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Examining the variation in daily and peak electricity use in urban Indian households by AC ownership

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Abstract

Recent forecasts reveal a significant increase in residential air conditioning (AC) units in India leading to increased absolute and peak electricity demand. This study conducts statistical analysis of high-resolution time-series electricity data to examine the variation in daily and peak electricity use by extent of AC ownership across 54 urban Indian households.

Mean annual electricity use in households with one AC unit was found to be 3,482kWh, which was 13% less than two-AC households (4,180kWh), and 37% less than households with three or more AC units (5,472kWh). The peak electricity use period was from 9pm to 2am confirming prevalence of overnight AC use. Policies supporting demand response could help manage absolute and peak electricity demand.

Key Innovations

- Understanding diversity and magnitude in peak periods of AC electricity use by the extent of AC ownership in Indian households.
- Daily electricity use in households with three or more AC units (19 kWh/day) was nearly double that of households with one AC units (11 kWh/day) regardless of season.
- As AC units get installed in multiple rooms to achieve similar levels of thermal comfort, this could notably increase residential electricity demand in India.

Practical Implications

The mean hourly minimum electricity use was observed to be 0.2kWh, while the mean hourly maximum peak use ranged from 1.1 to 2.1kWh across the study sample. This huge difference in peak and off-peak periods of electricity use needs to be tackled to avoid blackouts in India, especially during the extreme summer and monsoon seasons.

Introduction

The International Energy Agency (2019) predicted India will have 240 million air conditioning (AC) units by 2030 which is 42 times the increase in growth from 2016 (IEA, 2019). The Government of India has already recognised the necessity of cooling as a priority in state and national level by adopting India Cooling Action Plan (ICAP) in 2019. According to ICAP, room AC will dominate the building sector's cooling energy consumption, with 50% of the 600 TWh by 2037-38 (GoI, 2019). In light of this, ICAP has aimed to reduce cooling demand across sectors by 20-25% by 2037-38 (IEA, 2019).

Most parts of India including Delhi have witnessed periodic blackouts, ranging from 1-2 hours to 6-7 hours. This occurs due to issues in ineffective electricity supply, theft and other fuel shortages. When there is a sudden increase in demand the generators generate more power and feeds the consumer especially during peak hours, but this is a huge cause of increased demand. To meet this demand, the generators reduce speed and reduced frequency and thereby reducing the quality in supply ultimately leading to unstable conditions resulting in load shedding (where utilities switch off power to certain areas or a large consumer). The high power of AC consumption can cause fluctuations in energy demand, and this has to be controlled or reduced to ensure the stability of utility grid system (Hassan et al., 2014). Therefore, examining AC electricity consumption pattern is vital for understanding the peak periods of electricity use and how that varies over a day, season and by AC ownership.

Several studies in literature have identified methodologies to understand usage of AC. Ren et al. (2017) developed a quantitative stochastic model to predict AC usage across three families. In the study, environmental triggers (indoor temperature) and event triggers (i.e., turning the AC on when feeling hot) were the driving factors. However, the model was too complex to predict the AC on/off behaviour over time. Yasue et al. (2013) used AC usage data in residential buildings and to identify relation between indoor temperature and AC switching probability. Yao et al. (2018) used measured data, statistical analysis, and logistic regression to calculate the probability of above which temperature occupants may use their AC and when as well as at which temperature occupants may set and turn off their AC. Zaki et al. (2012) used a field survey on the AC usage behaviour of occupants in 38 households in Kuala Lumpur, Malaysia, and proposed an algorithm to identify timing of AC usage. However, their model was not able to predict the AC on/off status under certain environmental conditions.

