Highly recommended paper

Examining the variation in residential electricity use in urban Indian households with and without air-conditioning

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Abstract

Residential electricity use (REC) in India is projected to increase five times by 2032 driven by urbanisation and climate change, yet there is paucity of data on residential electricity use and how it varies across space (climatic zones) and time (seasons).This paper empirically investigates the climatic and seasonal variation (summer, winter) of residential electricity use in India using statistical analyses of nationwide survey data of 4,877 urban households (single-family/multi-family, different income groups), which were located in 21 cities representing all five climates ranging from cold, composite, hot-dry, warm humid and temperate climates. The survey data were gathered as part of a national NEEM-CLASP study during 2018-2019, and included household characteristics, income group, socio-demographics, electricity use, ownership of air conditioning (AC) units and appliance usage data.

As expected, high income households (n: 1,084) reported the highest mean monthly summer electricity consumption at 280 kWh followed by middle income households (n: 1,058) at 229 kWh, while low income households (n: 2,984) experienced the lowest summer electricity consumption of 166 kWh. In AC households, mean monthly summer electricity consumption was 1.6 times more than winter consumption, while for non-AC households mean summer use was 1.4 times more than winter use, implying that seasonal variation was prevalent irrespective of presence of AC. Climate zone was found to influence seasonal electricity use. The highest mean monthly summer electricity use was observed for AC households (n: 561) at 307kWh in the composite zone, while the highest monthly winter electricity use was 210kWh in non-AC households (n: 308) located in the cold zone. Based on the Least Absolute Shrinkage and selection operator (LASSO) method, number of residents, number/usage of appliances and floor area (m^2) were found to have the biggest impact on electricity consumption. To curtail the growth of REC in India, the seasonal and climatic variation in REC should be addressed through national energy policy.

1. INTRODUCTION

The residential sector in India contributes to one fourth of the country's total electricity consumption (Bureau of Energy Efficiency (BEE, 2019)). Residential electricity consumption (REC) has been growing at an annual growth rate of 8% every year and is projected to

double over the next decade due to increased urbanisation, housing growth, higher electricity access and affordable lifestyles alongside rising temperatures (Ministry of Power and Central Electricity Authority, 2020). Space-cooling has been recognised to be the key driver of REC as confirmed by a study by the Indian Bureau of Energy Efficiency (BEE) which reported that consumption from space cooling devices (AC and other space cooling devices) reached up to 65% of REC in multifamily residential buildings (BEE, 2014). Another recent study based on real-time data found that daily REC driven AC usage in summer season was twice that of the monsoon season (Gupta and Antony, 2021). Despite the projected sales of room air-conditioners, currently per capita space cooling energy consumption in India is 69kWh which is a quarter of the world average. Studies have also reported that 91-93% of the Indian households do not own an AC (Sharma et al., 2021) . A study by Agarwal et al. (2020a) found that only 2% of the non-AC households actually planned to buy an AC in the next two years. The demand for ACs may get further subdued due to the economic impact of the COVID-19 crisis. Moreover less energy-intensive space-cooling devices like air-coolers which use 10-20% of the electricity used by a similar capacity of AC, may be preferred by households with lower affordability (ibid).
A few studies have investigated differences in REC between AC and non-AC households. A study by Singh et al. (2018) showed that REC in AC households was 34% more than non-AC households within a sample of 1026 households. Similar findings were observed in a small-scale study of 20 households wherein mean annual electricity use of AC households were 29% higher than non-AC households (Gupta et al., 2020). Other regional studies by Khosla et al. (2021) and Rawal and Shukla (2014) have also reported how seasonal consumption of AC use in dwellings tends to vary with climatic factors. However these studies have focussed on specific climate zones or geographic regions. It is evident that a comprehensive nation-wide study of REC, underpinning physical and social characteristics across AC and non-AC households has been lacking in the Indian context. Within this context, this paper investigates the extent of variation in REC in AC and non-AC households by climate zone, seasons and income group, using detailed statistical analysis of nationwide empirical data for 4,877 households representing all five climatic zones. The survey data were gathered as part of a national NEEM-CLASP study in 2018-2019. The determinants that drive REC across summer and winter were also identified using the Least Absolute Shrinkage and selection operator (LASSO) method.

