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Investigation on air conditioning load patterns and electricity consumption of typical residential buildings in tropical wet and dry climate in India

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Abstract

The residential sector accounts for around 24% of the total electricity consumption in India. Recent studies show that air conditioners (ACs) have become a significant contributor to residential electricity consumption. Further, it is predicted that by 2037, the demand for ACs will increase by four times due to their affordability and availability. Not many studies have been found on residential AC usage patterns and the factors (AC load, setpoint, hours of usage) that influence household electricity consumption. This paper investigates the residential AC usage patterns and AC's contribution to total residential electricity consumption. Twenty-five urban homes from a wet and dry climatic region of India were monitored for nine months (in 2019) to determine overall household electricity consumption patterns, AC usage, and indoor environment during summer, monsoon, and winter. Analysis of seasonal consumption patterns shows a significant difference in electricity usage between homes with ACs and homes without ACs during the summer season. The average electricity consumption for AC homes was 15.1 kWh/day during summer, 6.6 kWh/day during monsoon, and 6.1 kWh/day during the winter season. Results showed that AC alone contributed to 39% of the total household consumption in summers. The peak AC usage in all homes is observed during sleep hours which was generally between 10:00 pm and 6:00 am and the average AC runtime was 6.2 h. The average indoor temperature was recorded as 26.9 °C during the AC ON period. The AC peak load, i.e., the maximum electricity demand during the AC ON period, is 1.7 kW on average during the study period. The average annual consumption of homes with ACs was 2881 kWh, and for non-AC homes, the consumption was 2230 kWh. Findings from our analysis provide a detailed understanding of AC consumption profiles and the difference in electricity consumption characteristics between AC and non-AC homes across different seasons.

Keywords: Residential electricity, Household consumption patterns, Household load monitoring, Air conditioning load monitoring, AC homes, Non-AC homes, India

Introduction

India is the fifth largest producer and the sixth-largest consumer of electricity in the world (Kumar et al. 2020; Sonawane and Gumaste 2020) accounting for 3.4% of the global energy consumption (Sonawane and Gumaste 2020). India's energy demand is expected to grow by 2.3 times in the next two decades (Gupta et al. 2020) and is likely to increase by 25% by the year 2040 in the global energy market (Praveen et al. 2020). The residential sector (electricity) in India is among the most significant consumers of energy (Qarnain et al. 2021a), and it is expected to grow fourfold by 2030 (Gupta et al. 2020). As per the data published by the Central Electricity Authority (CEA) of India, the 2019–2020 statistics show that the residential sector is responsible for 24.01% of total energy consumption (Central Electricity Authority 2020). The number of electrified homes throughout the country has increased from 55% in 2001 to 87% in 2020, and the per house energy consumption is also rising (Aayog 2022; Debnath et al. 2020). Therefore, it is vital to understand the household energy requirement and usage patterns for a large developing country like India.

In recent years, studies have shown that appliance ownership, occupant behaviour, thermal comfort, socio-economic factors, building features, and climate are the prominent contributors to household electricity consumption in India (Garg et al. 2021; Qarnain et al. 2021b). Further, the type of appliances, number of appliances, and usage period were some of the most significant contributors to energy consumption (Fan et al. 2017). The demand for electrical appliances has been proliferating for the past few years due to increased income levels and decreased appliance costs (Csoknyai et al. 2019). It was further projected that by 2030, 60–70% of the peak load in India would be due to major energy-consuming appliances such as air conditioners, electric water heaters, refrigerators, washing machines, motors, and televisions (Csoknyai et al. 2019; Abhyankar et al. 2017).

A 2018 study stated that about 20% of the total electricity used in buildings around the world goes towards air conditioners and electric fans (Government of India 2019a). Studies suggest that by 2037, AC consumption in India would increase by 4.3 times than that in 2017–18 (Sansaniwal et al. 2020). The 'International Energy Agency' (IEA) projected that the residential AC units will increase from 48 million units in 2020 to approximately 1144 million units in 2050 (International Energy Agency 2022). Studies on AC electricity consumption in India are focused on the relation between AC usage patterns and factors such as climate change, occupant thermal comfort (Debnath et al. 2020), gender, lifestyle, and purchase of energy-efficient ACs (Waseem et al. 2020). In another study, insights were provided on the impact on the environment due to the increasing demand for ACs in India (Government of India 2019b). A few other studies used artificial intelligence, machine learning, and deep learning approaches to develop recommendation systems for AC energy prediction and energy-saving (Osunmuyiwa et al. 2020; Rajasekhar et al. 2020; Kannan et al. 2020).

Though ACs in residences run only for a few months each year and generally during the night-time, they significantly increase the energy demand during their operation time (Thapar 2020). Rise in demand for energy, results in usage of more fossil fuels, which increases the amount of CO_2 emissions that are harmful for the environment. Also, majority of air-conditioners have refrigerant which produce gases that contribute to global warming and thinning of ozone layer. Therefore, it is essential to understand AC usage patterns and analyze their contribution to the overall load. Not many studies have been found on monitoring of residential electricity consumption, especially in homes with AC and without AC. Most of the studies related to AC electricity consumption collected data through household surveys. The questionnaire data collected by Thapar (2020) was used to analyze energy usage and seasonal consumption trends correlating with climatic parameters. A research survey conducted in Gujarat, India (Garg et al. 2021) was used to project electricity savings because of appliance replacement. The study has also found that the transition from old and inefficient ACs to new ones significantly impacts the cumulative energy savings. Household survey data from across 4 Indian states (Richmond et al. 2020) was collected to explore the potential drivers of electric appliance usage. They have found that cooling appliances like ACs that require powering for extended periods use significantly more electricity. A door-to-door survey was organized to collect information related to the purchase, use, and maintenance of cooling appliances (Khosla et al. 2021) to estimate the effect of energy-efficient ACs on household energy consumption and the environment. Statistical analysis of monitoring data by Gupta et al. (2021) assessed the electricity usage patterns, AC usage and its relationship with indoor environment (Gupta et al. 2021).

To investigate India's total household electricity consumption and AC electricity consumption profiles, 25 dwellings from Hyderabad were selected. Time-series data were collected using household current and RHT (relative humidity and temperature) loggers, along with household surveys and electricity bills. The fine-grained data was used to determine monthly patterns across different seasons, daily patterns for each season, and identify peak demand. The objectives were to:

- Understand the seasonal electricity consumption trends for AC and non-AC homes
- Understand the AC usage patterns and their impact on total annual energy consumption

Data on household electricity consumption can help analyze occupant behaviour, energy-use forecasting, demand-side management, creating real-time feedback systems for energy efficiency, and measuring building energy performance through benchmarking.

