Unraveling Urban Household Energy Use Patterns in India

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ABSTRACT

To address its rapidly growing residential energy use, India has introduced building energy codes and appliance standards in recent years. Development of such codes and standards relies on aggregate and end-use data from energy use models. These are often based on limited surveys and assumptions, which are difficult to validate in a country as diverse as India.

To arrive at a better understanding of building and appliance energy end-use patterns and validate such assumptions, a comprehensive residential energy end-use research was conducted for the Bureau of Energy Efficiency (BEE), by CLASP and EDS in 2018. The research included a nationwide survey of 5,242 households and detailed energy use monitoring of 194 urban households in cities across the country. These households were selected based on statistical sampling to represent diverse climatic, socio-cultural, and economic contexts.

In addition to energy use patterns, the study provides insights into end-user behavior related to appliance purchase, usage, and disposal. This information will be useful for designing building and appliance energy efficiency policies in the future. The monitoring outcomes identify the variability in use and performance of appliances. Aggregating energy use across households lends insights into energy consumption and demand profile at a granular resolution.

Learnings from this study can help in informed policy making. Study outcomes have potential to contribute to demand side management, appliance standards and labeling, and manufacturing smart and energy efficient appliances.

Background

India is estimated to overtake China as the most populous country around 2027 (UN, 2019, 1). Riding on this growth India is expected to surpass other countries in its demand for energy (IEO, 2015, 11). As evidence, over the last few years, India's Consumer Durables Sector stocks have outperformed the Bombay Stock Exchange (BSE) Sensex (Edelweiss, 2017, 3). The National Family Health Survey (NFHS), too, has recorded a rapid increase in penetration of several appliances such as refrigerators, televisions, air conditioners, evaporative coolers, washing machines, and water heaters (liveMint, 2018). If India follows the trajectory of growth of appliances in other economies, the residential energy use will surge exponentially. For example, the penetration of air conditioners (AC) in USA jumped from 15% in 1960 to 50% in 1975. This transition was even more dramatic for China, with penetration going from 8% in 1995 to 70% in 2011 (Motilal Oswal. 2018, 4). The rise in the residential sector's share of total electricity consumption in India from 4% in 1971 to 24% in 2019 (CSO, 2019, 56) bears evidence to this impending growth.

India has a well-established appliance energy efficiency standards and labeling (S&L) program covering 25 products. For 10 of these products Mandatory Energy Performance

Standards (MEPS) are already in force. Several other residential appliances are slated to come under its purview in the future. Currently, in India, all policy formulation related to appliance use and residential energy end-use is based on assumptions and limited information. A recent study highlights the need for a robust nation-wide residential energy consumption survey (RECS) and time-series data of end-use distribution of household energy use (PEG, 2016, 14). With advancements in technology such as connected appliances and techniques such as Non-Intrusive Load Monitoring (NILM), more information can now be made available. As both, the penetration of appliances and potential for leveraging technology to capture end-use information improve, it is becoming increasingly important and feasible to establish a realistic end-use baseline for assessing the potential impact of energy policies like S&L.

Approach

The study adopts a three-tier approach to implementation.

- Tier 1: At national level, the RECS establishes appliance ownership, usage patterns and behavioral characteristics. The sample size of 5,242 households has been established through multi-stage sampling technique. Geography, climate, urban classification, and socio-economic indicators form successive stages of the sampling construct. Figure 2 captures the nature of diversities considered.
- Tier 2: At household level, remote energy monitoring of 194 households at minute resolution establishes residential energy use patterns. The households for monitoring have been established by statistical down sampling based on dwelling size, location, appliance ownership, and family size. NILM is applied on collected datasets to discern major end-uses.
- Tier 3: Finally, 13 of the 194 households are being monitored at the circuit level to establish appliance characteristics and validate NILM findings.

This approach effectively captures the diversity of India's socio-economic and climatic context, while optimizing the number of households that must be monitored.

Methodology

The study has been conducted in three distinct phases:

- Residential energy consumption survey (RECS),
- Deployment of energy monitoring kits, and,
- Data acquisition and analysis

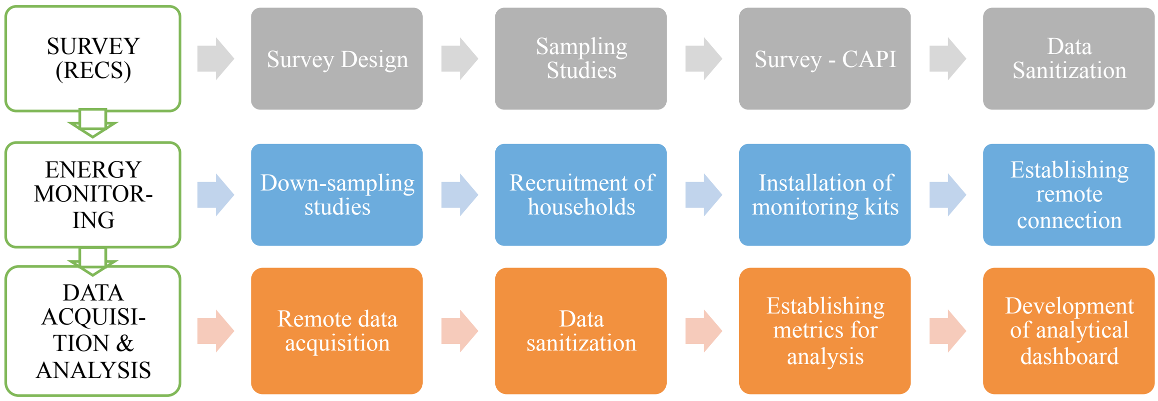

Figure 1 Process overview of program implementation. *Source:* Authors

Residential Energy Consumption Survey

Geographic, climatic, urban, and socio-economic factors that have direct or indirect impact on residential energy use were identified through desk research. The sampling studies and survey instruments were developed based on the findings of this research.