2. EVIDENCE TO DATE

A number of studies in India were identified that were published in the last 21 years (2000-2021), with a sample size of at least 30 households and adopted a survey based approach for understanding urban REC and the factors driving it. These studies are summarised in table 1 below.

Table 1: Studies on REC in India using survey data

No	Study authors	Study period	Type of data	Climatic zone covered	Sample size	Analysis method
1	Khosla et al.,(2021), Tewathia	2012-18	Primary and secondary	Composite	100-5000	LASSO regression, Multi-variate

	(2014), Thapar (2020)					regression, Descriptive statistics
2	Agrawal et al., (2020b)	2019	Primary	Warm-Humid	93	Multi-variate regression and Descriptive statistics
3	Murthy et al., (2001), Ramachandra et al., (2017)	1994-2014	Primary and secondary	Temperate	1000-2000	Appliance stock method, Descriptive statistics, Spatial analysis
4	TERI, (2008), Cibi et al., (2020)	2007-2019	Primary and secondary	Warm-Humid, Temperate	1500-4000	Descriptive statistics, Appliance stock method and Multi-variate regression
5	BEE, (2014)	2006-13	Primary	Composite, Hot-Dry	732	Descriptive statistics
6	Rawal and Shukla, (2014), Singh et al., (2018), Sachar et al., (2018)	2016-17	Primary	Composite, Warm-Humid, Hot-Dry	500-1500	Descriptive statistics, Step wise ordinary least square regression, regression
7	Tiwari, (2000), Chindarkar and Goyal (2019), Pachauri, (2004), Agrawal et al., (2020a), Filippini and Pachauri, (2004)	1987-2019	Primary and secondary	All (Composite, Warm-Humid, Hot-Dry, Temperate and Cold)		Ridge Regression, Step wise ordinary least square regression, Descriptive statistics, Regression

A study by Thapar (2020) found that summer months accounted for 60% of annual REC due to greater use of air-conditioners and refrigerators while winter months accounted for 20%. Late-night peaks (10pm-1am) during the summer months were prevalent wherein ACs were used for sleep. The seasonal consumption correlated with climatic factors, income and inefficient appliances (non-star rated). Tewathia (2014) reported that stock of appliances and their usage was a key determinant of REC. The average monthly electricity in summer was found to be 470kWh, which was almost two times more than winter consumption (276kWh). Another study by Agarwal et al., (2020b) found income group to be one of the major drivers of the ownership and usage of these cooling appliances. The impact of reduced income on REC was shown by Pathak et al., (2020) during the pandemic of 2020. Ramachandra et al., (2017) confirmed the variation in REC by income group and region. A study by the Indian BEE (2014) discovered that AC households could adopt a mixed mode operation even during the summer season; however, the differentiation within climatic zones or income groups was not studied.

The ownership and use of air conditioner (AC) was a key factor in determining the household's REC and its load profile during summer and monsoon (Agrawal et al., 2020b). Singh et al.,(2018) also found that REC was more sensitive to ownership of air conditioner rather than other demographic variables and other appliances. Regression analysis revealed

that households in composite and warm-humid climate zones consumed relatively more electricity than households located in the hot-dry climate. However, the cause for this disparity was not explored (ibid). Cibi et al,(2020) used correlation analysis to find variation in correlation of appliance stock and consumption across different cities. Several studies reported summer months to be more price-inelastic than during the other seasons of the year (Chindarkar and Goyal, 2019, Filippini and Pachauri, 2004, Pachauri and Jiang, 2008, Tiwari, 2000). The seasonal price inelasticity indicated that the residents did not reduce their consumption due to higher temperatures, where AC was used as a necessity.
The key drivers of REC identified in the studies included income group, stock of appliances and usage, climate, seasons, floor area and number of occupants. These studies were either based on specific regions or cities or based on limited information. As a result, there is limited comparative evaluation of REC use between AC and non-AC households in India by climatic zones, seasons and income groups to deepen the understanding of the factors that influence any variation by space (climatic zone) or time (seasons) which this study seeks to address.

