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Performance evaluation of a certified green-rated housing development in the warm humid climate of India

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Abstract. The Indian Green Building Council (IGBC) claims that India has the second largest registered green building footprint in the world. However, there is no evidence-based approach to ascertain the actual energy performance and occupant satisfaction vis-a-vis the building design and indoor environment. This paper seeks to apply a customised post-occupancy *building performance evaluation* approach for *Indian* green buildings (I-BPE), to evaluate the actual performance of a certified green housing development in the warm humid climate of India, from both technical and occupants' perspectives. Electricity consumption, environmental data, and occupant opinion of 29 flats are gathered and assessed over a period of one month in the monsoon season of 2018. Results show that flats with air-conditioning (AC) units tend to have slightly higher electricity use than those without; however, mean temperature and relative humidity measurements tend to be about the same and the level of perceived comfort is no different across the two groups. Building and occupant surveys revealed that storage facilities were insufficient, resulting in corridor space becoming a dumping ground, making it unsightly and unhygienic. The methodological approach developed in the study can be used for gathering empirical data on the actual energy and environmental performance of housing in India.

1. Introduction

Rapid growth and urbanization [1], rising incomes, aspirations for comfort and a changing climate (combined with the compounding feed-back cycle of the urban heat island and air-conditioning) will, among many things, lead households in India to use more energy intensive means for cooling [2]. For these reasons, India has been an important focus for mitigated energy consumption in buildings. In housing, for example, careful design with priority for thermal comfort has the potential to delay this shift for air-conditioned comfort. Green building certification councils have seen this as an opportunity; the Indian Green Building Council (IGBC) claims that India is the second country in the world with the largest registered green building footprint with over 4,981 projects registered for green building ratings, of which 1,571 certified and fully functional (as of November 2018) [3]. Research, however, continually demonstrates that green building rating and certification systems do not always ensure greater energy performance [4], occupant satisfaction [5] or better indoor environmental quality (IEQ) over conventional buildings [6]. For these reasons, it is important to verify the performance of buildings built to sustainability standards.

The energy performance gap has been thoroughly demonstrated in international research. Research has shown a LEED (Leadership in Energy and Environmental Design) certified building using twice the energy beyond model predictions in the USA [7]. In the UK this has been reported as up to nine times the energy predicted for exceptionally energy efficient designed buildings funded by the UK government's Building Performance Evaluation (BPE) programme [8]. Also, in India [9], LEED certified buildings are not performing as expected with respect to certification, i.e. the LEED Silver and Gold facilities of the same type are performing better than one certified as LEED Platinum. Though there is no evidence found on the energy performance gap in green housing in India, it is hypothesized that it does exist and will persist as more green certified dwellings are rapidly built to meet demand.

BPE is one useful way to identify, quantify and resolve the gap between 'as designed' and 'in use' performance through a systematic collection and analysis of qualitative and quantitative information related to fabric performance, energy performance and environmental conditions. BPE can involve feedback and evaluation reviews at every phase of the building delivery from strategic planning to occupancy, adaptive reuse and recycling [10]. This paper seeks to apply a customised post-occupancy BPE approach developed in [11] (I-BPE) for the Indian green buildings, to evaluate the actual performance of a certified green housing development in the warm humid climate of India, from both technical and occupants' perspectives. Following with the next section, the paper first reviews literature on what has been performed to-date in post-occupancy evaluation (POE) / BPE on housing in India. The paper then introduces a green certified housing case study and the BPE methods used to evaluate the case study. The results are then presented followed by a discussion on future application and the conclusion.

