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UNDERSTANDING RESIDENTIAL OCCUPANT COOLING BEHAVIOUR THROUGH ELECTRICITY CONSUMPTION IN INDIA

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Abstract

The India Energy Security Scenario 2047 (IESS, 2047) suggests that residential air conditioners will increase from 21.8 million in 2017 —about 8% of the Indian households—to approximately 68.9 and 154.4 million in 2027 and 2037, respectively. Also, the related energy consumption is likely to increase by a factor of four in the next two decades, according to the Indian cooling action plan. Therefore, the study of occupant cooling behaviour is essential to reduce and manage this significant electricity demand, helping to formulate and implement climate-specific cooling policies at the state level, and to adopt new low energy and low-cost cooling technologies at mass-market scale. The study aims to examine residential electricity consumption to investigate occupant behaviour by analysing the use of space cooling and mechanical ventilation technologies. Among the five climate zones in India, this study focuses on the occupant cooling behaviour in a warm-humid climate —using the village of Auroville as a case study— where summer and wintertime temperature can be 25-35°C and 20-30°C, respectively, with relative humidity 70-90%. For the analysis, electricity consumption data from 18 households (flats) are monitored for seven months (November 2018- June 2019). The results demonstrate the characteristics and complexities in occupant behaviour and insight on the operation schedule for different space cooling technologies in residential buildings.

Introduction

India — the second-most populous country of the world (1.35 billion in 2018) (WB, 2019) — is expected to have the largest population of the world by the year 2030 (UN, 2019). According to the 2011 census data, India's population was 1.2 billion, and the number of households was 246 million (GoI, 2017). Under the 2011 average household size (4.9) assumption, there will be 307 million households in 2030. However, another study showed that there would be 386 million households in India (WEF, 2019). In addition to the population growth, India's GDP growth — 7.3% in 2018 and forecasted to be 7.5% from 2019-2022 (WB, 2019) — is one of the highest in the world. According to the World Economic Forum, India will become the third-largest consumer market driven by the affluent middle class — 168 million upper-middle (44% of total households) and 132 million lower middle (34% of total households) — by 2030 (WEF, 2019).

Furthermore, India has one of the highest cooling degree days (CDD) in the world. The average annual cooling degree days — Madras (3954), Ahmadabad (3514), Hyderabad (3221), Kolkata (3211), Delhi (2881) and Bangalore (2280) (Sivak, 2009)— is estimated to be more than 3000 annually. With the high heat due to climate change, the temperature can increase further in many cities by 2100 which will overwhelmingly increase air conditioning demand in cities in developing countries such as China, India, Indonesia, and Brazil (UN & WB, 2018). Therefore, the annual CDD in many Indian cities may increase significantly. However, only 5% of households in India have air conditioners (A/Cs) in 2018, which significantly lower than that of China (60%) and USA (90%) (IEA, 2019). There were 293 million households in India in 2018 (WEF, 2019), which means only 14.7 million households had A/C units.

The high population and increased household affluence may lead to a significant rise of A/C unit ownership in India as access to cooling become viewed as an essential tool to provide comfort. India energy security scenario 2047 suggests that residential A/C units will increase from 21.8 million in 2017 —about 8% of the Indian households—to approximately 68.9 and 154.4 million in 2027-28 and 2037-38, respectively (GoI, 2015). In another study, IEA suggested that India will have 240 million A/C units by 2030 which will reach to 1144 million by 2050 (IEA, 2019), which will be a 42 times growth than that of 2016.

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 A/C will dominate the building sector's cooling energy consumption, with 50% of the 600 TWh by 2037-38. Moreover, there will be a significant presence of non-refrigerant based cooling from fans and air coolers (which use evaporative cooling from passing air over water) at around 40%. ICAP set forth several ambitious goals, such as reducing cooling demand across sectors by 20-25% by 2037-38 (GoI, 2019). ICAP also aims at improving the A/Cs efficiency and development of sustainable technologies. There has been a successful standard and labelling policy implementation by Bureau of Energy Efficiency (BEE) for improved room A/Cs efficiencies 35% between 2006 and 2016 (3% annually) (Abhyankar, Shah, Park, & Phadke, 2017). Despite the A/C improvement targets the success of ICAP might largely depend on reducing the space cooling demand in India.