3. METHODOLOGY

This study conducts statistical analyses of nationwide survey data of 4,877 urban households (single-family/multi-family, different income groups), which were located in 21 cities representing all five climates ranging from cold, composite, hot-dry, warm humid and temperate climates. The survey data were gathered as part of a national NEEM-CLASP study during 2018-2019 and made available to the authors by NEEM-CLASP. As shown in Table 2, the face-to-face survey gathered data on physical characteristics, household characteristics, non-AC appliances, space cooling devices including AC units and their annual usage, level of energy awareness of householders as well as cost and amount of electricity used during summer and winter months.

Table 2: Survey data variables

Variable group	Variable categories
Physical characteristics	*Climatic zone* (Composite, Cold, Temperate, Warm-humid, Hot-dry)
	Built form (Flats/Apartment in a society, Flats/Apartment-standalone, Villas (gated community), Independent houses/bungalows)
	Ownership (Rented, self-owned, employer provided)
	Dwelling size (1BHK, 2BHK,3BHK,4 or more BHK)
	Built-up area (m^2)
Household characteristics	*Income group* (LIG, HIG, MIG)
	Family size (Number of residents)
	Family structure (Nuclear, Nuclear with elders, Joint)
Non-AC appliances	*Number of non-AC appliances* (Wet appliances, Cold appliances, ICT, Cooking & Kitchen appliances, Other electrical appliances)
Air conditioners	*Number of AC units*
	AC usage hours per day (day and night)
	AC set point temperature (° C)
	Type of AC unit (Window or Split)
	Age of AC units (less than 1 year, 1-5 years, 5-10 years, Over 10 years)
	Cooling capacity of AC units (Ton)
	Condition of AC units (First hand, Second hand)
Other space cooling devices	*Number of space cooling appliances* Fans [Ceiling fans, Wall/table/mounted fans] and desert coolers

Behaviour and level of energy awareness	Very concerned about environment and always purchase star rated appliances
	Prefer to purchase star rated appliances
	Switch-off Appliances when not in use
	Importance to cost and performance than environment
	Changed appliance settings with respect to weather
	Somewhat concerned about environment but no purchases on this
	Neither aware nor concerned on environmental issues
Electricity use and cost	*Mean monthly electricity use in summer* (kWh/month) *Mean monthly electricity use in winter* (kWh/month)
	Mean monthly electricity cost in summer (INR) *Mean monthly electricity cost in winter* (INR)

The raw data were first recoded into groups that were used in the analysis. For example, *household income* was recoded to LIG, MIG and HIG based on the Pradhan Mantri Awas Yojana), *BHK (bedroom, hallway, kitchen) group* was recoded into 1BHK to 4 or more BHK, AC and non-AC household group as well 0AC to 3 or more AC. Climatic zone classifications were extracted from the National Energy conservation Building Code (ECBC). Annual usage hours per minute, hour, day and month were calculated for all the available electric appliances. The survey responses were checked for inconsistencies - straight-line responses, odd responses, partially filled forms and outliers. After a through data cleaning of the sample, the survey data for 4,877 households was available for analysis.
Descriptive statistical analysis was undertaken for numeric variables to determine the mean, median, maximum, minimum and standard deviation. Transformation of variables was done where appropriate. In order to address the objective of this study, the data was analysed at the overall sample level stratified by climatic zone, income group and AC/-non-AC household to understand the variation in REC among these groups. The study assumed summer period from April-June while winter was presumed to run from November-February across all cities for uniformity. Correlation analysis was conducted to identify variables that were strongly associated with energy consumption (summer or winter). Highly correlated variables were excluded for regression. The statistical method of least absolute shrinkage and selection operator (LASSO) regression was then used to identify the variables that drive the seasonal electricity use. This process reduces overfitting, helps feature selection (by removing redundant variables) and focusses on the key variables that affect REC.

4. RESULTS

The sample of 4,877 households was split by 3,340 non-AC (68.5%) and 1,537 AC households (31.5%) Across both AC and non-AC households, it was identified that 50% of the households were stand-alone houses of 3BHK, located predominantly in composite or warm-humid climatic zones. As expected, none of the households located in the cold zone owned an AC. It was also observed that across the LIG group, only 22% owned an AC unit, while within the MIG households 39% owned one or more AC units and almost half of HIG (49%) households owned one or more AC units. The mean floor area across AC households ($98m^2$) was 27% higher than non-AC households ($72m^2$).