2. Review of building evaluation in India

The following intends to provide an overview of the current extent of BPE in general but more specifically details on housing performance evaluations in India which range from urban apartments [12] to vernacular houses [13]. As BPE can vary in form, intensity, and length of time required, the following review differentiates between field studies in thermal comfort (FSTC) and POE / BPE but counts them all as performance evaluation studies with something to learn and take forward to improve future building. FSTC differs in that it is concerned only with the occupant's immediate response to a building and the immediate measurements taken in relation to that response [14], sometimes referred to as 'right here, right now' surveys [15, 16]. FSTC generally involves spot readings and predicted mean vote (PMV) analysis. POE/BPE collects a long range memory of the occupant's response along with energy and environmental features for a glimpse of the building's performance [14, 17] but BPE, beyond POE can also include the entire life-cycle of the building, whereas POE is limited to the life of the (occupied) building (post-completion) [18].

There is a notable collection of published research that demonstrate the use of BPE-related methods in India. Most of these studies are focussed on FSTC, understandably so, considering the temperature extremes in some locations, ongoing criticism of comfort specifications in the National Building Code (NBC) and other standards [12, 15, 19, 20], and the rising availability and accessibility of air-conditioning (AC) [2, 21, 22]. Most FSTC utilise thermal comfort questionnaires, interviews, temperature and relative humidity (RH) logging, and spot measurement devices as tools to evaluate environmental parameters of the buildings. A useful development in the FSTC research has been the customization of clothing (clo) values for the Class-II field experiment protocols for thermal comfort [12, 15, 20, 21, 23].

Residential interior environment assessment methods in the literature included, spot measurements at the time of survey, thermal comfort questionnaires (including long-term/seasonal outlook and/or thermal sensation and preference votes) [13, 20, 24, 25], and long-term logging/monitoring of temperature and relative humidity [13, 25]. A majority of the FSTC studies found that subjects in naturally ventilated buildings are comfortable at temperatures greater than comfort ranges recommended by ASHRAE 55, ISO-7730 standards, and the National Building code of India.

Generally, POE/BPE studies differ from the FSTC in that they include the addition of a long range questionnaire on such variables as work area satisfaction, lighting, productivity, and health [21]; a review of project information, interviews with key stakeholders [16]; monitored the impact of material changes on the interior environment [26]; design and system installation review, monitoring plan

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walkthrough, monthly energy bill collection for one year combined with seasonal energy monitoring, data logging of electricity distribution, spot measurements of lighting, temperature, RH, and envelope temperature [27]. The largest gap in BPE methods relate to those generally applied before post-occupancy, e.g. evaluation of systems installation, commissioning, and fabric performance.

Studies have estimated residential electricity consumption in India [28, 29], simulated the future difference between naturally ventilated or air-conditioned dwellings [30], and simulated the impact of replacing the urban and rural stock with decent living conditions under different climatic conditions, residential behavioural patterns, considering conventional as well as low-cost materials and energy-savings measures [31]. One study went further and used an occupant survey in 700 low-income households to understand appliance usage levels [32]; however, few have monitored electricity consumption from a real performance evaluation perspective.

However, Batra et al. [33] monitored voltage, current, frequency, phase and power at the home aggregate level, sub-metered grouped appliance level and monitored at plug level for appliances. It was of their opinion that no acceptable commercial solution was available for the sub-metered and plug-load level therefore they developed their own data logging and data collection system; this along with cost limitations is likely a reason for the lack of detailed energy monitoring in Indian studies. The study, focused more on the sensor development and testing rather than the performance of the dwelling, demonstrating the issues of excessive load and poor infrastructure in India which makes load shedding and rolling blackouts commonplace. During the monitoring period, a total of 107 power outages were reported in the 61-day period, with and average duration of one hour. For this reason, the authors found that load measurement devices should measure both current and voltage and ensure that loggers were capable of automatically restarting after a power outage with data collection and upload scripts execution as part of system start-up process.

Karthikeyan and Bhuvaneswari (34) proposed and tested in a single dwelling, a cost-effective real-time monitoring system for residential energy meters. The developed system provides continuous access to energy consumption data for the householder via mobile phone texting set up to provide usage updates in scheduled intervals and on-the-spot queries from the user. From the monitoring, the study found that energy was consumed more during the night and early morning when heavy load appliances such as air-conditioners and geysers are used.