In this study, the objective was to analyse residential cooling behaviour through electricity consumption data. For the case study area Auroville was selected, representing a warm-humid climate from the southern part of India in Tamil-Nadu. The results demonstrate the characteristics and complexities in occupant behaviour and insight on the operation schedule for different space cooling technologies in residential buildings.

Methodology

Among the five climate zones in India, this study focuses on the occupant cooling behaviour in a warm-humid climate —using the village of Auroville as a case study— where summer and wintertime temperature can be 25-35°C and 20-30°C, respectively, with relative humidity 70-90%. For the analysis, electricity consumption data from 18 households (flats) are monitored for seven months (November 2018- June 2019). The study had two parts: electricity consumption data from the monitored households and weather data collection, with accompanying data analysis.

Two types of data were collected from the households, from a more general energy audit and metered electricity consumption. The monitored households were audited for the appliance ownership, rated power of the appliances, layout of the households and total monthly electricity consumption. Blink meters were installed with electric meter readers for initially 20 households, where 11 had three-phase, and nine had single phase meters to monitor the electricity consumption. The data collection starting in July 2018. After three months of the trial period, the three-phase meters showed inaccuracies as the electricity demand in the majority of the households was significantly lower than expected, with low-power features in the demand profile poorly recorded. However, single-phase meters were demonstrating better low consumption profiles. Therefore, another ten single-phase meters were installed, which made the total number of households monitored to 30. Among those 30 households, 11 households have 3 phase meters, and 19 houses have single-phase meters. Moreover, whilst collecting the electricity demand data, the study faced several challenges such as load shedding (power cuts), disconnecting the blink meters due to lack of awareness and technical issues (equipment break down).

Weather: Auroville

In Auroville, the weather data (from an external data source) demonstrated high temperatures all around the year, with a maximum average of 31.8°C during June and the minimum average 24.3°C during January. During the monitored November, the average, maximum and minimum temperatures were 25.7°C, 29.0°C and 22.4°C, respectively (CD, n.d.). The average, maximum and minimum temperature reduced to 24.4°C, 27.9°C and 21.0°C, respectively (CD, n.d.). Our monitored data showed, during the relatively warmer period of 3-9th November 2018, the highest, lowest and average temperatures were 31.7°C, 28.6 °C and 30.0°C, respectively. The average temperature in the weekends was 29.4°C (3rd November, Saturday) and 30.0°C (4th November, Sunday), respectively. The average temperature at the weekends was 30.1°C (5-9th November). At the end of December, the temperature became comparatively low. During 22-28th December 2018, the highest, lowest and average temperature were 29.2°C, 26.8°C and 27.9°C, respectively. The average temperature in the weekends was 28.6°C (22nd December, Saturday) and 27.7°C (23rd December, Sunday), respectively. The average temperature in the weekends was 27.9°C (24-28 November).

Residential energy demand monitoring: Auroville

Auroville is an experimental township (established 1968) in south India, with approximately 50 thousand population from different countries (Auroville, 2017). The case study buildings are located in the north of Matrimandir —a large golden sphere established in the very centre of Auroville that symbolises the birth of a new consciousness (Auroville, 2017)— in Tamil Nadu, India. Two apartment buildings— Citadines (34 flats) and Inspiration (14 flats) — are being monitored as case studies. 21 and 9 households were chosen to be observed in Citadines and Inspiration, respectively.

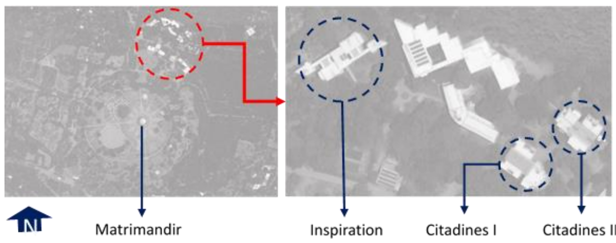


Figure 1: Monitored buildings (Auroville); source (Google Maps, 2019).

