Investigating the relationship between residential AC, indoor temperature and relative humidity in Indian dwellings

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Abstract. Residential electricity consumption (REC) in India has tripled in the past two decades accounting for 24% of the overall electricity consumption during 2018-19. Residential air conditioning (AC) usage is responsible for about 20%-40% of REC in India. This paper investigates the relationship of residential AC use with indoor temperature and relative humidity (RH) using concurrent time-series monitoring data gathered in eight dwellings during summer and monsoon seasons. Contextual data about the dwelling (physical) and household characteristics were gathered using face-to-face interview based surveys. The dwellings were located in Hyderabad representing the composite climate of India. The mean daily electricity consumption was found to be higher in summer (11.5kWh) possibly due to the higher usage of AC (because of higher ambient conditions) as compared to 6.5kWh/day during monsoon season. Binary logistic regression identified the trigger indoor temperature and RH at which AC was likely to be switched on in the summer as 29 °C - 31.9 °C for indoor temperature and 36%-38.9% RH. In the monsoon season AC was predicted to come on sooner at 26°C-28.9°C but at higher RH range of 59%-61.9%. These empirical findings can be used to reduce residential cooling energy demand through smart management of ACs in Indian dwellings.

1 Introduction

Residential electricity consumption (REC) in India has nearly tripled in the past two decades and accounted for 24% of the overall electricity consumption during 2018-19. It is projected to rise by at least three fold by 2030 [1, 2]. If left unaddressed, the scale of this demand will have serious implications on the already strained national grid posing more issues [3]. A number of studies have revealed that residential air conditioning (AC) is a large contributor (20-40%) of annual residential electricity use in urban dwellings and expected to treble by 2030 [3]. However there is limited measured data on the actual use of residential AC in real homes and how this varies across seasons [4, 5]. Chunekar et al. have recommended a step-change in the quality and accessibility of data through energy utilities and Government agencies (EESL) [6] however most of the field studies in India tend to adopt survey-based approaches using self-reported data from residents. Recently there have been some studies that used monitored energy data collected from a small number of dwellings to understand electricity use patterns.

A recent study across 4 cities and 400 surveyed houses and 20 monitored houses revealed that AC contributed to 75% of the energy use in summer, spring and even had an impact in the autumn [7]. The Bureau of Energy Efficiency (BEE) in India studied multi-storeyed apartments and found that space cooling and fans contributed to 33-55% of the annual energy consumption and one of the major reasons for increase in peak energy demand was the use of residential AC [8]. Another study
examined concurrent monitoring of indoor temperature, relative humidity and electricity use to validate the self-reported AC usage hours data from a household survey [9]. The daily peak demand period was found to be 6pm-8pm (late evening) along with a morning peak observed from 9am to 10am [10]. A field study by Agarwal et al. found that while dwellings with low energy demand utilised fans during the summer, those with a medium energy demand used desert coolers with AC units [11]. Intensive monitoring of a single dwelling during May-August 2013 with 33 sensors that measured electricity and water consumption, major appliance load monitoring, ambient temperature, light and motion sensors discovered that AC usage accounted for 70% of the electricity consumption during summer [12]. A recent study called NEEM (National Energy End-use Monitoring) measured overall electricity use at 15' intervals from 100 dwellings across India but the data is aggregated and not available publicly at dwelling level [13]. Similarly another study monitored electricity consumed (kWh), active power (kW), voltage, and power factor (pf) per minute across 40 dwellings to assess the patterns of electricity use during peak period [14]. However, none of the studies monitored electricity use, indoor temperature and relative humidity concurrently to understand the pattern of residential AC use and its relationship with indoor environment.

Within this context, this paper investigates the relationship of residential AC use with indoor temperature and RH using concurrent time-series monitoring data gathered in eight dwellings during summer and monsoon seasons. Contextual data about the dwelling (physical) and household characteristics were gathered using face-to-face interview-based surveys. The dwellings are located in Hyderabad representing the composite climate of India. The study is part of a five-year Indo-UK research programme called RESIDE – Residential Building Energy Demand Reduction.