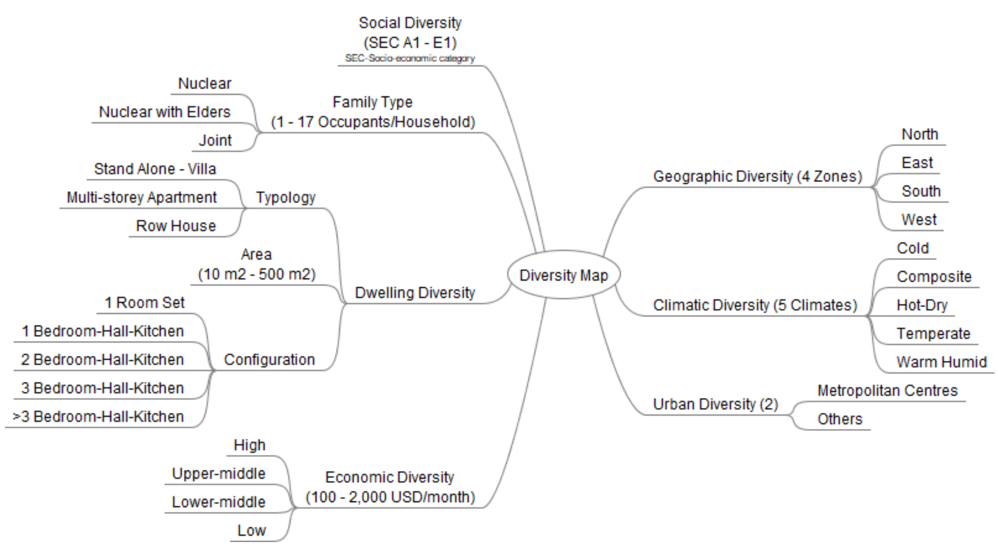

Figure 2 The program accounts for 7 key diversities that have impact on residential energy use. *Source:* Authors

A detailed survey questionnaire that compiles information on 7 key classifications has been developed after conducting preliminary research studies. The survey questionnaire compiles information on,

- household income, family structure and size, occupation, and educational qualification,
- appliance ownership, usage patterns, purchase, and disposal behavior,
- dwelling typology, ownership status, area, water supply,
- billing information from electricity distribution companies and cooking fuel use,
- vehicle ownership and usage pattern, and
- awareness and attitude towards energy efficiency

The urban sector accounts for approximately two-thirds of the consumer durables market by revenue (IBEF, 2018, 10). Since the program objective is to capture appliance use data, the scope of the study has been limited to urban areas where the potential for studying a range of appliances, especially Star Labeled appliances, is better. A preliminary research of census data led to a national representative sample of 8,448 households which included urban and rural households. To capture the gamut of urban households, the study scope has been restricted to metropolitan cities and Tier 2 and 3 cities. Further, the socio-economic categorization (SEC) distribution is modeled with a skew towards urban upper and middle-class. The surveyed information from 5,242 households is representative of 380 million urban population in India. Statistically, the sample is representative with 95% confidence interval. A multi-stage sampling approach has been used. Distribution of population across climate classification is the primary criterion followed by urban and socio-economic classifications.

Trained surveyors conducted face-to-face interviews on digital devices using computer-assisted personal interview (CAPI) technique. On an average, each interview lasted between 40-45 minutes. The use of an electronic device minimized recording errors. Moreover, the compiled data was filtered for anomalies. Incorrect entries were identified using case specific verifications. For example, for ACs, appliance per habitable room and cooling capacity per unit area were used to filter erroneous data. Identified errors and data gaps were imputed using nearest match for household characteristics.

Deployment of Energy Monitoring Kits

Monitoring 5,242 households was not only unviable, but also unnecessary. Therefore, down sampling studies were used to arrive at required sample size and characteristics that were sufficient for capturing the diverse socio-economic and climatic context of India and extrapolating national residential energy use. Down sampling studies optimized energy monitoring requirements to 194 households. Energy monitoring kits for these households were installed after the utility meter at the distribution box.

The installed monitoring equipment included multi-function meter (MFM), current transformers (CTs), Wi-Fi enabled temperature sensor, GPRS dongle and a controller. The controller is a processor board with local storage capability to interface with multiple RS485 enabled meters.

Each installed kit had the capability of logging information from up to three circuits. These circuits were mapped to segregate major appliances like room air conditioners (RAC), refrigerators, water heaters and washing machines. The kit was capable of monitoring mains usage and circuit level information at 30-seconds intervals for electrical parameters such as voltage, current, power factor, frequency, energy consumption, and demand. The controller logged this information and computed energy use and peak demand at a minute interval. This information was communicated to a cloud server using the GPRS dongle.

Since the installed kit had a limitation of monitoring only three circuits, NILM algorithms were applied to perform load segregation. The NILM algorithms used in this study are trained for Indian conditions. However, at the time of development, limited field data for Indian context was available. Further, 13 of the 194 households were shortlisted for circuit level monitoring. Two additional kits were installed at these sites to enhance monitoring capability to nine circuits.

