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Residential Peak Demand Management of Space Cooling Systems Through Thermal Storage and rooftop PV in Brisbane

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Abstract

This paper studies the potential benefits of implementing distributed thermal energy storage units in residential buildings. Peak demand management of space cooling systems is regarded as an important issue, as the sudden peaks in summer can create electrical network instabilities, and possibly state-wide blackout as well as very high electricity spot prices. Current instantaneous air-conditioning (AC) systems in the built environment are not able to store thermal energy and shift the cooling demand of buildings, which is one of the main reasons causing sudden peaks in summer. In this research, a range of evaluation and quantitative analysis have been performed for a real 5-star (Nationwide House Energy Rating Scheme) house in Brisbane. The results show that the space cooling system with cold storage, powered by a 5.0-kW solar PV system results in a reduction of 79% in its summer grid-electricity demand. The peak hourly cooling load was also observed to shift and reduce by 47%. In comparison, the PV size is reduced to 2.8 kW, the summer grid consumption and peak demand reductions decline by 60% and 22% respectively. This decline is due to the lower hourly output power of the smaller PV system. However, in terms of PV self-consumption, the 2.8-kW system obtains higher improvement by employing a thermal storage system. The study demonstrated that adding thermal storage systems in residential houses can effectively manage space cooling demand, reduce peak cooling load, and shift the peak load.

Keywords: Thermal storage, Demand management, Photovoltaic system, Energy simulation

1. Introduction

Peak demand from residential AC systems has become a major issue with network operators and generators. Firstly, the peak demand is one of the significant factors which decides the investment in the electrical and gas network (Smith et al., 2013). The peak load of a residential air conditioner only occurs over very small periods during a year; but to satisfy this peak demand, the initial capital investment in grid must be heavily augmented (Oliphant, 2008). Furthermore, in terms of grid operation and regulation, peak demand can create network instabilities and high electricity spot prices (Palmer, 2012). A recent example is the two-day heat wave of 24–25 Jan 2019 in Victoria that resulted in forced power cuts to around 60,000 customers to avoid exceeding the power generation limit and to prevent a state-wide blackout (Latimer, 2019). During this period, the electricity spot price climbed to the market price cap of $14,500/MWh (AEMO, 2019).

Additionally, on the supply side, extensive adoption of rooftop PV has also posed challenges to network stability. Due to the unpredictable characteristics of renewable energy and the “duck curve” caused by high penetration of solar power on the grid, it often brings abrupt changes to grid demand (Arteconi et al., 2017). The rooftop PV deployment is predicted to increase with time, and the “duck curve” is predicted to occur more often and be more pronounced (Kosowatz, 2018). Operators and regulators of the grid experience increased difficulty in balancing the network and increase ancillary services, leading to instability of the power supply, larger cost to taxpayers, and more pollution

(AEMC, 2017). Although, employing new inverters that limit the PV electricity output can mitigate the grid over-voltage problem; this approach is not an ideal solution, because it leads to the lower system capacity factor and the underutilization of the PV power.

To address this issue, a distributed thermal storage system in residential buildings with roof-top PV is proposed in this research. The storage system uses the PV output to generate heat/cool for the building's thermal comfort using a vapour compression heat pump. The thermal storage coupled to the heat pump is used to utilize the PV output at the time of PV generation. The benefit of employing a thermal storage coupled with an onsite PV system for the purpose of demand management and load shifting in an industrial building has been previously demonstrated (Arteconi et al., 2016). Williams, Binder and Kelm (2012) also proved that adding thermal storage into residential space heating system can help to improve the PV electricity utilization and grid compatibility. The novelty of the current paper is to quantitatively evaluate the effects of integrating thermal storage and roof-top PV system into a residential AC system located in Brisbane. As Brisbane is a cooling demand dominant area, the space cooling demand management is the focus of this paper. The combined system solution which can potentially satisfy space cooling, heating and domestic hot water requirement will be further investigated in the next stage.

