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ENVIRONMENTAL ENGINEERING

Examining the magnitude and causes of variation in electricity use in a sample of Indian dwellings with and without air conditioning

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ABSTRACT

Understanding the factors that drive the use of residential electricity in India is essential for designing policies that can reduce its expected growth. This study empirically examines the *magnitude* and *causes* of variation in electricity use in a sample of Indian dwellings with and without air conditioning (AC), using an interview-based survey approach applied in 41 dwellings located across two cities representing the composite climate of India. Statistical analysis was used to unpack the relationship between electricity use and socio-technical factors. Despite the small sample size and having the same climatological realm, there was a wide variation observed in electricity use by income groups and the presence of ACs. The mean annual residential electricity consumption (REC) was observed to be highest in high-income group dwellings (5,618 kWh/year), followed by middle-income group dwellings (3,870 kWh/year) and lowest in low-income group dwellings (2,169 kWh/year). The mean REC of AC dwellings (4,208 kWh/year) was found to be nearly double that of non-AC dwellings (2,260 kWh/year) with significant seasonal variation. Multivariate regression analysis revealed that the presence of ACs, household size (number of occupants), annual non-AC appliance hours, dwelling size (number of rooms) and income group accounted for 80% of the variability in REC across the study sample. Residential energy policy in India should consider these key factors that drive REC. To be effective, such policy programmes need to be customised for different income groups, adopting incentives as well as energy awareness campaigns to influence both purchasing and habitual behaviours.

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KEYWORDS
Residential energy; survey; electricity use; India

1. Introduction

Residential electricity (energy) consumption (REC) in India has nearly tripled in the past two decades and accounted for 24% of the overall electricity consumption in 2019 (MoSPI 2018, 2019). With programmes like "Make in India" and "Housing for All by 2022" (by the National Mission for Urban Housing), residential energy demand is expected to grow further by fivefold by 2032 (BEE 2019). Recent census in India has revealed that there are 74 million urban residential households (under good and liveable conditions) that have been electrified and electricity demand in these homes increased by 7.5% every year during 2009–2019 (MHA 2011; MoSPI 2019). Moreover, the higher GDP growth is associated with increased purchasing power and higher comfort expectations, leading to higher penetration of household appliances with associated electricity demand.

Historically, lighting has been a major end use for residential electricity in India, but this trend has been overtaken by the increase in ownership of refrigerators and air conditioners (ACs) (Agrawal et al. 2020). As reported by the International Energy Agency (IEA), about 5.4% of electricity demand rise in 2017 was observed due to the usage of space cooling (as temperature rises) (IEA 2018). Within space cooling, ACs consumed 40% of the energy in 2017–18, and this is projected to rise to 50% in 2037–38 as the residential AC stock is expected to rise from 27 million units in 2016 to 564 million units in 2037 (IEA 2019, 2020). This increase in ownership of energy-intensive appliances and subsequently higher energy demand is expected due to rapid urbanisation, increasing household incomes and climate change (Bhattacharyya 2015; Parikh and Parikh 2016; World Development Indicators 2019). India also ranks first among the lower-middle income countries with an affluent middle-class purchasing their first ACs (Sustainable Energy for All 2020). Currently, 8% of the Indian households have room ACs; however, this is predicted to grow sixfold in less than 20 years as stated in

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the India Cooling Action Plan (2019) which aims to reduce cooling demand across all sectors by 20–25% by 2037–38 (Ministry of Environment Forest & Climate Change 2019). This will be challenging since India has the highest exposure to increased cooling degree days anywhere in the world (Biardeau et al. 2020).

Although the magnitude of the expected rise in residential electricity demand in India is evident, yet there is a paucity of empirical data on residential electricity consumption (REC) in India. A 2015 publication identified that India had the weakest data quality for the residential sector among the four regions – India, China, United States and EU (Shnapp 2015). The reasons for the absence of good quality data were identified as challenges in funding, technology and a general lack of interest to gather residential energy data, which is why public availability of empirical data has been a long standing issue in India.

Majority of studies on residential electricity have used National Sample Survey Organisation (NSSO) data or India Human Development Survey (IHDS-II). However, the five-yearly NSSO does not gather data on seasonal variation in electricity consumption or usage patterns of appliances. The Indian Human Development Survey (IHDS) provides appliance ownership data; however, it does not collect detailed information on AC units owned by a household. A recent survey by Council on Energy, Environment and Water (CEEW) called the India Residential Energy Survey (IRES) has attempted to capture data on electricity access, energy use patterns (including cooking), appliance inventory and energy awareness of Bureau of Energy Efficiency (BEE) star-rated equipment for rural and urban homes, but it has not explored the drivers of electricity use in Indian households (Agrawal et al. 2020). Overall, studies that conduct surveys for understanding the actors that determine REC in urban dwellings are limited (Chunekar et al. 2016).

India's BEE has extended Energy Conservation Building Code (ECBC) guidelines to the residential sector with Eco-Niwas Samhita (BEE 2018). BEE initiated the Standards & Labelling (S&L) programme for appliances and electrical equipment, which has enhanced the influx of low energy appliances into the market (Dhingra et al., 2016; TERI 2008). However, implementation of such energy policies and regulations requires empirical data for implementation (Gupta et al. 2019). Research emphasises that the success of such policies and programmes depend on householders' purchasing behaviours. A study by Garg et al. (2014) indicates that several policies and market initiatives like consumer awareness, and ease of accessibility to information through appliance labelling are pertinent but require a deeper understanding of the drivers for residential electricity use (Chindarkar and Goyal 2019; Garg et al. 2014). Attempts to reduce residential electricity use in India will require a detailed examination of the factors that drive its use across different income groups and households with and without AC.

Within this context, this paper empirically examines the *magnitude* and *causes* of variation in electricity (energy) use in a sample of Indian dwellings with and without AC, using an interview-based survey approach applied to 41 dwellings (households) located across two cities (Hyderabad and Jaipur) representing the composite climate of India. Hyderabad and Jaipur, although geographically separated, display similar climate characteristics with extremes of temperatures defined by seasons. The composite climate zone is typically characterised by very high diurnal variation, variable humidity and sky conditions and seasonal precipitation. These zones experience hot winds in summer, cold winds in winter and strong winds in monsoon. The two different cities were selected to represent diversity of samples. Statistical analysis (multivariate regression) is used to unpack the relationship between physical characteristics of dwellings (built form, size), income groups, occupancy factors (number of occupants), socio-demographics, appliance usage and electricity use. Since monitoring as a means of analysis was not in the scope of this pilot study, the study was limited to questionnaire surveys using interview-based approach to obtain results for variables used in regression analyses. The intent of this pilot study was to test the appropriateness of methods for data collection and analysis of REC in India, which is why a considerably small sample of dwellings in different cities has been taken. The success of the pilot study is expected to guide future studies in this area with much larger samples and datasets across different climatic zones to understand REC at a national level. The study is part of a five-year Indo-UK research programme called RESIDE – Residential Building Energy Demand Reduction in India.

2. Literature review

Internationally, a number of studies have adopted survey-based approaches to characterise the drivers of residential energy consumption in different countries. Such surveys tend to gather data about physical characteristics, socio-demographic attributes, appliance stock and usage. They are typically dispensed through person-to-person interactions (Gupta et al. 2020). About 24 studies were identified from an extensive review of literature, wherein 60% of the studies were based on analysis of secondary survey-based data, while 40% of the studies gathered primary data through surveys. The key characteristics of these studies are summarised in Table 1.

As shown in Table 1, statistical methods based on regression analysis were used in these studies with

Table 1. Characteristics of international studies (outside India) that use survey-based approach to examine residential energy use.

