UNDERSTANDING THE RELATIONSHIP BETWEEN INDOOR ENVIRONMENT, ELECTRICITY USE AND HOUSEHOLD SOCIO-DEMOGRAPHICS: INSIGHTS FROM AN EMPIRICAL STUDY IN HYDERABAD

Gupta, Rajat[1], Tuteja, Sanjoli[1], Garg, Vishal[2], Agarwal, Rishika[2], Ramapragada, Pavan[2]

[1]*Low Carbon Building Research Group*
Oxford Brookes University
Oxford, United Kingdom
rgupta@brookes.ac.uk

[2]*Centre for IT in Building Science*
International Institute of Information Technology
Hyderabad, India
vishal@iiit.ac.in

ABSTRACT

Residential energy (electricity) use in India is expected to grow four-fold by 2030, yet there is paucity of empirical data that is essential for developing energy policy or programme. This study describes the methodology, findings and wider learning gathered from the concurrent monitoring of residential electricity use (current CT clamps) and indoor environment (temperature, relative humidity) every 15 minutes, along with household survey (occupancy, socio-demographics) of 20 dwellings located in the composite climate of Hyderabad. Statistical analysis of monitoring and survey data helps to better understand *what*, *when* and *why* electricity is used in dwellings with and without air-conditioning (AC). The 20 dwellings represent a variety of built forms (standalone houses/apartments), income groups (low/medium/high income) and ownership of AC units (from 0 to 4, average 1 AC). Mean annual electricity use of dwellings with AC units (2,881 kWh/year) was found to be 29% more than non-AC dwellings (2,230 kWh/year), while peak current consumption in AC homes was 228% more than non-AC homes. The coincidental monitoring of electricity current and indoor temperature confirmed the hours of AC usage, since indoor temperature decreased with rise of electricity current. This is why mean indoor temperature was higher (35°C) and relative humidity lower (38%) in non-AC dwellings than dwellings with AC units (32°C and 42%). The study also offers interesting lessons for future field studies in terms of *technology to technology interaction* (internet connectivity for data transmission), *technology to person interaction* (deploying loggers in appropriate location), and *person to person interaction* (sustaining householder engagement).

Keywords: **residential energy, monitoring, survey, indoor environment, electricity use**

INTRODUCTION

India is at the cusp of a major socio-economic development that suggest a four-fold increase in the country's carbon emissions by the year 2050 (du Can et al., 2019) Electricity consumption in residential buildings in India has nearly tripled since 2000 and today residential buildings account for about 24% of total electricity use in India (MOSPI, 2018). The annual average electricity consumption per electrified household for electrical appliances and lighting increased at a rate of about 3.7% per annum from the year 2000 to 2014 (WEC, 2014). This rising trend in India's residential energy consumption pattern is expected to further grow due to various factors such as the addition of nearly 20 billion square metres of new building footprint by the year 2030 (Kumar et al., 2010). Moreover the higher GDP growth is associated with increased purchasing power and higher comfort expectations, leading to higher penetration of household appliances, resulting in residential electricity consumption growth of about four-fold by 2030. Yet there is paucity of empirical data on residential energy use that is essential for developing energy policy or programme.

In 2013, a review of data quality related to building performance for residential and commercial buildings in four regions (India, China, United States and EU) found that building performance data for residential (and commercial buildings) sector was weakest in India. Moreover, the quality of data available for residential buildings in India was found to be weaker than commercial buildings. Lack of interest, technology and finance were identified as barriers to gathering residential energy data, which is why public availability of empirical data has been a long standing issue in India. Incentive programmes and regulations that promote continuous monitoring and reporting of building performance data were suggested as ways to overcome barriers (Shnapp and Laustsen, 2013).