4.1 Seasonal variation in electricity use

As shown in Table 3, AC households consumed 1.6 times more electricity use than non-AC households in summer and 1.4 times more in winter, which is why monthly electricity cost of non-AC households was found to be almost half of AC households. Objectively, AC households spent around 21 USD for an average of 275kWh per month in summer while non-AC households spent 12USD for 177kWh per month in summer. In winter months, AC households spent around 13 USD or 186kWh per month and non-AC households spent 8USD or 133 kWh per month. Within AC households, monthly summer REC was 1.5 times more than winter consumption and this variation was 1.3 times in non-AC households, indicating that seasonal variation was prevalent in both AC and non-AC households.

Table 3: Mean monthly REC shown by AC and non-AC households

	Mean monthly summer REC kWh (median)	Mean monthly winter REC kWh (median)
All households (n: 4,877)	208 (150)	149 (100)
Non-AC households (n: 3,340)	177 (139)	132 (99)
AC households (n:1,537)	275 (200)	186 (130)

The percentile distribution of residential electricity consumption (REC) as shown in figure 1 below, indicates that the 90th percentile consumed almost seven times (for AC households) and at least five times (in non-AC households) more than the 10th percentile across both summer and winter. The summer and winter REC variation was found to be quite similar for AC and non-AC households with summer season showing a larger tail on its normal curve, exhibiting a higher usage in summer than winter as seen in Figure 1.

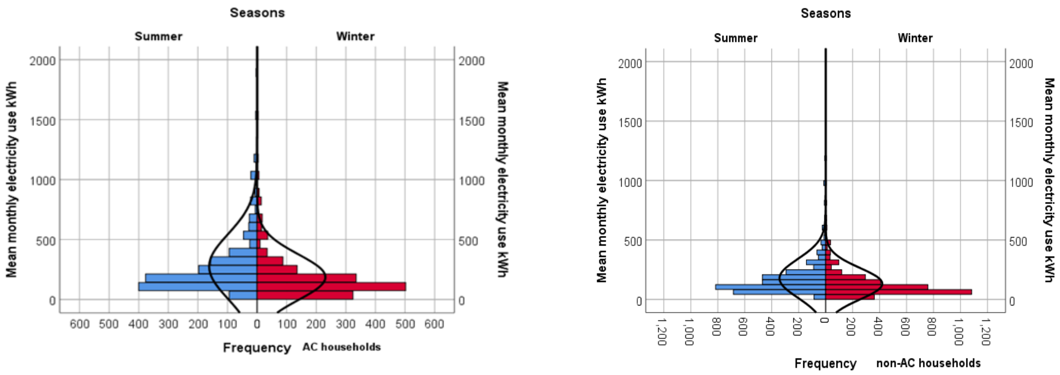
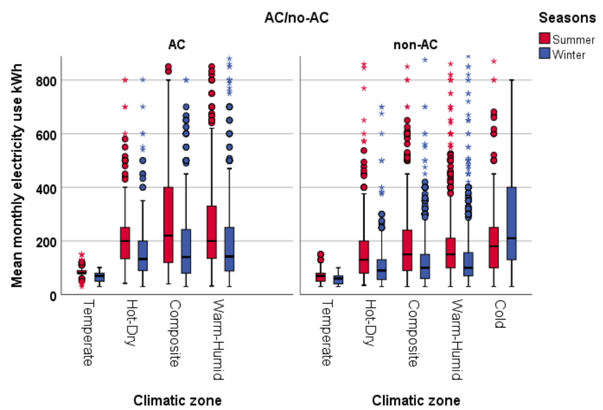


Figure 1: Distribution of mean monthly summer and winter REC in AC households (right) and non-AC households (left)