Sample Size range	References	Location coverage	Type of Data
1–500	(Al-Sulaiman and Zubair 1996; Baker and Rylatt 2008; Hara et al. 2015; Jaffar et al. 2018; Le and Pitts 2019; Poznaka et al. 2015) (Bedir et al. 2013; Famuyibo et al. 2012)	Kuwait, Latvia, Vietnam, Saudi-Arabia, Japan, UK, Ireland, Netherlands	Primary and Secondary Data
501–1,000	(Huebner et al. 2015)	UK	Secondary Data
1,001–5,000	(Hu et al. 2017) (Fan et al. 2015; Frondel et al. 2019; Sanquist et al. 2012; Xie et al. 2020)	China, USA, Germany, China, Australia	Primary and Secondary Data
5,001–10,000	(Karatasou and Santamouris 2019; Kostakis 2020; Wiesmann et al. 2011)	Portugal, USA, Greece	Secondary Data
10,001–15,000	(Ohler et al. 2020)	USA	Secondary Data

varying sample sizes (from less than 500 to 15,000) to investigate the relationship of variables such as appliance usage, floor area, age of building, electricity tariff, appliance ownership, AC usage and ownership, and number of occupants, with residential energy use (Hara et al. 2015; Le and Pitts 2019). In a few studies, AC consumption was used as proxy for electricity consumption (Hara et al. 2015; Singh et al. 2018b) while in others, geo-spatial data were used to estimate floor area of dwellings (Baker and Rylatt 2008).

Interestingly, a review of literature revealed that there are relatively few studies that gathered primary data on residential energy use in India – these studies are summarised in Table 2. Half of the studies have emphasised the effect of appliance ownership and usage on electricity consumption (Jain et al. 2014; Parikh and Parikh 2016; TERI 2008; The World Bank 2008), although the appliance data were sometimes estimated using market data from Bureau of Energy Efficiency (BEE) (Chindarkar and Goyal 2019). There is no longitudinal national residential energy consumption survey conducted in India, like the Residential Energy Consumption Survey (RECS) in the USA that is collected every 4 years (Chunekar and Sreenivas 2018). The Indian Human Development Survey (IHDS) is the only national survey that measures AC ownership as a separate variable, but its last available dataset was from 2011 to 2012, making it dated given the rapid growth of urbanisation in India (Desai and Vanneman 2011). CEEW has recently conducted an India Residential Energy Survey (IRES) covering 15,000 homes (Agrawal et al. 2020) – however, the survey has been undertaken once and does not examine the drivers of residential electricity use in India.

The frequency of factors in international and Indian studies was analysed to identify the key factors that influence residential electricity use, as seen in Figure 1. The commonly identified factors included appliance ownership, number of occupants, occupancy pattern and income. Less emphasis was given to factors such as ownership of ACs, their set point temperatures and usage. It was also noted that most of the studies were not empirical in nature, relied on secondary data and the analysis methods largely involved modelling. Since the identified studies were conducted in different countries, they sometimes revealed contradictory findings implying the relevance of context on residential electricity use. While Wiesmann (2011) reported a lower effect of income on REC in Portugal, Pachauri and Hara et al. reported a significant effect of income on electricity consumption in India (Hara et al. 2015; Pachauri and Jiang 2008). Floor area and family size were also found to have a positive effect on REC especially in USA and Australia (Fan et al. 2015; Karatasou and Santamouris 2019), while studies conducted in Europe found socio-economic variables, demographic variables, occupancy patterns and dwelling characteristics playing an important role in REC (Bedir et al. 2013; Huebner et al. 2015; Kostakis 2020). A meta-study by Jones et al (2015) on 18 studies found that the number of occupants had a positive effect on electricity consumption. On the other hand, an Indian study showed negative effect of number of occupants on REC (Filippini and Pachauri 2004), while another Indian study reported positive effects of floor area, number of occupants, AC use and appliances on REC (Singh et al. 2018b). A survey-based study in Kuwait found AC set point temperature, number of rooms and number of occupants to be key drivers of residential energy use (Jaffar et al. 2018). Outdoor climatic condition was found to be a significant driver of REC in studies conducted in

Table 2. Summary of Indian studies that use survey-based approach to assess residential energy (electricity) use.

Sample Size range	References	Type of Data	REC % variance explained by regression
1–500	(Tewathia 2014; Thapar 2020)	Primary Data	52.8%
1,001–10,000	(Singh et al. 2018b) (Tiwari 2000)	Primary Data & Secondary Data	54.3% – 98%
>15,000	(Chindarkar and Goyal 2019; Filippini and Pachauri 2004; Pachauri and Jiang 2008)	Secondary Data	42% – 66.6%

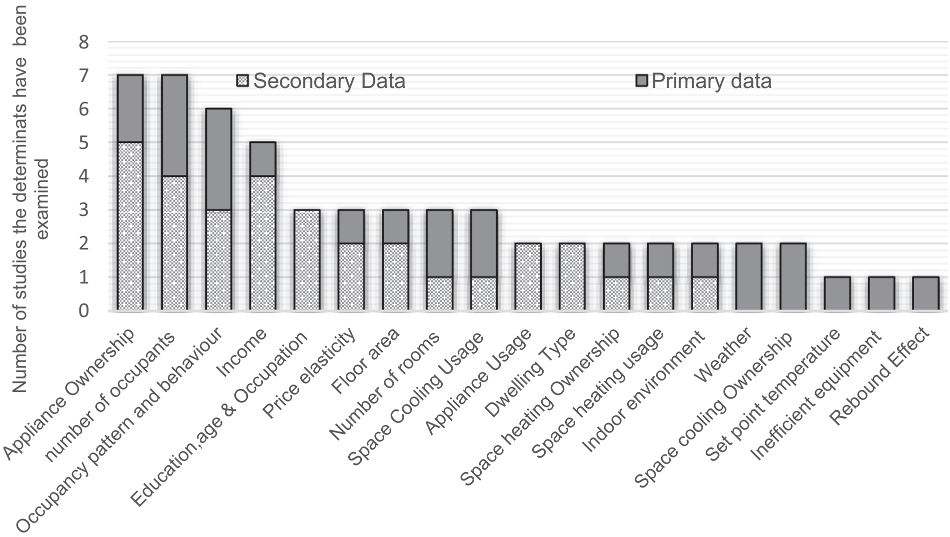

Figure 1. Frequency of factors that influence residential electricity use in international and Indian studies (primary data were measured on site; secondary data mostly modelled).

Ireland and Saudi Arabia (Al-Sulaiman and Zubair 1996; Famuyibo et al. 2012), while appliance usage was found to be a major contributor of electricity use in Vietnam for a sample of 60 households (Le and Pitts 2019).

Although various empirical studies provide a useful account of factors that affect REC in different contexts, it is doubtful that this set of factors can be applied to the Indian context, given the difference in climatological, building and socio-demographic realms. The studies also emphasise the need to gather empirical data on building and occupant-related factors. This study addresses these factors for the Indian context focusing on the composite climatic zone of India.

3. Methodology

A survey-based approach was formulated to collect data on socio-technical factors that may drive REC in India, as revealed by the review of literature. Electricity consumption data for one year (2018–2019) was gathered by collecting historic electricity bills from the householders. Monthly meter readings were noted to examine seasonal variation in electricity use.

3.1. Survey design

A survey framework was developed to gather data on *dwelling physical characteristics* (dwelling form, dwelling size, number of rooms, dwelling ownership, dwelling unit location, construction system, built up area, percentage of roof exposure to sun); *socio-demographics* (income group, number of occupants); *appliances* (types and number of appliances owned, space cooling appliances, usage hours) and *AC usage* (number, type and age of AC units, set point temperature, energy rating, cooling capacity and usage hours). The questionnaire survey variables along with their categories and type of data gathered are shown in Table 3. The survey data were gathered using online Google Forms. Utilising an interview-based approach, trained field researchers completed the online questionnaire while reading out the survey questions and recording the participant responses, to ensure the intent was rightly conveyed and to avoid misinterpretation. Informed consent was gained from each survey participant.