With the emergence of smart meters providing an opportunity to collect granular time-series data on energy use of buildings, efforts are being made to make such data publicly available (Rashid et al., 2019, EDS, 2019). However, such initiatives are recent and still at a nascent stage. Furthermore, gathering data for residential buildings is particularly complex due to the heterogeneity of the building stock and lack of unified sources (Carpino et al., 2019). The unreliability of the electricity grid and internet also poses challenges for gathering data using remote monitoring (Batra et al., 2013)

Within this context, this study describes the methodology, findings and wider learnings gathered from the continuous and concurrent monitoring of residential electricity use (using current CT clamps) and indoor environment (temperature and relative humidity) every 15 minutes, along with a questionnaire survey of property (age, area) and household characteristics (occupancy, socio-demographics) of 20 dwellings located in the composite climate of Hyderabad. The study also draws lessons in terms of *person-person, technology-technology and person-technology interactions* when undertaking empirical studies for residential energy use in India. The study is part of a wider Indo-UK research programme called RESIDE – Residential Building Energy Demand Reduction.

METHODS

A socio-technical approach was adopted to gather in-depth qualitative and quantitative data about various social and technical aspects influencing electricity consumption of households in India. Building upon previous international (Gupta et al., 2014) and national studies (Rawal and Shukla, 2014, Sachar et al., 2018, BEE, 2014), a comprehensive monitoring and survey framework was developed, bringing together techniques of physical monitoring of electricity use and indoor environment, with a survey of property and household characteristics to explain *how much electricity is used* and *why it is being used.* These methods are explained below:

PHYSICAL MONITORING

Coincidental and continuous monitoring of dwelling electricity use (current CT clamps) and indoor environment (indoor temperature and RH) at every 15 minutes was performed using low-cost sensors developed and customised by the research team. Electric current measurements were used as a proxy to determine the trends in household electricity use. For this a low-cost battery operated CT logger- called GARUD (**Figure 1**), was developed, which consists of three CT clamps that can be installed on the main circuit board of a dwelling having one, two or three phase connection. The accuracy of Garud logger was tested in the lab and also in a dwelling (Tejaswani et al., 2019), by comparing Garud measurements with a more sophisticated logger that measures current, voltage and power factor. Yokogawa-WT330 meter was used for calibration of Garud. The data gathered using Garud was tested and calibrated against the WT330 meter. The device was calibrated on a wide range of current across the CT. Measurements were then compared to the true values over the range of current values. The comparison showed that Garud logger has an accuracy of +/- 3% to 5% (compared with standard meter with 60A/0.33V CT).

The logger for monitoring indoor temperature and RH logger called RHT BT (**Figure 1**) was customised by modifying an existing device to suit the requirements of the project. The accuracy of RHT BT was compared with that of i-button and Hobo U-12, and was found to be ± 0.3 deg.C for temperature and ± 3% for RH. Both devices recorded and stored data at every 15 minutes intervals. The data download process was simplified for Garud and RHT BT using Bluetooth. This allowed researchers to download the data on site using a customised app on their smart-phones, without removing and reinstalling any device.

One Garud and one RHT BT logger were installed in each of the 20 dwellings. While Garud was installed at the main circuit board by a trained electrician, the researcher installed the RHT BT in the most occupied room of the dwelling (with AC in case the dwellings had AC). Standard protocols (height from the floor, distance from external door/window or source heat and cold etc.) for installing an indoor temperature and RH logger were followed. The monitoring was conducted for a period of 14 days (15 May to 28 May), during the peak summer month of May 2019.

(a) (b) (c) (d)

Figure 1: a) GARUD; b) GARUD installed on the main circuit board; c) T-zone; d) T-zone installed in a surveyed dwelling

SURVEY

The questionnaire survey was designed to gather data about the property characteristics as well as socio-demographic aspects of the households, covering the following aspects.

- *Built form* of the dwelling such as dwelling type (house, apartment), dwelling age, and floor area.
- *Building envelope* such as construction materials, architectural features such as shading.
- *Household characteristics* such as number of occupants, family size, socio-demographic (age, gender), income group.
- *Appliance* ownership, energy efficiency rating (BEE star rating) appliance usage hours.
- *Occupant thermal comfort* using thermal comfort sensation and preference votes.