Khosla et al. (2021) reported that AC use primarily stemmed from the function of household habits, socio-demographic features and other structural features. AC usage has been found to account for 70% of electricity consumption during summer where plug level switching data was useful to identify the appliance usage (turned on/off) in the dwelling (Batra, Gulati et al. 2013). The electricity consumption (kWh/dwelling) more than doubled, from around 300 kWh per dwelling when desert coolers were switched with room air-conditioners. A Government of India supported project called NEEM (national energy end-use monitoring) identified that AC use in homes contributed to at least 50% of energy use (EDS 2019). Monitoring residential electricity consumption to understand cooling behaviour among occupants has become an area of interest. For example, some residents were found to switch off their AC once the room was cool and used fans to circulate the cool air, thereby reducing AC usage through the night (Debnath and Jenkins 2019). Another study undertook concurrent monitoring of indoor temperature, relative humidity and electricity use to establish AC usage hours (Gupta et al. 2020). It was identified that residential users in India consume more energy at night and late evening. Study by Agarwal et al. (2019) revealed that households switched on AC, on average, for around five hours per day. AC use was found to be influenced by income, weather, occupant behaviour, energy awareness, condition of AC unit and AC usage patterns (Chaturvedi, Gorthi et al. 2021). However there is limited research on examining the peak period of residential electricity use and how that varies across dwellings with multiple AC units.

Against this context, this study conducts statistical analysis of high-resolution time-series electricity data (at 30' intervals) to examine the variation in daily and peak electricity use in 54 urban Indian households by the extent of AC ownership. The households were located across composite, hot-dry and warm-humid climatic zones of India where AC use is dominant. The 54 households (representing 54 dwellings) were divided into three groups based on the extent of AC ownership – one AC unit (21 households), two AC units (18 households) and three or more AC units (15 households).

Methods

Smart meter data was gathered for a small sample of 54 AC households by Environmental Design Solutions as part of a Government of India- Bureau of Energy Efficiency supported NEEM-CLASP study. The NEEM-CLASP study dataset was provided to the authors for statistical analysis of the time-series electricity data to examine the variation in daily and seasonal profile of electricity use by AC ownership in 54 households located in the composite, hot-dry and warm-humid climatic zones. About 30% of households occupied less than 100 m^2 of floor area, while more than 30% of households with three or more AC units occupied more than 100 m^2 of floor space.

Electricity data was collected every 30 seconds on electricity use (Wh), peak demand (W), Power factor, voltage (V) and frequency (Hz) from January 2018 to November 2018 translating to 9,53,280 data points per household. Negative values more than five minutes were ignored. All values were normalised and rescaled between 0-1 to eliminate the bias from higher kWh values. These values were aggregated to one-min kWh data to develop distinct clusters profiles of electricity. Once the clusters were extracted, the absolute values were averaged.

The proportion of AC usage in daily mean electricity was determined to find out when the AC unit was likely to be switched on. A typical split AC unit of 1.5 ton rated at 3-star capacity was assumed (based on survey literature) which consumes around 1560-1980W ranging for a running current rating of 7.6-8 A at 220-240V. The energy consumption (typical) provides a rough estimation of the AC consumption, the period of when the AC turns ON and the peak usage during this period. Once the type of AC was estimated, the percentage contribution to energy use was estimated. The usage of AC ranging more than 30 minutes was accounted here when AC turns on and off otherwise high on/off action frequency indicates discontinuous AC usage, thus leading to frequent energy demand fluctuations which could be detrimental to the supply system. However, it should be noted that while another high-power consuming device such as a washing machine could have also been interpreted as AC use (as it can run for more than 30 minutes) this method could still provide a rough estimation of when AC was turned on or at least indicate the period of peak usage. The variation of AC use against daily mean electricity use was assessed across weekdays and weekends in the summer and monsoon seasons.