2 Methodology
The monitoring data was gathered across eight dwellings located in Hyderabad (India), using two data loggers designed for the RESIDE project (Garud and Envilog) which are Bluetooth enabled and battery operated. Electricity current (proxy for electricity use) was measured using Garud, while indoor temperature and RH were monitored by Envilog every 15 minutes concurrently during April 2019-December 2019. Complete and high quality data for 30 days for the months of May (summer) and August (monsoon) was used for this analysis. Outdoor temperature and relative humidity for the same time period and location were collected from Weather Online platform [15]. Interview-based surveys were conducted in the eight dwellings using the online Google platform to gather contextual data on dwelling and household characteristics including socio-demographics, occupancy and appliance usage. Annual data on residential electricity use for the year 2018-2019 was gathered using historic bills. Income group was classified using the 'Pradhan Mantri Awas Yojana’ as LIG (low income group), MIG (middle income group), and HIG (high income group). The survey data gathered for the eight dwellings are summarised in Table 1 below.

Table 1: Key characteristics of eight dwellings gathered using surveys and electricity bills

| Dwelling ID | Income group | Total floor area (sq.m) | Total no. of occupants | Dwelling type | Annual electricity consumption (kWh) | Annual electricity consumption per sq.m (kWh)/m² | No. of AC units |
|-------------|--------------|-------------------------|------------------------|---------------|--------------------------------------|-------------------------------------------------|----------------|
| HP3018      | LIG          | 214                     | 3                      | Stand-alone house | 3258                                | 15.2                                             | 1              |
| HP3019      | LIG          | 186                     | 2                      | Stand-alone house | 2177                                | 11.7                                             | 2              |
| HP3002      | MIG          | 101                     | 2                      | Stand-alone house | 1796                                | 17.8                                             | 1              |
| HP3017      | MIG          | 93                      | 4                      | Stand-alone house | 2929.5                              | 31.5                                             | 1              |
Since the case study dwellings had masonry construction, U-values of the building elements were assumed to be in line with the construction, as follows: external wall (230mm thickness) 2 W/m²K, roof 3.7 W/m²K, and single glazing window 5.8 W/m²K. Statistical analysis was conducted to analyse empirical data gathered using monitoring and surveys. To examine the relationship between indoor and outdoor temperature, indoor temperature and relative humidity, scatter plots were used. The seasonal variation of the electricity current across AC dwellings were analysed in terms of hourly electricity profiles by income group and number of ACs. Concurrent daily profiles of electricity current, indoor temperature and RH AC use were analysed using binary logistic regression. The indoor temperature and relative humidity were divided into equal width intervals of 2.9 °C and 2.9% respectively to identify the most likely range of indoor temperature and RH at which AC was turned on in the summer and monsoon seasons.

### Results

The annual mean electricity use for the eight dwellings was found to be 20.6/m²/year for the year 2018-2019. The mean daily electricity consumption was found to be higher in summer (11.5kWh) possibly due to the higher usage of AC (because of higher ambient conditions), as compared to 6.5kWh/day during the monsoon season. The AC units were on average of 1.5 ton capacity and were mostly split units where the compressor was located in the outdoor unit. Six out of the eight dwellings had AC units that were no more than five years old. While the majority of the AC units were of three star rating, only dwelling HP3017-MIG-1AC had an AC unit with a two star rating.