The surveys were implemented using online Google forms, which the researchers completed on-site using their smart phones. Researchers read out the survey questions and noted participant responses on Google forms, which were recorded and saved online, thereby eliminating the effort for filling in the survey responses later on. The surveys were conducted through multiple visits wherein the researchers took photographs of the dwelling features (such as shading) and also noted their observations. At the end of each survey researchers were asked to fill a feedback form highlighting any issues faced while conducting the surveys and make any suggestions for improving the survey forms.

CASE STUDY DWELLINGS

A total of 20 dwellings (comprising 20 households) representing a variety of built forms, income groups and ownership of air-conditioning (AC) units were selected and recruited for the study. The availability of electricity data for the past one year (mid 2018 to 2019) was a key criterion for selecting the dwelling. Based on the annual household income data gathered from the residents the dwellings were categorised as low, medium and high income groups as defined under the Pradhan Mantari Awas Yojana. Nearly, 50% of the surveyed dwellings (9 out of 20) belong to the middle income group (MIG), while seven dwellings fell in low income group (LIG) and four in the high income group (HIG). The average number of occupants in the HIG, MIG and LIG households were found to be 3, 3.7 and 4.1 persons per household respectively. About a quarter of the dwellings (6 out of 20) did not have any AC units, while nearly half of the surveyed dwellings (9 out of 20) had one AC unit. The remaining five dwellings owned two, three and four AC units.

Though AC ownership was found to be highest in the high income group (HIG) (avg. 2.3 ACs/household) and lowest in LIG (avg. 0.6 AC/household), there were a few high income households with no ACs, as well as middle income households with 2 or 3 ACs. The number of occupants in a dwelling did not have any association with the number of ACs owned by the household (**Figure 2**). While majority of the dwellings without AC or with one AC had single phase electricity connection, dwellings with more than one AC also had three phase connection. There were a few dwellings with no AC units (n: 3) which had three phase connection.

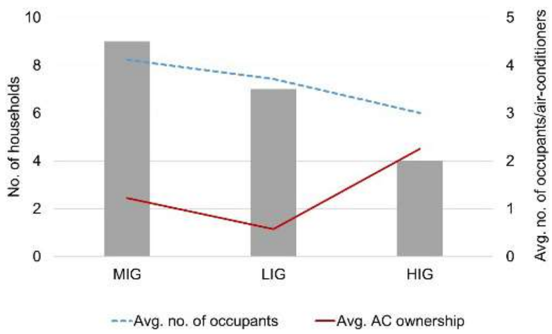

Figure 2: Income group distribution of the surveyed dwellings vs avg. number of occupants and ACs owned

Majority of the dwellings (13 out of 20) were stand-alone houses or bungalows with one electricity meter, seven dwellings were flats located in a low rise (< 4 story high) apartment building. Nearly all the surveyed dwellings were owner occupied, constructed using RCC frame structure with burnt clay bricks as infill. The windows were single glazed with fixed external shading. The average age of dwellings was about 10 years.

FINDINGS

Electricity consumption data for 20 dwellings were gathered for a period of one year (Aug 2018 to July 2019), through electricity bills from the householders

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or accessed online through the electricity supplier's website, with consent from the householder. **Figure 3** shows the annual electricity consumption of the six non-AC and 14 dwellings with AC units. A wide range in electricity use is observed, regardless of AC ownership. The overall mean and median annual electricity consumption for the 20 dwellings was found to be 2,686 kWh/year and 2,765 kWh/year respectively.