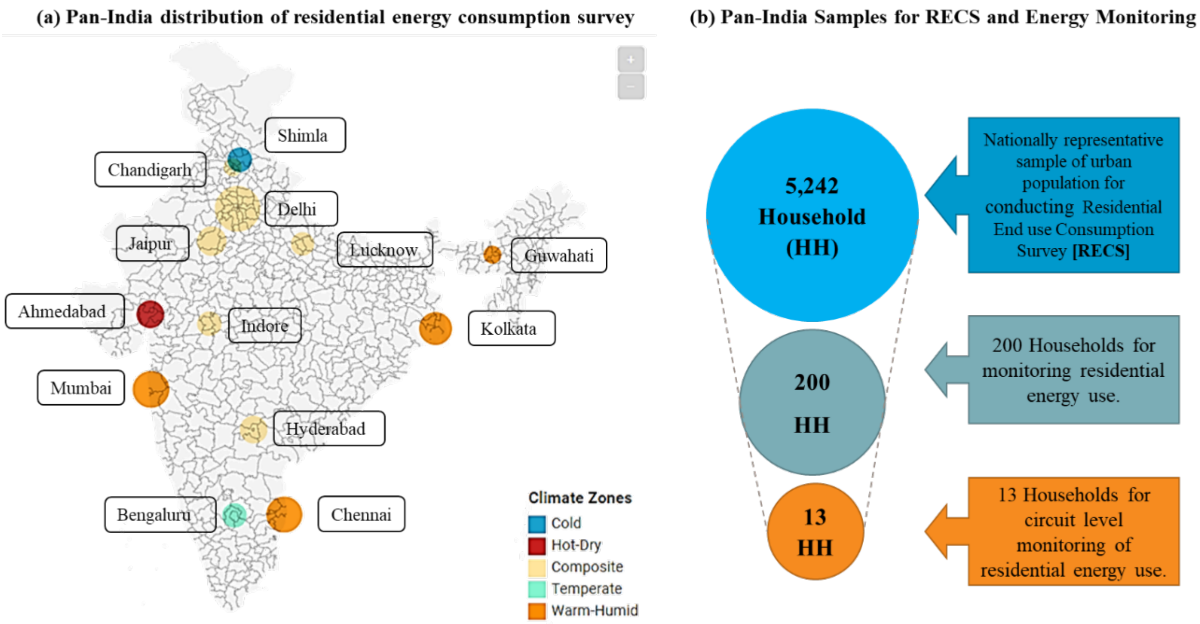

Figure 3 (a) Pan India distribution of samples for RECS, and, (b) Sampling outcomes for RECS, Households Energy Monitoring and Circuit level Energy Monitoring. *Source:* Authors

Data Analysis

Data was acquired remotely from the deployments and collected on a server. The data underwent quality control processes and deployments were assessed on several health parameters to ensure data up-time. Data reporting metrics were established and these are being displayed on an online dashboard.

Results - Survey findings

The RECS is comprehensive and reveals ownership, usage, and appliance age for 42 equipment across categorizations for income, climate, and city. This spread of information provides insights into market trends, prevalent technologies, and behavioral aspects.

Revisiting anecdotal information on appliance ownership and usage patterns

Appliance usage and life information compiled from the survey has been compared with existing information on appliance ownership and usage patterns reported in the Product Policy Analysis Tool (PPAT). PPAT has been developed by Collaborative Labeling and Appliance Standards Program (CLASP) and Environmental Design Solutions (EDS) for modeling appliance policy scenarios in India. The PPAT dataset for India was last updated in 2013 through a systematic approach that involved market research and stakeholder consultations. While the usage information compiled in the PPAT database is similar to the information compiled in the survey, the product life information varies. Comparing survey outcomes and PPAT dataset, only 7 out of 32 products show a deviation of less than 10% in life. This has implications on modeling policy scenarios as life of product has impact on stock retirement.

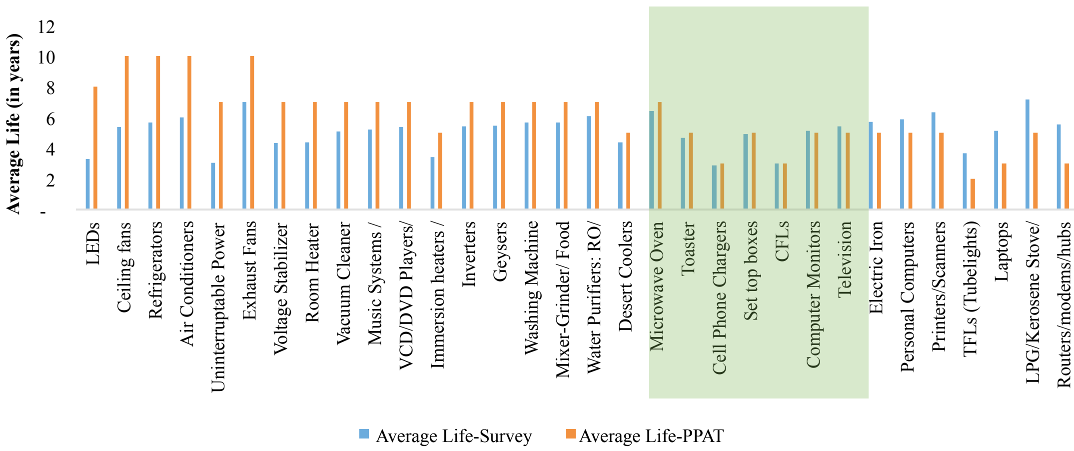

Figure 4 Equipment Life estimates are comparable with earlier held assumptions for only 7 out of 32 products. *Source:* Author

Survey findings for Room Air Conditioner

Ownership

- Survey findings indicate that RAC ownership in urban areas exceeds 30%. These findings reveal a chasm in national and urban ownership. While nation-wide penetration of AC is estimated at 4% (IBEF, 2019, 5), the survey reveals ownership in urban centers ranges between 42% for New Delhi (metropolitan city, composite climate) to 22% for Patna (non-metropolitan city, composite climate) which is significantly higher than the national ownership. Shimla (cold climate) has not been considered as preliminary findings indicated no penetration of RACs among representative households surveyed.
- Income disparity is evident in ownership of RACs. This indicates that economically weaker sections are more sensitive to climate change and have limited access to thermal comfort equipment in a cooling dominated country. Even among the high-income homes surveyed, only half own an RAC.

Usage

- Testing guidelines issued by BEE for evaluating Indian Seasonal Energy Efficiency Ratio (ISEER) is based on 1,600 operating hours (BEE, 2015, 3), while annual usage estimated from survey is 1,200 hours. This may be an area of investigation for future labeling.