Citadine

23 occupants (mostly living alone and working in Auroville community) are living in the selected 21 dwellings in Citadine. However, the majority of the dwellings have housemaids who work 4-8 hours weekly. The monitored households use Incandescent (18.2%), Compact fluorescent lamp (CFL) (90.9%), Light-emitting diode (LED) (63.6%) and T5 with Electronic Ballast (90.9%) lighting (Figure 2). According to India Cooling Action Plan (ICAP), there are three types of space cooling technologies in Indian buildings: Refrigerant-based (Room A/Cs, Chiller System, Variable Refrigerant Flow (VRF) System, Packaged DX), Non-refrigerant-based (Fan, Air Cooler), and "not-in-kind" (Indirect Direct Evaporative Cooling System, Radiant Cooling System, Solar VAM System and otehrs) (GoI, 2019). There are two types of space conditioning appliances used in the

monitored dwellings for aiding comfort — electric fans (in 100% of dwellings) and room A/Cs (9.1%). Another most common household appliance is a refrigerator (100%). In terms of cooking, Citadines has a community kitchen, where most of the residents have their food. Most of the dwellings use gas cylinders for cooking in general, though a smaller number have electric stoves. There are also some other appliances used in households such as laptops, TV, router, modem, monitor, speaker, blender, iron, oven, kettle and toaster (Figure 2). The majority of the dwellings have single-phase meters for monitoring electricity consumption.

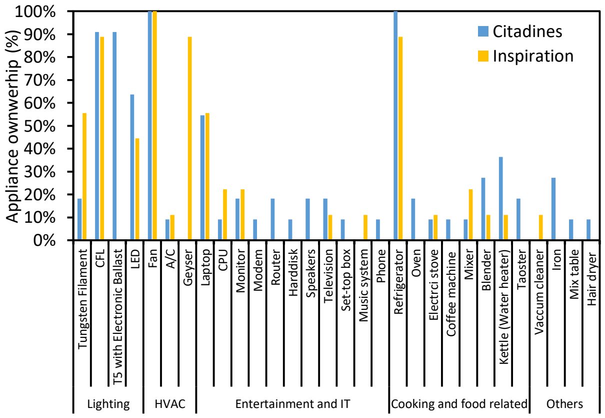


Figure 2: Appliance ownership in monitored households

Inspiration

In the case of Inspiration, 10 occupants live in the selected nine dwellings. The household size and working destinations are similar to occupants of Citadines. The significant difference between the occupants in Inspiration with Citadines is in the usage of types of appliances. Three types of lights, incandescent (55.4%), CFL (88.9%), and LED (44.4%), are used in the dwellings of Inspiration. In the case of Heating, Ventilation, and Air Conditioning (HVAC), electric fans (100%) and A/C (11.1%) are used. In general, as with Citadines, most of the dwellings use gas cylinders for cooking. However, one household has an induction stove. In the case of a refrigerator, eight dwellings have one, and one household has two. The other appliances in use in Inspiration are similar to households in Citadines, except 88.9% of households use geysers for hot water in the bathroom (Figure 2). The dwellings have three-phase meters for monitoring electricity consumption.

Results and discussion

The majority of the monitored households showed a lower level of electricity consumption because of the absence of A/C and high power consuming appliances such as hairdryers, electric kettles, and irons. During early November 2018, only five households had more than 350 W of peak electricity consumption out of the 18 monitored households (Figure 3A). Only one household (Home 1) among the five households has an A/C and, therefore, the highest frequency of high electricity features (i.e. spikes in demand) in November. The other

