Solar pre-cooling with different tariff structures and household time of use patterns

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Abstract

This paper presents a clustering-based solar pre-cooling (SPC) analysis to evaluate the SPC potential of Australian housing stock. 450 households with solar PV systems and Air Conditioning (AC) are clustered into different groups based on their net electricity demand profiles excluding any AC operation. Then, the AC excluded net demand profile of each household is combined with nine different building types, creating nine virtual building envelopes for each household. Solar pre-cooling is simulated for all the virtual buildings and the results are compared with a baseline scenario in terms of maximum demand reduction, minimum demand mitigation, and cost savings, considering three different tariff structures. The results show that regardless of the energy efficiency and construction materials of a building, the SPC potential varies significantly based on the AC excluded net demand profile of the household. SPC offers high minimum demand mitigation while maximum demand reduction is not considerable. The cost savings highly depends on the tariff structure, and the Feed-in Tariff (FiT).

Keywords: demand response, air conditioning, energy efficiency, rooftop PV, clustering, data mining

Introduction

Air Conditioning (AC) demand is a major contributor to peak electricity demand of residential buildings and the Australian National Electricity Market (NEM) [1], especially on hot days [2]. The peak AC demand usually occurs in the early evening when households return home and switch on their AC units [3]. Even though the penetration of rooftop Photovoltaics (PV) in Australia is high, households cannot typically use their PV generation to meet their peak AC demand, because of the mismatch between the timing of PV generation and AC demand [4].

During the day, households' consumption is usually less than their PV generation, and the surplus PV is exported to the grid, reducing electricity network's minimum operational demand. In the early evening, residential demand peaks, mainly due to AC demand, and because there is no surplus PV generation in the evening, the imported electricity from the grid is used to run AC units, adding to evening peak demand of the electricity network.

The mismatch between the demand profile of buildings and solar generation highlights the need for energy storage to increase self-consumption (SC) and reduce import from, and export to the grid [4]. SPC is a form of energy storage, and involves shifting AC demand to earlier times in the day by using the surplus PV generation to run the AC unit, hence utilizing the thermal mass of the building as a thermal battery. It helps mitigate the low minimum demand of the electricity network during the day and reduces the peak AC demand through the pre-cooling thermal mass of the buildings.

SPC also has economic benefits for households. Because the Feed-in Tariff (FiT) is significantly lower than the retail electricity prices, households can save money by consuming their on-site PV generation, and reducing imports from the grid during the evening. SPC cost savings and the level of demand profile improvement depend on the SPC potential of a building, which is a function of the building's thermal dynamics, and households' consumption pattern [4]. This paper evaluates the SPC potential of existing buildings in the Australian housing stock.

Datasets

Two different datasets are used in this study. The first dataset is hourly AC demand, net household demand, and PV generation of 450 Australian households in Adelaide, Brisbane, Melbourne, and Sydney, provided by Solar Analytics Pty. Ltd [5]. The second dataset is the simulated thermal dynamics of nine residential building types with three different star ratings (2-star, 6-star, and 8-star) and three different construction weights (light, medium, and heavy). Thermal dynamics includes one year of AC demand, indoor temperature, and outdoor temperature, simulated using AccuRate, a tool used for rating Australian buildings based on their thermal demand. More details about this dataset can be found in the authors' previous works [6, 7].

Clustering

To cluster households into different groups, they are clustered using AC excluded net demand profiles, which is the mostly temperature insensitive part of the net demand profile. AC excluded net demand profile includes PV generation, imports from and to the grid, and household's consumption except for AC demand. It contains the amount of surplus PV generation after meeting the household's gross demand, which can be used for SPC.

For each household, AC excluded net demand profile, from 1 December 2018 to 28 February 2019, is grouped by day type (weekdays, weekends), and then averaged hourly values are obtained for each group. The result is a feature vector with 48 features (number of features per day × number of day types = 24×2). Then, all feature vectors are normalized using the z-score normalization method. In the next step, Principal Component Analysis (PCA) is implemented to further reduce the dimensionality of the feature vectors, by preserving 95% of the variance, resulting to feature vectors with 7 features. Since the K-means clustering method is used in this research, and it requires the number of clusters as an input, the optimal number of clusters (4 clusters) is found using gap statistics and Silhouette score methods.