2. Approach

In this study, a NatHERS 5-star-rating Brisbane house, which was monitored for several years by the CSIRO, is chosen as the research subject. Its original building performance calculation file and monitored electricity consumption data of domestic hot water system, AC system and other household electrical appliances are provided by the CSIRO. The basic building information is presented in Table 1.

Table 1. Basic building information

Location		Brisbane
NatHERS Climate Zone		10
Occupancy		24 hr
Conditioned area		113.4 m^2 – 4 bedrooms,1 living room / kitchen / dining room, 1 garage
NatHERS Energy Star Rating		5.2
Building construction	External wall	Brick veneer DSF, R=1.03
	Ceiling	Glass fibre batts and plasterboard, R=2.56
	Roof	Concrete tiles No sarking, discontinuous
	Floor	Concrete slab 85mm and polystyrene expanded 38 mm, R=1.04
	Window	U=6.7 SHGC=0.7
	Eave shading	Yes
Air-conditioning system		Wall-split air-conditioning units
Domestic hot water system		Electrical water heater

The approach of the research is based on simulations, which include simulation of PV hourly generation, the electricity demand from space cooling system, domestic hot water system and other household electrical appliances.

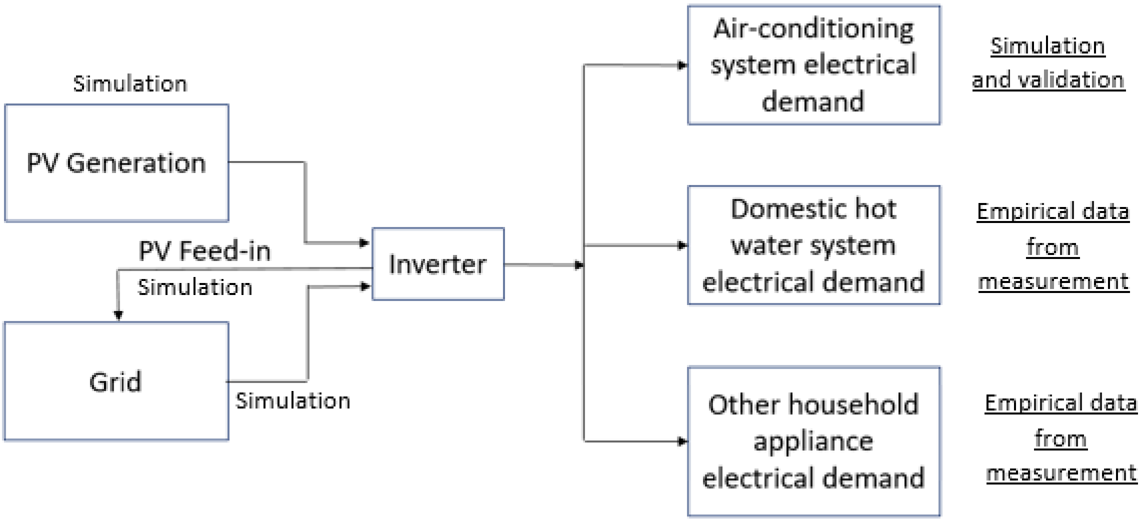

Figure 1. Model description

2.1. PV generation simulation

The hourly output power of the PV system is simulated in Transient System Simulation Tool (TRNSYS). TRNSYS is a graphically based software tool to simulate the dynamic behavior of thermal and electrical energy systems.

The NatHERS 2013 climate data for climate zone 10 is imported into the TRNSYS model. Then the PV and inverter component Type 190 in TRNSYS extracts data from this weather data file, the necessary data the weather file including dry bulb temperature, wind velocity, beam radiation, total tilted surface radiation, sky diffuse radiation, angle of incidence on the surface etc. 5.0-kW and 2.8-kW PV systems were investigated and simulated in this model. The 5.0-kW PV system consisted of 280-W polycrystalline solar modules, arranged in 2 parallel strings each of 9 panels. The 2.8-kW system consisted 2 parallel strings of 5 panels. The parameters for solar panels and inverters, which are used in TRNSYS, were acquired from Perlightsolar co., Ltd. The PV panels were assumed to be installed on the north roof with a slope of 15° (roof pitch).