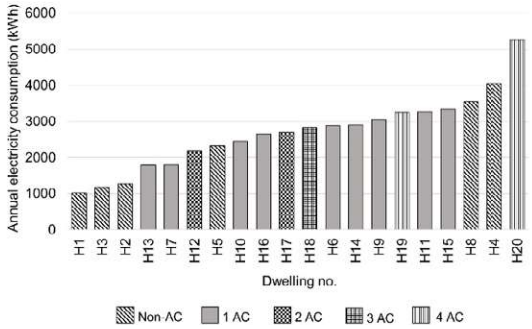

Figure 3: Annual electricity consumption of the surveyed households (August 2018 to July 2019)

Overall, the mean annual electricity consumption for AC dwellings was found to be about 29% higher than the non-AC dwellings. Understandably the mean annual electricity consumption was found to be lowest for non-AC dwellings (2,230 kWh/year) (n: 6) and highest for dwellings with four ACs (4,248 kWh/year) (n: 2) **(Figure 4**). The difference between H20 (highest electricity user with AC) and H4 (highest electricity user without AC) is much less (1,210kWh), indicating that AC usage may not always be the most energy consuming end use and there are other factors influencing residential energy usage.

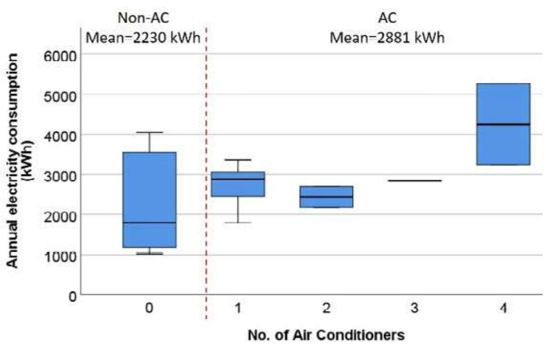

Figure 4: Box plot showing distribution of annual electricity consumption for non-AC and Ac dwellings

The mean daily electricity consumption for the 20 dwellings (based on 9 months data - Jan to Sept) was found to be 7.7 kWh. This daily electricity use is higher than the mean daily electricity consumption of 5 kWh (for Jan-Sep) measured by the NEEM study for Hyderabad by BEE and CLASP (EDS, 2019).

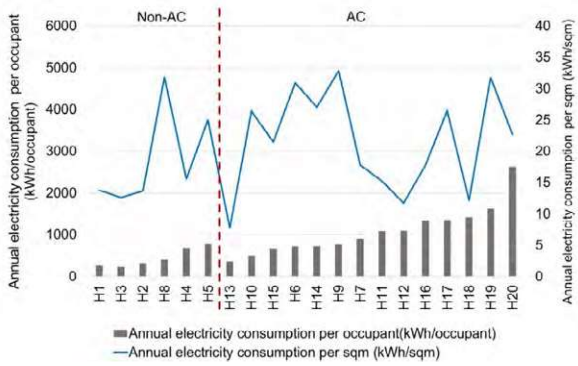

Figure 5: Annual electricity consumption per person vs per sqm electricity consumption of surveyed households

When electricity use was normalised by floor area and number of occupants, the annual electricity use of AC dwellings was found to be higher than non-AC dwellings (**Figure 5**). Within AC dwellings, the consumption varied significantly by conditioned floor area. Stronger correlation was observed between annual electricity use and electricity use per occupant (r: 0.67), as compared to moderate correlation (r: 0.44) between annual electricity consumption and electricity use per square metre. This implies that annual electricity use per occupant should be considered as a key metric, alongside annual electricity use per square meter (also called Energy Performance Index), especially in the Indian context where number of occupants can vary depending upon a nuclear or joint family structure. This is further reinforced by the weak correlation (coefficient value of 0.16) between annual electricity use per square meter and annual electricity use per person.

While mean monthly electricity consumption of non-AC dwellings was less affected by changes in external temperature, it had a major impact on electricity use of AC dwellings, with consumption being highest during summer months (May to June), and increasing with number of ACs and their usage (**Figure 6**).