Cluster analysis (CA) of electricity consumption data was conducted to identify typical profiles of electricity use. This was done to validate the estimated peaks from modelling AC on/off method as it maximizes the similarity of cases within each cluster and maximizes the dissimilarity between groups that are initially unknown. The data here for each household were normalised by subtracting the minimum and maximum value from the 1440 individual measurement time points. After creating these curves for each home for each season, the curves were put into groups via a k-means clustering analysis. K-means is an iterative process that attempts to partition each curve (the seasonal average curve – a 24-valued vector) into groups such that the sum of squares (Euclidean distance) from each group member to its group centre is minimized. After each step, the centres were recalculated, and the curves redistributed until the process converged. The performance of the clusters was validated using the Davies-Bouldin or Silhouette Index.

Results

Daily electricity use

The mean daily electricity use over the available period was found to be 11kWh for one AC households, 14kWh for two AC households and 19 kWh for three or more AC households, as shown in Table 1. It is evident that daily electricity use increased slightly between one and two AC households and more drastically with three or more AC units.

Table 1: Mean daily electricity use across the AC households for summer and monsoon periods.

Daily mean electricity kWh	1AC	2AC	3 or more AC
Summer and monsoon	11	13.8	19.3
Summer	11.7	14.5	20.4
Monsoon	9.9	13.1	18.1

Table 2: Percentage contribution of AC use.

Contribution (%)	AC use in summer	AC use in monsoon	Max AC use in Summer	Max AC use in monsoon
1AC	22%	14%	10%	21%
2AC	20%	22%	13%	20%
3+AC	43%	34%	25%	50%

To understand AC usage pattern, the compressor on/off events were identified by locating the events in electricity current when current increases above the typical current rating of a 1.5-ton AC unit (around 8A). The typical AC on/off events were plotted against the current values of households with different AC units in summer and monsoon. AC cycles that were at least more than 30 minutes long were taken to be from AC usage. To detect AC cycle from the entire consumption cycle, data tagging was done for each current record of 54 households. Although several cycles were observed, the peak load during the hour was plotted to extract peak usage during AC operation. Peak electricity use was observed to happen during night-time as seen in Figure 1.

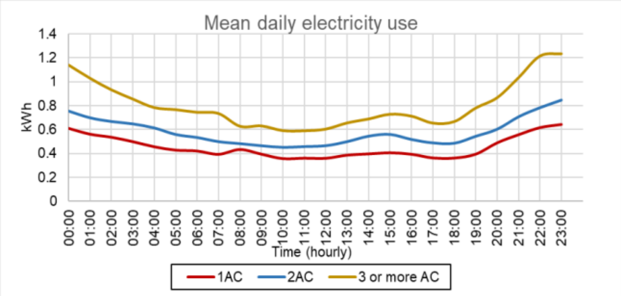

Figure 1: Mean daily electricity use across the AC households for summer and monsoon periods.

The usage patterns of AC units were assessed for a weekday and weekend day. It was identified that all three groups had higher AC usage in the weekend day rather than the week day. For 1 AC household's weekday, AC usage ranged from 13-11 hours per day with 50% chance of using an AC. In weekend day this usage ranged increased to a maximum of 15 hours per day. For 2 AC households, weekday AC usage stayed at a maximum of 16 hours per day with weekend day usage increasing to 17 hours of AC usage per day. For households with three or more AC units, the weekday usage ranged from 19-21 hours of usage per day increasing to 22 hours on a weekend day.

Estimated daily AC use during summer and monsoon

AC use among households with three or more AC units contributed to around 43% of the electricity use in summer and 34% in the monsoon season. The annual contribution of AC ranged from a mean of 10% in 1AC households, to a mean of 13% in 2 AC households. This increased to 25% of the annual electricity for households with three or more AC units

To further investigate the effect of AC usage for monsoon and summer, day by day analysis from April to September for each of the 54 households was conducted and the averages of these values for each group was plotted in Figures 2-4 below.