Table 2. Simulated PV generated power and available power for the air-conditioning system

Parameter	**Rated PV power output**	
	5.0 kW	2.8 kW
Solar panel	18 x 280 W polycrystalline solar modules	10 x 280 W polycrystalline solar modules
Summer PV power generation	4,238 kWh	2,396 kWh
Max. hourly power output	4.83 kW	2.74 kW

The hourly PV generated power is calculated from each time step in TRNSYS. The total energy generated is around 4,238 kWh and 2,396 kWh for the 5.0-kW and 2.8-kW PV system in summer (January, February, March, October, November and December) and the maximum hourly power output is about 4.83 kW and 2.74 kW respectively (Table 2).

The electricity produced by PV panels is assumed to take priority to satisfy the electrical demand of domestic hot water and other household electrical appliances (except AC). The rest of the PV electricity is taken as the available power which can drive AC equipment when there is space cooling demand. Any remaining excess PV electricity is fed into the grid. The hourly electricity consumption data of other household electrical appliances and domestic hot water are extracted from the field measured data. The available power for air-conditioning system is calculated for each hourly time-step in TRNSYS by subtracting the electrical appliance load from the total PV output.

2.2. Space cooling system electrical demand simulation

2.2.1. Building thermal demand simulation

The annual thermal demand of the house was simulated in AccuRate Sustainability Software (AccuRate). The CSIRO's Chenath Engine (Chenath) which supports AccuRate to perform the calculation was validated against ANSI/ASHRAE 140-2001 (NatHERS, 2019). The results agreed well with the reference programs in the standard. The original calculation file of the selected house was supplied by CSIRO. The operation schedule of AC equipment and the settings of room thermostats as well as internal heat were the same as the software default settings for climate zone 10.

After obtaining the hourly space cooling demand, the simulation of dynamic electricity consuming behaviors of AC system was carried out in TRNSYS to investigate the difference of hourly electricity consumption between 'non-thermal-storage' and 'with-thermal-storage' systems.

2.2.2. Electricity demand simulation of space cooling system

The system design schematic of the AC system with thermal storage is shown in Figure 2.