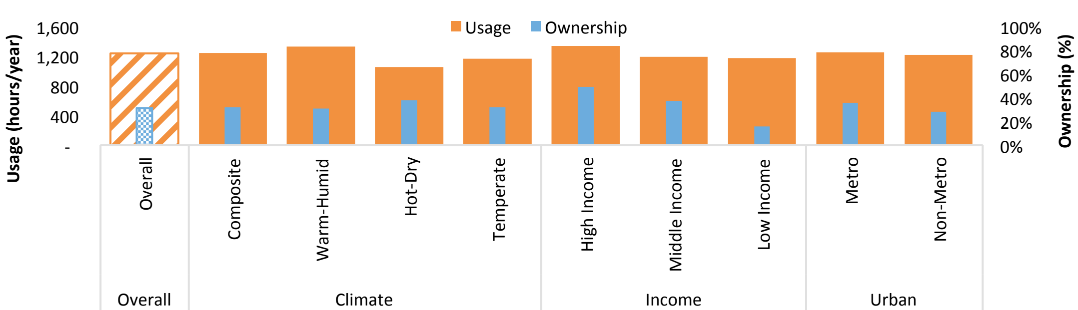

Figure 5 Ownership and Usage of RACs across urban, income and climate classifications. *Source:* Authors

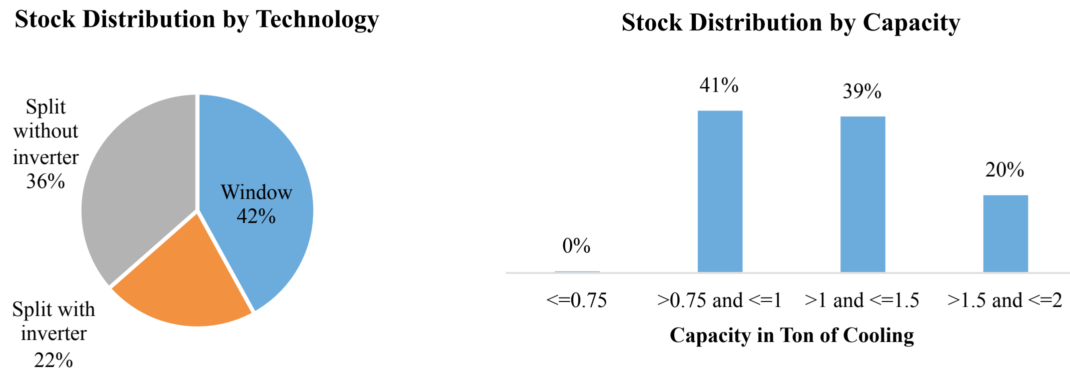

Figure 6 (a) Installed RAC stock indicates a shift towards efficient AC technology. (b) 80% market is evenly distributed between 1 and 1.5 Ton (12,000 – 18,000 Btu/hour) capacity. *Source:* Authors

Market Trends

- The survey outcomes indicate that 58% of respondents have adopted split air conditioners. Split ACs with inverter technology are a recent entrant in the market, and yet their share (22%) is significant. It appears split ACs with inverter compressor are a growing trend.
- 1 ton and 1.5 ton are the most prevalent capacities and account for 80% of installed stock.

Appliance Age

- Approximately 85% stock in surveyed households is less than 5 years old. Inverter compressor RACs are a relatively new technology and already have more than a fifth of ownership in surveyed households. This is indicative of recent purchase as well.

Other behavioral insights

Survey outcomes indicate purchase and disposal behavior, and attitudes towards energy efficiency as well. Although majority respondents are concerned about environment, it does not affect their purchase decision. The survey indicates that respondents wish to purchase labeled goods, but often their purchase decision is governed by cost. This may be indicative of lack of awareness about cost benefits of energy saving equipment or lack of financial mechanisms to aid purchase of energy efficient equipment.

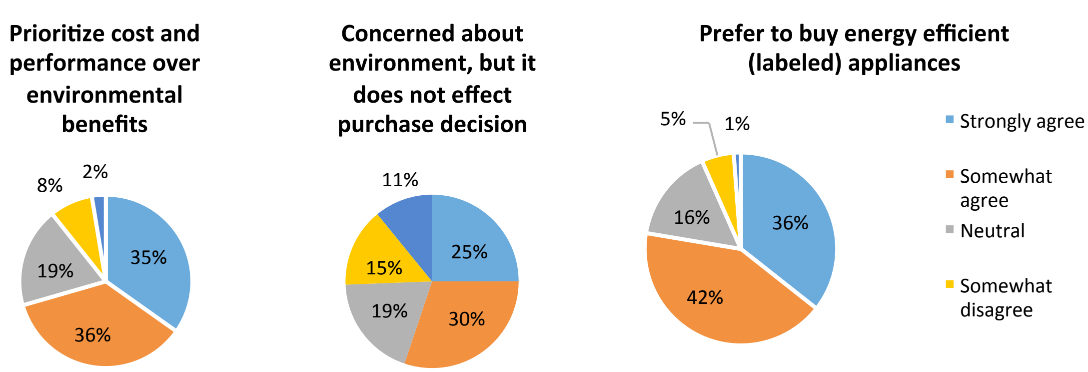

Figure 7 Purchase decision of respondents is shaped by cost, although they prefer energy efficient appliances/ *Source:* Author

Macro view of urban residential energy use

The ownership and usage patterns derived from the survey has been used to evaluate annual energy use and energy savings potential for each equipment. This data is scalable at a national level. Extrapolating the findings at national level reveals that if energy efficiency measures such as MEPS were to be applied with immediate effect, there is potential for saving 90 TWh, i.e. approximately 34% of national urban residential energy use. Of these savings, five appliances - room air conditioners (RAC), refrigerators, ceiling fans, evaporative coolers and electric water heaters - account for nearly 80% of savings. These outcomes are different from earlier studies that were conducted to identify appliances for labeling. It is critical to note that 4 of these 5 appliances are already accounted in the India's labeling program – BEE Star Rating.

Results - Energy Monitoring

Surveys reflect the user perception and are merely indicative. Energy monitoring findings on the other hand present measured data. High resolution data and non-intrusive load monitoring findings complemented with meta information on households and equipment from RECS over a period of two years, reveals insights into energy use patterns, occupant behavior, and equipment performance. The outcomes have been detailed at three levels: equipment, household, and national.

Energy monitoring findings at equipment resolution

Energy monitoring outcomes reveal that equipment use behavior and performance varies across diverse segments considered in this paper. Since space cooling equipment has significant impact, the outcomes for RAC have been presented for two-bedroom homes in New Delhi (composite climate).