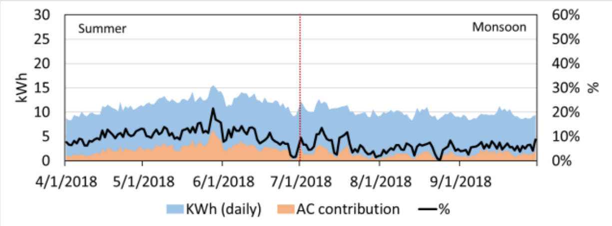

Figure 2: Mean daily electricity use and AC contribution across the 1AC households for summer and monsoon period.

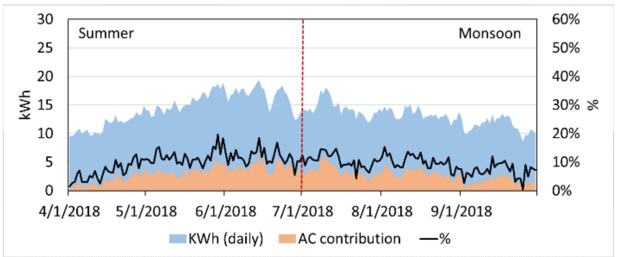

Figure 3: Mean daily electricity use and AC contribution across the 2AC households for summer and monsoon period.

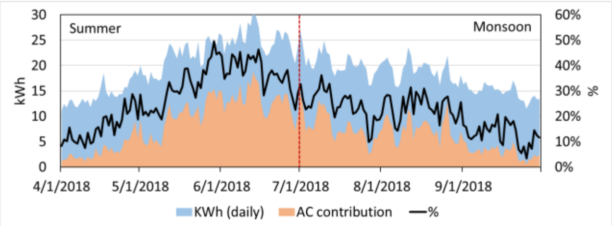

Figure 4: Mean daily electricity use and AC contribution across the 3 or more AC households for summer and monsoon period.

Overall air conditioning was used almost 18-38% of the time in the summer and monsoon seasons. Across the three groups of households, both daily electricity use and proportion of AC was higher in the summer than monsoon seasons, possibly due to higher ambient temperatures in the summer. As expected, the proportion of AC use against daily electricity use in households with 3 or more units was highest (going up to 50%) as compared to those with 2 or 1 AC units. Daily electricity use was found to increase to nearly 30kWh for 3 or more AC units, as compared to 19kWh for 2 or more AC units, and 15 kWh for households with one AC unit.

Mean daily minimum and maximum (peak) electricity use by extent of AC ownership

The daily peak electricity demand is defined as the maximum power consumed in a day. The highest power consumed from one-min data on each day was represented as the daily peak demand. As mentioned by Tran et al. (2020), the peak demand reported by different time in one day and different days in a week helps energy policies with reducing wasted energy. Peak demand of total electricity consumption, AC electricity consumption, and other appliances (i.e., the difference between the total and AC electricity consumption) were calculated for the study sample. The fraction of daily peak demand which indicates the fraction of how many times the peak happened daily.

The maximum daily mean electricity use across all households was seven to nine times more than the minimum daily electricity use, and at least two to three times the mean daily electricity use. This indicates the scale of the challenge that electricity grids need to meet. Agarwal et al. (2020), found that 8pm-5am was the peak period of usage where residential users consume most electricity during late evening and night when most household members are at home, and most of the cooling appliances are switched on. Khosla et al. (2021), also found that AC units were used for an average of 3–6 h daily during peak summer months; however, even during the hottest months of the year, only about 15% of their total sample households used ACs for more than eight hours per day in contrast to the estimated cooling usage by the Indian cooling action plan (where AC use was estimated to reach eight hours per day for five months of the year). Gupta et al. (2020) also found a late-night peak from 8pm to 2 am.

In this study, air conditioning was more frequently used in households with a greater number of AC units especially during late night for sleeping. Cluster was undertaken to identify the level of peak that arises among households with different number of AC units for the summer and monsoon periods. Interestingly two peak electricity use periods emerged - one short daytime peak electricity use of lower magnitude (1.1kWh) in one AC households, as compared to a longer night time peak electricity use period of larger magnitude (2.1 kWh). This is shown in Table 3.