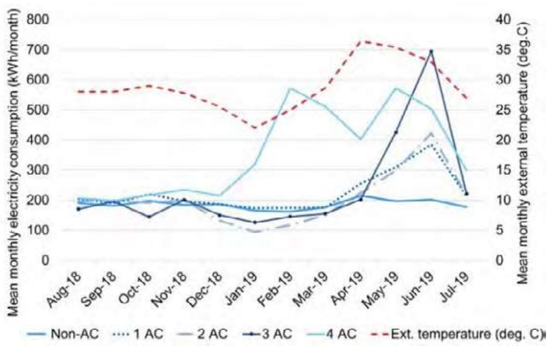

Figure 6: Mean monthly electricity use vs outdoor temperature

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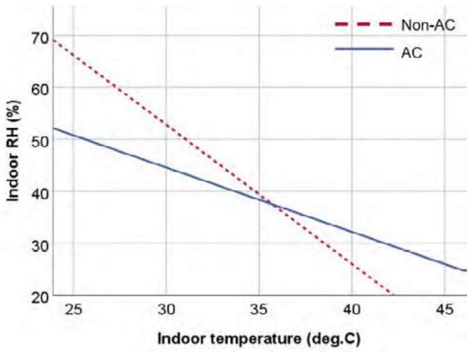
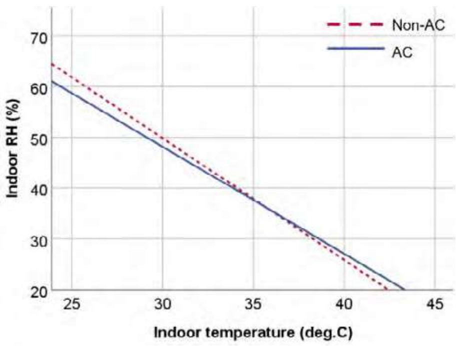
The mean indoor temperature (for the 14 day monitoring period in May 2019) for non-AC dwellings was found to be highest (35ºC) and similar to the mean outdoor temperature, whereas mean indoor RH was found to be lowest in these homes (38%). The mean indoor temperature for AC dwellings was lower (34ºC) but mean indoor RH (41%) was slightly higher than non-AC dwellings.

A scatter plot of indoor temperature and RH measurements during AC usage hours (9pm to 7am for 18 dwellings, and 9pm to 7am and 2pm to 7pm for two dwellings) for AC and non-AC dwellings (**Figure 7a**) showed that indoor relative humidity was maintained within a tight range (30% - 48%) in AC dwellings, as compared to non-AC dwellings (20%-75%). Interestingly during the period when AC was not used, dwellings with AC units behaved similar to dwellings with no ACs (**Figure 7b**), indicating the inability of the building envelope to retain coolth.



(a) during hours when AC is used



(b) during hours when AC is not used

Figure 7: Indoor temperature vs indoor RH (a) non AC; (b) AC dwellings

Within the group of dwellings with AC units, much wider variation was observed in the mean indoor temperature (**Figure 8**). While the mean as well as minimum indoor temperatures in dwellings with ACs are much lower than dwellings without ACs, given the wide range observed between minimum and maximum indoor temperatures in majority of the dwellings with ACs, it is evident that AC usage is not constant.

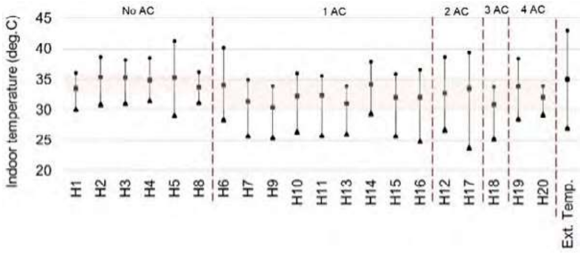


Figure 8: Mean indoor temperature of the surveyed dwellings vs mean external temperature