Table 1 lists the Indian residential studies and their coverage of BPE elements. The table clearly shows the heavier focus on occupant and environment as opposed to energy with a gap in pre-occupancy design, fabric and systems analysis (note because no assessments of design review or fabric and systems were found, these are not in the table). Overall, most studies are focused on thermal comfort with less of a focus on energy consumption, with little cross-over between the two subjects.

Table 1. Review of Indian residential POE/BPE related methods

Building type	Source of method / study	Energy	Environment	Occupant questionnaire / interview
Multi-unit (n=45 flats)	[12, 20]		x (FSTC)	x (FSTC)
Vernacular houses (n=50)	[13, 35]		x (FSTC)	x (FSTC)
Single dwelling	[33]	x	x	
Boys' university hostel	[25]		x (FSTC)	x (FSTC)
Multi-unit (n=18 flats)	[15]		x (FSTC)	x (FSTC)
Dwellings (n=700)	[32, 36]	x		
Single dwelling	[34]	x		

3. Case study and research methods

A previously developed BPE methodology [11] developed for the Indian context (I-BPE), as part of a Newton Fund UK-India research project was tested on a case study green building, as part of a postgraduate dissertation (by one of the co-authors), with the intent to provide feedback on the relevance and effectiveness of the I-BPE methods as a research tool in the Indian context. A key aim of the case study application is to better understand the challenges in applying the methods and tools of the I-BPE methodology, and how these may be addressed if necessary, for undertaking further BPE studies in an Indian context.

The case study development is an affordable housing development completed in 2015 (phase 1) and located on the outskirts of Chennai, South India. The first phase of the development was awarded a Platinum Rating by the IGBC. The housing development consists of six blocks comprised of 604 households with three types of units, 1 bedroom (two different configurations) and a 2-bedroom unit. The blocks were designed to accommodate public amenities like children's play area, an open gym, and jogging tracks.

To find appropriate households for the study, a walkthrough of the development was performed with a public relations (PR) manager. The PR manager was able to suggest households that would be open to the study and helped to develop a rapport with the occupants to initiate a conversation. This helped in gaining the householder’s trust in the research as well as developing interest in this study. Following this introductory session, a total of 40 householders were shortlisted. A second visit was planned with these selected householders where the details of the study were explained, permissions gained, and consent forms were signed. In the end, a total of 29 households agreed to be subject in the study.

3.1. BPE Field study methods

The field study was carried out in 29 selected residential units for the duration of one summer month (4 July – 4 August 2018). The primary components of the study included energy audit, environmental audit and occupant survey. Table 2 shows the I-BPE recommend study elements divided in four levels of increased complexity. For each level, the table indicates the action taken and/or tools used. As would be expected for a one-month master’s student dissertation, the implementation is limited to the lower levels. The review of design, fabric, and systems was limited to available background design documentation (design drawings and IGBC point-by-point certification details), an interview with the PR manager, and a walkthrough survey to observe design aspirations as they relate to reality of the occupied product. The energy assessment was also somewhat limited; however, through consent, access to energy data provided electricity usage of the selected households at an interval of every two months for one year (mid-2017 – mid-2018). Indoor environmental parameters (temperature and relative humidity (RH)) were monitored every five minutes in a subset of ten flats for four weeks and six days in the remaining flats during the monsoon season. An occupant satisfaction survey (BUS[1] questionnaire [37]) was conducted in 38 flats to ascertain satisfaction with the living space and indoor environment. All questionnaires and interviews were carried out on the same day. The BUS had to be filled by the researcher due to a language barrier and illiteracy.

[1] The Building Use Studies (BUS) methodology obtains feedback data on building performance through a self-completion occupant questionnaire; the results can be compared against a national benchmark database. The questionnaire prompts the respondents to comment on the building’s image and layout, comfort, and daily use of the building features.