The paper is divided into several sections. Method section briefly talks about the climatic information of Hyderabad and the methodology of the study. Followed by analysis section which talks about the observations made from the analyses done using the monthly energy bills data, Garud (household current logger) and Envilog (Indoor RHT logger) data. Followed by a conclusion section that summarises the study and discuss the scope for future work.

Method

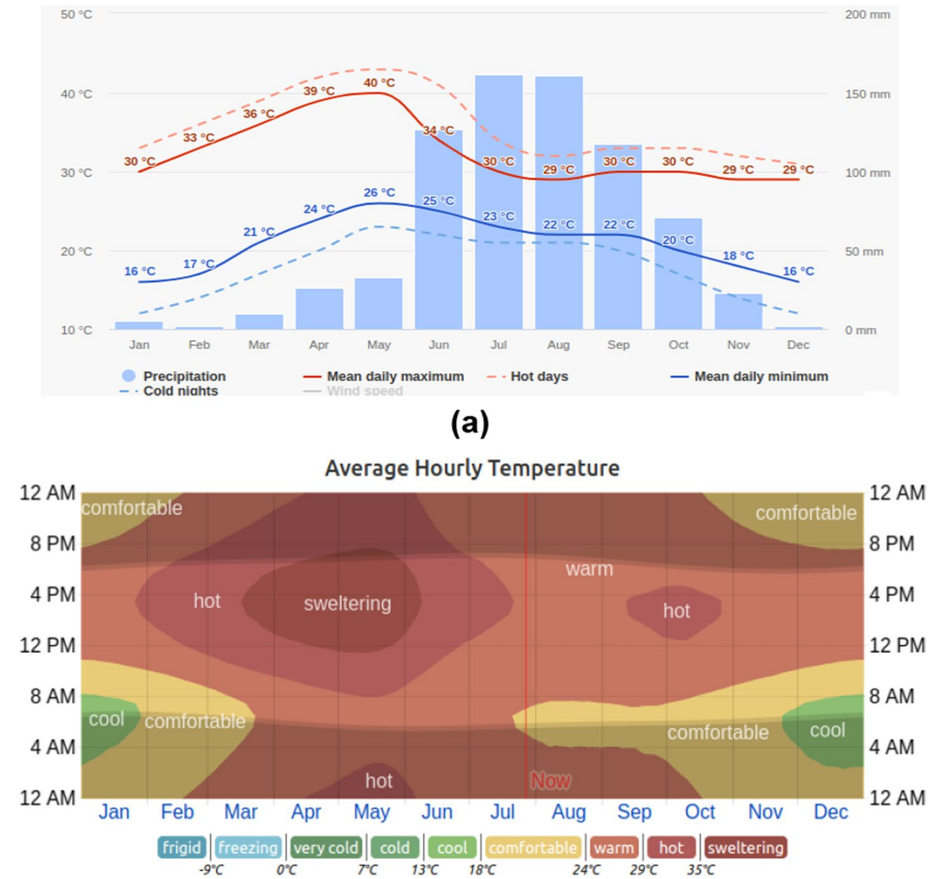
Twenty-five dwellings in Hyderabad were selected (voluntary participation by the home-owners) for survey and monitoring in 2019. Monthly electricity bills were collected for 1 year, and current, temperature, and humidity were monitored at a high sampling rate for eight months. Of the 25 homes, 19 of them were AC homes, and 6 were non-AC homes. The data collected through the study is used for three different analyses: monthly electricity consumption pattern by using monthly electricity bills; hourly consumption patterns across 3 seasons by using 14 days Garud and Envilog data for 19 homes; primary AC analysis using 19 days (during summer) Garud and Envilog data from 11 homes.

Study area

The city of Hyderabad, shown in Fig. 1, occupies an area of 650 square kilometers on the Deccan Plateau in the northern part of South India. The city lies on predominantly sloping terrain with an average altitude of 542 m above mean sea level. The city has a tropical wet and dry climate. Annual temperature averages above 26.6 °C, and the monthly mean temperatures range from 21 to 33 °C. Summers start from March and go up to June with hot and humid climatic conditions (Wikipedia 2022). Maximum temperatures during summer sometimes exceed 40 °C during the April–May months. The coolest temperatures occur during December and January, when the lowest temperature occasionally dips to 10 °C. May is the hottest month when daily temperatures range from 26–39 °C, and December the coldest has temperatures varying from 14.5 to 28 °C (Richmond et al. 2020; Meteoblue 2022; WeatherSpark 2022).

The solid red line in Fig. 2a indicates the maximum temperature of an average day for every month. Similarly, the solid blue line in Fig. 2a shows the average minimum temperature. The dashed red and blue lines show the average temperatures of the hottest day and coldest night for every month of the last 30 years (Meteoblue 2022). The bar plot demonstrates the precipitation chart. Figure 2b shows the hourly average temperatures for all the months (WeatherSpark 2022). Color codes are used to indicate the average temperature for the respective hours.

Fig. 1 Study area (Hyderabad, India)



(b)

Fig. 2 **a** Hyderabad average temperatures and precipitation graph (Meteoblue 2022), **b** Hyderabad average hourly temperature, color-coded into bands (WeatherSpark 2022)

Table 1 Homes considered for analysis using energy bills

	Number of HIG	Number of MIG	Number of LIG
AC homes	6	8	5
Non-AC homes	1	1	4

Characteristics of homes

A total of 25 homes were selected in Hyderabad. The majority of selected dwellings were independent units or within low-rise multi-family buildings. Nearly all the surveyed dwellings were owner-occupied, constructed using an RCC (reinforced cement concrete) frame structure with burnt clay bricks as infill. The windows are single glazed with fixed external shading. The average age of dwellings was around ten years. The homes were categorized into three income groups: low-income (LIG), middle-income (MIG), and high-income (HIG) according to categorizations given by the PMAY (Pradhan Mantri Awas Yojna) Scheme (Ministry of Housing and Urban Affairs 2022). The breakdown homes based on household income and availability of AC is given in Table 1.

Out of the 25 homes, 19 homes had AC and six did not have AC. Table 2 shows the number of ACs in each home and the location of the primary AC (the most used AC in a home, i.e. the one which is being monitored in this study). Different types of residential AC (split AC and window AC) are installed in individual rooms in contrast to the centralized ACs that are common in the West. Most of the homes have split AC systems which are on an average 5–10 years old. Homes with single AC units have the ACs installed in the master bedroom. Homes with multiple ACs had one AC in the master bedroom and the additional AC in the other bedroom or living room. The preferred average AC set point was 25 °C as per the information collected through a survey. Homes with no AC relied primarily on evaporative coolers and fans to maintain indoor thermal comfort.