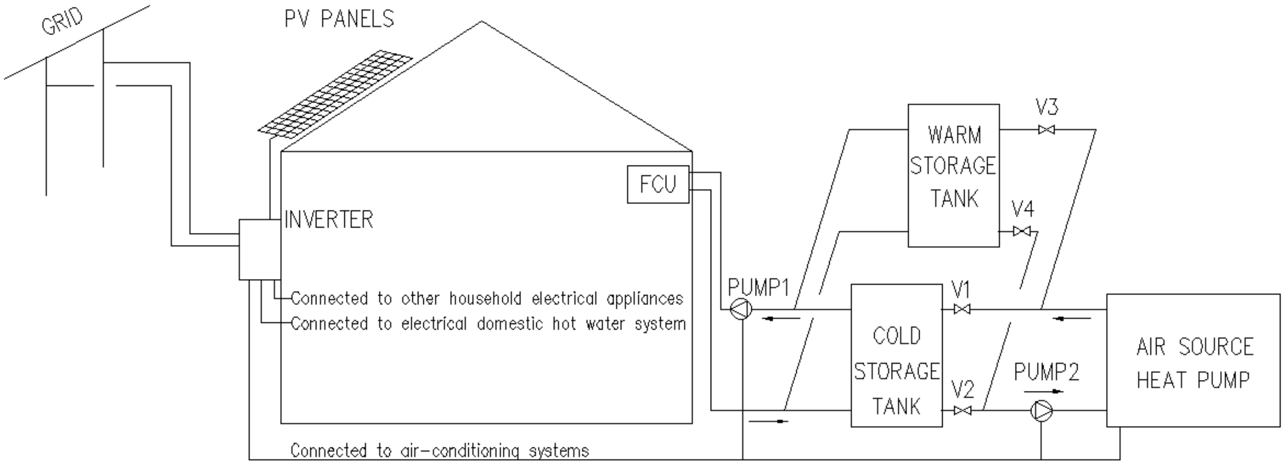

Figure 2. The design diagram of air-conditioning system with thermal storage

The air source heat pump provides chilled water or heating hot water to the AC system. In summer, valve 3 and 4 will be shut off and air source heat pump will supply chilled water to the tank which then will satisfy the space cooling requirement in the house. In winter, valve 1 and 2 will be shut off and air source heat pump will supply heating water to the tank which will then satisfy the space heating and domestic hot water requirement in the house. The space cooling system with cold storage tank is the research subject of the current paper.

The hourly electricity consumption of AC system is simulated in TRNSYS as shown in Figure 3. Firstly, the building hourly space cooling demand is imported into TRNSYS by using component Type 9. Pump 1 is a fix-speed pump that is controlled by the value of cooling load. It will be shut off when there is no load. The on/off control of pump 2 and heat pump are controlled by tank temperature and PV power as described in Table 5. The cooling capacity and performance parameters of heat pump are listed in table 3. The pumps and fan coil units (FCU) were sized accordingly. The electricity data of system components (heat pump, pumps and FCU) were calculated in each time step automatically in TRNSYS.

Table 3. Specification of heat pump, pumps and fan coil unit

Heat Pump					
Chilled Water Temperature (°C)	5.5				
Ambient Air Dry-Bulb Temperatures (°C)	23.89	29.44	35.00	40.56	46.11
Capacity (kW)	10.39	9.97	9.56	9.07	8.58
COP	3.20	2.75	2.40	2.00	1.69
Assumptions of heat pump partial load performance					
Part Load Ratio	0.00	0.25	0.50	0.75	1.00
Fraction of Full Load Power	0.00	0.25	0.50	0.75	1.00
Pump	Flow rate (kg/h)	Head (m)	Rated power (w)	Overall pump efficiency	Motor efficiency
	1700	10	180	60%	90%
FCU	Total cooling capacity (kW)	Airflow med. Speed (m^3/h)	External pressure (Pa)	Rated power (w)	
	10	1900	30	250W	

3. Result

3.1. Space cooling electricity load of the AC system without thermal storage

The simulated electricity consumption of the AC system without any thermal storage unit is summarized in Table 4. The year 2013 weather data was used in TRNSYS18 simulation in order to compare with real monitored data measured in 2013. It is found that the discrepancy between simulation and monitored data of the peak cooling load was about 10%. We hypothesize the following reasons for this discrepancy:

1- the personalized habits of occupants and thermostat settings,
2- the actual system Coefficient of Performance (COP),
3- differences in the building envelope and construction quality.

Table 4. Simulation and measurement results comparison

Parameter	**Period**	**Value**
Simulated space cooling system electricity demand	Summer	658 kWh
	Max. hourly	3.88 kW
Monitored space cooling system electricity demand	Summer	827 kWh
	Max. hourly	4.31 kW

3.2. Electrical requirement from the grid for different system configurations

Based on the simulated space cooling load, a range of system configurations as in Table 5 were investigated. The cold storage tank in Case 2 was assumed to have capacities to store about 20 kWh of cooling energy, covering the daily cooling demand of approx. 90% of summer days; while in case 4, the storage was increased to 40 kWh (equivalent to a 450-L ice slurry storage), which equates to approx. 98% of summer days' cooling demand (ice storage reduces volume and keeps the tank temperature in the reasonable range). The control logic in Case 2 was based on the tank temperature as follows:

1- when the top temperature of the tank exceeds 10°C, the chiller turns on
2- when the top temperature of tank falls below 8°C, the chiller turns off.

