attention to minimising the peak demand alongside energy and emissions reduction in order to reduce the reliance on the electrical grid. A potential avenue for designing a no peak demand home is the integration of electrical and/or thermal storage systems.

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