Solar pre-cooling and baseline scenarios

For all virtual buildings, the SPC scenario is simulated and compared with a baseline scenario which is a thermostat-based AC control strategy. In the baseline scenario, in each hour, if the indoor temperature is higher than the upper limit of thermal comfort, AC is turned on. Otherwise, the algorithm goes to the next hour. In the SPC scenario, in each hour, if there is no surplus PV generation, the algorithm works like the baseline scenario. If there is surplus PV generation, it is used to pre-cool the building. If at the end of the hour the indoor temperature is lower than the upper limit of thermal comfort, the algorithm goes to the next hour. If the indoor temperature is above the upper limit of thermal comfort, imported electricity from the grid is used to run the AC, with a setpoint equal to the upper limit of thermal comfort. A linear model which is developed using the thermal dynamics dataset is used to simulate buildings in both scenarios. The simulations are based on full-time occupancy for all case studies. An open-source tool developed by the author [8], which simulates SPC for Australian households, gives an detailed description of the simulation methods.

Tariff structures

Three different tariff structures are investigated in this paper, as follows:

1- Single rate tariff rate of 23.84 c/kWh, based on Essential Energy’s network tariff from the 2022/23 pricing proposal, and the average of the cheapest tariff offered by Origin, Energy Australia, and AGL.

2- Time of Use (TOU) tariff structure with 17.54 c/kWh, 29.88 c/kWh, and 32.68 c/kWh rates for off-peak, shoulder, and peak hours, respectively. The peak period is 5 - 8 pm on weekdays, the shoulder is 7 am - 5 pm and 8 - 10 pm on weekdays, with the off-peak period being all other times. The prices are taken from the same sources as the single-rate tariff.

3- Daytime saver, which is based on the new tariff structure offered to Victorian households [9], with free electricity from 10 am - 3 pm, 16 c/kWh 4 - 9 pm, and 5.7 c/kWh all other times.

Results and discussion

The centroids of the obtained AC excluded net demand profile clusters are shown in Figure 1. There are two clusters (Clusters 2 and 4) with large duck belly in the AC excluded net demand profile. A belly is also observerd in cluster 1, but smaller than clusters 2 and 4. The last cluster, cluster 3, has an AC excluded net demand profile which is always positive during the day. More than 80% of households are in clusters 2 and 4, and 15% of households fall into cluster 1, with cluster 3 being the minority cluster, with only 3% of households.

For each cluster and building type, the obtained average net demand profile of the SPC and baseline scenarios are shown in Figure 2. The first noticeable improvement of net demand profile through SPC is low minimum demand mitigation. The maximum observed low minimum demand mitigation is more than 1 kW, in clusters 2 and 4. These two clusters offer the highest minimum demand mitigation because of the large belly in their AC excluded net demand profile. Cluster 3, which does not have a negative AC excluded net demand profile, cannot offer any minimum demand mitigation. In terms of maximum demand reduction, there is a not noticeable improvement in the averaged net demand profiles, in all clusters.