Surveys

The survey included the use of questionnaires and the collection of electricity bills. The questionnaire was created using Google forms and accessed online through mobile phones (Tejaswini et al. 2019). Researchers collected data through personal interviews by visiting the homes multiple times. During the visits, photographs of the dwellings were taken, and site plans were also collected. Electricity bills were accessed online through the electricity supplier's website with consent from the owners. The survey content was anchored on the following areas: building characteristics (dwelling type, dwelling age, floor area, construction materials, architectural features such as shading), socio-demographic characteristics (number of occupants, family size, age, gender, income group), occupancy thermal comfort (thermal comfort sensation and preference votes), building heating and cooling (heaters, ACs, run-time during various seasons, cooling capacity, maintenance) and appliances (ownership, energy efficiency rating: BEE star rating, appliance usage hours).

Monitoring devices

Continuous monitoring of the household electricity and the indoor environment was performed using low-cost sensors that were developed in the research lab (Tejaswini et al. 2019). Garud (Fig. 3a, b), a current consumption logger, recorded electric current at 1-min interval. It consists of three CT clamps that can be installed on the main circuit board having a one-phase or three-phase connection. The accuracy of the Garud logger was tested in the lab by comparing and calibrating its results with reference devices such as Yokogwa (WT330) and Wattnode (WNC-3Y-480-MB) power meter. The comparison showed that the Garud data was accurate to within 95 to 97% of the standard meter. Along with electricity use monitoring, monthly electricity consumption data was collected through electricity bills for one year from householders or accessed online through the electricity supplier's

Table 2 Number of dwellings having 0, 1, and 2 + ACs

Number of ACs	Number of homes	Primary AC location
0	6	NA
1	9	Most used bedroom
2 or more	10	Bedroom(s) and living room

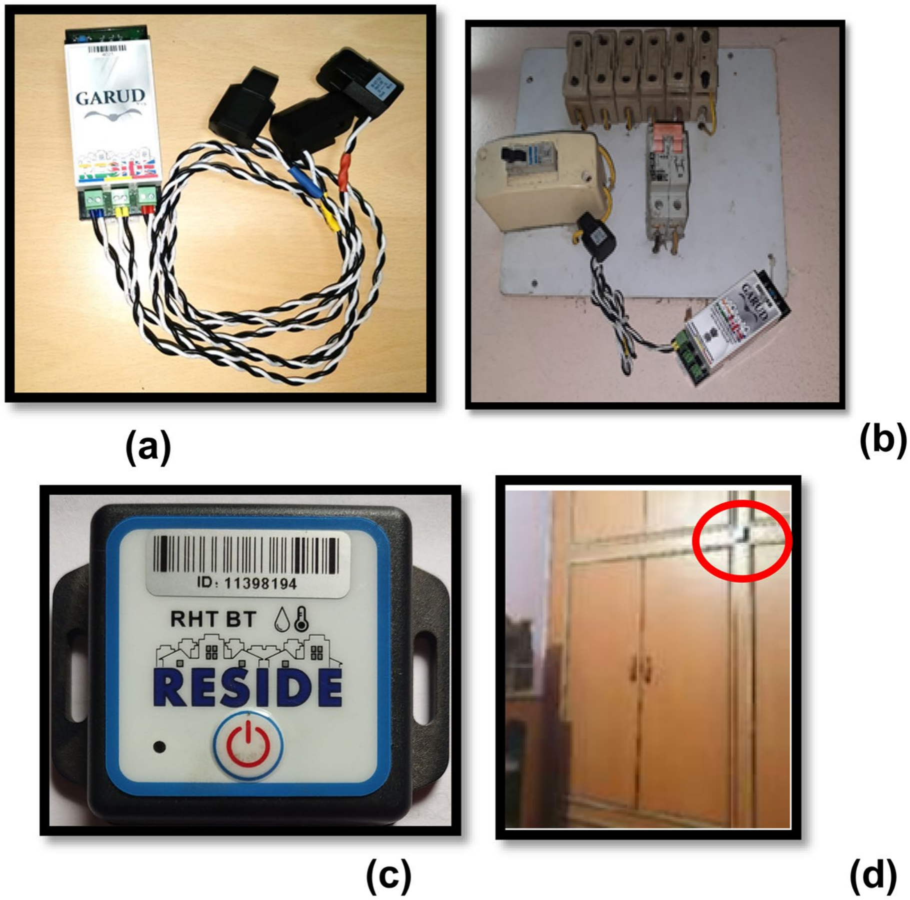


Fig. 3 **a** Garud **b** Garud installed on the Main Circuit Board **c** Envilog **d** Envilog installed in a surveyed dwelling

website with the consent of householders. As Garud is a current logger, the recorded values are in 'Milliamperes (mA)' which are then converted to 'Kilo Watt-hour (kWh)' using the 'Voltage (V)' derived using the current bills of the respective dwellings.

Envilog (Fig. 3c, d), relative humidity and temperature logger, was used to measure the indoor temperature and relative humidity at 15-min interval. The accuracy of Envilog was compared with I-button and Hobo U-12 devices. The comparison showed that Envilog has an accuracy of ∓3% for relative humidity and ∓0.3 °C for temperature. Garud devices were installed by a trained electricians at the main circuit board, whereas Envilog devices were installed by a researcher in the room where primary AC was installed away from the AC at a height of approximately 1 m from the ground. The data was collected for a period of 9 months from April 2019 to December 2019. The dwellings were visited once in 3 months to download the data using a mobile phone and upload it to a central server.

Data collection

Electricity consumption data was collected using the current logger–Garud at a one-minute interval for 9 months (Apr to Dec) and then resampled to a 15-min interval for analysis using simple mean. The 1-min data was useful for applying Non-Intrusive Load

Monitoring for AC Identification. Typical two weeks data for every season: Summer (May), Monsoon (July–August), and Winter (December) was selected for seasonal analysis and AC consumption patterns. Temperature-Humidity logger, Envilog, was used to collect 15-min data across seasons. The temperature information was employed in training the AC identification model (increase in load accompanied by a decrease in temperature was used as an indicator for AC usage) and understanding the indoor environment of homes.

Along with electricity-use and indoor environment monitoring, monthly electricity consumption data was collected through electricity bills for a period of one year. The bills were either collected from householders or accessed online through the electricity supplier's website with the consent of householders. Figure 4 shows the data overview chart. Mean monthly electricity bills from 25 dwellings (19 AC and 6 non-AC) (2019), mean monthly outdoor temperature of Hyderabad (2019), and survey questionnaire data of the 25 homes were used for the analysis of annual energy consumption. The seasonal analysis used Garud and Envilog data from 19 homes (15 AC and 4 non-AC) for 14 days in each season (summer, monsoon, winter). Finally, Garud and Envilog data of 19 summer days from 8 single AC and 3 multiple AC homes were considered for primary AC analysis.