RAC use behavior and patterns

Survey reveals that in addition to cooling the bedrooms, the RACs are now being increasingly used to cool living rooms. The findings suggest that this change in application brings about different behavioral and usage patterns. Since isolating RAC circuits being used for different applications in the same household was not feasible, RAC use has been studied for different applications from characteristically similar households in the same city. Characteristically similar households imply similar demographics and typology. The RAC in the living room and the bedroom (Figure 9 (a) and (b) respectively) have distinct schedules of use through the day. This is expected to impact utility load curves in the future as more RACs are being installed in living rooms.

Along with distinct times of use and peak, the usage of RACs is also significantly different. The RAC use in the living room is approximately 40% lower (418 hours of use for living room compared with 714 hours of use for bedroom). Other notable difference is although the RAC use in living room begins earlier, the energy use is considerably lower. During peak summer months (May-June) the living room RAC use is 45-65% lower than the bedroom RAC use (Figure 10).

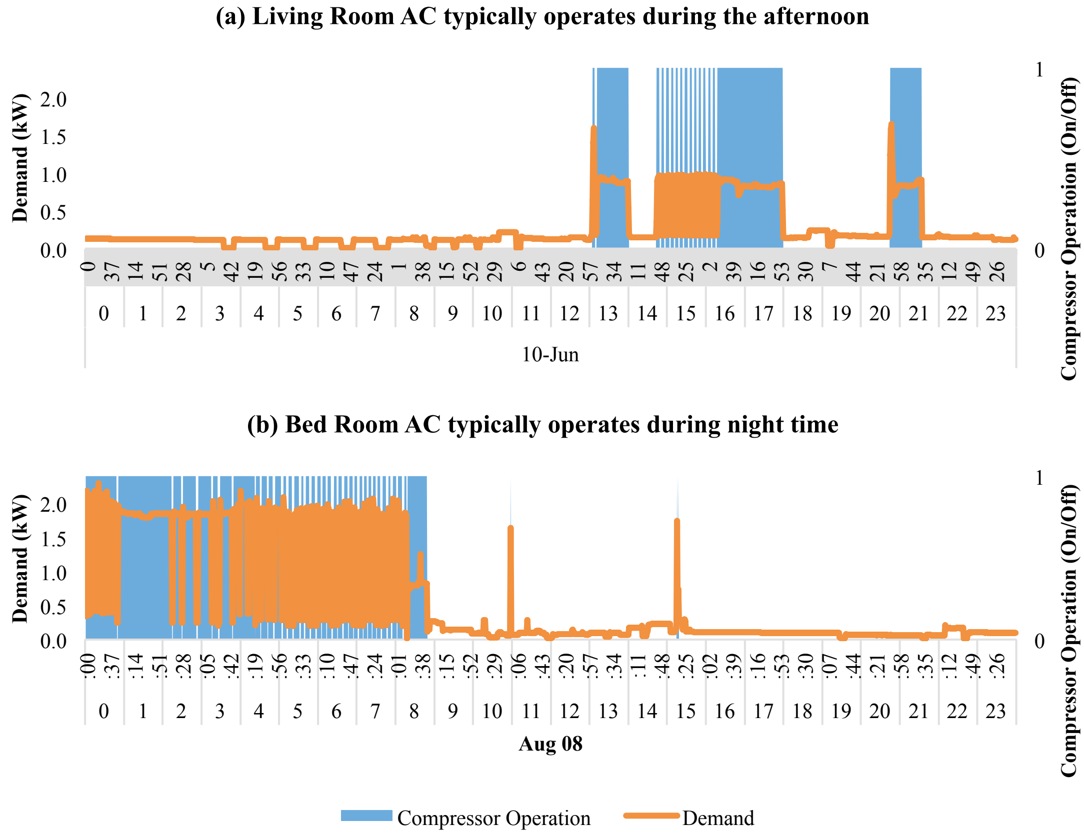

Figure 8 (a) Split AC with inverter based compressor installed in the living room is used through the day-time (1PM – 6PM) and briefly from 9-10PM. (b) Window RAC with a fixed speed compressor installed in bedroom is used through the night during the resting hours from 12 AM to 8AM. *Source:* Author

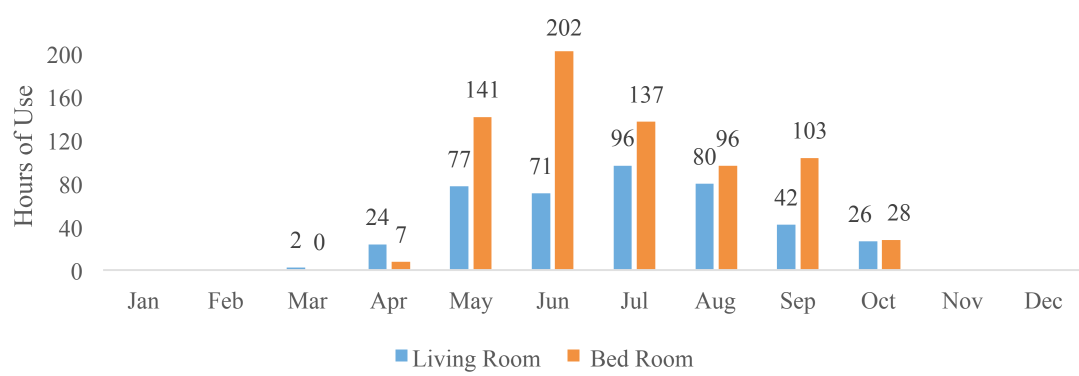

Figure 9 Living room RAC use begins early in the year, but it is not used as much as the Bedroom RAC. Source: Author

Energy monitoring findings at household resolution

Outcomes reveal variation in use patterns across diversities considered in this paper. For discussion, this section uses energy monitoring data gathered in 2018 for a 2-BHK (term for a house with 2 bedrooms, 1 hall and kitchen) air-conditioned household in New Delhi (composite climate).

Quantifying household energy use through circuit level monitoring

Circuit level monitoring reveals detailed insights into a variety of end uses and their contribution. For example, a 2-BHK air-conditioned household in New Delhi (composite climate) uses 42% of its annual energy use in space cooling and food refrigeration. Figure 14 shows three circuits - serving AC & refrigerator, lights & fans, and kitchen equipment - account for 70% of annual energy use. A breakdown of use across time reveals that four consecutive months, May – August account for 70% of annual use.