In case 4, the control is optimized to the AC system will run only if the PV power available for AC system is bigger than 2 kW. The results of respective summer electricity demand and maximum hourly demand from grid are summarized in Figure 3 and 4.

Table 5. Case explanation

Case 1	space cooling system (no storage)
Case 2	space cooling system + storage + tank temperature control
Case 3	space cooling system (no storage) + PV system
Case 4	space cooling system + storage+ PV system, heat pump only running when the PV power available for AC system >=2 kW (in 5.0-kW PV system) and >=1kW (in 2.8-kW PV system)

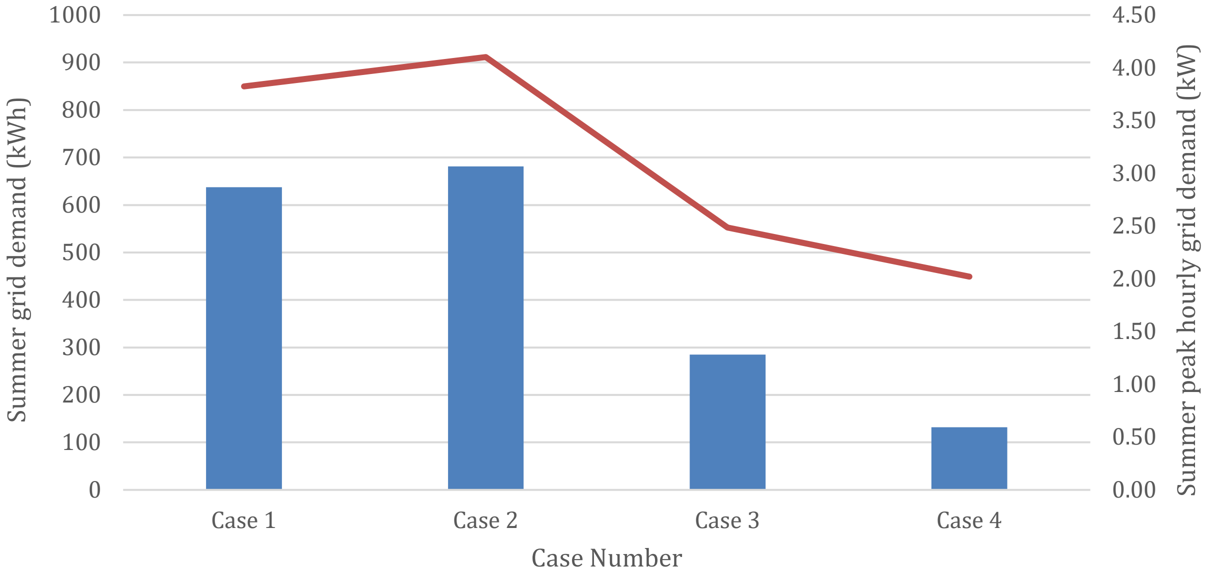

Figure 3. Summer and peak hourly electricity demand from grid in the 5.0-kW PV system