AC detection and identification model

ACs are used to regulate the temperature levels in the room or any closed spaces, to achieve thermal comfort levels of the occupants. They attain the desired temperatures as set by the user in the thermostat. The basic functionalities of an AC are:

- Maintaining the set-point temperature levels,
- De-humidification of the space, and
- Good air circulation

An 'AC usage cycle' is the window or time period where the AC unit is run in order to maintain the room at setpoint temperature specified on the thermostat. During this cycle, the air conditioner's compressor is turned on and stays on until the room temperature reaches the setpoint temperature. The compressor goes off after the desired setpoint is reached and starts again when the room temperature rises. In a single usage cycle of an AC, there will be 'n' such instances of 'Compressor ON' and 'Compressor OFF' time. When the thermostat is set to much lower temperature relative to the room

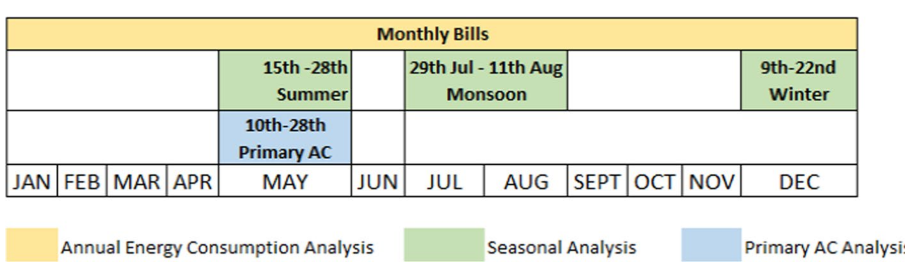


Fig. 4 Data overview chart

temperature, the compressor would work for a longer period of time to lower the room temperature. Meaning, the bigger the gap between the room and the setpoint temperatures, the longer the 'Compressor ON' instances will be, and vice versa.

Detection of AC usage

During the AC usage hours, though the AC is ON, the compressor in it doesn't run all the time; it runs and actively cools the room until the target temperature is reached, and then it stops. If an AC is undersized, then it will take too long to cool the room, which means it will run for a long time and stop only briefly. With an oversized AC, the compressor will be stopping more frequently and for a longer duration. Hence, to identify the 'True Current Consumption of AC'(which is only when the compressor is 'ON'), the 'Total Current Consumption' needs to be identified during the 'Compressor ON' time and eliminate 'Non-AC current consumption' from it. The next section will discuss the 'Identification of AC'. There are two types of ACs, an 'Inverter AC' and a 'Fixed-speed compressor AC' or a 'normal AC'. They both have different consumption signatures and are shown in Fig. 5 and 6.

The 'AC ON' time periods were identified manually by plotting the Garud and Envilog data of respective homes. The sudden peak in 'Current consumption' and sudden fall in 'Indoor Temperature' curves suggests that AC was used during that time window. This data was manually tagged in a separate column named 'Tag' with values filled with '1000 s' and '0 s'. AC usage cycles and energy consumed were then extracted from the tagged datasets, with the help of the Non-Intrusive Load Monitoring (NILM) algorithm that is developed specifically for our dataset.

Identifying compressor ON cycle

In the above graphs, the yellow colour line represents the 'Envilog data (Indoor Temperature)', the blue line represents the 'Garud data (Current Consumption)' and the orange line represents the 'AC Status'. The X-axis is for Datetime, Primary Y-axis is for Current (mA) readings (However, in the case of 'AC Status' the Primary Y-axis represents the status of the Tag), Secondary Y-axis is for Temperature (℃) readings.

In the below graph, the highlighted area '1' and '4' is the 'Normal Load', where the room temperature is above 32 ℃ and constant and the current consumption is low and normal, hence the 'AC Status' is manually marked as '0'. The area between the {} is, when the room temperature drops, and the current consumption shoots up to 6000 mA (Fig. 7) and 10000 mA (Fig. 8) (in this example) until the fall of current

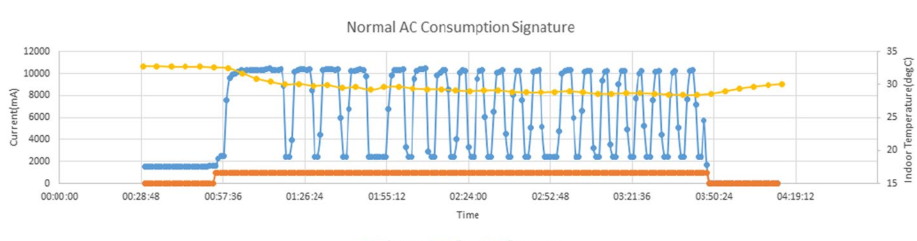


Fig. 5 Sample graph with tagging when there is a drop in temperature and increase in electricity consumption for a fixed-speed compressor AC

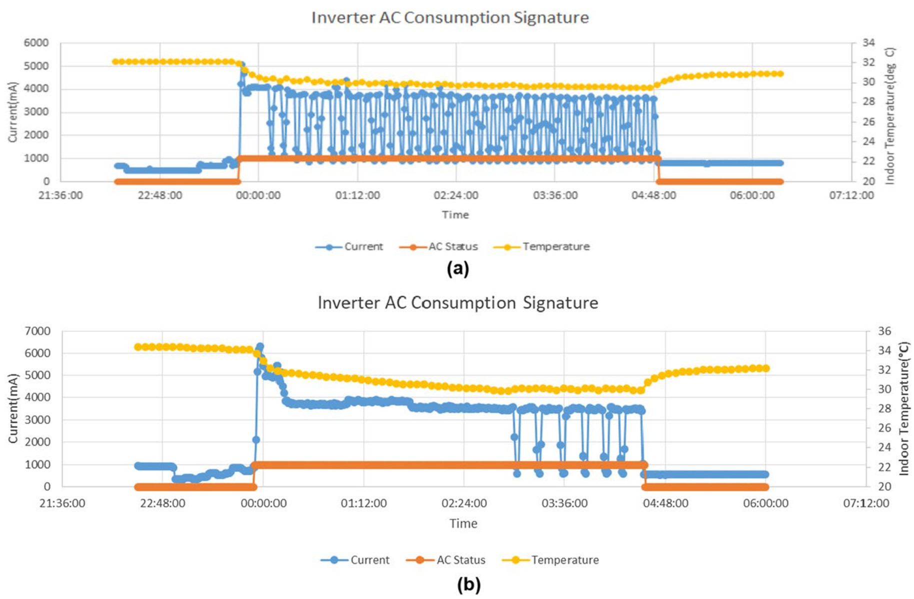


Fig. 6 **a**, **b** Sample graphs with tagging when there is a drop in temperature and increase in electricity consumption for two different types of Inverter AC

consumption to around 1000 mA or back to 'Normal Load', and there is a rise in temperature. Such parts of the data where the usage of AC is identified are manually marked with the value of 1000 in the 'AC Status' column, making it a binary column of manual tags 0 and 1000, in respective dwellings data files. The highlighted areas '2' and '3' show the 'Current' consumption values with 'Compressor ON' as peak values and 'Compressor OFF' as low values respectively.