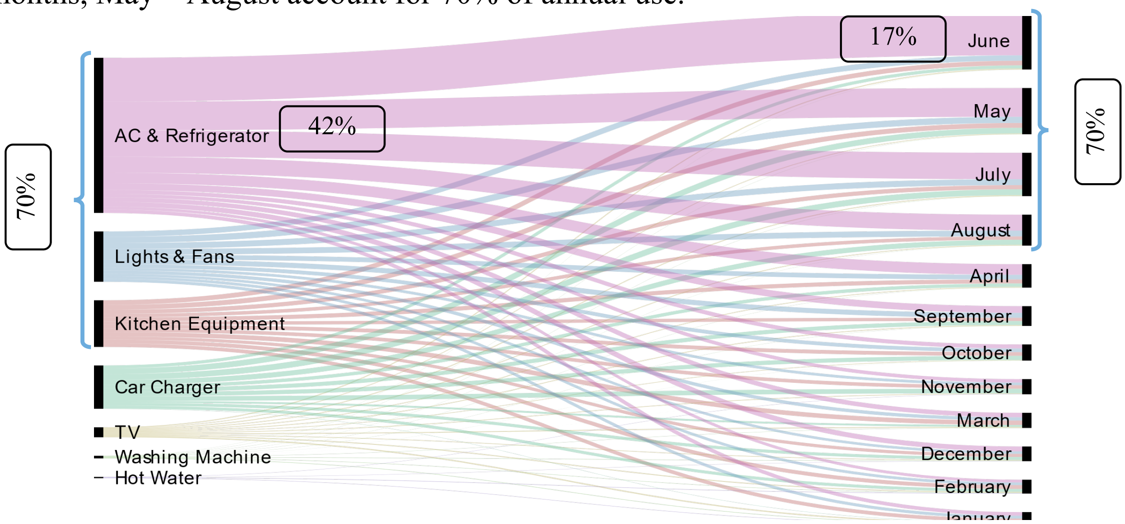

Figure 10 3 end uses and 4 months account for 70% of annual energy use. *Source:* Authors

Identifying common energy use trends

Each household is unique, and even similar households show significant variations in energy use. However, it is critical to identify commonalities to facilitate policy action. Two air-conditioned households of similar configuration (2-BHK) have been compared (Figure 11). The comparison indicates air conditioning is the primary contributor to energy use. Kitchen equipment and uninterruptible power supply (UPS, an electrical equipment with battery storage that provides backup in case of an outage) are significant end-uses as well. Together, these three uses account for more than two-thirds of the energy use in both households.

Although air conditioning for both households indicates variation in use, the patterns indicated by the peaks and trough coincide with each other. The plot reveals that for peak cooling months (May to July), median daily energy use for both households is similar (Figure 17).

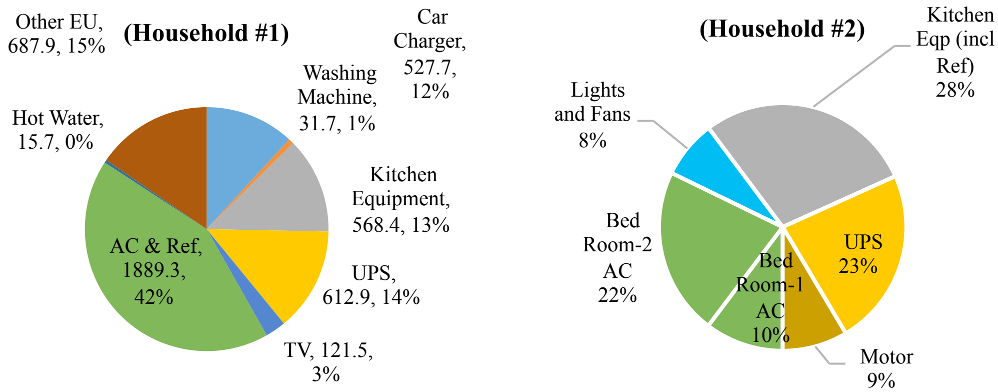

Figure 11 Air-conditioning is the primary contributor to energy use. Kitchen equipment and UPS are other significant end uses. *Source:* Authors

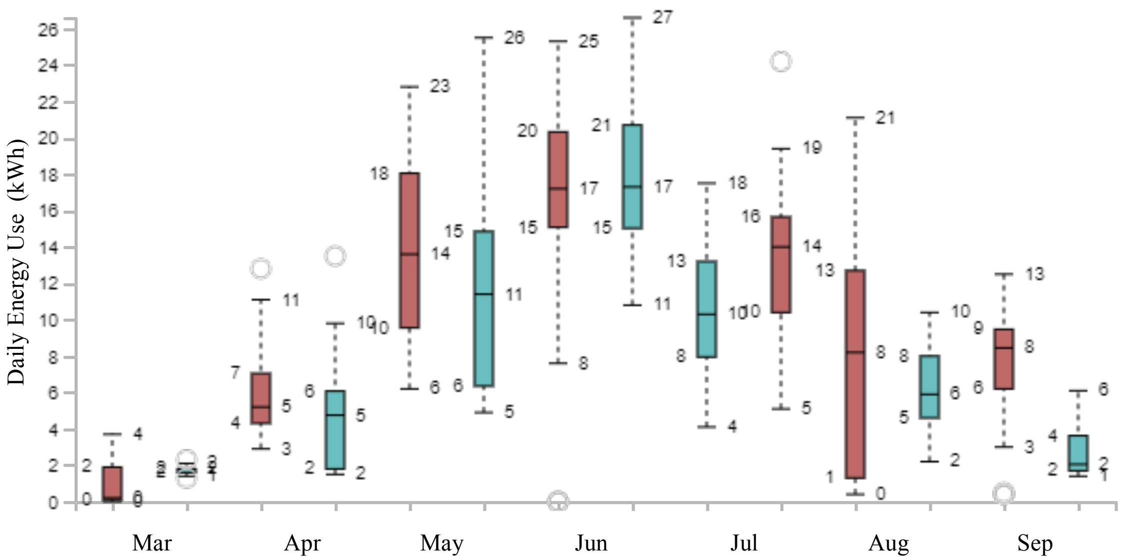

Figure 12 Median daily use for peak summer month (June) for both households is 17 kWh. *Source:* Authors

Energy monitoring findings for urban households at country resolution

Energy use information collated from energy monitoring kits reveals the range of energy metrics for urban households in India. The outcomes reveal that the median values indicate per-capita energy use of 1,537 kWh per year and energy use intensity (EUI) of 56 kWh/m^2 per year.