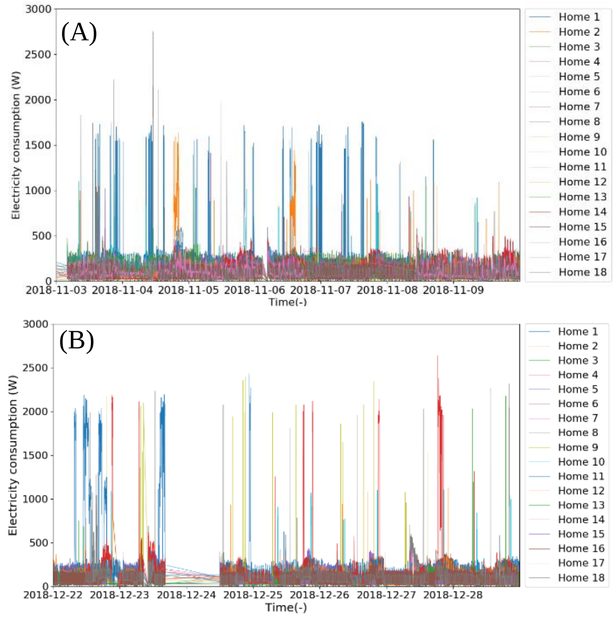


Figure 3: (A) Electricity consumption in 3-9 November 2018; (B) Electricity consumption in 22-28 December 2018

electricity consumption spikes in Figure 3A are from high electricity consuming appliances in the other four households. However, the number of electricity consumption spikes after mid-December 2018 decreases significantly because the A/C usage in 'Home 1' household reduced due to lower air temperature (Figure 3B). Both Figure 3A and Figure 3B show some gaps in the data due to load shedding and internet issues.

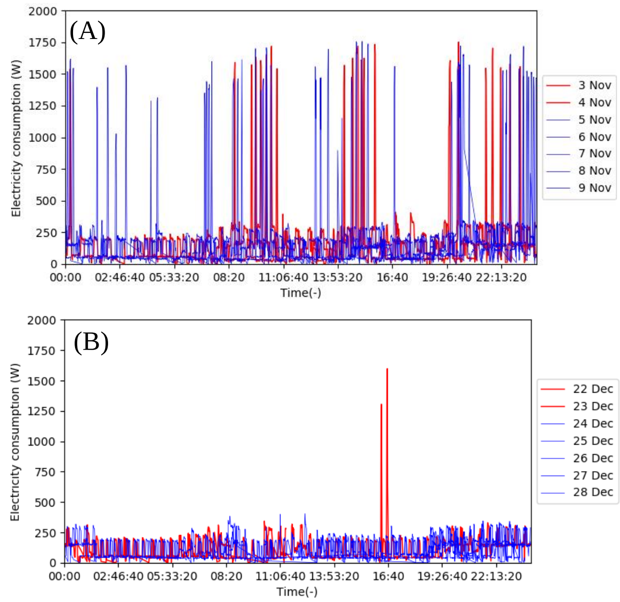


Figure 4: Daily electricity demand profile for 'Home 1' with A/C ([A] 3-9 November 2018, [B] 22-28

December 2018); Red is for weekends, and blue is for weekdays.

The 'Home 1' household has one of the highest numbers of high electricity consuming spikes among the combined profiles (Figure 3). The household has a bedroom, a living room, a bathroom, a kitchen and a balcony for one person with an area of 50 m^2. The detailed analysis of appliances in the household shows five categories of appliances: lighting, HVAC, entertainment and IT, cooking and food-related, and others. CFL and T5 with Electronic Ballast are used for lighting. There are three CFLs (18 W) in the living room, one each in the bathroom, balcony and kitchen, respectively. There are three T5 with Electronic Ballast (14 W) in the bathroom. The household has a 1000 W A/C unit in the bedroom for space cooling. Moreover, there is a 75 W ceiling fan in the bedroom for increasing air change rate. There is also a refrigerator (548 kW/year), a television (78 W) and an Iron (1400 W) in the household.