Descriptive statistical analysis revealed wide variation in the indoor temperature for the summer season across the eight dwellings. While the mean indoor temperature across the eight dwellings in the summer ranged from 30.9 °C to 35.9 °C, the range was narrower in the monsoon, ranging from 27.6 °C to 29.8 °C. The highest maximum indoor temperature in summer was measured as 41.5 °C in dwelling HP3017-MIG-1AC, while the lowest minimum indoor temperature was measured as 24.8 °C for dwelling HP3002-MIG-1AC. During the monsoon season, the highest maximum temperature was again observed in dwelling HP3017-MIG-1AC (34.9 °C) and lowest in HP3002-MIG-1AC (24.8 °C) as seen in table 2. Dwelling HP3017-MIG-1AC which had the highest EPI also had the AC unit which was more than 5 years old and two star rated. The number of AC did not have any influence on the magnitude of indoor temperatures indicating that hours and pattern of AC usage likely to have a bigger influence on indoor temperature than the number of AC units.

| Dwelling ID – Income group Number of AC | Summer (n:1440) | Monsoon (n:1440) |
|----------------------------------------|----------------|-----------------|
| HP3002- MIG-1AC | HP3003- HIG-1AC | HP3004- HIG-4AC | HP3017- MIG-1AC | HP3018- LIG-1AC | HP3019- LIG-2AC | HP3020- MIG-3AC | HP3024- MIG-1AC |
| Mean | 32.0 | 31.9 | 34.4 | 35.9 | 32.4 | 32.8 | 30.9 | 34.6 |
| Min | 24.8 | 25.4 | 29.9 | 28.9 | 29.2 | 27.3 | 27.0 | 29.4 |
| Max | 34.9 | 36.0 | 37.2 | 41.5 | 35.2 | 37.9 | 33.3 | 37.9 |
| SD | 2.2 | 2.3 | 1.3 | 2.7 | 1.5 | 2.6 | 1.5 | 1.5 |
| Mean | 27.6 | 28.2 | 28.5 | 29.8 | 28.0 | 28.4 | 27.8 | 27.8 |
| Min | 24.8 | 24.9 | 25.0 | 25.5 | 25.3 | 24.5 | 25.2 | 25.2 |
| Max | 30.8 | 31.0 | 32.0 | 34.9 | 30.3 | 32.0 | 29.9 | 29.9 |
| SD | 1.5 | 1.7 | 1.7 | 2.3 | 1.5 | 1.9 | 1.4 | 1.4 |
Similar analysis was conducted for indoor RH (Table 3) and a similar trend was observed. While unsurprisingly the mean RH was lower in summer than monsoon across all eight dwellings, the range of RH across the sample was wider (35.5%-46.8%) in the summer than the monsoon (68.9%-73.4%). It was also observed that dwelling HP3002-MIG-1AC had the highest maximum RH of 83%. The lowest minimum RH of 23% was measured in dwelling HP3003-MIG-2AC in summer, whereas the lowest minimum RH found to be 53% in dwelling HP3003-HIG-1AC. Dwellings HP3020-MIG-3AC, HP3024-MIG-1AC and HP3002-MIG-1AC had the highest maximum RH of 84%, indicating that number of ACs had no effect on the magnitude of RH experienced.

| Dwelling ID - Income group - Number of AC | Mean  | Min  | Max  | SD    |
|------------------------------------------|-------|------|------|-------|
| HP3002-MIG-1AC                          | 44.2  | 24   | 83   | 8.9   |
| HP3003-HIG-1AC                          | 39.1  | 25   | 60   | 7.2   |
| HP3004-HIG-4AC                          | 37.6  | 25   | 55   | 6.5   |
| HP3017-MIG-1AC                          | 35.5  | 23   | 53   | 5.1   |
| HP3018-LIG-1AC                          | 42.4  | 26   | 58   | 7.3   |
| HP3019-MIG-4AC                          | 37.5  | 24   | 55   | 6.3   |
| HP3020-MIG-3AC                          | 46.8  | 24   | 66   | 6.6   |
| HP3024-MIG-1AC                          | 39.8  | 24   | 56   | 6.2   |

It was also observed (Figure 1) that the indoor temperature and outdoor temperature were not correlated in the eight dwellings given that $R^2$ values were found to be less than 0.5, implying the untapped potential of controlling AC operation in line with outside weather to save energy and cost. However the scatter plot between indoor temperature and indoor RH (Figure 1) across the eight dwellings revealed a stronger correlation of $R^2 \geq 0.6$, showing that as indoor temperature decreased there was a drop in indoor RH, probably driven by the use of AC in the dwellings.