3.2. Sampling

A total of 47 urban dwelling units representing diverse dwelling forms, income groups and ownership of AC units were recruited using purposive sampling in two cities (23 in Hyderabad and 24 in Jaipur) representing the composite climate of India. These representative forms (apartments with less and more than four storeys and standalone houses) along with the exterior and interior of dwellings in Jaipur and Hyderabad are shown in Figure 2. Since there is a lack of a standard dwelling typology in India, the housing typologies vary greatly across geographies, despite being in the same climatic zone. Thus, the selected sample reflects diversity of the varied representative forms of dwellings. The income groups defined under the "Pradhan Mantri Awas Yojana" (Ministry of Housing & Urban Affairs 2021) were used to categorise income groups as low-income (LIG), middle-income (MIG) and high-income (HIG) groups. While survey data and electricity bills for one year (2018–19) were gathered from 47 dwellings, due to missing data points, complete dataset of only 41 dwellings was available for analysis. All of the 41 dwellings were regularly occupied during the period.

Table 3. Survey variables used in the study.

Variable Group	Variables	Categories/unit of measurement	Type of Data
Physical characteristics	Dwelling form	Standalone House (having one common wall with adjacent house), Row houses, Apartment block (less than or up to 4 storeys high), Apartment block (greater than 4 storeys high)	Categorical
	Dwelling size	1BHK (Bedroom, Hall and Kitchen), 2BHK, 3BHK, 4BHK, 5BHK or more	Categorical
	Number of rooms	Drawing room, Dining room, Kitchen, Bedroom 1, Bedroom 2, Bedroom 3, Study, Balcony/ Garden, Other	Numeric
	Ownership of dwelling	Self-Owned, rented	Categorical
	Dwelling unit location	Ground floor (directly on ground), Ground floor (directly above stilt parking), Middle floor, Top floor or name floor level	Categorical
	Primary construction system	Brick - Masonry structure (load bearing walls), Stone - Masonry structure (load bearing walls), RCC framed structure + masonry walls (non-load bearing), Reinforced concrete (RCC) structure, Timber, Other	Categorical
	Built up area	Square meters	Numeric
	Percentage of roof exposure to sun	Greater than 50%, 50%, 40%, 30%, 20%, less than 20%, NA	Categorical
Socio-demographics	Income group	LIG (low-income group), HIG (high-income group), MIG (middle-income group)	Categorical
	Number of occupants	Number	Numeric
Appliances	Number of appliances owned	Number	Numeric
	Space cooling appliances	AC, Ceiling fan, table fan, Wall Fan, Desert cooler and Air cooler	Categorical
	Other appliances	Refrigerator, Mixer-grinder, Microwave/oven, induction plate, Electric cooker, Electric chimney, Electric kettle, Toaster, Exhaust fan, Water purifier, Television, Set-up box, Music system, Desktop Computer, Laptop, Router, Printer/Scanner, Washing machine, Dishwasher, Voltage stabilizer, Iron, Vacuum cleaner, Water pump/motor, Dehumidifier, Non-electrical heating, Incandescent light (bulb), TFL, CFL, LED	Categorical
	Annual appliance usage hours	Hours	Numeric
Air conditioning usage	No. of AC units	Number	Numeric
	Type of AC units	Window, Split, Unknown	Categorical
	Age of AC units	Less than 1 year, 1–5 years, 5–10 years, Over 10 years, Not known, NA	Categorical
	Rating of AC units	1, 2, 3, 4, 5 star	Ordinal
	Cooling capacity of AC units	Ton	Numeric
	Preferred set point temperature	Degree Celsius	Numeric
	Annual AC usage hours	Hours	Numeric
Electricity use	Annual electricity consumption	kWh	Numeric
	Monthly electricity consumption	kWh	Numeric

In line with other studies (Indraganti 2010), summer season was presumed to run from March to June, monsoon season from July to October, and the winter period from November to February, to understand seasonal variation across income groups and dwellings with and without ACs. As stated by Flyvbjerg (2006), although large-scale studies provide breadth, smaller sample studies can help to provide depth, which is essential in social science. Despite the problems in generalising from smaller studies, the strategic method of choosing the sample and examining the study findings in depth can provide valuable contribution to science (Flyvbjerg 2006).

3.3. Analysis approach

In line with literature based on multivariate regression analysis method, independent variables were selected based on their theoretical significance to the dependent variable. Multiple regression was used since it has been found to be suitable for analysis of small samples for detecting relationships. Compromise power analysis for linear regression was conducted to identify the error and power of the test. Although the number of samples were less, they were sufficient for a feasible analysis ($N > 30$). Collinearity was checked using Pearson correlation for numeric values. Central limit theorem states that violation of normality is not up for dispute when the sample size is greater than 100. A quick understanding of normality was done by observation of mean and standard deviation.

Multi-linear regression was used to test the relationship between the *hypothesis variables* (number of rooms, number of occupants, appliance usage hours (of AC and appliances), non-AC appliances and AC units as well as income group) and the *dependent variable* of annual REC. As the number of AC units and the presence of AC explain the same variables, only one variable was appropriately used to signify the impact on REC (presence/ownership of AC was selected here). Similarly, the effect of BHK, floor area and number of rooms was also explaining the effect of the size of the dwelling; here, the number of rooms was selected based on

Figure 2. Exterior and interior photographs of case study dwellings in Jaipur and Hyderabad.

Table 4. Electricity tariffs in Hyderabad and Jaipur.

Slabs	INR/kWh
Hyderabad (domestic category)	
0–200 units (kWh) per month	5
201–300 units (kWh) per month	7.3
301–400 units (kWh) per month	8.5
401–800 units (kWh) per month	9
Above 800 units (kWh) per month	9.5
Jaipur (General domestic –4)	
First 50 units (kWh) per month	4.75
50–150 units (kWh) per month	6.5
150–300 units (kWh) per month	7.35
300–500 units (kWh) per month	7.65
Above 500 units (kWh) per month	7.95

literature. Prior to conducting regression analysis, data were prepared for collinearity and normality. Based on monthly electricity consumption, electricity costs were calculated using published electricity tariffs for Jaipur and Hyderabad, as shown in Table 4.

Logarithmic transformation was done to normalise the numeric data. Non-categorical variables were run through Shapiro–Wilk test since the sample size was small (<50) where significance < 0.05 identifies non-normal data. To establish the validity of regression values, Variance Inflation Factor (VIF) and partial R-square were validated against the values obtained. VIF > 5 reveals multi-collinearity, while partial R square can also reveal any collinearity issues (Huebner et al. 2015; Min et al. 2010; Pachauri and Jiang 2008). The residuals that are standardized predictors of variables should have a mean of zero and standard deviation of nearly one. If residuals were found to be normally distributed, then 95% of them would fall between −2 and 2. If they fell above 2 or below −2, then the model was considered abnormal (UCLA 2020). Filtered out redundant variables based on the six literature variables were analysed through multiple regression analysis. Insignificant variables with p-value >0.05 were excluded from the results. Interaction effects among these variables were accounted for. For example, since both "AC usage hours" and "presence of AC" had a moderate correlation with REC, "AC usage hours" was not used in the regression analysis. The variables that showed significant variance are explained in the results. Regression equation with REC as the dependent variable was represented by the following equation.