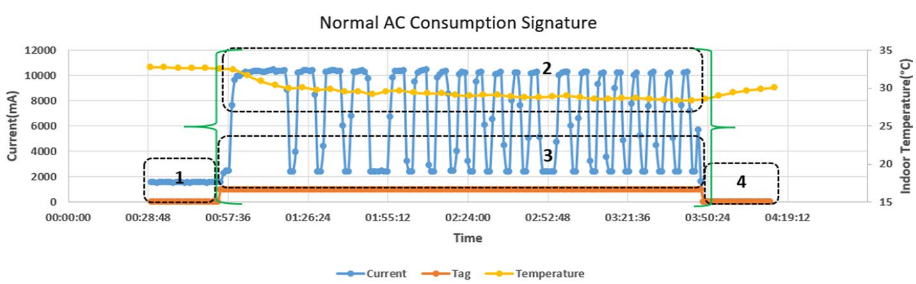


Fig. 7 Sample graph of identifying a fixed-speed compressor AC usage cycle

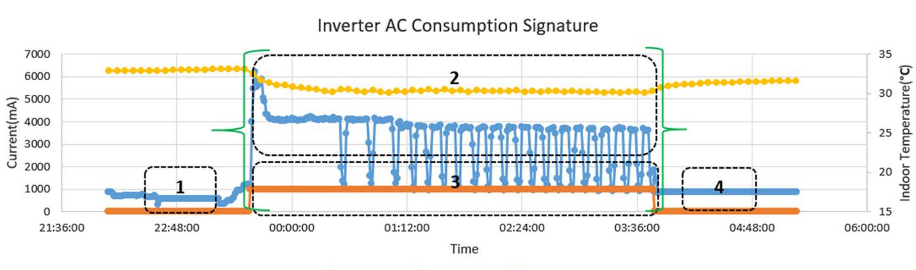


Fig. 8 Sample graph of identifying an inverter AC usage cycle

Analysis

To understand the yearly consumption pattern for each household, electricity bills from 25 dwellings and outdoor temperature (obtained from weather data provider (TimeandDate 2022)) were collected for 1 year. Out of 300 data points (25 homes × 12 months), 4% (i.e., 13 data points) were estimated. Out of the 13 missing data points, eight were missing because the bills were not generated in that month. For the dwellings with electricity bills missing, readings of the preceding and subsequent months were compared with the electricity consumption data recorded by Garud for the respective months and a ratio was calculated. The average of this ratio was then used as a factor in estimating the missing values using the Garud readings in respective homes. In one home, the occupants vacated in the month of July 2019. For the remaining five months in 2019, electricity bills from corresponding months in 2018 were considered. The electricity consumption for each month is shown in Fig. 9 for different income groups and in Fig. 10 for AC and non-AC homes. Figure 9 focuses on identifying the electricity demand across all the months in Hyderabad for different income groups. An apparent increase in energy demand is visible during March–June, irrespective of the income groups. This intuitively implies the rise in usage of Air Conditioners during the summer months. To verify this hypothesis, the 25 dwellings were split into AC homes and non-AC homes.

Figure 10 shows the monthly electricity consumption for AC and non-AC homes. It is observed that AC homes' energy consumption increases in summer in line with the increase in outdoor temperature. Change in outdoor temperature has no significant impact on the monthly electricity consumption of non-AC dwellings. An increase in energy consumption in AC homes during summer clearly indicates the use of AC and its contribution to home energy consumption. To quantify the AC energy consumption, seasonal analysis was performed as given in the next section.

Seasonal analysis

To understand hourly electricity consumption patterns across the 3 different seasons (summer, winter, and monsoon), 14 days of Garud and Envilog data were considered in each season. The 14 days (Table 3) selected from each season had complete data and

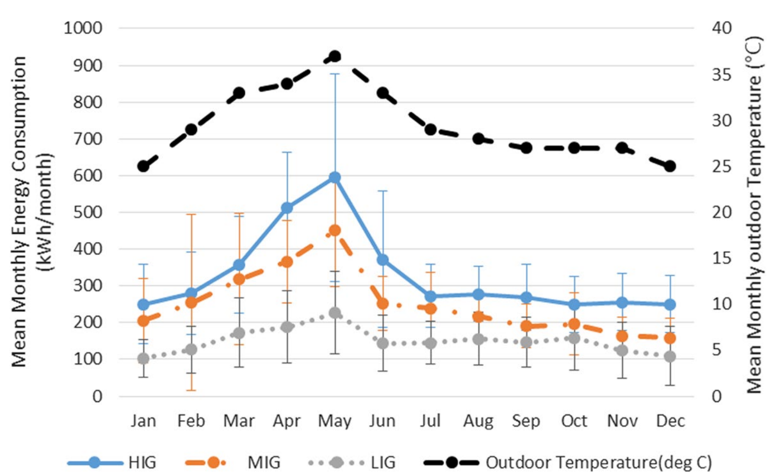


Fig. 9 Mean monthly electricity usage and outdoor temperature (income group)

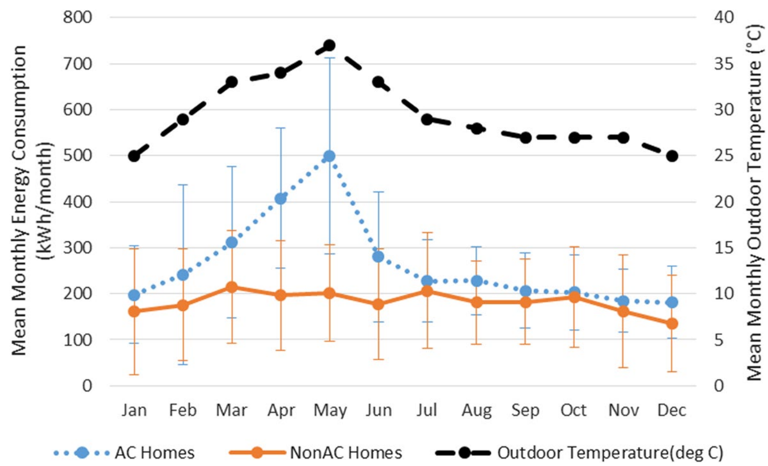


Fig. 10 Mean monthly electricity usage vs outdoor temperature (AC ownership)

Table 3 Data considered for seasonal analysis

Season	Start date	End date	Number of days	AC homes	Non-AC homes
Summer	15-May-2019	28-May-2019	14	15	4
Monsoon	29-Jul-2019	11-Aug-2019	14	15	4
Winter	09-Dec-2019	22-Dec-2019	14	15	4

represented the best period of the season for analysis. Out of the 25 dwellings, 23 homes that were available for all the days in at least one season were considered for seasonal analysis. In each season, 19 homes (out of 23 homes) were available for analysis.