The mean of the difference between outdoor and indoor temperature ($\Delta T$) and RH ($\Delta RH$) was plotted against the electricity current profile, as shown in Figure 2. Interestingly in the summer season, as $\Delta T$ decreased, $\Delta RH$ increased and more electricity current was used especially during night time from 8:00pm to 2:00am which was likely to be for AC use. In the monsoon season $\Delta RH$ increased between 7:00am-9:00am accompanied by an increase in electricity current, although the magnitude of the increase was much lower than the summer season.
There were further interesting findings when electricity current profiles of the eight dwellings were related to concurrent indoor temperature and RH profiles (Figure 3). In the LIG dwelling with one AC unit (HP3018-LIG-1AC) the electricity current profile ranged from 3000-4000 mA accompanied by a corresponding drop in indoor temperature and RH during night-time in summer and monsoon, indicating use of AC. Across all MIG dwellings (HP3002-MIG-1AC, HP3017-MIG-1AC & HP3024-MIG-1AC), a range of 4000-5000 mA led to a drop in temperature and RH indicating AC usage during the night. For the HIG dwelling with 1 AC (HP3003-HIG-1AC), electricity current of 8000 mA led to a drop in indoor temperature and RH during the night.

The MIG dwelling with AC units observed a higher threshold of electricity current at 9000 mA when the indoor temperature and RH were lowered, indicating use of AC. The higher thresholds of electricity current that related with the drop in indoor temperature and RH indicate the different level of base loads in these dwellings. It was clear that predominantly AC use was happening during night-time for ensuring good quality sleep. Interestingly across all the dwellings AC usage was found to be much lower in the monsoon season.

The sub-hourly electricity current was also cross-related with delta T for AC and non AC modes, as shown in Figure 4. Across the majority of dwellings, the correlation was found to be stronger when AC was on than off, implying the effect of AC use on indoor temperature. As AC was switched off,
delta T was reduced significantly, which is why the coefficient of correlation was found to be lower.

Figure 4. Scatter plot of Delta T and electricity current (mA) in AC off mode (left) and AC on mode (right).

To understand when AC use was triggered with respect to indoor temperature and RH, logistic regression analysis was conducted when the AC unit was switched on (using observed electricity current profiles and indoor temperature and RH changes). The monitored indoor temperature and RH were binned into equal width intervals as categories to predict the interval most likely when AC could be turned on. It was observed that RH variable showed p-values<0.05. Those variables that were insignificant (p>0.05) have been unshaded as shown in table 4.

Table 4. Predicted AC trigger temperatures and relative humidity for summer and monsoon