Equation 1

$$\begin{aligned} Annual\ REC = {} & \alpha_0 + \alpha_1.NumRooms \\ & + \alpha_2.AnnualnonACuse + \alpha_3.Numapp \\ & + \alpha_4.presenceofAC + \alpha_5.\sum_i incomegrp \\ & + \alpha_6.Numocc \end{aligned} \tag{1}$$

where

- Annual REC – Annual Residential Energy Consumption

- NumRooms – Number of rooms
- AnnualnonACuse- Annual non-AC appliance usage hours
- Numapp – Number of non-AC appliances
- Presence of AC -AC/non-AC dwelling
- Income grp – Income group (LIG, MIG, HIG)
- Num occu – Family size
- α_{0}- Intercept
- α_1-$\alpha_{7,}$ - Slope for each variable

4. Results

4.1. Dwelling and occupancy characteristics

The 41 dwellings sample included 16 LIG, 16 MIG and 9 HIG households occupying eight apartments greater than four storeys tall, four apartments lesser than four storeys and 29 stand-alone houses. About 28 dwellings had AC with one or more AC units, while 13 dwellings had no AC. About 75% of dwellings had a roof that was more than 50% exposed to the sun, while the rest were less exposed or did not have exposed roofs. Over 80% of dwellings were constructed using Reinforced Cement Concrete (RCC) structure and masonry walls, with remaining 20% having load-bearing masonry structures. The average age of the structure of the dwellings sample was 10 years old, and only 17% of the dwellings were less than five years old. Some of the physical characteristics of the dwellings are shown in Table 5 along with their annual electricity consumption, which is discussed in subsequent sections. Nearly 80% of the dwellings were self-owned and 20% were rented. Although the average number of occupants in the dwellings were about four, a few cases may be considered as outliers (for example, J4004 with 14 occupants and J4020 with 10 occupants). Further, the annual REC per occupant in J4016 is high; this may well be considered as an outlier suggesting inefficiency of envelope, as the LIG dwelling is at least over 15 years old, with a single AC unit in a three BHK covering built-up area of 137 m^2. Table 5 summarises of physical characteristics of dwellings and annual electricity use (n: 41).

Analysing the data for the number of appliances owned (Figure 3) revealed that 98% of the dwellings owned a refrigerator and television. This compared favourably with the 2019 CLASP-NEEM study that found that more than 80% of Indian urban households owned a TV and refrigerator (Walia et al., 2019). LEDs, water pump motors and washing machines were the next commonly owned appliances, while 68% of dwellings owned an AC. It would be useful to compare the magnitude of variation in electricity used by space cooling and non-space cooling appliances in dwellings with ACs and those without them. This could further be observed across income groups, which was studied in the next section. It was also observed that HIG dwellings owned more appliances than LIG and MIG dwellings, although LIG dwellings had a higher annual appliance usage than MIG dwellings in monsoon and winter seasons.

Along with the extent of ownership of appliances, data on appliance usage hours were analysed to understand how electricity was used in Indian dwellings. As expected, always-on refrigerators had the maximum annual hours (8,147 h), followed by televisions (1,686 h), AC (1,516 h) and desert coolers (633 h). This trend was also observed in the CLASP-NEEM study (Walia et al., 2019) where refrigerators and televisions

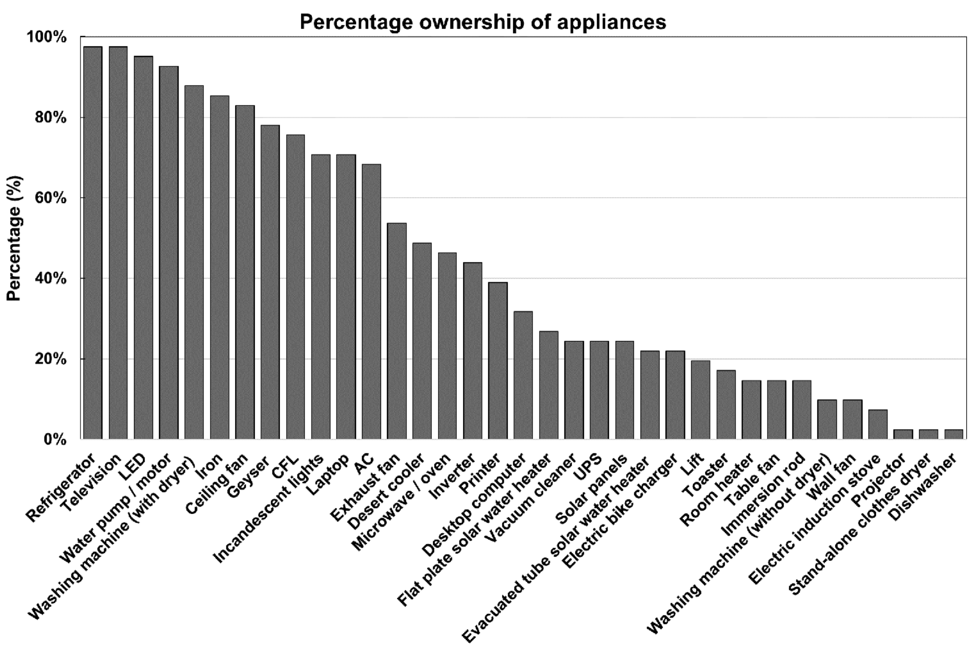

Figure 3. Percentage ownership of appliances across the sample of 41 dwellings.

Table 5. Physical characteristics and annual electricity consumption of the dwellings.

Income group	Dwelling ID	Built up area (m^2)	No. of occupants	Dwelling type	AC/non-AC dwelling	No. of AC units	Annual REC (2018–2019)	EPI (kWh/ m^2/year)	Annual REC per occupant (kWh/occupant)
LIG	J4007	70	2	Apartment block (>4 storeys high)	non-AC	0	683	10	342
LIG	HP3006	74	7	Standalone house	non-AC	0	1,020	14	146
LIG	HP3009	93	4	Apartment block (<4 storeys high)	non-AC	0	1,173	13	293
LIG	HP3008	93	4	Apartment block (<4 storeys high)	non-AC	0	1,269	14	317
LIG	J4018	172	5	Standalone house	non-AC	0	1,308	8	262
LIG	J4006	96	2	Apartment block (<4 storeys high)	AC	1	1,362	14	681
LIG	J4001	167	3	Standalone house	non-AC	0	1,943	12	648
LIG	J4025	121	3	Apartment block (<4 storeys high)	AC	1	1,957	16	652
LIG	J4003	152	7	Standalone house	non-AC	0	2,032	13	290
LIG	J4013	84	3	Standalone house	non-AC	0	2,082	25	694
LIG	HP3019	186	2	Standalone house	AC	2	2,177	12	1,089
LIG	HP3022	93	4	Standalone house	non-AC	0	2,326	25	582
LIG	J4002	78	4	Standalone house	AC	2	3,021	39	755
LIG	J4016	137	2	Standalone house	AC	1	3,238	24	1,619
LIG	HP3018	214	3	Standalone house	AC	1	3,258	15	1,086
LIG	J4009	183	9	Standalone house	non-AC	0	5,856	32	651
MIG	HP3002	101	2	Standalone house	AC	1	1,796	18	898
MIG	J4023	107	9	Standalone house	non-AC	0	2,090	20	232
MIG	J4017	316	3	Apartment block (>4 storeys high)	AC	2	2,159	7	720
MIG	HP3011	93	5	Apartment block (<4 storeys high)	AC	1	2,451	26	490
MIG	HP3013	102	2	Standalone house	AC	2	2,699	26	1,349
MIG	HP3020	232	2	Standalone house	AC	3	2,831	12	1,416
MIG	HP3001	93	4	Standalone house	AC	1	2,875	31	719
MIG	HP3024	107	4	Standalone house	AC	1	2,896	27	724
MIG	HP3017	93	4	Standalone house	AC	1	2,930	32	732
MIG	HP3007	93	4	Apartment block (<4 storeys high)	AC	1	3,052	33	763
MIG	HP3025	156	4	Standalone house	AC	1	3,349	22	837
MIG	HP3005	111	6	Apartment block (>4 storeys high)	non-AC	0	3,548	32	591
MIG	J4008	195	6	Standalone house	AC	2	5,848	30	975
MIG	J4004	334	14	Standalone house	AC	4	6,865	21	490
MIG	J4021	143	4	Standalone house	AC	1	6,898	48	1,725
MIG	J4010	300	6	Standalone house	AC	3	9,644	32	1,607
HIG	HP3003	149	2	Apartment block (<4 storeys high)	AC	1	2,656	18	1,328
HIG	HP3004	102	2	Standalone house	AC	4	3,240	32	1,620
HIG	HP3015	260	6	Standalone house	non-AC	0	4,047	16	675
HIG	HP3012	232	2	Standalone house	AC	4	5,257	23	2,629
HIG	J4012	139	3	Apartment block (<4 storeys high)	AC	3	5,492	39	1,831
HIG	HP3023	186	4	Standalone house	AC	3	5,611	30	1,403
HIG	HP3014	130	4	Apartment block (>4 storeys high)	AC	4	5,924	46	1,481
HIG	J4020	372	10	Standalone house	AC	1	6,765	18	677
HIG	J4022	138	6	Standalone house	AC	3	11,570	84	1,928

