Correlating room air conditioner energy consumption with thermostat setting to encourage occupant behavioural change towards enhanced energy efficiency and thermal comfort

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Abstract
With less than 10 % penetration today, the installed base of room air conditioners (RACs) in India is 39 million units which is expected to grow exponentially in the coming decades owing to increasing population, rising temperatures and rising aspirations for improved quality of life. Surveys conducted by AEEE to understand RAC operating behaviour show that approx. half of the surveyed population prefer to operate RACs at set-points 24 °C or lower. With research efforts worldwide focused around thermal adaptation of people living in tropical climates, adaptive thermal comfort (ATC) based RAC operation is gaining traction among policy makers in India. The Government of India is planning to frame definitive guidelines around optimal thermostat setting for RACs to encourage occupant behavioural change towards enhanced energy efficiency and thermal comfort. However scientific lab-based research to correlate RAC energy consumption with ATC based set-point is largely missing. To support evidence-based policy formulation, AEEE took upon a study to establish energy savings impact through the adoption of ATC. While reviewing various test standards it was found that none of the accepted protocols support such testing and hence customized tests were designed in collaboration with a state-of-the-art balanced ambient calorimeter testing facility (NABL accredited) in India. Three RACs of the predominant ~1.5 TR cooling capacity of different make, efficiency and refrigerant type were tested at all combinations of three indoor conditions 22 °C, 24 °C, 27 °C and three outdoor conditions 30 °C, 35 °C, 40 °C. The test results reveal that an energy saving potential of 8 to 10 % per degree Celsius set-point increase could be reaped while increasing the indoor set-point from 22 to 27 °C in inverter RACs. The energy saving potential in case of used fixed speed RAC was observed to be only one third as compared to new inverter RACs. Empirical evidence on the energy savings or penalties due to thermostat setting presented in this paper shall help both policy makers to frame informed guidelines for occupants on optimal thermostat setting as well as manufacturers to set optimal default set-point and raise the minimum allowable thermostat setting.

Introduction
The current penetration of Room Air Conditioners (RAC) in India is 7–9 % with 39 million units in use today. With the growing cooling demand driven primarily by the hot tropical climate, RAC market is expected to grow at 10 % to 15 % growth rate, increasing the penetration to ~40 % within the next two decades. However, this rise in cooling demand is aligned with developmental needs of a prospering economy. Apart from climatic influences, the amount of energy needed to meet space cooling depends mainly upon the type & efficiency of the equipment and how it is operated. Decisions by building occupants and operators about appropriate operating temperature settings is less understood and far less practised, notwithstanding the considerable impact on cooling energy demand. Adaptive thermal comfort (ATC) has been recognized as an important strategy to achieve energy savings by building scientists and research groups the world over and

Table 1. Neutral temperature range in various building types and climates.

Sr. No.	Ventilation type (NV/MM/AC)	Neutral temp. range	Location	Climate type
1	AC	26.1 °C–28.1 °C	Hyderabad, Chennai, (India)	Warm and humid
2	AC	28 °C	Kyoto, Japan	Composite
3	MM	24 °C–28.5 °C	India (Ahmedabad, Gurgaon)	Hot and dry, Warm and humid
4	MM	22.6 °C–29.9 °C	China	Sub-tropical
5	NV/AC	26.4 °C–28 °C	Hyderabad, India	Warm and humid
6	NV/AC	26 °C–27.9 °C	China	Humid, Sub-tropical
7	NV/AC	24.7 °C–27.4 °C	Thailand	Tropical and humid
8	NV/MM/AC	21.5 °C–28.7 °C	India	Hot and Dry, Moderate, Warm and humid, Composite, Cold

Note: Adopted from Kumar et al (2018b).

offers a low-cost intervention opportunity to achieve savings through user adaptation and behavioural changes. Although the concept of ATC and its energy savings potential has been demonstrated over the last 3–4 decades (de Dear *et al* (1998), Nicol *et al* (2002)), ASHRAE formally accepted this concept only in its ASHRAE 55 (2004)[1] standard, which formalised the accruing experimental evidence over decades that people, who get acclimatised long-term with "higher" or "lower" temperatures outside of typically accepted comfort range, are tolerant of wider temperature ranges without experiencing thermal discomfort. This concept has evinced remarkable interest within the Indian research and policy community in the recent past. The Indian model for adaptive comfort (IMAC) is a pioneering research, which provides the neutral temperature in naturally ventilated (NV), air-conditioned (AC) and mixed mode (MM) buildings in India. Per this study, the neutral temperature range in naturally ventilated buildings varies from 19.6 °C–28.5 °C while in air-conditioned and mixed mode buildings it is ranged between 21.5 °C–28.7 °C. Several studies globally and in the Indian context, as summarized in Table 1, have reinforced that the thermal comfort band ranges between 21.5 °C–29.9 °C. Dhaka *et al* (2013) conducted a questionnaire-based evaluation of occupants' thermal comfort sensation and estimated energy savings, through eQUEST simulation software. A study carried out by Ghawghawe *et al* (2014), gave a detailed account of the percentage reduction in cooling energy consumption at different temperature set-points for five cities representing different climatic zones of India by employing DesignBuilder simulation software. A study by Kumar *et al* (2018b) was first of its kind to employ psychrometric lab testing of RACs to establish energy saving impact through adoption of ATC at the national level.