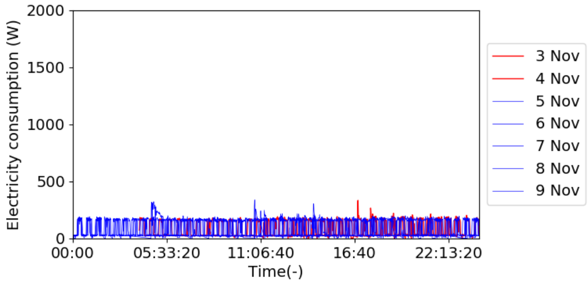
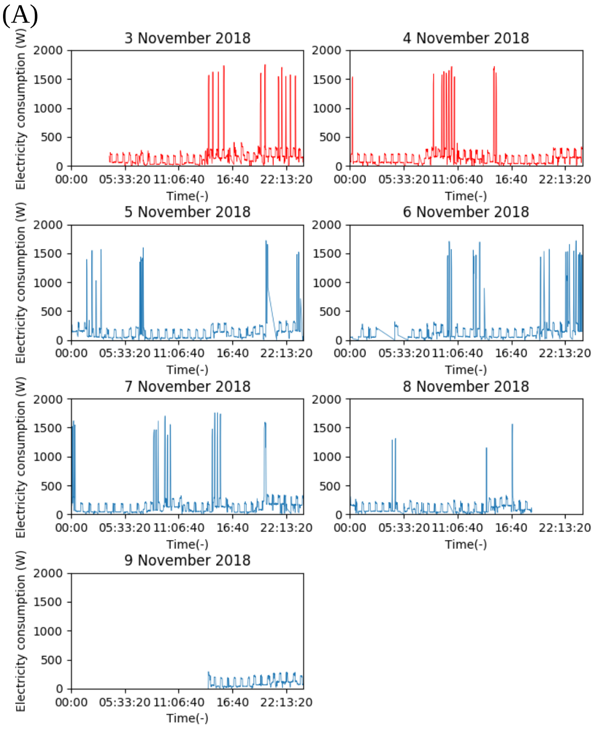


Figure 5: Daily electricity demand profile for 'Home 4' without A/C (3-9 November 2018); Red and blue are for weekends and weekdays, respectively.

During 3-4th November in Figure 4A, the household showed three main periods with high electricity consumptions: morning (7-11:15 am), afternoon (12-5 pm) and night (7pm-1am). However, during weekdays, the use of high consuming appliances increases at night period. The baseline electricity consumption in the households is around 300 W, and the high demand spikes reach up to 1600-1700 W. Cross-checking the electricity consumption pattern with the appliances ownership of the household suggests that the high demand spikes may have been caused by the use of A/C for cooling and use of Iron. However, the frequency and periods of electricity use suggest that the A/C is the primary cause of high demand. Moreover, the demand profile during 22-28th December 2018 in Figure 4B showed none/minimal use of A/C as the air temperature was on average 27.9°C, around 3°C less than that of 3-9th November 2018. At the same time, the highest relative humidity value was 98% (in the weekends), lowest 84% (during weekdays), and average 92%, which may have contributed to the truncated use of A/C. There is only one high demand spike in the weekend which may have caused by the use of other appliances. If the high consumption is removed, the demand profile would resemble a household (Home 4) with only fans for space conditioning (Figure 5).

Although the 'Home 4' household does not have any A/C, it has an oven (1200 W), a refrigerator, a coffee machine (800 W), a kettle (1350 W), and an iron (750 W). The week demonstrated here, does not show any use of high consuming appliances. The base demand appears to exhibit a typical refrigerator profile.

(A)



(B)

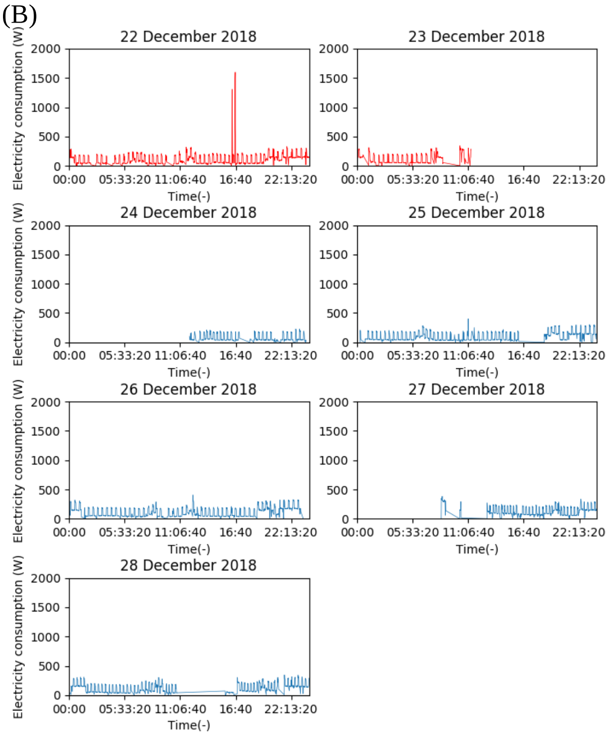


Figure 6: Daily electricity demand profile for 'Home 1' household with A/C ([A] 3-9th November 2018, [B]