Since the temperature and RH logger was installed in the room with AC, the relationship between AC usage pattern and indoor temperature is examined further. **Figure 9** (a, b and c) shows the hourly average current and indoor temperature profiles over a 14 day period in May 2019, for dwellings with one, two, three and four ACs respectively. The peaks observed in the current profiles are likely to be due to AC usage given that as electricity current increases, indoor temperature decreases. The difference in mean indoor temperatures when AC was on (32ºC) and off (34 ºC) was found to be only 2ºC. The AC usage hours were estimated from the graphs to be from late evening to early morning hours, with some variation in the on/off time. However significant variation in the time and duration of AC usage was observed amongst dwellings with one AC unit indicating difference in occupant preferences. The preference to switch-on the AC seemed driven more due to the time of the day (when the occupants were home) rather than change in temperature. The hours estimated for AC usage from the electricity current profiles compared favourably with self-reported AC usage hours from the survey (**Table 1**), giving confidence in the estimate.

Interestingly the analysis of current profiles for dwellings with two AC units showed considerable differences in their AC usage. In dwelling H12, two ACs were used between 8pm and 5am (about 7 hours) and between 1pm and 4 pm (about 3 hours), while in dwelling H17 (with two AC units), only one AC was used during the monitoring period. This was validated by the survey data, wherein the occupants of H17 reported using one AC during summer (**Table 1**).

Similarly for dwellings H18, H19 and H20 having three and four AC units respectively, the current consumption for dwelling H19 from 9 pm to about 10 am is much lesser as compared to that of dwelling

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H18 which has three AC units. Likewise, the current profile for H19 and H20 show that while majority AC units in these dwellings were being used during night time (sleeping hours), one AC was also used for a few hours during daytime. While the AC usage during daytime in H19 was similar to H20, the usage hours were less. These observations were validated by the number of AC usage hours reported in the survey. These findings indicate that dwellings with more number of ACs may not have higher electricity use than dwellings with lesser number, since the number of ACs that are actually used and their usage hours may vary significantly.

When electricity current consumption profiles of AC and non AC dwellings were compared, peak current consumption in AC homes is found to be 228 % more than non-AC homes. Furthermore the current consumption pattern of an AC and Non-AC dwelling during weekdays and weekends showed that there is increased consumption of current during weekends in the afternoon hours for both AC and non-AC dwellings. The consumption increased by 11.9% during weekends in the dwellings with AC whereas the increase was much less (1.7%) in non-AC homes.

DISCUSSION

This study has tested an interdisciplinary approach combining physical monitoring of electricity use and indoor environment with household surveys to better understand *what*, *when* and *why* electricity is used in a sample of dwellings with and without air-conditioning. Meaningful insights are drawn about the electricity use patterns and peak usage of residential air conditioning.

The metric of annual electricity consumption per occupant (kWh/occupant/year) was found to better explain the variability of electricity use across the 20 dwelling sample, than the conventional metric of annual electricity consumption per square meter (kWh/sqm/year). It is evident that annual electricity use normalised by number of occupants can be a useful metric in characterising the diversity of household electricity consumption across different climates and cultures of India.

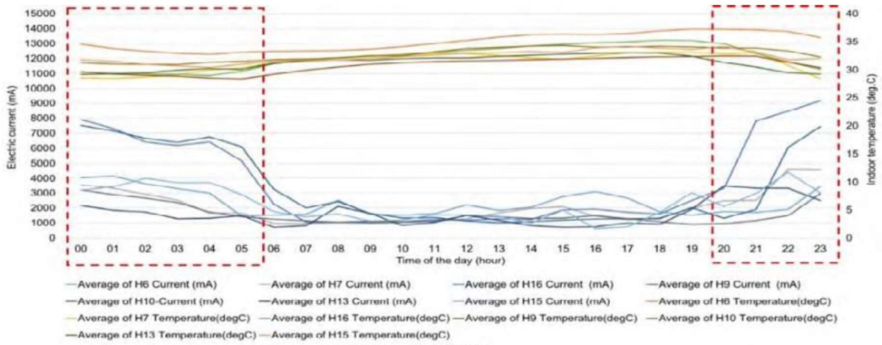
The annual and peak electricity use of dwellings with AC units was found to be much higher than non-AC dwellings. However it was not the number of ACs, but the usage pattern of AC units that influenced the magnitude of electricity use amongst AC dwellings. The continuous monitoring of electricity current and indoor temperature confirmed the use of AC, since indoor temperature decreased with rise of electricity current. The time of AC use and the peak period of electricity coincided, and was found to be between 9pm and 7 am for the majority of AC dwellings. As the mains electricity grid in India gets decarbonised with introduction of more renewable energy (that is variable and intermittent), this residential peak period will need to be addressed through demand-side response and electricity storage.