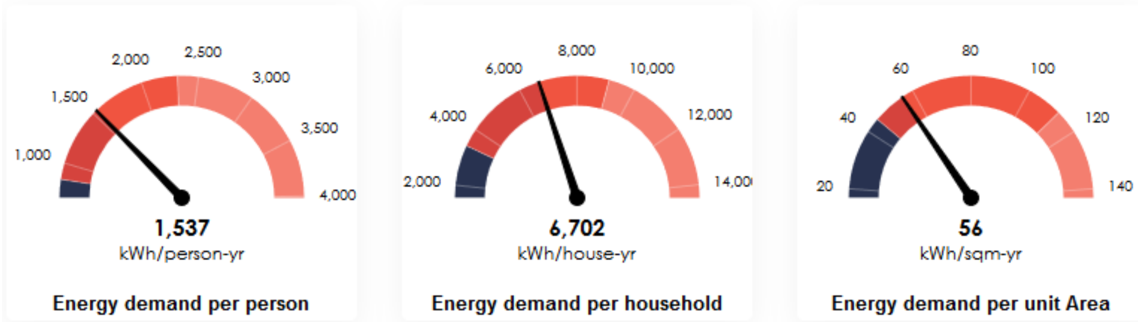

Figure 13 Energy use metrics derived from energy monitoring data compiled on the dashboard. *Source:* NEEM

The data across 194 households has been aggregated to reflect a median household. The resulting profile is representative of power draw of a typical residential unit on the national grid. While energy use is lower in the winter months, these months see high peak demand. This peak demand may be on account of water heaters and space heaters which have high power draw compared to that of space cooling equipment in summer.

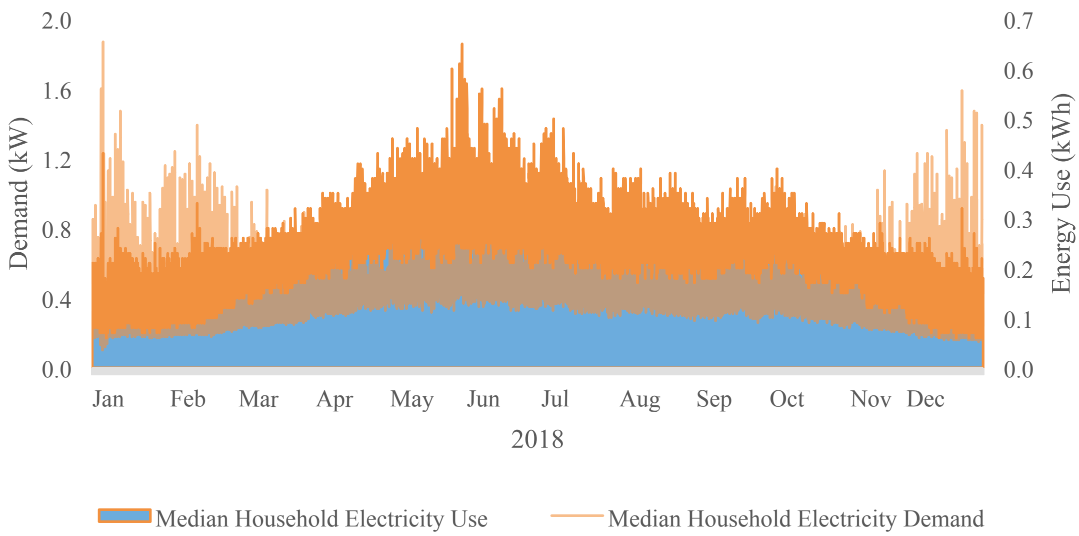

Figure 14 Model of a nationally representative house highlights that while summers have higher energy use, winters contribute to peak demand. *Source:* Authors

Filtering aggregated energy use data by climate, city, family type, status (conditioned/unconditioned), and house type, outlines distinct characteristics. For discussion, the comparison of an air-conditioned and unconditioned household has been presented. While average energy use for an unconditioned household is less than 1,800 kWh per year, average energy use for an air-conditioned household exceeds 5,850 kWh per year. The average energy use in winter for both households is comparable, but the summer use for air-conditioned households is significantly higher (Figure 20).

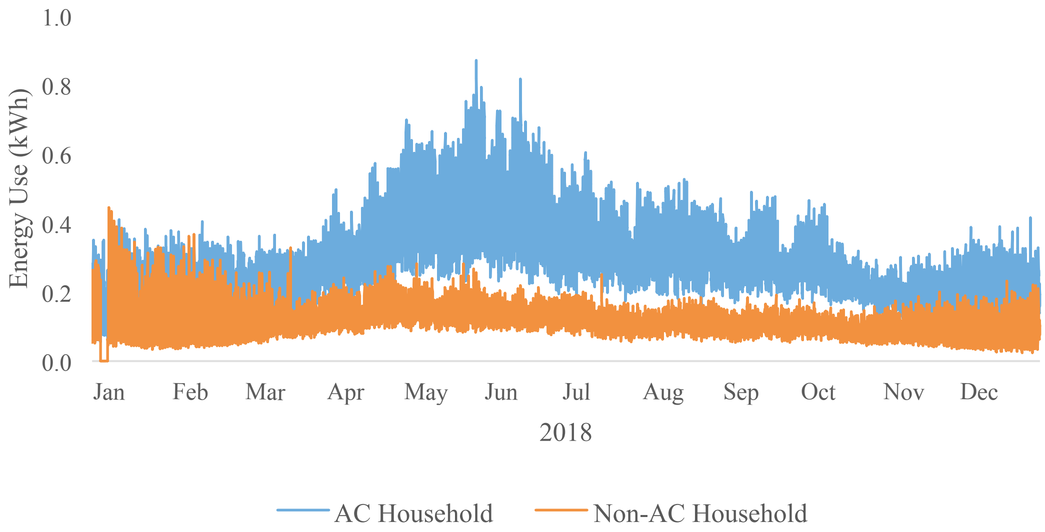

Figure 15 Annual energy use for an average Non-Air-conditioned household is less than 1/3rd of an Air-conditioned household.