Table 2. Adaptation of the I-BPE methodology for this study *(NP = not performed)*

BPE study elements	Level 1	Level 2	Level 3	Level 4
Review of design intent	Collection and review of design docs.: *Plans and IGBC credit doc.*	Review of services and energy systems: NP	Interviews with key stakeholders: *PR manager*	Walkthrough with key stakeholders: *PR manager*
Technical building survey	Inspection of build quality and services: *photographic survey*	Controls interface survey: NP	Review of installation and commissioning of services: NP	Thermography of building fabric: NP
Energy assessment	Annual / monthly energy data: *1 year of bi-monthly energy data; appliance audit*	Energy monitoring: NP	Sub-metering: NP	Plug load monitoring of individual appliances: NP
Env. monitoring	Temperature and RH spot readings: *tool: WatchDog A160*	Temperature and RH monitoring: *5-min. 4-week duration; tools: Hobo UX-100, I-button*	Additional spot read/ logging (e.g. CO_2, lux, wind speed): *CO_2 readings; tool: WatchDog A160*	Additional pollutant measurement (e.g. PM, VOC): NP
Occupant feedback	Occupant satisfaction survey: *BUS (83 of 100 returned) / Monsoon season specific comfort questionnaire (28 flats)*	Semi-structured interview: *28 householders interviewed*	Thermal sensation and preference survey: *self-completed diary (2 of 29 returned)*	Focus group: NP

4. Results

4.1. Review of design intent

The case study flats were designed to maximise cross-ventilation for comfort (not installed with AC); however, some occupants have since installed AC, potentially changing the overall as-designed energy target of the development. As an effort to optimise thermal efficiency, the window-to-wall ratio was maintained to less than 30%; therefore, window U-value (value not mentioned in design documents) did not require a minimum value to comply. Wall and roof assembly U-values were listed at 1.2 W/K·m^2 and 0.5 W/K·m^2 respectively. To optimize lighting energy use, the common areas were designed and maintained with specified low energy lighting and the flats were provided with recommended specifications of lighting fixtures in a Home User Guide provided during handover; however, few occupants followed this recommendation while others selected fixtures according to personal choices and/or affordability. Rainwater harvesting, water-efficient fixtures, and on-site sewage treatment for reuse were used as green design features to obtain certification. In reality, the sewage treatment plant, located in a public area, and the foul smell from it, possibly due to poor maintenance, was found to be a major cause for hygiene concern in the blocks surrounding it.

4.2. Energy and indoor environment

In total there were 19 flats with AC installed and 10 flats which remain naturally ventilated (NV). AC use in the flats varied widely, with long periods of time when the 'AC' flats were naturally ventilated. The reasons given range from financial concerns to varied occupancy. When assessing total annual energy consumption for the flats combined, AC flats were found to use 32% more energy on an annual basis and 42% more for the month of July 2018 (temperature monitoring period):

- AC flats (n=19) mean / max / min consumption (kWh/year) = 2,194 / 3,970 / 730
- NV flats (n=10) mean / max / min consumption (kWh/year) = 1,662 / 3,070 / 260
- July 2018: AC flats averaged 238 kWh and NV flats averaged 168 kWh.

Figure 1 shows the energy consumption/m^2 indicating that the consumption is not as significant in difference when considering the conditioned area of the flats. Mean AC flat consumption/m^2 was only a 12% greater (vs. 32% above). The difference between H28 and H10 (highest representative users) was 2% (Consumption/m^2/year) vs. 29% (consumption/year). Though there is a positive trend in the correlation of number of occupants and annual energy use, the relationship is weak (r = 0.36).