were the most frequently used appliances annually. The usage of refrigerator and TV was constant throughout the year as compared to the seasonal usage of desert coolers which increased by five times in the summer as compared to the monsoon season. Likewise, usage of geyser (for hot water) increased three times in the winter season as compared to the monsoon season.

4.2. Variation of electricity use by income group

The annual REC, annual REC normalised by area (EPI) and annual REC normalised by number of occupants was found to increase with increasing income, as shown in Table 5 and Figure 4. Mean annual REC was observed to be 2,169 kWh/year for LIG dwellings (n: 16), increasing by 1.8 times to 3,870 kWh/year for MIG dwellings (n: 16), and by 2.6 times to 5,618 kWh/year for HIG dwellings (n: 8). Mean EPI was also found to increase with income group, equating to 18 kWh/m^2/year (19.9 kWh/m^2/year for AC and 16.4 for non-AC dwellings), 26 kWh/m^2/year (26 kWh/m^2/year for AC and 25.7 kWh/m^2/year for non- AC dwellings) and 34 kWh/m^2/year (36.2 kWh/m^2/year for AC and 15.6 kWh/m^2/year for non-AC dwellings) for LIG, MIG and HIG dwellings, respectively. It is to be noted that the mean EPI for MIG dwellings did not vary much between AC

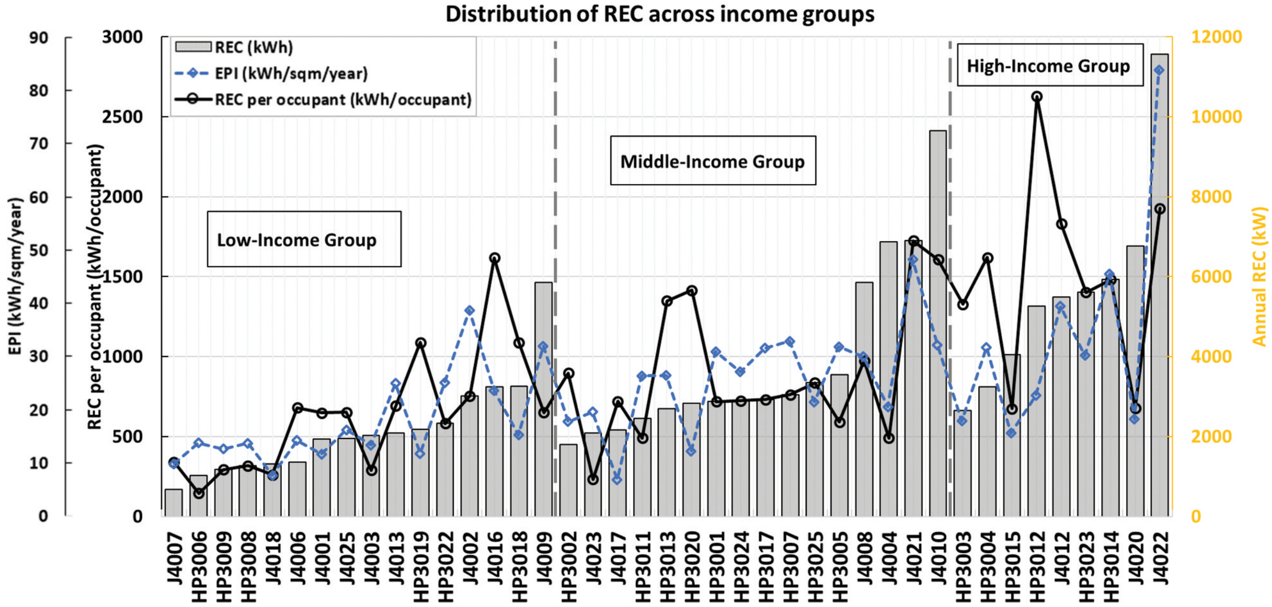

Figure 4. Variation of annual electricity use by area and number of occupants for 41 dwellings across income groups.

Table 6. Seasonal variation of REC across income groups.

Income group (as defined under PMAY - Pradhan Mantri Awas Yojana)	Mean Summer REC (kWh)	Mean Monsoon REC (kWh)	Mean Winter REC (kWh)
LIG	931	792	532
MIG	1,725	1,294	903
HIG	2,043	1,848	1,465

and non-AC dwellings, the reason behind which may simply be that only two dwellings from the 16-sample MIG dwellings were not AC. As LIG households become MIG with increasing income, a doubling of residential electricity use can be expected in India. A similar trend was observed when annual electricity use was normalised by number of occupants; varying from 632 kWh/occupant in LIG dwellings, to 892 kWh/occupant in MIG and 1,508 kWh/occupant in HIG dwellings.

Seasonal variations of REC were also explored for the summer, monsoon and winter seasons by income groups as shown in Table 6. It was found that HIG dwellings had the highest and LIG dwellings had the lowest mean REC across all three seasons. While summer electricity use was found to be 1.7–1.9 times more than the winter season in LIG and MIG dwellings due to the use of energy-intensive cooling devices, this reduced to 1.4 times for HIG dwellings indicating the all-year round use of non-cooling appliances in such dwellings.

The electricity tariffs in Hyderabad and Jaipur (Table 4) were used to estimate annual electricity costs (normalised by floor area) for each of the dwellings in the 41 dwelling sample, as shown in Figure 5. As expected, on average, HIG dwellings spent almost twice on annual electricity use than LIG dwellings. Annually, dwellings with ACs ($n = 28$) spent 71% more on total electricity use compared to dwellings without Acs ($n = 13$). However, HIG dwelling HP003 with AC spent lower annual electricity cost than a non-AC LIG dwelling J4009 because of the large difference in the number of occupants. HIG dwelling HP003 was inhabited by two occupants as compared to nine occupants in LIG dwelling J4009 which also had two times more non-AC appliances with 1.4 times usage hours. This strengthens the need to collect contextual survey data for better understanding the variation in energy use across dwellings.

In addition to income group, the relationship between dwelling size and electricity use, was examined by plotting annual REC (kWh) against floor area (m^2) (Figure 6), which was categorised into 50 m^2 ranges in reference with the GBPN report (Rawal and Shukla 2014). Interestingly, median and mean annual REC were found to have no relationship with dwelling size which was also confirmed by a weak correlation ($R^2 = 0.24$) between floor area and annual electricity use.