Indoor relative humidity was found to be well-controlled during the time of AC usage, implying that air conditioning in dwellings is mainly used to modulate indoor humidity levels. However during the period when AC was not used, the indoor temperature and relative humidity in AC dwellings was found to be similar to non-AC dwellings.

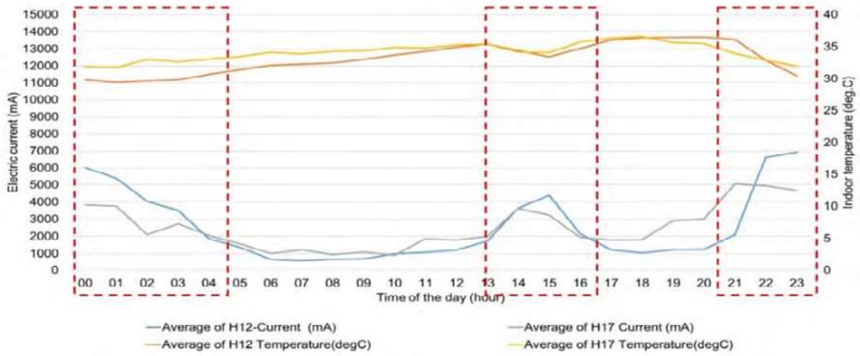
In addition to insights gathered through the field study data, lessons were learnt through the process of undertaking the field study. Challenges were faced (and most of them overcome) while conducting monitoring and surveys, and these are organised through a combination of interactions; technology-technology, technology-person, and person-person (Darby and Liddell, 2015), as explained below.

Technology-technology interaction: While the Bluetooth functionality of the data loggers facilitated easy and quick data download, the mobile app required for downloading the data was found to be temperamental possibly due to connectivity issues. A limitation of the loggers was the non-availability of the option to pre-set the data logging date and time, with the result that not all dwellings started gathering data at the same time. However, this limitation can be overcome by installing the loggers for longer duration (say a year) such that substantial data for all seasons can be gathered. While conducting the survey, completing the forms online using smart phones was found to be an efficient method of gathering data, since it eliminated the process of filling in survey responses later. However connectivity issues were faced due to intermittent internet connection in some locations.

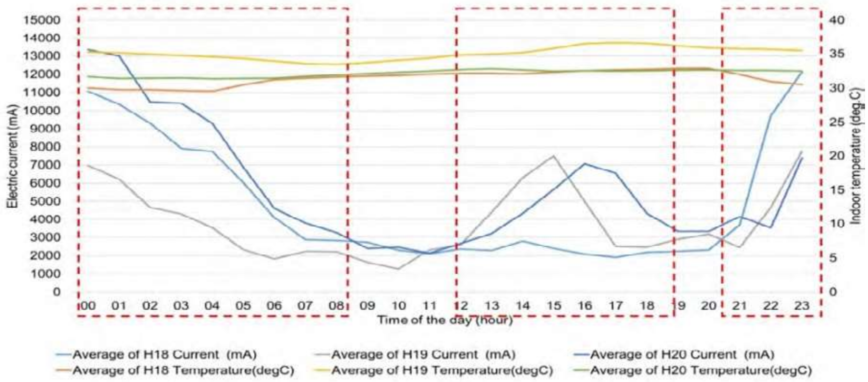
Technology-person interaction: Installation of data loggers in dwellings also posed challenges. Since the CT logger for monitoring electricity current had to be installed by an electrician at the main circuit board, it was vital to check beforehand that main circuit board was accessible and had enough space for installing the CT logger. Also the electrician had to ensure that no damage was caused due to the installation. To avoid any claims by the householders at a later stage, they were requested to sign a 'no damage form' following the installation. Photographic evidence of the installation was also gathered as part of the survey. The researchers were trained to carefully select the location while installing the temperature & RH logger.