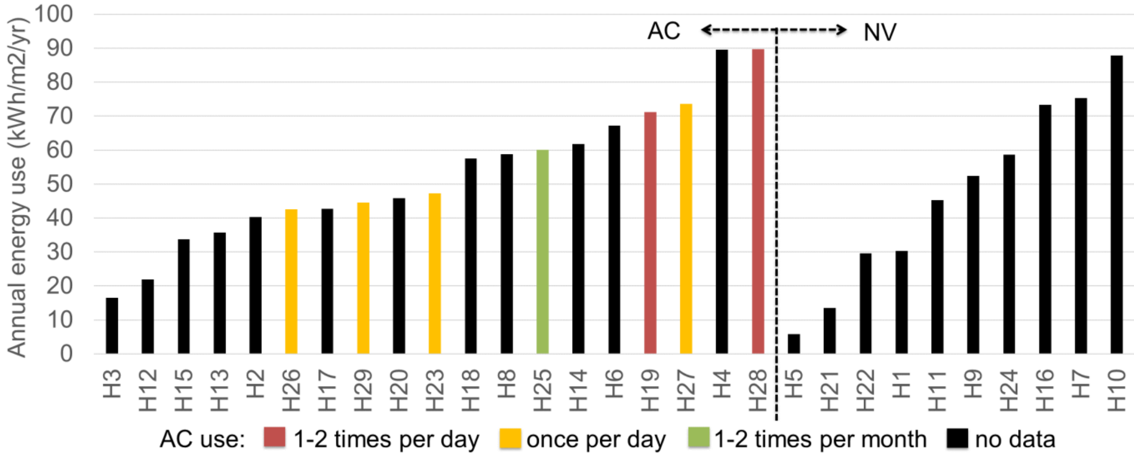

Figure 1. annual energy consumption of the flats

Figure 2 shows the relationship between temperature and energy consumption for the month of July 2018. There is a moderate correlation between temperature and energy consumption in the AC flats, and though the correlation is a little stronger in AC flats, NV flats are not that far behind. Though a limitation is the small number of flats assessed here, this level of correlation would not be expected in the NV flats as there is no energy consumption related to the process of reducing the temperature. Again, limited AC use as described above is a possible explanation.

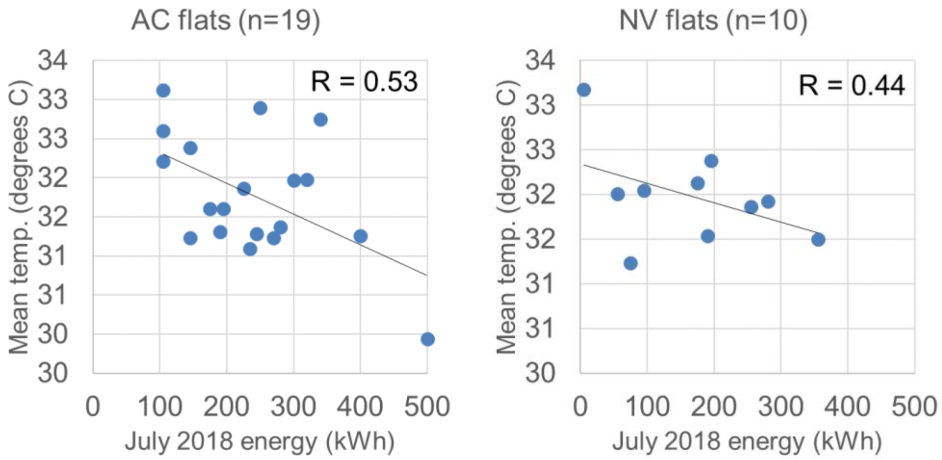

Figure 2. July 2018 temperature mean as related to energy consumption

Temperature data for both AC and NV flats showed periods of common temperature shifts also indicating free-running behaviour for even high energy using AC flats. Figure 3 shows a common trend in temperatures for both AC and NV flats. The figure shows temperature data for the period of 30 July – 4 August 2018. Note the recommended temperature range as suggested by ASHRAE 55[2] and the NBC is highlighted in the graph. Both types experience an average range from 31-33^{o}C, max ranges from 33-36^{o}C, and minimum ranges from 24-30^{o}C. Interestingly, however, it is a few AC flats that experienced the greatest maximum readings above 36^{o}C, up to 37^{o}C. Overall, the difference in the