Table 3: Descriptive statistics of electricity use across the sample

Descriptive statistics	1AC (kWh)	2AC (kWh)	3 or more AC (kWh)
Min	0.2	0.2	0.2
Max	1.1	1.3	2.1
Mean	0.5	0.6	0.8
Frequently used time period	9pm-12pm (three hours)	10pm-3am (five hours)	9pm-3am (six hours)

Clustered profiles

Two distinct clusters emerged following the cluster analysis of the 54 dwelling sample. Cluster 1 comprised of 29 households, while cluster 2 consisted of 25 households, with 70% of households in the clusters having one or two AC units. The number of households with three or more AC units were around 30% across the two clusters. The maximum point difference between diurnal and evening/night or late-night peaks was used to identify the period of peak electricity usage. Although the two cluster profiles were similar to each other, they showed differences in magnitude and duration of the peak period. Daily mean electricity use and peak electricity use were highest in cluster 2, wherein the peak usage was almost two times the peak usage by cluster 1.

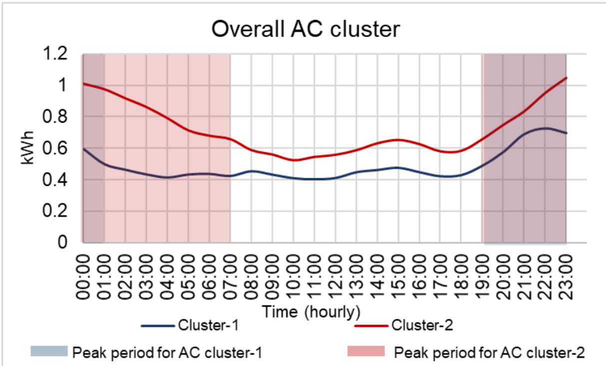

Figure 5: Clustered profiles of electricity use for summer and monsoon periods

The daily mean electricity use, amount of electricity used in the peak period along with its time duration are shown in Table 4. Cluster 1 showed a late evening peak of six hours lasting from 7pm until just after midnight (1am), while cluster 2's peak of 12 hours lasted all night until early morning (7pm to 7am). Electricity used in the cluster 2 peak period was nearly 2.5 times that of cluster 1.

Table 4: Electricity use across the two clusters for summer and monsoon seasons

	AC Cluster 1 (n:29)	AC Cluster 2 (n:25)
Daily mean electricity use in kWh	11.6	17.3
Peak period of electricity use	7pm- 1am	7pm-7am
Electricity used in the peak period	4.3	10.8

To understand seasonal variation, cluster analysis for summer season was conducted. Two similar cluster profiles emerged for the summer – one with an all-night peak and another with a late evening peak of lower magnitude. The two summer clusters – AC summer cluster 1 (n: 29) where 68% of households had one or two AC units with a late evening peak (7pm-12am) and AC summer cluster 2 (n: 35) with 73% of the households with

3 or more AC units experienced an all-night peak (7pm-7am). Electricity use during the peak period in f summer cluster 2 was again found to be twice that of summer cluster 1.

Two similar clusters emerged for the monsoon season. The AC monsoon cluster 1 (n: 31) experienced an extended evening/night-time peak from 7pm-1am, whiles AC monsoon cluster 2 (n: 23) had an all-night peak. Again, monsoon cluster 2 had higher daily electricity use and peak electricity use than monsoon cluster 1. The highest peak usage of cluster 2 was again two times more than cluster 1.

The variation in the use of electricity during the daily peak period for households with different number of AC units was also examined. The highest peak for one and two AC households was 4.6 kWh at night, while this was 6.9 kWh for households with three or more AC (table 5). The most frequent use of AC was recorded during night-time from 9pm-2am across the three different AC groups.

Table 5: Patterns of electricity use in households with different number of AC units.