AC homes

The graph in Fig. 11 shows the average hourly load for AC homes across summer, monsoon, and winter. In summer, an increase in the load during sleep hours (10:00 pm–6:00 am) is evident. During these hours, there is a drop-in indoor temperature, indicating the use of Air Conditioners at night. A short peak in load during the afternoon (2:00 pm–5:00 pm) shows the use of air conditioners by a few households. The average energy consumption of AC homes during the summer season is 15.1 kWh/day. In monsoon and winter seasons there is very little consumption during the sleep hours indicating little to no use of air conditioners. There is a slight peak during morning hours (7:00 am–10:00 am) which may be due to electric hot-water geysers and kitchen appliances. This peak is also visible during the summer but is smaller than monsoon and winter peaks because in monsoon and winter, besides kitchen appliances, electric geysers would have been used. It can also be observed that there is a rise in electricity consumption after 6:00 p.m. and drop after 10:00 pm, which must be the load due to lighting, television and kitchen appliances during evenings. The average energy consumption of AC homes in monsoon is 6.6 kWh/day and in winter 6.1 KWh/day which is less than half the average load consumed on a summer day as shown in Table 4.

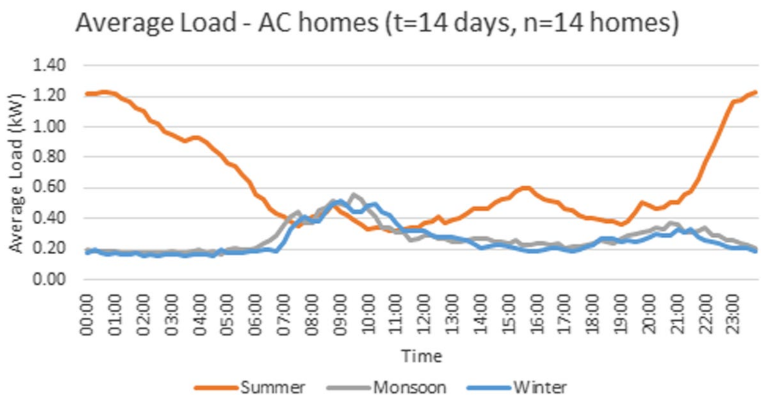


Fig. 11 Comparison of the current consumption of AC homes for Summer, Winter, and Monsoon

Non-AC homes

The graph in Fig. 12 shows the average load of non-AC dwellings during summer, monsoon, and winter seasons. During summers, there are two peaks observed in the load curve. One is the short peak in the morning hours between 7:00 a.m. to 10:00 a.m., which is also seen in the AC homes for every season, and the second peak is in the nighttime between 7:00 p.m. to 12:00 a.m. The average energy consumption of non-AC homes in summer is 5.5 kWh/day which is 36% of the daily average energy consumption of AC homes in summer. During monsoon, the morning peak between 7:00 a.m. and 10:00 a.m indicates the usage of geyser and kitchen appliances similar to the energy consumption peak in AC homes. Patterns are similar in all the seasons, however, in monsoon and winter, there is a more significant peak in the morning and the average load in summer is more than monsoon and winter, mostly because of fans and air coolers. AC homes

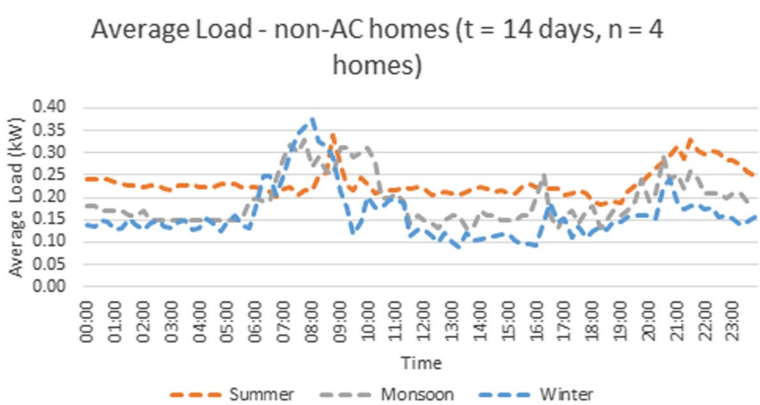


Fig. 12 Comparison of the current consumption of AC homes for Summer, Winter, and Monsoon

Table 4 Average energy consumption per day of AC and non-AC homes for each season

Type of home	Summer average daily energy consumption (kWh)	Monsoon average daily energy consumption (kWh)	Winter average daily energy consumption (kWh)
AC home	15.1	6.6	6.1
non-AC home	5.5	4.6	3.9

consume about 33% more as compared to non-AC in monsoon and winter. This is probably due to more appliances being used in AC homes as AC homes are generally occupied by people with Higher Income Group.

Primary AC analysis

Usage of AC can have a significant impact on the 'Annual Energy Consumption (AEC)' of a household. The energy consumption of AC is a function of set point temperature, AC efficiency, internal and external loads, and hours of use. The objective of primary AC analysis is to understand AC usage in Hyderabad homes. The most used AC in the home is considered as the primary AC. In the case of a home having single AC, that AC was considered as primary AC and in the case of homes with multiple ACs—the most often used AC in a bedroom, as identified by the home-owner, was considered as primary-AC. Data at a one-minute interval from Garud and Envilog of 11 homes (8 single AC homes and 3 multiple AC homes) out of the 19 AC homes was used for analysis during the summer season. The selection of homes was based on 100% availability of data for continuous 19 days during the hottest days (10/5/2019 00:00–28/5/2019 23:59) of the summer season. Only the homes that were occupied during these entire 19 days period and had properly functioning devices were selected. It was also ensured that primary AC was on a phase not overlapping with the secondary AC making it possible to detect the AC cycles using the identification and detection technique mentioned in Sect. 2.6.

Figure 13 presents the hourly AC run-time averaged across 11 homes. The most common AC usage window in all houses is during sleep hours which is generally between 10:00 pm to 06:00 am. AC use is the highest during the sleep hours with an average of 5.2 h out of 8 h and minimum during the day-time (7:00 am 9:00 pm) with an average of 1 h. In the afternoon (3:00 pm–5:00 pm) AC is switched ON by a few households for a brief period and therefore the average running time during this period goes up to 0.5 h. The average runtime of an AC across all the homes in 19 days is 6.2 h per day with a minimum being 3 h and the maximum being 8.9 h.