[2] https://www.ashrae.org/File%20Library/Technical%20Resources/Technical%20FAQs/TC-02.01-FAQ-92.pdf

average of the means between AC flats and NV flats is negligible at 0.2°C (31.9°C and 32.1°C respectively). When comparing the high energy AC flats[3] (H19, H27 and H4) against the high energy NV flats (H16, H7 and H10) the difference of their mean temperatures is less at 0.07°C the difference of their mean consumption/m^2 is -0.7 kWh/m^2. This would either suggest negligible use or impact of AC (during this period) on overall energy consumption and comfort temperatures in the flats, whether due to ineffective equipment or very low frequency of use for the reasons given above. Contrary to expectation, AC flats have slightly higher RH than NV flats (mean = 59.9% and 57.5% respectively; max = 81.9% and 74.6% respectively).

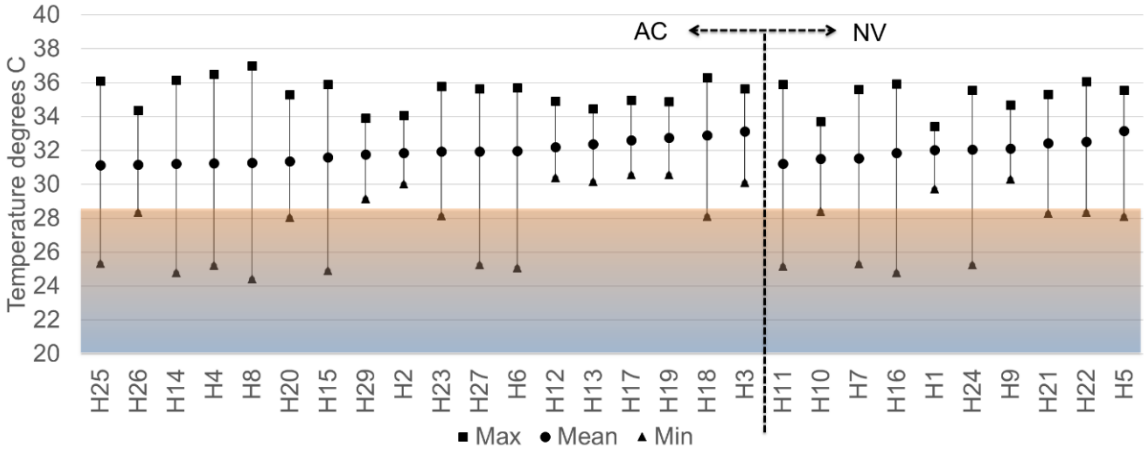

Figure 3. temperature data for the period of 30 July – 4 August 2018

4.3. Occupant survey

According to BUS survey results, the location, design, and appearance of the development and the layout and space of the living areas were all considered moderately satisfactory; however, a common complaint was the lack of storage space. A prominent design feature in the development was windows that open to the corridor from the living room / kitchen areas of the flats. The concept was to encourage both cross-ventilation and a social culture among residents. Contrary to this, interviews with the occupants revealed that windows were redundant, as it was considered a privacy and safety issue to use these windows. This resulted in windows being shut most of the time, in turn affecting the intended cross-ventilation of the flats. Paradoxically, on visits it was observed that the occupants not only used the corridors around their flat for storage but also treated it as a part of their home with women preparing vegetables, elderly sitting and talking, and children playing.

The flats were designed to provide maximum daylight and ventilation, partly through the provision of balconies. According to BUS results, satisfactory provision of daylight was achieved; however, natural ventilation was not maximized. This is seen through the opinion that the spaces were considered stuffy with little air movement. Through interviews it was found that there was acceptable natural ventilation in the flats located on the 3rd and 4th floor, whereas the flats located on the 1st and 2nd floor had little air movement due to the surrounding buildings. Many of the occupants suggested that the developer should make provision for the installation of AC; however, among the surveyed occupants, the level of perceived comfort was no different across the AC and NV flats.