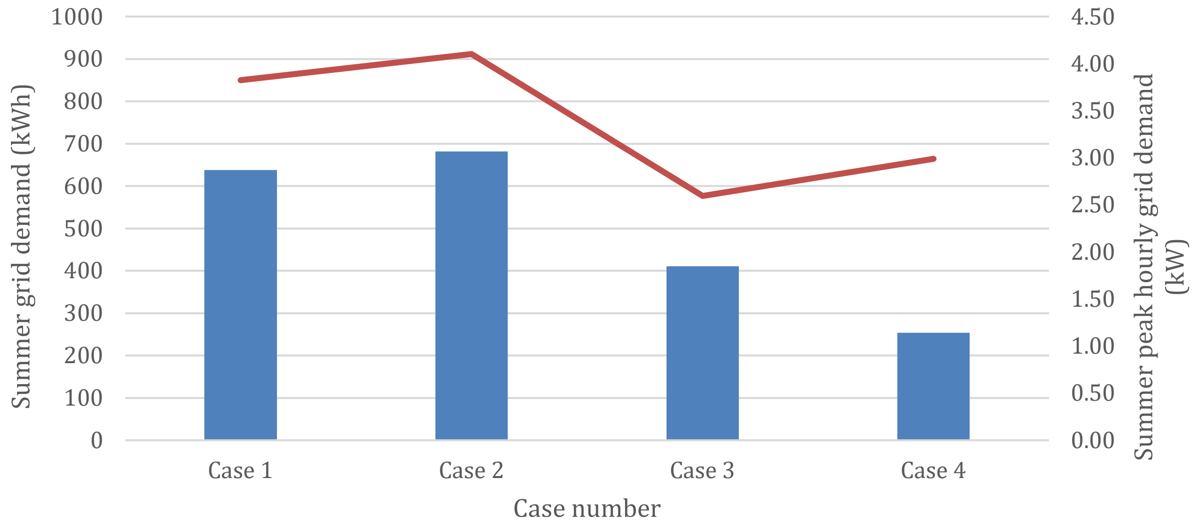

Figure 4. Summer and peak hourly electricity demand from grid in the 2.8-kW PV system

The results show that by combining the PV and thermal storage unit as well as utilizing effective control strategies, the overall electrical demand from the grid declines both in 5.0-kW PV system and 2.8-kW PV system cases. In the 5.0-kW PV case, the summer total consumption value drops by approximately 79%, from 638 kWh in Case 1 to 132 kWh in Case 4 (see Figure 3). In terms of its peak electrical demand, the figure declines by 47% from 3.82 kW in Case 1 to 2.02 kW in Case 4. In comparison, the summer total and peak demand in the 2.8-kW PV system show a lower reduction: the summer consumption drops by 60%, and peak demand drops by 23% (see Figure 4). The reason for the lower reduction of 2.8-kW system is because of its lower PV electricity generation as show in table 6. The maximum hourly power output of 2.8-kW system (2.74kW) is only about 60% of the maximum hourly electricity demand (4.29kW).

Table 6. PV generation versus Electricity demand

Period	**Parameter**	**Value**	**Value**
Summer PV generation	Rated PV power output	5.0 kW	2.8 kW
	Summer total PV power generation	4,238 kWh	2,396 kWh
	Max. hourly power output	4.83 kW	2.74 kW
Summer electricity demand	Total demand in summer	2390 kWh	
	-- AC system	638 kWh	
	-- Other domestic electrical appliances	1752 kWh	
	Max. hourly demand	4.29 kW	

3.3. Peak cooling load shift and reduction effect

Data from the simulation shows that the peak hourly cooling demand occurs at 5:00 pm on 29 Jan, which was the hottest day of the year (the week from 23 – 29 Jan was also the hottest week).

Table 7. Simulated space cooling load summary

Parameter	**Value**
Total summer load	1,001 kWh
Max. hourly load	10.40 kW
Max. hourly load time	29/01/2013 17:00 pm
Max. daily load	44.66 kWh
Max. daily load date	29/01/2013