The monitored data has been used to establish median energy use intensity for classifications by climate type, status, house type, family type, and other meta information tags. For discussion, range of energy use intensity across monitored households classified by climate zones has been presented in Figure 16. This information may be applied for residential labeling program. This information has been further categorized as conditioned and unconditioned households. Table 1 compares median energy use intensity for both conditioned and unconditioned households. Lower energy use intensity of unconditioned households can be attributed to absence of space conditioning and relatively lower appliance ownership. Composite climate shows highest energy use for both conditioned and unconditioned households as it witnesses extreme conditions during both, winters and summers.

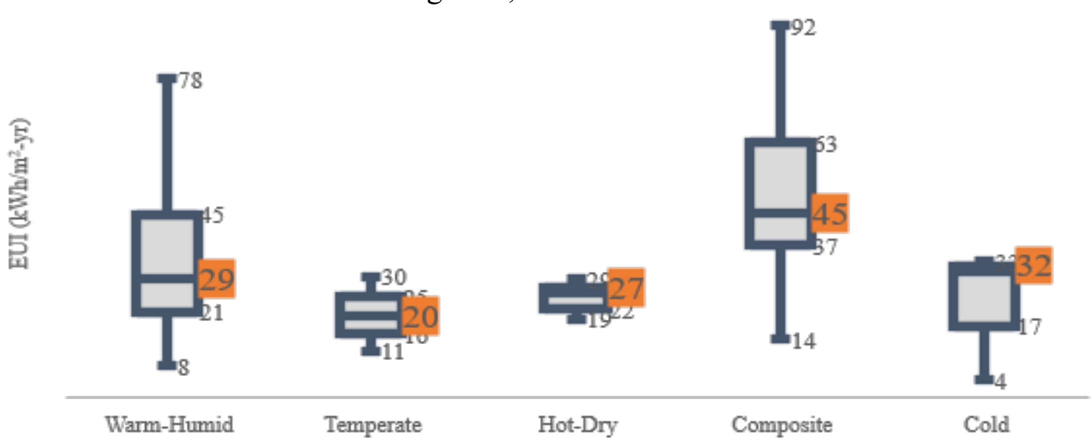

Figure 16 Range of EUIs for all households (AC and Non-AC) across climates. *Source:* Authors

Table 1 Reference EUIs established for Air-conditioned households in all Climate Zones from monitored data

Climate Zone	Non-AC Household Energy Use Intensity (EUI) (kWh/m^2-yr)	AC Household Energy Use Intensity (EUI) (kWh/m^2-yr)
Cold	22	27*
Composite	46	62
Hot-Dry	24	30
Temperate	20	24
Warm-Humid	26	45
Note: Since the program did not include any Air-Conditioned (AC) Households in Cold climate, the EUI has been approximated as 18% over the Non-AC household. As AC use is anticipated to be lowest in Cold climate and lowest increase in AC household EUI, vis-à-vis Non-AC households is 18%, the same has been used.		

Results - NILM

Appliance use patterns have been studied through application of NILM algorithms on energy use data. Electricity (load, energy, power quality) use information across deployments is being recorded to identify distinct load signatures of air conditioners, storage water heaters, washing machines and refrigerators. The NILM algorithm output has been validated against raw circuit data. The outcomes indicate that the NILM algorithm is able to discern periodic signatures of compressor (for refrigerator and AC) and constant power draw of storage water heater. However, NILM overestimates hours of use. Comparing monitored energy use with NILM prediction for refrigerator compressor operation yielded relative error in excess of 400%. For complex devices such as washing machines, the algorithm did not provide reliable results.

Although NILM outcomes suggest few anomalies, the successful identification of cooling devices supports the NILM approach for identifying appliance use and behavior from overall load signatures.

Conclusions

Survey outcomes reveal that 50% of the households do not own 30 of the 40 appliances studied. The limited penetration underscores the opportunity for affordable and energy efficient products as ownership increases.

The granular energy use and demand information from the energy monitoring studies facilitates understanding of energy use patterns, user behavior, and equipment performance. Despite variations, the expanse of the monitored dataset suggests that there is potential of extrapolating the aggregated demand and use information for forecasting at national scale. This study provides evidence for informing energy efficiency retrofit programs (appliance replacement), product development, awareness programs, financial instruments, and predictive demand analytics. This platform may be instrumental in influencing national policies such as demand response strategies, standards and labeling for equipment, energy efficiency codes for residential buildings, among others.

Aggregated data from monitoring reveals that heating contributes significantly to peak demand. This evidence can be used for re-aligning energy efficiency programs and policies.

NILM is a tested and proven technology. The application in this study indicates limited success with refrigeration and water heating appliances. The limited success may be attributed to unique Indian conditions. Power quality, new set of appliances (like desert coolers and immersion rods) and usage behavior are some unique characteristics that demand comprehensive field training of the NILM algorithms for reliable predictions. The energy monitoring dataset compiled from detailed monitoring sites can serve as training data set for this purpose.

This study presents a holistic evaluation of households through survey instruments, energy monitoring kits, and NILM to draw insights about residential energy use, appliance ownership, and use. This study bridges the information gap and provides a maintainable infrastructure to regularly update usage and assumption information from authentic monitored data. The monitored data effectively captures the social, cultural, economic, climatic and geographic diversities of India. This study underscores the need for evidence-based approach for policy development and implementation.

Way forward

The study furthers the existing knowledge and has the potential to serve as a model for further research. Both, the survey and the data monitoring, need to be scaled up to arrive at a better understanding of appliance end-use in India. The study indicates that energy use patterns and behaviors are changing and it is important to track these changes over time.

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