4.2 Climatic variation in electricity use

The climatic zones of India as defined by ECBC states that the hot-dry region had the highest mean temperature for midday in summer at 42.5°C, followed by composite zone at 37.5°C, warm-humid zone at 32.5°C, temperate at 32°C and cold zone at 23.5°C. Cold zone climate had the lowest mean temperature in winter at -5°C, followed by hot-dry at 5°C , warm-humid at 7°C, temperate at 17°C and the highest in composite at 22.5°C. In summer, across both AC and non-AC households, highest REC was found in households located in the composite zone (307kWh) and lowest REC was in households located in the temperate zone (87 kWh). In winter, REC was observed to be highest in the warm-humid zone (214kWh) and lowest in the temperate zone (64kWh). As shown in figure 3 below, the climatic variation in REC was observed to be substantial, given that monthly REC in the relatively milder temperate climate zone was a third of the monthly REC in more extreme zones such as the composite and warm-humid climates. This is because households in the composite climate zone showed preference for a lower set point at 22°C, had the longest AC usage hours, while the majority of AC households in warm-humid climate had set point temperature below 24°C. This finding was in line with the study by Sachar et al (2018) which revealed that AC runtime was highest in the composite climate zone in India.



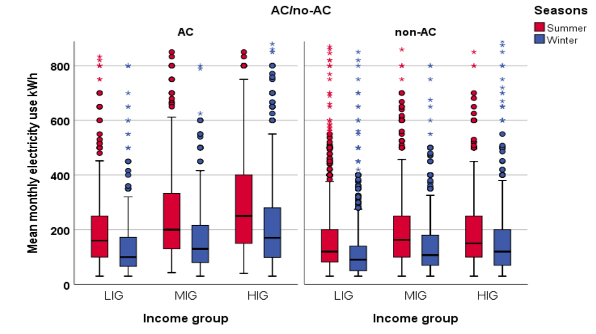
	Climatic zones	Mean monthly summer consumption kWh	Mean monthly winter consumption kWh
AC	Temperate	88	66
	Hot-Dry	232	158
	Composite	311	201
	Warm-Humid	296	208
non-AC	Temperate	71	56
	Hot-Dry	165	107
	Composite	183	126
	Warm-Humid	188	138
	Cold	218	296

Figure 2: Summer/winter variation of mean monthly electricity consumption across AC/non-AC households in climatic zones

The above figure also shows that climatic variation was evident across AC and non-AC households. In summer, AC households in composite zone consumed highest monthly electricity use amounting to 311kWh, while the lowest monthly REC was 88 kWh in AC households in the temperate zone. While non-AC households in cold-zone consumed the highest REC 218 kWh during the winter, the lowest monthly REC in non-AC households was observed to be 56kWh in the temperate zone. The climatic variation was also evident across seasons with 45% of households in composite zone using ACs in the summer, while the wintertime use of room heaters was three times more in households in cold zone due to colder climatic conditions.

4.3 Income group variation in electricity use

The variation in REC by income group was prevalent in AC and non-AC households as shown in figure 3 in the following page. Among AC households, in summer the high income group (HIG) households reported the highest mean electricity consumption at 349 kWh, followed by medium income group (MIG) households with a mean monthly electricity consumption of 272 kWh, and 216 kWh in low income group (LIG) households. HIG households consumed 1.6 times more than LIG households across both summer and winter months. As shown in figure 3, the variation in monthly REC in non-AC households followed a similar trend with HIG households using the highest monthly REC of 221 kWh, followed by MIG (205 kWh) and LIG households (159 kWh). With each income group, monthly REC in the summer was nearly 1.4 times more than that of the winter, irrespective of AC ownership, indicating the influence of seasons over AC ownership.



	Climatic zones	Mean monthly summer consumptio n kWh	Mean monthly winter consumptio n kWh
AC	LIG	216	151
	MIG	272	176
	HIG	349	238
non -AC	LIG	159	115
	MIG	205	148
	HIG	221	182

Figure 3: Distribution of summer and winter electricity consumption across income groups

Interestingly when the variation of monthly electricity consumption was analysed by income group in each climate zone, it was found that monthly electricity use of non-AC HIG households in cold climate zone was comparable to summertime monthly electricity use of AC households in composite and warm-humid zones, as seen in Figure 4. The reinforced the influence that climate factors have on REC.