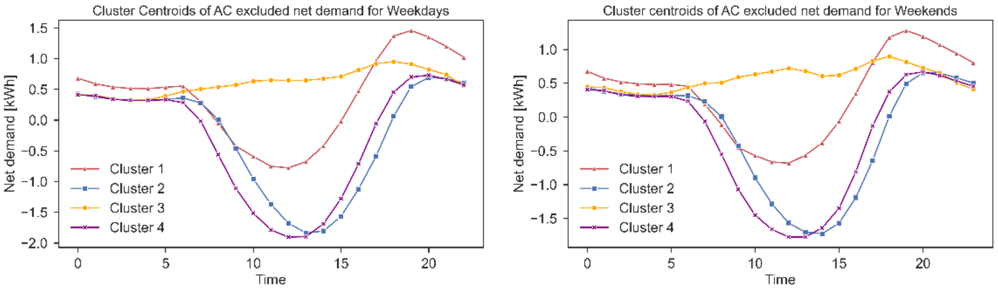


Figure 1 Obtained clusters of AC excluded net demand profile

The figures for 2-star buildings show significant change of net demand profile with different construction weights. In the baseline scenario, a larger duck belly is observed for buildings with heavier construction weights. However, through implementing SPC, heavier buildings offer higher minimum demand mitigation, which means more thermal energy can be injected into such buildings, highlighting their higher thermal capacity.

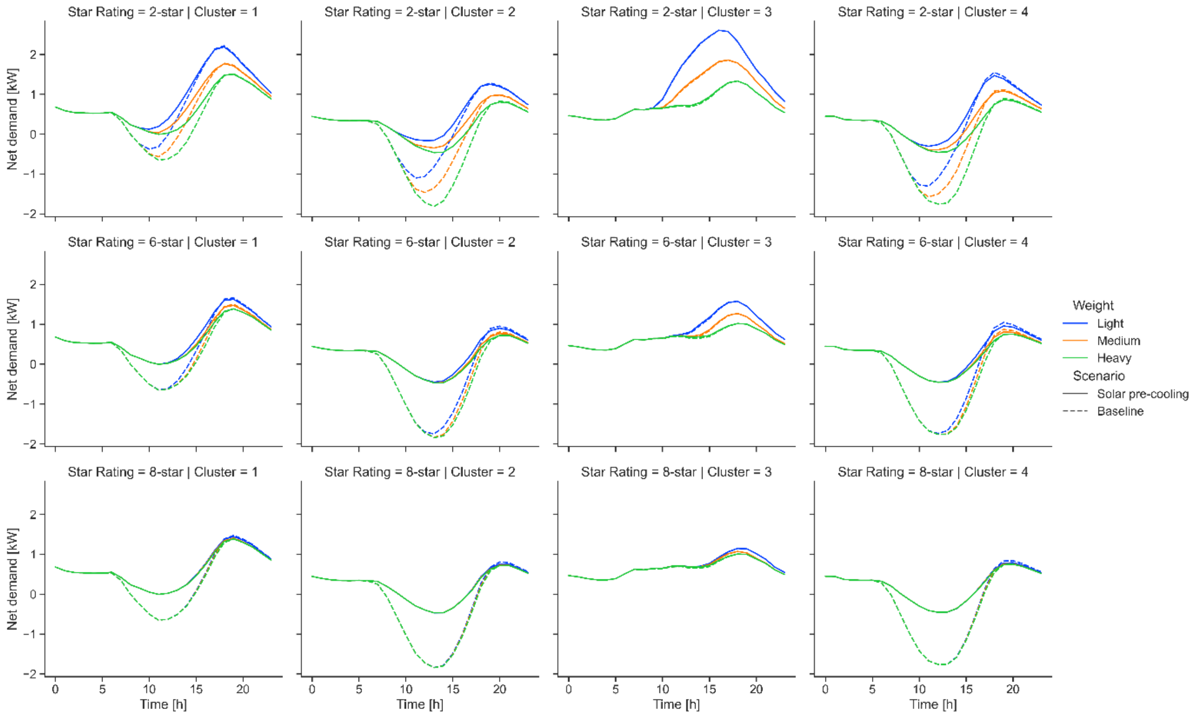
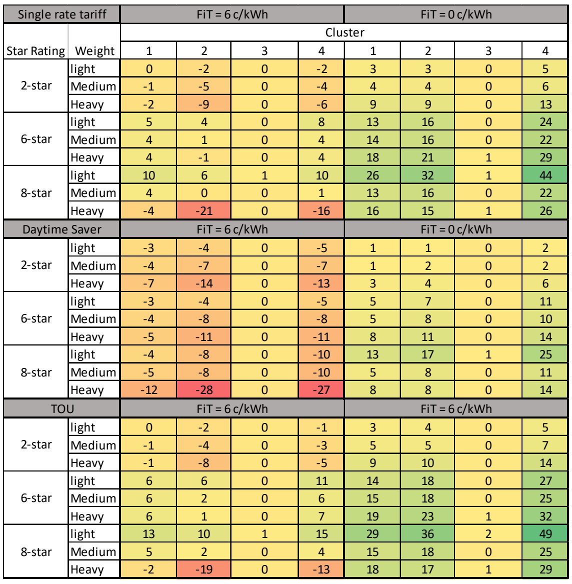