The summer season (March – June) is generally considered harsh in this hot and humid region of India. For the summer season, occupants considered indoor temperatures to be ‘too hot' but with good humidity levels. As is shown above, the mean temperatures are far beyond recommended (for the months following the summer season); however, humidity is found to be low. Overall, the air quality/comfort is considered unsatisfactory and uncomfortable. Though there is no winter season, the cooler season, post-monsoon is considered quite comfortable overall.

[3] H28 temperature data is unavailable.

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5. Discussion

The green building movement in most countries in the world, including India, are for the most part lacking an important link: ensuring that the design intent of such buildings is realized. For the design-IGBC certified case study residential development, no performance evaluation was officially performed after the certification process. However, the Green Rating for Integrated Habitat Assessment (GRIHA), also used in India, includes a performance assessment requirement which reviews whether energy systems, water systems and solid waste management systems of the building are performing as predicted and match the information provided at the time of award of provisional GRIHA rating. LEED, also used in India, has an optional credit path which prescribe POE/aftercare or other elements of performance evaluation after certification has been awarded [38, 39]. This is a step forward, however; these evaluations are not mandatory. Another significant limitation is the current lack of published findings, data or feedback on these POE/BPE-related credits. Currently, a limitation in the overall analysis of the case study is that neither the green building rating systems in India nor any published results provide a benchmark standard or common results for the findings of dwellings in specific climates in India. Therefore, the performance of the flats cannot be compared or marked against any benchmarks, best or standard practices.

At a case study level, one of the major challenges in India lies in educating occupants, managers, and developers about BPE and its benefits to them. Suggestions include, providing photographic or video-graphic demonstrations of the process and benefits, especially where there are language barriers. As a recommendation, the researcher found it necessary to educate the concerned authorities and people related to the building about the entire process of BPE. To do this, a meeting was arranged and the concerned people were briefed about their role in the activity along with the timeline. A question and answer session also helped to address the queries and familiarise the researcher with the householders and management. Only a few of the residents who were acquainted with the idea of green buildings could grasp the need for the study and were fully supportive. Other occupants were provided with more relatable concepts to encourage acceptance. As an example, the relationship between thermal comfort, indoor air quality and their daily routine. This helped people comprehend the process and importance of the study.

To further ease concerns, householders were shown the data loggers and the researcher allowed them to install the loggers in desired but approved locations in front of the researcher. This helped in gaining their confidence in the researcher and assuring them of the simple function of the data loggers. Regardless of effort to gain trust, including data privacy promises, most of the occupants did not allow the researcher to record the conversation. Occupants required the researcher to ask questions from questionnaires and were not interested in filling in questionnaires on their own, likely due to a language barrier or illiteracy. This limitation, coupled with the lack of knowledge about the importance of the study and/or disinterest, resulted in the low return rate of thermal comfort diaries. Furthermore, occupant related survey material, generally developed in the USA and Europe needs further testing and development to be fit for the Indian culture and context. The challenge lies in doing this whilst collecting results that can be cross-culturally comparable to all other research in the field.

6. Conclusion

This study shows the process of testing the I-BPE methodology on a Platinum-certified green residential development in India. The field study was carried out for 30 days which included spot measurements, data monitoring, walkthroughs and occupant surveys. The field study offers a template for replication of BPE and benchmarking data for green residential buildings in India and specifically for southeast India. The next step in the Learn-BPE project involves testing the I-BPE approach on several other case studies implemented by students using a programme developed for this purpose. The I-BPE case studies intend to demonstrate actual performance of certified green buildings in India, publish the data, and continually provide a testing platform for refinement of the I-BPE framework for application in India. Finally, the I-BPE case studies are also intended to build trust in the industry by strengthening the relationship between the industry professionals and researchers in academia.

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