AC units	Attribute	Summer	Monsoon
1 AC unit	Peak period	9pm-3am	10pm-3am
	Electricity use during peak	3.8-4.6kWh	2.3-2.9kWh
2 AC units	Peak period	8pm-2 am	8pm-2am and 3pm-4 pm
	Electricity use during estimated period	3.7-4.6 kWh	3.2-4.4kWh
3 or more AC units	Peak period	8pm-2 am	8pm-2 am
	Electricity use during estimated period	4.9-6.3 kWh	4.2-5.9 kWh

Discussion

The variation in daily and peak period of electricity use for households with one, two and three or more AC units were statistically examined in this study. Electricity use during the summer and monsoon seasons accounted for around 60% of the annual electricity use, with AC use contributing 43% of daily electricity use in the summer and 34% in the monsoon season.

The extent of AC ownership be it one, two and three or more AC units contributed from 20% to half the daily electricity use. No significant difference in daily electricity consumption was observed across summer and monsoon seasons, indicating the constant use of AC in these hot and humid seasons. AC use during the night-time occurred mostly from 9pm to 2am across the sample, with a small afternoon peak from 3pm-4pm in households with two AC units. Sleeping and resting activities are likely to happen during these two periods.

Households with more than three ACs were found to use almost two times more daily electricity than other households, making them suitable for action for demand reduction as well as demand side response measures. Time of use (ToU) pricing can be targeted towards such households for enabling automated or consumer-led shifting of electricity use. Given the expected rise in residential air conditioning in India, making new AC units internet-enabled and demand response ready for actively interacting with the grid is necessary to manage electricity demand and supply.

The all-night peak usage prevalent in households with higher number AC units could be tackled through an integrated approach with fans (and coolers) wherein ACs are used intermittently along with a fan or cooler to reduce the duration of AC use during night-time. Energy feedback may also be utilised to stimulate behaviour change. Although studies have shown that with more disposable income there is less motivation to take part in electricity saving practice, this may change with increasing electricity prices.

This study could also serve as a starting point for energy utilities looking to reduce electricity use during peak periods. The clustering methodology that has been developed can be used to understand how the pattern of AC use affects electricity use daily, seasonally and annually and this can be used to understand the influence of AC on the local electricity network. A limitation of this study is that AC on-off state was assumed using a three star-rated split AC unit with 1.5-ton capacity. In future studies, the characteristics of different types of AC units and coincident measurement of outdoor temperature can be measured so they can be used to better understand the triggers of AC use.

Conclusion

Based on statistical analysis of high-resolution time-series data from a sample of 54 urban Indian households, this study has found that AC use was concentrated mainly during night-time, lasting from 9pm to 2am with an hour of peak use in the afternoon (3pm to 4pm) in some households. Similar patterns of AC use were observed in the summer and monsoon seasons, although with different magnitude of the electricity use during the peak period. Summer electricity use was responsible for 32-35% of annual energy use, while monsoon electricity use accounted for about 27-30%. Together summer and monsoon electricity use contributed to nearly 60% of annual electricity use.

AC usage in the summer and monsoon seasons contributed to around 25% of the annual energy, and up to 50% of daily electricity use. The annual electricity use amongst one AC households was 3,482 kWh increasing to 4,180 kWh and 5,472 kWh for households with two and three or more AC units respectively. Although the study is not statistically representative, it shows diversity in electricity use patterns by AC ownership even for a small sample. Policy could be targeted towards households based on ownership of AC units to enable peak load management through demand response to avoid blackouts especially during the summer and monsoon periods.

Due to increasing urbanisation and more people working from home (even post-pandemic) along with increasing outdoor temperatures, number of AC units in households may increase further for achieving thermal comfort across multiple rooms. This could result in an exponential increase in peak period of electricity use which can be six to ten times more than minimum electricity use during a day. Without a robust demand side response strategy in place driven by time-of-use tariffs to tackle this rise in electricity demand, electricity distribution companies in India will need to make expensive and disruptive reinforcement to the electricity network.

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