Figure 2. Figure legends should be placed at the bottom of the figure

The figure also highlights that increasing the star rating of light- and medium-wight buildings leads to a larger duck belly in the baseline scenario. This highlights that improving the energy efficiency of buildings might reduce their overall thermal demand, but increases the size of the duck belly in their net demand profile, exacerbating the low minimum demand of the electricity network.

Table 1 presents SPC cost savings for each cluster and building type, with the three different tariff structures and two FiTs. Buildings in cluster 3, offer almost no cost savings, regardless of their building type, electricity tariff, and FiT. This highlights that households' TOU pattern can limit the SPC potential, even for energy efficient buildings. The table also highlights that with the current FITs (6 c/kWh), SPC might lead to negative cost savings. This problem is solved with a zero FiT, and in average households can save up to around $50. The comparison of different tariff structures also shows more savings with the TOU tariff, followed by the single rate tariff and then zero cost daytime tariff offers the least cost savings through SPC.

Table 1 Cost savings from pre-cooling in different clusters



Single rate tariff		FiT = 6 c/kWh				FiT = 0 c/kWh			
		Cluster							
Star Rating	Weight	1	2	3	4	1	2	3	4
2-star	light	0	-2	0	-2	3	3	0	5
	Medium	-1	-5	0	-4	4	4	0	6
	Heavy	-2	-9	0	-6	9	9	0	13
6-star	light	5	4	0	8	13	16	0	24
	Medium	4	1	0	4	14	16	0	22
	Heavy	4	-1	0	4	18	21	1	29
8-star	light	10	6	1	10	26	32	1	44
	Medium	4	0	0	1	13	16	0	22
	Heavy	-4	-21	0	-16	16	15	1	26
Daytime Saver		FiT = 6 c/kWh				FiT = 0 c/kWh			
2-star	light	-3	-4	0	-5	1	1	0	2
	Medium	-4	-7	0	-7	1	2	0	2
	Heavy	-7	-14	0	-13	3	4	0	6
6-star	light	-3	-4	0	-5	5	7	0	11
	Medium	-4	-8	0	-8	5	8	0	10
	Heavy	-5	-11	0	-11	8	11	0	14
8-star	light	-4	-8	0	-10	13	17	1	25
	Medium	-5	-8	0	-10	5	8	0	11
	Heavy	-12	-28	0	-27	8	8	0	14
TOU		FiT = 6 c/kWh				FiT = 6 c/kWh			
2-star	light	0	-2	0	-1	3	4	0	5
	Medium	-1	-4	0	-3	5	5	0	7
	Heavy	-1	-8	0	-5	9	10	0	14
6-star	light	6	6	0	11	14	18	0	27
	Medium	6	2	0	6	15	18	0	25
	Heavy	6	1	0	7	19	23	1	32
8-star	light	13	10	1	15	29	36	2	49
	Medium	5	2	0	4	15	18	0	25
	Heavy	-2	-19	0	-13	18	17	1	29

Conclusions

This paper evaluates the solar pre-cooling (SPC) potential of the Australian housing stock through clustering households based on their air conditioning excluded net demand profile and considering buildings with different star ratings and construction weights, representing the available buildings in Australia. The results show that SPC improves the net demand profile of buildings, mainly through mitigating the minimum demand, but that the offered maximum demand reduction is not considerable compared with minimum demand mitigation. Moreover, simulating SPC with three different tariff structures shows that when on TOU tariff a household can save up to $50 per summer, on average.

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