| Dwelling ID- | Season | Indoor temperature range AC is ON (shaded p<0.05) | Indoor relative humidity range AC is ON (shaded p<0.05) | Mean threshold current at which AC is predicted to be triggered | Mean daily electricity consumption (kWh) |
|-------------|--------|--------------------------------------------------|-------------------------------------------------------|-------------------------------------------------------------|-----------------------------------------|
| HP3002-MIG-1AC | Summer | 26-28.9°C | 39-41.9% | 4597 mA | 7 |
| HP3002-MIG-1AC | Monsoon | 29-31.9°C | 62-64.9% | 3951 mA | 4 |
| HP3003-HIG-1AC | Summer | 26-28.9°C | 36-38.9% | 3929 mA | 13 |
| HP3003-HIG-1AC | Monsoon | 24.5-25.9°C | 59-61.9% | 4856 mA | 7 |
| HP3004-HIG-4AC | Summer | 29-31.9°C | 36-38.9% | 8172 mA | 14 |
| HP3004-HIG-4AC | Monsoon | 26-28.9°C | 59-61.9% | 6201 mA | 7 |
| HP3017-MIG-1AC | Summer | 29-31.9°C | 23-26.9% | 8543 mA | 17 |
| HP3017-MIG-1AC | Monsoon | 29-31.9°C | 59-61.9% | 4715 mA | 9 |
| HP3018-LIG-1AC | Summer | 29-31.9°C | 39-41.9% | 3931 mA | 11 |
| HP3018-LIG-1AC | Monsoon | 24.5-25.9°C | 65-67.9% | 6432 mA | 5 |
| HP3019-LIG-2AC | Summer | 26-28.9°C | 36-38.9% | 5891 mA | 9 |
| HP3019-LIG-2AC | Monsoon | 26-28.9°C | 65-67.9% | 6456 mA | 6 |
| HP3020-MIG-3AC | Summer | 29-31.9°C | 36-38.9% | 7434 mA | 14 |
| HP3020-MIG-3AC | Monsoon | 26-28.9°C | 68-70.9% | 3914 mA | 6 |
As shown in Table 4, the threshold temperature and RH range at which the AC was most likely to come on across the eight dwellings. In the summer, indoor temperature band of 29°C-31.9 °C was found to be the threshold at which the AC was most likely to be switched on, which relates to relative humidity of 36%-38.9%. In the monsoon period, this threshold was lower for indoor temperature at 26°C-28.9°C and higher for RH at 59%-61.9%. The reason for the difference in the threshold of electricity current at which indoor temperature changes and AC was switched on in the summer (HP3004-HIG-4AC and HP3018-LIG-1AC) was likely to be because only one temperature/ RH logger was installed in the room with the AC. Hence until that room’s AC turned on there was no major change in the indoor temperature. The only dwelling HP3003-HIG-1AC that used AC in the monsoon experienced a lower trigger indoor temperature of 24.5°C-25.9°C. Although the analysis is based on a small set of dwellings, the methodological approach is transferable to a larger sample as more empirical data are gathered.

4 Discussion

The empirical study revealed insights on how AC dwellings operate in Indian dwellings in relation to the trigger temperature and RH at which AC came on, as well as the pattern of indoor temperature and RH experienced by the dwellings during the AC on and off modes. The electricity current (range) threshold at which AC was turned on increased from LIG dwellings with one AC to MIG and HIG dwellings, thereby indicating a lower base load in LIG dwellings. All eight dwellings used AC during the late evening and night time, which fell within the peak period of electricity use in India. Given the exponential rise in residential AC in India, it is vital to integrate some level of smart management of AC use for example through pre-cooling to avoid over-loading the local electricity networks during the peak period.

Although there was strong correlation observed between indoor temperature and indoor RH indicating the use of AC, indoor temperature and indoor RH had no correlation with the outdoor temperature and RH. This indicated the untapped potential for integrating some form of weather compensation within the AC units to enable the running of ACs as per outside weather, potentially leading to lower AC use. This could be supplemented by promotion of energy saving behaviours amongst householders to encourage them to use AC as per outside weather.

While the survey data found the mean set point temperature for AC to be 25°C, monitoring data analysis showed that the most likely indoor temperature and RH at which the AC use was triggered in the summer season was 29°C-31.9 °C and 36%-38.9%, while during the monsoon season the trigger temperature was lower at 26°C-28.9°C and higher RH at 59%-61.9%. Since the design guidelines of the National Building Code (NBC) recommend indoor temperature of 23°C to 26°C and RH of 50% to 60% for air-conditioned residential buildings during the summer, there may be energy savings possible in delaying the start of AC until indoor temperatures reach the top level of NBC (26°C), since every 1°C increase in AC set point temperature can provide at least 6% energy savings from AC [16]. These energy savings are significant given that there are 74,344,779 urban residential households (at good and liveable conditions) as per the housing census data in India [17] of which 5% are estimated to be equipped with ACs i.e. 3,717,239 households [18]. Such empirical findings can inform the India Cooling Action Plan that aims to reduce cooling energy demand by 20%-25 % by 2037-2038 [19].