22-28th December 2018); Red is for weekends, and blue is for weekdays.

In the case of cooling, two types of user patterns are observed in the 'Home 1' household: Only electric fan and A/C with a fan. During the warmer period of November, the space cooling was mostly conducted with a combination of A/C and electric fan. On 3-7th November especially at night, the occupant may have used the A/C for some time and then used a fan to circulate the cooled air around the room to reduce the use of high electricity-intensive appliance (Figure 6A). The use of space cooling appliances in 'Home 1' reduced in December (Figure 6B), most probably due to lower temperature and humidity than that of early November. In Figure 6B, approximately less than 100 W rise at night (7pm-2am), which may be the use of electric fan (75 W in the bedroom) for space conditioning. The residential space cooling user behaviour demonstrates some intriguing patterns, which is in contrast to, for example, the UK's domestic space heating behaviour. User profiles for space heating have a certain degree of homogeneity across most households (McCallum, et al., 2019), where the heating is mostly centralised in the dwelling. The residential space conditioning in monitored households in Auroville suggests that fans and A/Cs are separate, room-based appliances, mostly in bedrooms, which means a more complex occupancy behaviour. Although the electricity demand profiles presented begins to show some correlation between behaviour and space cooling demand, there is a need for more detailed data and information from the occupants.

The observed appliance use behaviours would be utilised to generate user profile schedules for appliances in the simulated virtual environment such as Design Builder and Energy Plus to investigate the effect of different demand reduction scenarios for the CEDRI project. There is a substantial gap in the understating of the residential electricity consumption behaviours in India due to the significant diverse influence of demography, local geography/climate, economy, culture and technological variables and complexities. This study is an initial step towards understanding the electricity use behaviour on a household scale, and to aggregate to a community scale to simulate the effect of different electricity demand reduction strategies.

Conclusion

The objective of this study was to understand the characteristics of occupancies in households of warm-humid climate —using the village of Auroville as a case study— through the analysis of electricity demand profile. The electricity consumption profile of 18 households was collected and analysed. There were several issues such as load shedding (power cuts), the human factor (lack of awareness) and technical issue (equipment break down) caused some data gaps. More data collection may help to reduce the effect of these gaps in the profile analysis.

The analysis of the demand profiles demonstrated several intriguing occupancy behaviours. Most of the households use ceiling fans for space conditioning. Although some households also use A/C for space cooling, they also have ceiling fans too. These households with A/C and ceiling fans do not use A/C continuously for space cooling. The demand profile showed that the occupancies might use the A/C to cool the indoor air and the use fans to circulate the cooled air until it gets warm and then again use A/C. The main reason behind these characteristics may be to reduce the use of an electricity-intensive appliance to minimise the consumption and associated bills. Further occupancy interview will reveal the nuances behind this behaviour, but this initial work has illustrated that pattern recognition of demand profiles may be effective at characterising usage of cooling and fan technologies in Indian dwellings.

The monitored profiles will be collectively used to develop seasonal user profile for the households and applied in a building physics model to simulate the real energy demand with the virtual environment in the next stage of the study. Moreover, the users of the monitored households will be interviewed to understand their appliance use characteristics in detail. The research intends to crosscheck the interview data and monitored data to get more insight into the demand characteristics of the households in Auroville. The research will further be used to inform the work of the Community-scale Energy Demand Reduction in India (CEDRI) project (funded by DST in India and EPSRC in the UK), to combine energy network and building modelling with behavioural studies to tailor demand reduction strategies for Indian communities.

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