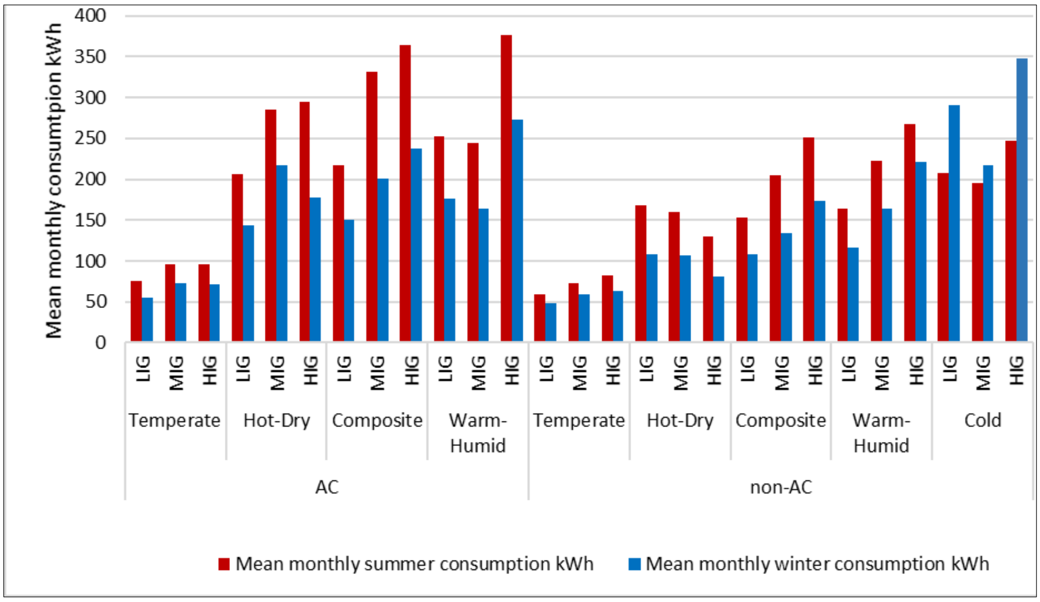


Figure 4: Distribution of summer and winter electricity consumption across income groups, climatic zones for AC and non-AC households

4.4 AC ownership and usage

All AC households owned ceiling fans along with an AC unit, while 96% of non-households owned ceiling fans. Electric geysers were owned by more than half of AC households (52%) and owned by only 13% of non-AC households. Desert coolers were interestingly not very commonly owned or used amongst AC households (only 20% owned them), but were more commonplace in non-AC households where 45% owned them. This indicates the untapped potential of introducing non-AC cooling appliances in AC households to encourage to mixed-mode operation of cooling devices to reduce electricity consumption. The most common type of AC system used was split system with a capacity of 1-1.5 ton, with 72% of AC units less than five years old. The average daily use of AC was found to be 5.6 hours per day. The mean daily AC usage varied from 5 hours in LIG households to 5.9 hours for MIG and 6 hours for HIG.

The usage hours of AC units varied from 5.5 hours for households with one AC, to 6.8 hours in households with two AC units and 8.6 hours in households with three or more AC units. Across income groups, AC set point temperature ranged widely - from as low as 16°C to as high as 28°C. Interestingly, those who set their mean AC temperatures to 23°C or lower (mostly households with three or more than three AC units) were observed to have twice the amount of electricity consumption than households with set-point temperatures below 24°C. About 61% of all AC and non-AC households reported to be using energy star rated products. Although LIG households preferred to have an energy rated appliances to save electricity, understandably a higher percentage of AC HIG households purchased and used energy rated appliances due to the higher upfront cost.

4.5 Determinants of REC

Correlation analysis was conducted for survey variables to identify any relationships between variables. It was found that presence of AC, AC set point, AC usage hours during daytime and night time were moderately correlated ($r>0.5$). A similar observation was made for family structure and number of occupants ($r>0.5$).The number of appliance and their usage hours were also correlated.

The variables that were not strongly correlated were further used for regression analysis. LASSO regression was used to select the variables that influenced seasonal electricity use for the overall sample of AC and non-AC households. The mean summer and winter electricity use as dependant variables were analysed with 10 fold cross validation method for different variables including family structure/family size, usage hours of AC units/number of AC units, number of non ac appliances/usage of non-AC appliances, floor area in m^2/BHK, climatic zone, floor level/household type and income group.