5 Conclusion

The study provides analysis of concurrent time-series data on residential electricity current, indoor temperature and RH in India to predict the timing of AC usage in relation to indoor environment in the

|        | Summer | Monsoon |
|--------|--------|---------|
| HP3024-MIG- | 29-31.9°C | 26-28.9°C |
| 1AC    | 36.38.9% | 62-64.9%  |
|        | 5398 mA  | 6975 mA  |
|        | 8       | 8       |
summer and monsoon seasons. The study found that dwellings had higher daily mean consumption of 11.5kWh in the summer as compared to the monsoon season (6.5kWh). The trigger temperature and RH at which AC was found to be switched on varied from 29°C and 36% in the summer to 26 °C and 59% in the monsoon season. One of the limitations of the study was the lack of data on the power factor and voltage to calculate the electricity consumed, however, this variable was not a central factor in this study. The data on electricity consumption was gathered from fuel bills. Although the study is based on a small sample and is indicative rather than conclusive, it provides important methodological advancement for large-scale survey and monitoring campaigns. The study findings have important implications for smart management of ACs in line with indoor and outdoor temperatures and RHs for achieving absolute and peak energy demand reduction.

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References

[1] MoSPI 2018 Energy statistics (New Delhi Ministry Of Statistics and Programme Implementation, Government of India)
[2] MoSPI 2019 Energy statistics 2019 Edited by: Office CS
[3] Khosla R 2017 A collection of insights on electricity use in indian homes Center for Policy Research & Prayas Energy Group) p 32
[4] Gambhir A, Napp T A, Emmott C J M and Anandarajah G 2014 India's CO2 emissions pathways to 2050: Energy system, economic and fossil fuel impacts with and without carbon permit trading Energy 77 11
[5] Shnapp S and Laustsen J 2013 Robust building data: A driver for policy development Global Buildings Performance Network) p 11
[6] Chunekar A, Varshney S and Dixit S 2016 Residential electricity consumption in india: What do we know? Prayas Energy Group) p 60
[7] TERI 2008 “ Energy end use ” study for residential electrical equipments (India: The Energy Resources Institute) p 70
[8] BEE 2014 Design guidelines for energy-efficient multi-storey residential buildings: Composite and hot-dry climates (India: BEE) p 209
[9] Gupta R, Tuteja S, Garg V, Agarwal R and Ramapragada P 2020 Understanding the relationship between indoor environment, electricity use and household socio-demographics:Insights from an empirical study in hyderabad (Hyderabad AEEE)
[10] Parray M T and Tongia R 2019 Understanding india's power capacity; surplus or not and for how long? (India: Brookings Institution India Center) p 37
[11] Agrawal S, Mani S, Ganesan K and Jain A 2020 What smart meters can tell us insights on electricity supply and use in madhura and bareilly households. (New Delhi: CEEW) p 78
[12] Batra N, Gulati M, Singh A and Srivastava M B 2013 It's different:Insights into home energy consumption in india August Proceedings of the 5th ACM Workshop on Embedded Systems for Energy-Efficient Buildings)
[13] EDS 2019 Household energy monitoring dashboard 'national energy end-use monitoring
[14] eMArc 2020 Monitoring and analysis of residential electricity consumption
[15] Weatheronline 2020 Historical data download
[16] Press Information Bureau 2020 Bee recommendations on temperature setting of air conditioners
[17] MHA 2011 Hh-1: Households by the condition of census houses occupied by them
[18] IEA 2018 Percentage of households equiped with ac in selected countries, 2018, tea, paris
[19] IEA 2020 India cooling action plan (icap)