4.3. *Variation of electricity use by AC use*

Among the 41 dwellings, there were 55 AC units and 40 desert coolers owned by the residents. From the sample, about 38% of LIG dwellings, 88% of MIG dwellings and 89% of HIG dwellings were AC. About 84% of the dwellings with AC units (n: 28) had a split AC system installed, with capacity of 1.5 ton, of which

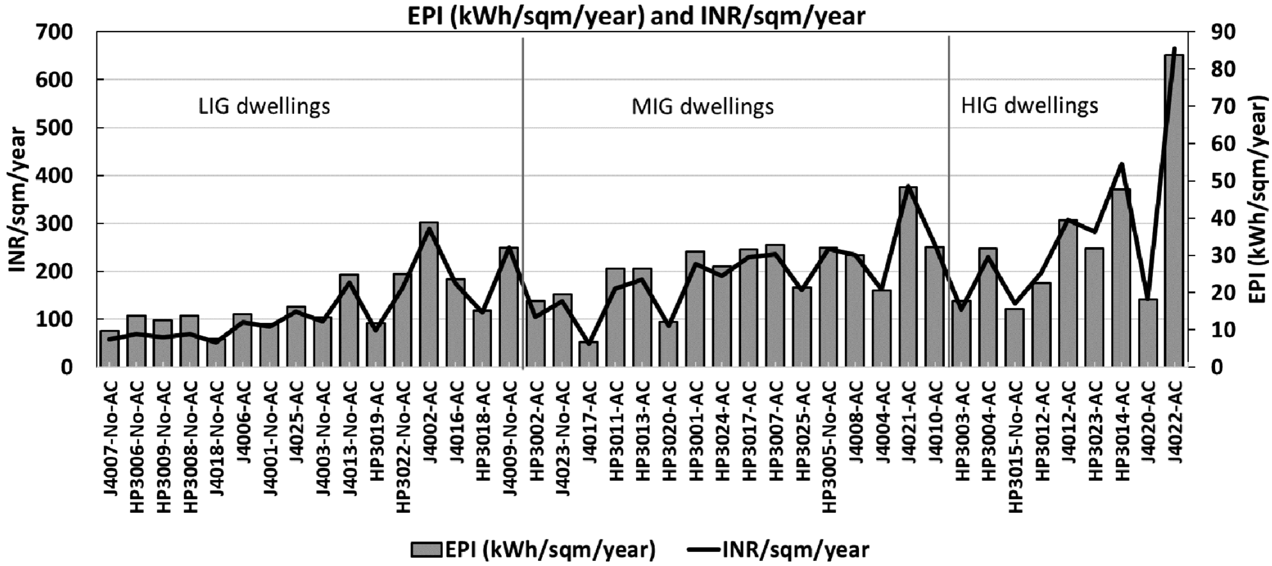

Figure 5. Variation of annual electricity consumption/m^2/year and estimated annual electricity cost in INR by income group.

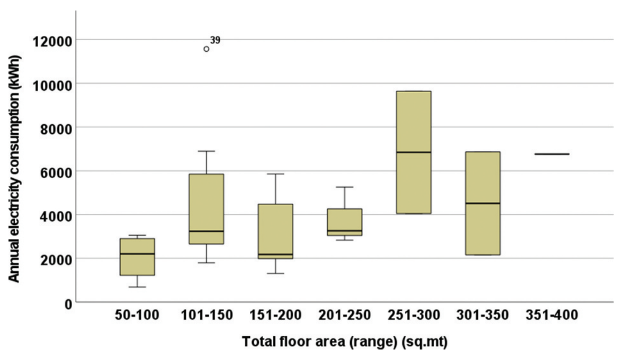

Figure 6. Variation of annual electricity consumption by floor area range in steps of 50 m^2.

64% were less than five years old. As shown in Figure 7, more than 50% of the dwellings used a 3-star rated AC which had mid-level energy efficiency, indicating the untapped potential of deploying energy efficient 5-star appliances.

The mean annual electricity consumption for AC dwellings (n: 28) was found to be 4,208 kWh/year, which was nearly double that of the non-AC dwellings (n: 13) amounting to 2,260 kWh/year. This implies that if AC usage became widespread in India, it could potentially lead to a doubling up of residential electricity use. Seasonal variation in electricity use was significant in dwellings with ACs, as shown in Figure 8.

While AC dwellings were found to consume two times more electricity during the summer months as compared to their consumption in winter season, the variation in electricity use in summer, monsoon and winter seasons was less significant in non-AC dwellings, as shown in monthly electricity use of AC and non-AC dwellings in Table 7.

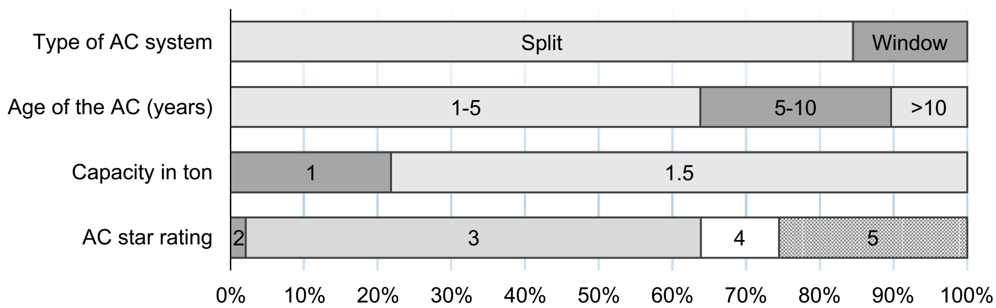

Figure 7. Characteristics of AC appliances across AC dwellings.

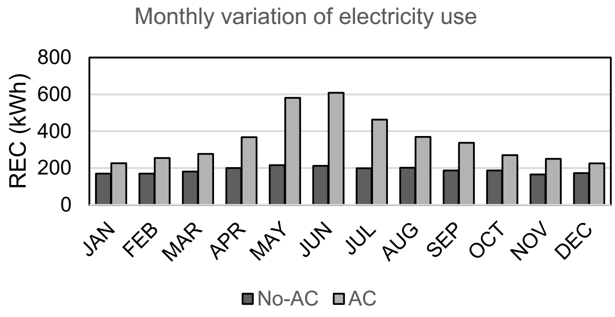

Figure 8. Energy use per month across AC and non-AC dwellings.

This difference in electricity use was reflected in electricity costs, wherein for AC dwellings, the average monthly electricity cost in summer and monsoon seasons was found to be US$ 14/month, which was 3.5 times more than the winter season (US$ 4/month). On the other hand, non-AC dwellings used US$ 8/month in the summer/monsoon seasons as compared to US$ 3/month in the winter season.

The monthly variation reflected in the mean daily electricity consumption for summer (May), monsoon (July) and winter (January) seasons, as shown in Figure 9. Daily electricity use of AC dwellings in the summer/monsoon seasons was nearly three times more than the winter consumption. Non-AC dwellings, on the other hand, did not experience such a stark difference in electricity use across seasons despite there being up to 15°C seasonal difference in the outdoor temperature in the composite climatic zone, as seen in the Figure. The seasonal variation in electricity use due to AC will need to be addressed as more numbers of dwellings in India get AC due to changing expectations, urbanisation and a warming climate.

Despite the seasonal use of AC, there was a weak correlation observed between the AC set point temperature and annual REC ($R^2 = 0.09$) in AC dwellings. Furthermore, the mean REC for AC dwellings in winter (977 kWh) season was similar to the mean REC of non-AC dwellings in the summer (950 kWh), indicating that all 41 dwellings were running in non-AC mode in the winter, indicating the mixed-mode nature of Indian dwellings even with ACs. The relationship of number of AC units, their usage hours and residential electricity use was also analysed (Figure 10). The correlation between AC usage hours and the number of AC units was found to be moderate ($R^2 = 0.53$), implying that not all AC units were used all the time, possibly because of the room-level (decentralised) nature of AC usage in India. Summer AC usage hours were found to be the highest for HIG dwellings and lowest for LIG dwellings.