(a) 1 AC



(b) 2 AC



(c) 3 & 4 AC

Figure 9: Hourly average daily electricity current and indoor temperature profile (based on 14 days data at every 15 minutes) for dwellings with a) 1 AC; b) 2 AC; c) 3 & 4 AC

Table 1: AC usage hours (per day during summer) reported by occupants & calculated from electric current profile

DWELL-ING NO.	NO. OF AC	AVG. AC USAGE HOURS/DAY (AS REPORTED BY THE OCCUPANTS) 1ST AC	AVG. AC USAGE HOURS/DAY (AS REPORTED BY THE OCCUPANTS) 2ND AC	AVG. AC USAGE HOURS/DAY (AS REPORTED BY THE OCCUPANTS) 3RD AC	AVG. AC USAGE HOURS/DAY (AS REPORTED BY THE OCCUPANTS) 4th AC	TOTAL CALCULATED AVG. USAGE HOURS/DAY (FROM ELECTRIC CURRENT PROFILE)
H6	1	5-8	-	-	-	7
H7	1	5-8	-	-	-	8
H16	1	9-12	-	-	-	11
H12	2	5-8	5-8	-	-	10
H17	2	9-12	Not used	-	-	11
H18	3	5-8	5-8	5-8	-	11
H19	4	5-8	1-4	1-4	Not used	10
H20	4	9-12	5-8	1-4	1-4	15

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For example, no loggers were installed in the vicinity of an AC, or near a window or balcony door, or near a source of direct cool air or heat. Again photographic evidence was gathered to confirm installation of RHT BT logger.

Person-person interaction: A key challenge was to get the householders interested in participating in such studies and making them aware about the significance and benefits of participation. During the study, although households were recruited through friends and family contacts, many householders lost interest and opted out of the study by the time the actual field study began. To address this in future, such studies must be mindful of the time lag between recruitment of dwellings and start of the field work. While some part of the survey (especially socio-demographics) could be self-completed by householders, in order to ensure complete set of responses, the surveys were undertaken in the form of interviews thereby increasing the duration of the survey. Providing some form of incentives (cash or in kind) to householders can help in sustaining their interest. The installation of the CT logger required an electrician accompanying the researcher, and on few occasions, householders requested the electrician to undertake additional electrical works. Since these works were not supported by the field study, researchers had to be trained to manage expectations of householders, without jeopardizing their participation in the study.

Such experiences from the field study provide useful lessons for conducting future empirical studies on residential energy in India.

CONCLUSION

This study has assessed the pattern of electricity use, AC usage and its relationship with indoor environment in a sample of 20 AC and non-AC dwellings in Hyderabad, using coincidental monitoring of electricity use (current monitoring using CT clamps) and indoor environment (temperature and RH) combined with household surveys. The learning from the process of undertaking the study offers useful insights for large-scale monitoring and survey based studies in India. While it can be argued that the advent and growing popularity of smart meters in India can eventually facilitate gathering of energy data, their penetration will be limited to certain socio-economic backgrounds and building typologies. The approach adopted in this project offers the means for gathering residential energy data on a nationwide scale.

ACKNOWLEDGEMENT

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