Table 4: Regression results of predictor variables on consumption in summer and winter

Standardized Coefficients Beta ($p<0.05$)	Summer consumption kWh (dependant variable)	Winter consumption kWh (dependant variable)
Family size	0.10	0.11

Number of electric geysers	0.04	0.04
Number of Air Conditioners	0.09	0.03
Number of room heaters	0.07	0.09
Number of space cooling appliances	0.14	0.09
Floor area	0.18	0.17
Multiple R	0.53	0.5
R Square	**0.29**	**0.24**
Adjusted R Square	0.28	0.24
Regularization "R Square" (1-Error)	0.28	0.24
Penalty	**0.08**	**0.08**

Based on LASSO analysis, family size (number of residents), floor area, number of non-AC appliances, number of AC appliances and number of non-AC cooling devices were found to have a significant impact on REC in summer and winter seasons.

5. DISCUSSION

This study confirmed that there was substantial variation in residential electricity use prevalent across different climatic zones, seasons and income groups in India. Given the similar trends observed for both AC and non-AC households, it was evident that AC ownership, although significant, was secondary to the climatic zone the household was based in, season in which electricity use was happening and what income group the households fell in. Households in composite zone used AC for longer hours and experienced the highest monthly REC, followed by households located in the warm-humid zone. Households in cold zone observed an increase in space heating almost three times more than other households. This disparity in REC needs to be recognised in national energy policy which needs to be customised to climate zones and income groups.

Seasonal variation in electricity use was also significant. For the overall sample, it was found that monthly summer REC was nearly 1.4 times the monthly winter electricity use for both AC and non-AC households. In summer, electricity consumption in AC households was almost two times more than non-AC households. Moreover only 20% of AC households owned desert coolers. Policy interventions could seek to supress summer peak of AC households by encouraging use of less energy-intensive cooling devices such as fans, desert coolers, along with smart control of AC use, especially in climate zones such as composite and hot dry.

The average AC set point temperature in AC households was observed to be 21°C, which was much below the BEE recommended set-point temperatures of 24°C for optimising AC operation and energy use. At set-point temperatures below 19°C which was found more commonly among households that owned three or more AC units, REC was found to be increase by 1.6 times. Encouraging householders to increase set point temperatures and mandating new energy rated AC units to not operate below 24°C could lead to rapid reduction in electricity use.

It was also identified that as households move to the next higher income group, REC is expected to rise by an average of 1.2 times be it summer or winter seasons. With the current rate of urbanisation, lifestyle improvement and aspiration to reach higher levels of comfort, the move to MIG and HIG groups will drive the growth of REC in India. Energy policy needs to be customised for these different income groups adopting a combination of incentives and subsidies to drive down electricity use.

6. CONCLUSION

This study undertook statistical analyses of nationwide survey data of 4,877 urban households (single-family/multi-family, different income groups), which were located in 21 cities representing all five climates ranging from cold, composite, hot-dry, warm humid and temperate climates. The survey data were gathered as part of a national NEEM-CLASP study during 2018-2019. Substantial variation in mean monthly REC was observed by climate zone, seasons, income groups as well as AC ownership. As expected, high income households (n: 1,084) reported the highest mean monthly summer electricity consumption at 280 kWh followed by middle income households (n: 1,058) at 229 kWh, while low income households (n: 2,984) experienced the lowest summer electricity consumption of 166 kWh. In AC households, mean monthly summer electricity consumption was 1.6 times more than winter consumption, while for non-AC households mean summer use was 1.4 times more than winter use, implying that seasonal variation was prevalent irrespective of presence of AC. Climate zone was found to influence seasonal electricity use. The highest mean monthly summer electricity use was observed for AC households (n: 561) at 307kWh in the composite zone, while the highest monthly winter electricity use was 210kWh in non-AC households (n: 308) located in the cold zone. Based on the LASSO method, number of residents, number and usage of appliances and floor area (m^2) were found to have the biggest impact on residential electricity consumption.

These empirical findings not only deepen the understanding of sociotechnical factors that shape urban residential electricity use in India, but can also be used to reduce energy demand through smart management of appliances in line with external weather. The findings also suggest that the Indian residential energy code would need to address the variability in energy use by climatic zones, across seasons and income groups. Future work should focus on gathering time-series electricity monitoring data for a large number of AC and non-AC households across different climate zones and seasons. This will help to understand where (climatic zones), when (seasons), for what type of households (income groups) and extent of AC ownership, surges in REC are likely to occur to avoid a gap between energy supply and demand.

7. ACKNOWLEDGEMENT

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