Monthly REC could also be correlated with outside weather conditions to examine the relationship between electricity use and weather. Degree days are commonly used to estimate building energy consumption accounting for weather. Cooling degree days (CDD) relate to energy required to cool buildings and are highest in summer. They are determined using the base temperature, which is the temperature above which cooling may become necessary. The estimated base temperature used for cooling and heating degree days calculation is 18°C for India (Bhatnagar et al. 2018). According to ASHRAE (The American Society of Heating, Refrigerating and Air-Conditioning Engineers), the daily degree days can be extracted by calculating the difference between the mean temperature (T_{max}-T_{min})/2 and base temperature (T_{base}) using the following equation. Utilising data from degree days for Jaipur and Hyderabad, the CDD at 18°C were

Table 7. Seasonal electricity consumption and AC usage in AC and non-AC dwellings.

	Mean Summer REC (kWh) March-June	Mean Monsoon REC (kWh) July-October	Mean Winter REC (kWh) November-February	AC usage hours in summer (in hours) March-June	AC usage hours in monsoon (in hours) July-October	AC usage hours in winter (in hours) November-February
AC	1,733	1,427	977	1,553	646	22
Non-AC	950	774	677	0	0	0

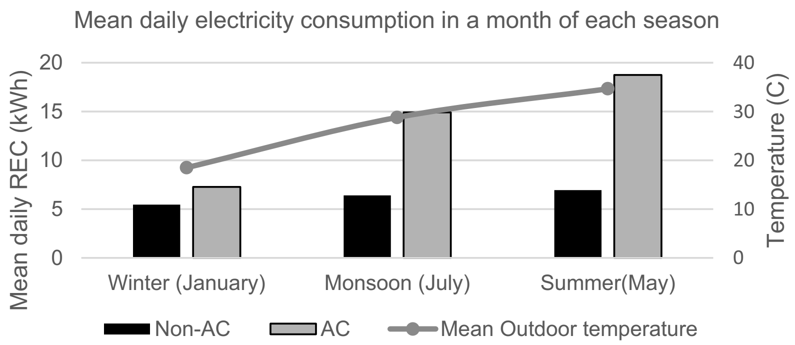

Figure 9. Mean daily REC (kWh) use in summer (May), monsoon (July) and winter (January) seasons for AC and non-AC dwellings.

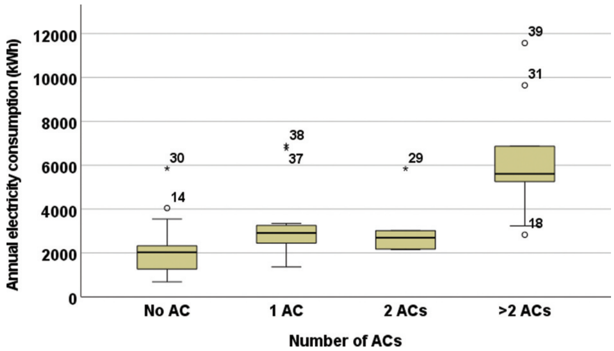

Figure 10. Boxplot of annual electricity consumption with respect to the number of AC units.

extracted (Bizee 2020). However, the survey data in this study found that the average preferred set point temperature of room ACs was 26°C on average.
Equation 2

$$CDD = \left(\frac{T_{\max} - T_{\min}}{2} - T_{base}\right)^{+} \qquad (2)$$

A scatter plot of the mean monthly electricity use against corresponding CDD revealed a slightly weaker correlation in AC dwellings ($R^2 = 0.50$) than non-AC dwellings ($R^2 = 0.56$) as shown in Figure 11. This indicates that there is a potential for managing electricity use in relation to outside weather through weather compensation and smart management.

4.4. Factors affecting residential electricity use

Since the study sample was small in size, compromise power analysis was conducted on six selected survey variables (factors) with power of 0.95 to examine their relative impact on REC. These variables included number of occupants, number of rooms, number of non-AC appliances, appliance usage hours (non-AC), and the presence of AC and income group. Since annual REC was not normally distributed, natural logarithmic transformation was applied to normalise the data. To include categorical values for multivariate regression (MVR), they were coded as dummy variables, in this case, the variables – income group and the presence of AC were recoded into dummy variables. All these transformed variables were used in the regression analysis model.

The six selected variables were correlated before analysis, and higher correlated variables were removed to avoid collinearity during analysis or to avoid a higher VIF. Correlations over 0.8 were flagged and removed. The collinearity diagnostics revealed a reasonable value of VIF (<2). A partial R-square value of less than 0.8 confirmed the absence of collinearity. Durbin-Watson value of 1.8 indicated a positive autocorrelation. The regression analysis using dummy variables also revealed significance of demographic variables relative to reference dummy variable. The coefficient for HIG and MIG dwellings was found to be positive with electricity

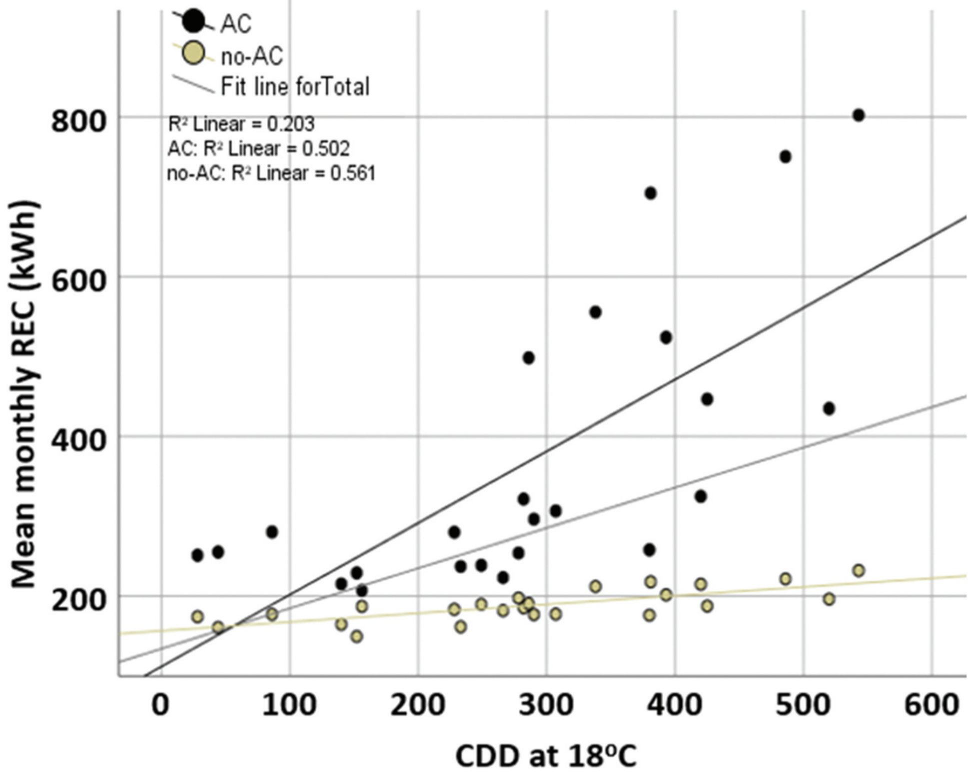

Figure 11. Scatter plot of mean monthly REC (kWh) vs CDD at 18°C.

Table 8. Regression model results.