To understand the desired room temperature that the occupants want to maintain, the temperature during the AC usage hours was noted. Only the AC cycles that were at least one hour long were considered, as at the beginning of the cycle, the temperatures are high, and it takes approximately an hour for the AC to bring down the temperature to the desired level, as shown in Figs. 7 and 8. Hence, the minimum temperature recorded in AC cycles for more than one hour is considered to be the desired room temperature. This temperature need not be equal to the AC set-point temperature. Across 11 homes, in these 19 days, 303 AC cycles (which were more than one hour each) were selected and the frequency distribution of minimum temperature in those cycles is plotted in Fig. 14. The graph shows a comfort temperature range of 28–32 °C during the AC ON period which is near to the comfort band evaluated by and way above the limits of 23–26 °C set by Indian standards (Indraganti 2010).

The general indoor temperature comfort band in an Indian home is 23–26 °C (Indraganti 2010) but based on the values in the graph it seems that the room is set to higher temperatures during night-time. The reasons may be due to: adaptation to higher temperatures, lower metabolism during the night-time and usage of fans for saving energy.

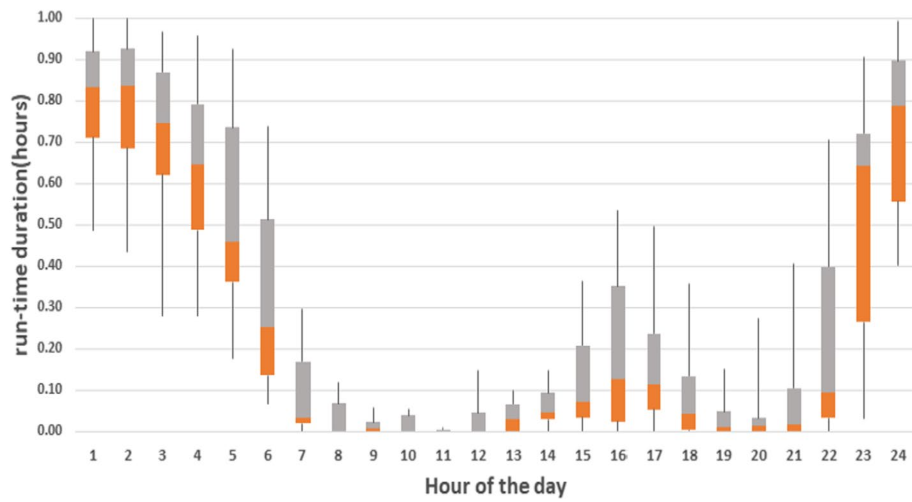


Fig. 13 Average AC Usage hours per day of 11 homes for 19 days

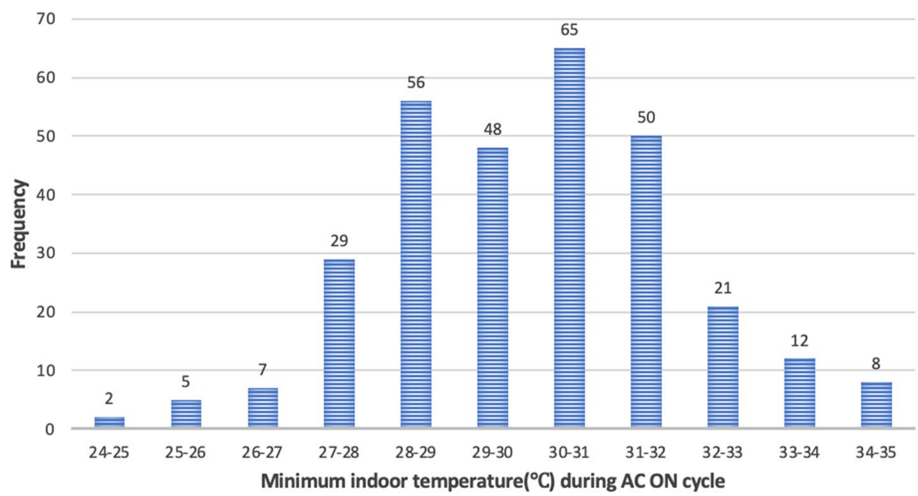


Fig. 14 frequency distribution of minimum indoor temperature during AC ON cycle for 19 days in 1

Figure 15 shows the average hourly temperature for AC homes (a) and non-AC homes (b). In summer, it was hottest during the late evenings (between 8:00 pm–10:00 pm) with an average temperature of 34 °C for AC homes and 36 °C for non-AC homes. For both AC and non-AC homes, the temperature curves of monsoon and winter have smaller swings as compared to the swing in summer. For AC homes, the average indoor temperature during monsoon was 26 ℃ which is 6.5 ℃ cooler than an average summer day and 1.2 ℃ warmer than winter. For non-AC homes, the average indoor temperature during summer was 35 ℃ which was 10 ℃ hotter than the temperature in winter and 8℃ hotter than in monsoon as shown in Table 5. During the summer season, AC homes were 2.5 ℃ cooler than non-AC homes.