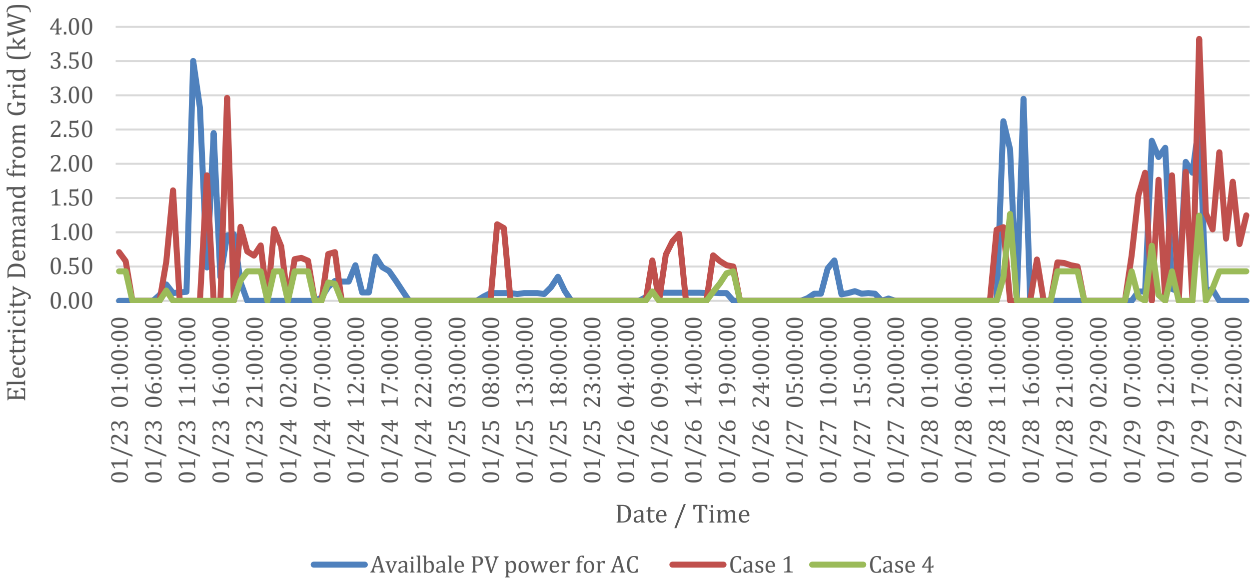

Figure 5. Hourly electrical demand from grid in the 5.0-kW PV system

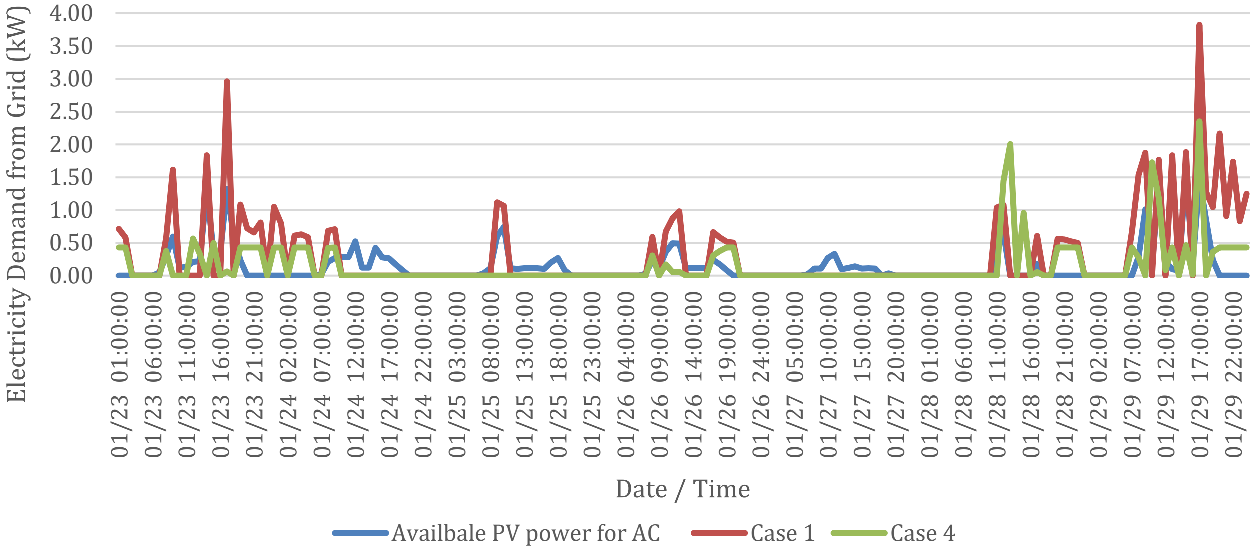

Figure 6. Hourly electrical demand from grid in the 2.8-kW PV system

The shift and reduction in the hourly electricity demand from the grid for cooling are investigated for this period. From figure 5, it is observed that by combining the thermal storage and the PV system, the peak electricity load required from the grid was effectively decreased and shifted. Comparing figure 5 and 6, the peak reduction and shift effects in the 2.8-kW PV system is not as significant as the effects in 5.0-kW PV system due to lower PV output.