	Unstandardized Coefficients		Standardized Coefficients		
	B	*Std. Error*	*Beta*	t	Sig.
(Constant)	6.00	0.25		24.00	0.00
Presence of AC	**0.49**	**0.14**	**0.37**	**3.54**	**0.00**
Annual non-AC appliance hours	**0.00**	**0.00**	**0.24**	**2.69**	**0.01**
Incomegroup=HIG	**0.45**	**0.16**	**0.30**	**2.85**	**0.01**
Incomegroup=MIG	0.19	0.14	0.15	1.34	0.19
Number of non-AC appliances	0.00	0.01	−0.02	−0.18	0.86
Number of rooms	**0.05**	**0.02**	**0.33**	**3.14**	**0.00**
Number of occupants	**0.09**	**0.02**	**0.39**	**3.77**	**0.00**
R	0.89				
R Square	0.80				
Adjusted R Square	0.76				
Std. Error of the Estimate	0.31				
R Square Change	0.80				
Durbin-Watson	1.80				

consumption, while it was negative for LIG dwellings, indicating that HIG and MIG dwellings have higher consumption than LIG dwellings. The insignificant variables ($p > 0.05$) were excluded and standardised coefficients with significance were used to explain the results.

As shown in Table 8, the multivariate regression model was reduced to five predictors (variables) – presence of AC, number of occupants, annual non-AC appliance hours, number of rooms, and income group (where HIG had a 45% increase in REC with respect to LIG dwellings). These five variables accounted for 80% of the variation in electricity consumption across the given dwelling sample. The key factor that impacted residential electricity use was found to be number of occupants (household size), while other factors in decreasing order of significance were as follows: presence of AC, number of rooms (dwelling size), income group (HIG as the highest consumption group) and annual non-AC appliance hours. The regression model results aligned well with the findings that electricity use higher in households with AC and those in the high-income group. Such households may need to be targeted first in any drive to reduce residential electricity use.

5. Discussion

This empirical study has revealed that despite having the same climatological realm for a small sample of 41 dwellings, annual residential electricity use (normalised by area and number of occupants) varied widely depending upon the income group, presence of AC and usage hours of appliances. This is a significant find for residential energy policy in India. Given that HIG dwellings consumed more than double the amount of electricity than LIG dwellings, and MIG consumed 1.8 times more electricity than LIG, it is vital to address these highest electricity consumers and ensure that the lowest electricity consumers do not rapidly move to these groups. This will be a social challenge given the rapidly rising middle class in India with aspirations for better thermal comfort. Furthermore, given the varying levels of electricity use across income groups, it is recommended that policy measures be customised for different income groups to make them relevant. While financial incentives to purchase energy-efficient appliances may not work for more affluent dwellings, these may be appropriate for the lower income groups. For the more affluent – MIG and HIG dwellings, enabling the purchase of rooftop solar systems to meet the electricity demand locally may be more appropriate and acceptable. Such measures will align with the national commitment of India to move to 500 gigawatts (GW) of non-fossil electricity capacity and produce half the energy from renewables by 2030.

The significant difference in the annual, seasonal, monthly and daily electricity use of dwellings with ACs in comparison with those without could direct policies to curtail the growth of AC through a combination of energy conservation measures and purchase of 5-star rated (energy-efficient) ACs. The untapped potential of energy-efficient ACs is vital given that 3-star rated AC units with mid-range level of energy efficiency were found to be most popular in the study sample. Moreover, given that evaporative coolers use 56% less electricity as compared to AC units (Sharma et al. 2021), it is vital that the use of desert coolers is promoted as the key cooling device during the summer period, with AC usage largely limited to the more humid monsoon season. Such seasonal use of cooling devices can lead to rapid reduction in REC.

Another important finding from the study was the prevalence of seasonal variation in REC, especially for dwellings with AC experiencing summertime electricity consumption twice that of the winter season. This finding aligned with another large-scale study conducted in the *composite* climate zone which reported that AC and refrigerators in summer contributed to around 70% of the total electricity consumption (Thapar 2020). Another study identified that REC almost doubled with the use of room AC units (Rawal and Shukla 2014). With the expected growth of residential AC in India driven by increasing incomes, urbanisation and a warming climate, uncontrolled increase in summertime residential electricity load would have a major impact on the electricity networks, potentially leading to blackouts. Although solar energy is plentiful during the summer, night-time peak of electricity use for AC would limit the use of solar energy. This reinforces the need for smartly managing AC usage in Indian dwellings to manage peak time loads.

Besides income group, number of rooms (dwelling size), presence of AC, usage of non-AC appliances and number of occupants were found to explain 80% of the variation in electricity use across the study sample. Again, this finding was in line with other large-scale studies in India. Within a composite zone study of 365 households, the major drivers of REC were found to be number of appliances, usage of appliances, income, dwelling size and family size (Tewathia 2014). Singh et al. conducted a large sample study of 1,026 households and reported that presence of AC, family size, dwelling size, number of appliances and climatic zone influenced the REC (Singh et al. 2018a&b). Another study based on 30,000 households (from NSS data) conducted at the national level found that income, family size and other household characteristics were major drivers of REC (Filippini and Pachauri 2004). Therefore, it is clear that regardless of the scale of the study, common drivers (factors) of REC were found to include income group, number of occupants, number of appliances/usage and dwelling size.

Given the influence of AC use on REC, it is clear that without bringing about a major reduction in AC use, the electricity demand in Indian dwellings will continue to rise. Since not all AC units were found to be used at the same time, there is some indication of energy awareness and energy thrifty behaviours amongst the study sample. Future energy policy should also focus on behavioural aspects, developing schemes for raising awareness amongst householders to use non-AC cooling devices such as fans and desert coolers in less extreme weather (habitual behaviour), as well as providing incentives to influence initial purchase decisions for energy-efficient cooling devices including ACs (purchase behaviours).

6. Conclusion

This study empirically examined the *magnitude* and *causes* of variation in electricity use in Indian dwellings with and without AC, using an interview-based survey approach applied to 41 dwellings located across two cities representing the composite climate of India. Statistical analysis was used to unpack the relationship between electricity use and socio-technical factors. Despite the small sample size, there was a wide variation observed in electricity use by income groups and presence of ACs. The mean annual REC was observed to be highest in HIG dwellings (5,618 kWh), followed by MIG dwellings (3,870 kWh) and lowest in LIG dwellings (2,169 kWh). The mean annual electricity use of AC dwellings (4,208 kWh/year) was found to be nearly double that of non-AC dwellings (2,260 kWh/year). Multivariate regression analysis revealed that presence of AC, household size (number of occupants), annual non-AC appliance usage hours, dwelling size (number of rooms) and income group accounted for 80% of the variability in electricity consumption across the study sample. These factors were similar to those identified in other large-scale studies, which imply that residential energy policy in India needs to consider these key factors that drive REC.

Financial support to purchase energy-efficient appliances could be more appropriate for the lower income groups. Enabling the purchase of renewable solar systems to meet the electricity demand locally may be more appropriate for more affluent groups. Significant seasonal differences in residential electricity use found in this study and other large-scale studies reinforce the need for upgrading thermal performance of the building fabric to reduce the demand for cooling in the summer.

The empirical survey-based approach adopted in this pilot study could be expanded at a national scale to help policymakers and researchers in India to understand *how*, *when* and *why* electricity is used across different climatic regions, seasons and income groups. Such empirical data and evidence are not only useful for designing appropriate energy policy programmes but also for validating the projections of residential electricity demand in India.

Future residential energy policy programmes could include *technological* changes, such as expanding the application of residential energy code to all types of residential buildings and moving from the use of AC to desert coolers in less extreme summer conditions, as well as *behavioural* aspects related to purchase of highly energy-efficient AC units (five-star energy rated). To be effective, such policy programmes need to be customised for different income groups, adopting incentives as well as energy awareness campaigns to influence both purchasing and habitual behaviours, which will require increased efforts on the part of policymakers (Carpino 2019).

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