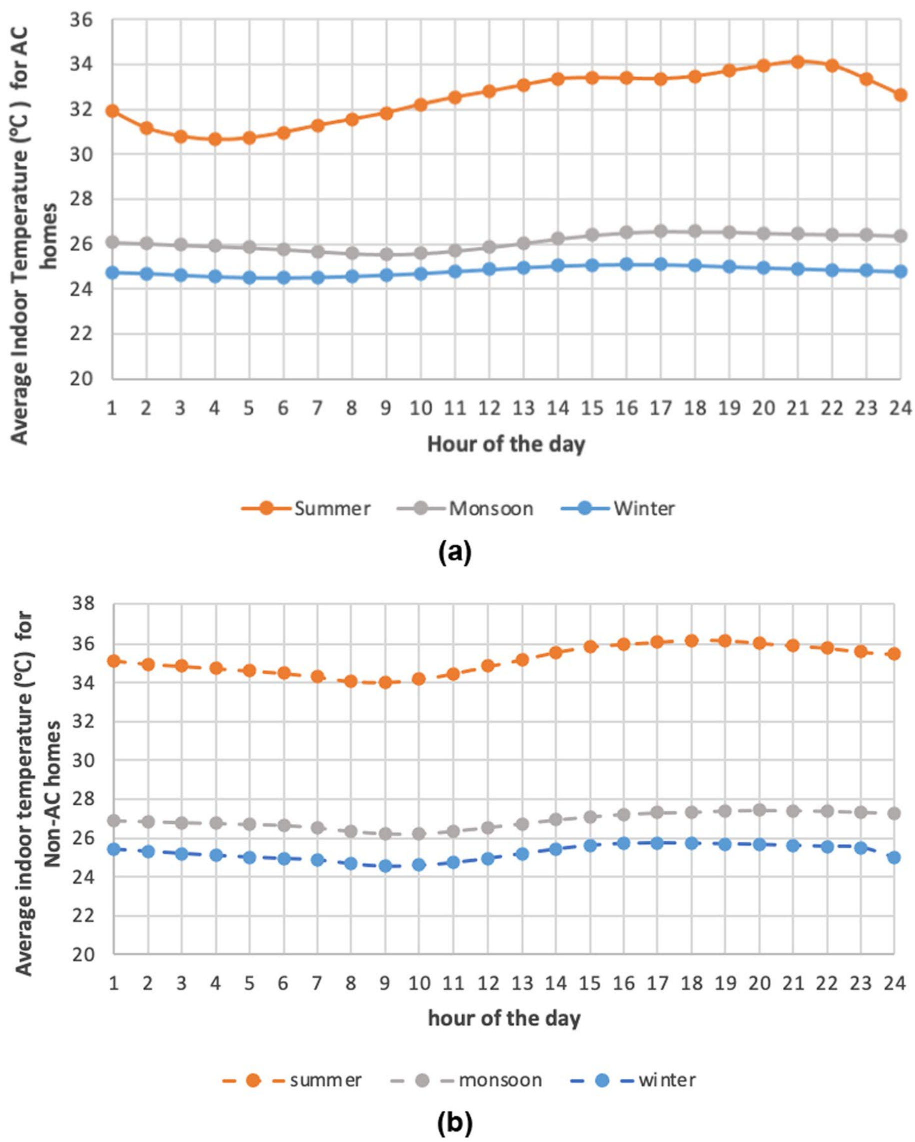


Fig. 15 Hourly average indoor temperature for **a** AC homes **b** non-AC homes

Discussion

Our analysis on household energy consumption and, residential AC and non-AC usage across different seasons has provided the following findings:

- The measurement results showed that the average electricity consumption of AC homes during the summer season is 15.1 kWh/day and the average AC consumption is 5.1 kWh/day. Malaysia, which has a similar climate condition conducted a related experiment on 19 dwellings and reported that the daily averages of the total and the AC electricity consumption are 14.5 and 3.9 kWh/day (Kubota et al. 2020). A similar study conducted on 66 households in Japan recorded 16.3 kWh/day as the daily average of total electricity usage during summer (Zheng et al. 2016).

Table 5 Average indoor temperature per day of AC and non-AC homes for each season

Type of home	Summer average daily temperature (°C)	Monsoon average daily temperature (°C)	Winter average daily temperature (°C)
AC home	32.5	26	24.8
Non-AC home	35	27	25

- ACs are known to have an excessively large impact on peak electricity load. With the increase in population, rising incomes, falling equipment prices, urbanization, and rise in temperatures due to climate change, the number of air conditioning units is expected to triple by 2050. IEA has predicted that the number of AC units purchased in India would increase from 48 million units in 2020 to approximately 1144 million units in 2050. In Hyderabad alone 0.35 million ACs were sold in 2015 and it was projected that the sales were increasing by 20% each year (Deccan Chronicle 2019). With the increase in the number of ACs, the demand for electricity is bound to increase. According to government figures, Hyderabad has 8.3 million households (Telungana Government 2022) of which 13% of them are equipped with ACs (1.8 million) (Deccan Herald 2021). The average AC electricity consumption for 11 households in 19 days is 98kWh. For all homes with ACs in Hyderabad, the average AC consumption for 19 days would be approximately 9.6 GWh and for the whole of summer, the consumption would be around 45 GWh.
- To meet this increasing demand for ACs, one solution would be to incorporate renewable energy sources such as photovoltaics. Our analysis shows that peak AC usage hours are generally during night-time between 10.00 pm and 7:00 am. During daytime (7:00 am to 9:00 pm) ACs consumed an average of 1 kWh/day and in the night-time, they consumed 5.2 kWh/day. A Malaysian study with 20 dwellings showed AC was almost used for 5 to 6 h per day at the rate of 0.93 kWh/day during daytime and 3.43 kWh/day during night-time (Hisham et al. 2021). To meet this peak demand, especially during night-time and when solar photovoltaic solutions do not help, larger investments in setting up new power plants may be required. Reduction of AC use during night-time will reduce the load on the grid and help in decarbonization.
- Adopting to energy-efficient room ACs can certainly help reduce the burden of increased electricity demand (Climate Institute 2018). The total energy savings by using efficient room ACs is estimated to be over 118 TWh in 2030. According to BEE (Bureau of Energy Efficiency), a 3-star rating inverter AC is 7% more energy efficient than a 3-star non-inverter AC. The electricity consumption of a 3-star AC (1.5 tons) is 1.6 units every hour and that of a 5-star AC (1.5 tons) is approximately 1.5 units every hour. This study consisted of 3 homes with 5-star ACs that ran for 362 h in 19 days consuming 121.5 K-Amps and 6 homes with 3-star ACs running for 626 h in 19 days consuming 278.2 K-Amps. The percentage difference in peak AC consumption between homes with 3-star and 5-star ACs was 14%.

- NILM techniques can further be used to identify individual AC load costs. Integrating feedback and energy-saving possibilities would also help in reducing electricity demand during peak time.

Conclusion

This study provides information about the total electricity consumption, seasonal consumption trends for AC and non-AC homes and AC usage patterns by collecting data from 25 dwellings in Hyderabad, a city with composite climate. Data was collected in the form of electricity bills, household surveys and monitoring through current and temperature-humidity loggers. Analysis on the collected data showed that AC use reduced the daily average indoor temperature by 2.5 °C compared to non-AC homes during the summer season. Also, the daily average energy consumption of AC homes was more than double during the peak summer days when compared to monsoon and winter seasons. In the summer season, ACs increased the load by five to six times during night-time and by two times during the evening time. 'International Energy Agency' (IEA) projected that by 2030 the number of ACs in India will increase to 240 million units from 27 million in 2016 (International Energy Agency 2022). This increasing demand for ACs is putting an enormous strain on the electric grid. Renewable energy, especially photovoltaic solutions produce energy only during the day-time; but because the usage of AC is mostly during night time, managing the load is a serious concern. This study will help energy scientists and policy makers to further investigate AC consumption patterns and put forward strategies related to efficient usage of ACs, efficient building envelope, and control and thermal storage.

Abbreviations

AC	Air conditioner
RHTBT	Relative humidity and temperature bluetooth logger
HIG	High Income Group
MIG	Middle Income Group
LIG	Low Income Group
PMAY	Pradhan Mantri Awas Yojana
NILM	Non-Intrusive Load Monitoring

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Author contributions

PR investigated, analyzed and visualized the data for seasonal and AC analysis. DT validated, analyzed and visualized the data for analysis and drafted the manuscript. VG conceptualized and supervised the study. VG also acquired funding and reviewed the manuscript along with JM and RM. All authors read and approved the final manuscript.

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Availability of data and materials

Data used for the study is submitted to the same conference as short paper titled "Residential electricity current dataset for AC-event detection from Indian Dwellings."

Declarations

Ethics approval and consent to participate
IRB, Ethics Approval Committee of IIIT-Hyderabad has approved the study.

Consent for publication
All authors have given their consent for publication.

Competing interests
The authors declare that they have no competing interests.

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