3.4. PV self-consumption rate and excess PV electricity injection to grid

The effect of thermal storage on improving the PV self-consumption and reducing the PV-to-grid export was also investigated for this house (see table 8 & 9). It is seen in Table 8 (5.0-kW PV) that the PV self-consumption increases by 8% by adding the thermal storage unit. This increase is not very high because the contribution of the AC system to the total energy demand of the house is only about 27% in this 5-star house. In houses which were built with relatively higher construction standard, the demand for electricity from other home appliances dominants the total electricity required from grid (Williams, Binder and Kelm, 2012). The other reason is that the PV system in this case is oversized i.e. the total PC generation is significantly more than the total demand. By downsizing the PV system to 2.8 kW, the contribution of the thermal storage unit to the PV self-consumption has been enlarged to 15%. Thus, obviously, the thermal storage system coupled with a matched-sized or under-sized PV system can obtain a higher improvement in terms of self-consumption rate. However, because of the lower hourly output power in this latter case, the reduction of the summer grid electrical demand and peak demand have been compromised.

Table 8. PV self-consumption figures (kWh) for different cases in the 5.0-kW PV system

Parameter	**Case Number**		
	0	3	4
	PV only for elec. appliance except AC	PV for elec. appliance and AC. No thermal storage	PV for elec. appliance and AC with thermal storage
PV total generation in summer	4,238 kWh	4,238 kWh	4,238 kWh
Original electricity demand in summer			
Total demand	2,390 kWh	2,390 kWh	2,590 kWh
Home appliance	1,752 kWh	1,752 kWh	1,752 kWh
Space Cooling	638 kWh	638 kWh	838 kWh
Total electricity from grid	1,529 kWh	1,176 kWh	1,023 kWh
Total electricity from PV	861 kWh	1,214 kWh	1,567 kWh
PV self-consumption rate	20%	29%	37%

Table 9. PV self-consumption figures (kWh) for different cases in the 2.8-kW PV system

Parameter	**Case Number**		
	0	3	4
	PV only for elec. appliance except AC	PV for elec. appliance and AC. No thermal storage	PV for elec. appliance and AC with thermal storage
PV total generation in summer	2,396 kWh	2,396 kWh	2,396 kWh
Original electricity demand in summer			
Total demand	2,390 kWh	2,390 kWh	2,586 kWh
Home appliance	1,752 kWh	1,752 kWh	1,752 kWh
Space Cooling	638 kWh	638 kWh	833 kWh
Total electricity from grid	1,627 kWh	1,400 kWh	1,243 kWh
Total electricity from PV	763 kWh	990 kWh	1,343 kWh
PV self-consumption rate	32%	41%	56%

Conclusion

In this paper, building and system simulation tools (AccuRate and TRNSYS) are applied to investigate the effect of adopting cold storage on the peak demand of AC systems in a 5-Star house in Brisbane. Results indicate that using thermal storage coupled to a domestic heat pump and PV system greatly reduces the summer grid-based energy consumption and shifts the peak load. In terms of the PV self-consumption, reducing the PV system size from 5.0 kW to 2.8 kW improves the total PV self-consumption by compromising the summer grid electrical demand and peak demand. The distributed thermal storage coupled with PV system is expected to be a potential new generation of thermal comfort system for residential dwellings which effectively manages the peak space cooling demand and eases the stress of grid.

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