Surveys conducted by AEEE to understand RAC operating behaviour show that approx. half of the surveyed population prefer to operate RACs at set-points much below 24 °C and a significant proportion of people (66 %) prefer using a fan in conjunction with air-conditioning (Sachar, 2018). However, there is still very limited lab research not just in India but globally on the energy consumption implications of thermostat setting of RACs. The correlation of RAC energy performance and indoor set-point temperatures has not been well quantified using lab or on-site testing. One probable reason could be the inadequacy of the current ISO testing standards. ISO 5151 (2017) specifies performance testing, standard conditions and the test methods for determining the capacity and efficiency ratings of RACs. However, it does not cover the determination of seasonal efficiencies, which provides a better indication of efficiency under actual operating conditions. ISO 16358-1 (2013) specifies the testing and calculating methods for seasonal performance factor of equipment covered by ISO 5151, ISO 13253 and ISO 15042. It specifies the seasonal performance test conditions and the corresponding test procedures for determining the seasonal performance factor of equipment, under mandatory test conditions and is intended for use in marking, comparison, and certification purposes. However, there are no standards or testing protocols/procedures available in the existing literature to assess the actual energy savings potential by adopting higher set-point temperature preferences.

The current study is an attempt to determine the potential energy savings attributed by adopting higher indoor set-points by designing a suitable lab test and then extrapolating the results to calculate annual energy savings estimate. This can then better inform HVAC designers, manufacturers, policymakers, facility managers, etc. to develop climate-responsive policies and operations & maintenance (O&M) practices.

Experimental Design

DESCRIPTION OF TEST SET UP

The performance of the air conditioning units is evaluated using a balanced ambient calorimeter testing facility. The facility, as represented in Figure 1, consists of an indoor and outdoor chamber partitioned by a common wall. The indoor chamber houses the indoor unit of test RAC whilst the outdoor unit is installed in the outdoor chamber. Both the chambers are equipped with suitable equipment and instrumentation to accurately control the temperature and RH in the chamber mimicking the required outdoor/indoor conditions. The energy balance in the indoor chamber determines the cooling capacity, i.e. the energy removed by the air conditioner is equivalent to the energy that the chamber equipment must supply to the system in order to keep the same temperature conditions. Each chamber also consists of an air sampling unit which draws air from the return grill of the RAC unit (as shown in Figure 1). The air sampling unit is equipped with resistance temperature

1. American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) Standard 55: Thermal Environmental Conditions for Human Occupancy.

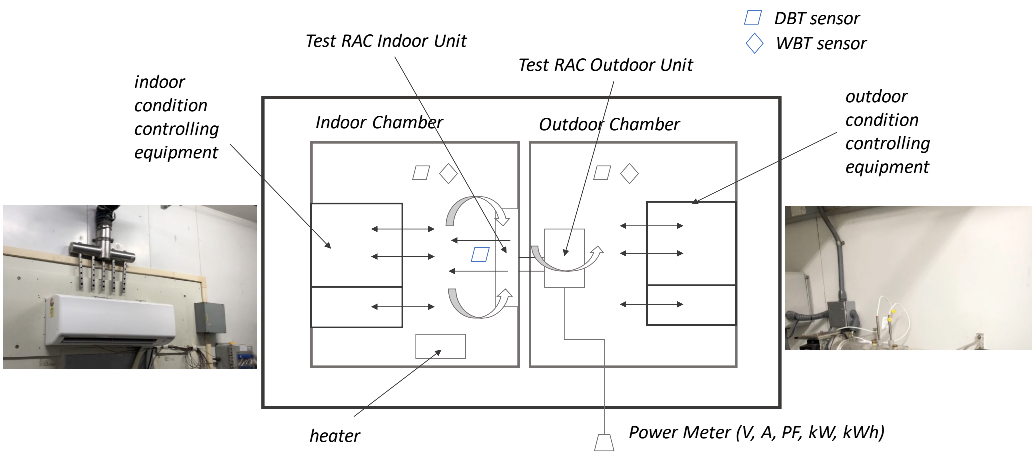

Figure 1. Test setup schematic and pictures of testing at balanced ambient calorimeter lab.

Table 2. Specifications of tested RAC Units.

Test Specimen	Cooling Capacity at Full Load	Type	BEE Star Rating	Energy Efficiency	Refrigerant Type
RAC Unit 1 (new)	5.0 kW (~1.4 TR)	Inverter – Split	3 Star (2018)	3.70 ISEER	R-32
RAC Unit 2 (new)	5.3 kW (~1.5 TR)	Inverter – Split	5 Star (2018)	5.20 ISEER	R-290
RAC Unit 3 (used for 3 years)	5.0 kW (~1.4 TR)	Fixed Speed – Split	5 Star (2015)	3.51 EER	R-22

detectors (RTDs) to measure the Dry Bulb Temperature (DBT) and Wet Bulb Temperature (WBT). Further, two and four T-type thermocouples are placed at the supply and return grills respectively to measure the corresponding DBT.

DEVELOPMENT OF THE TEST PROCEDURE

The current test standards being followed in India and globally are primarily formulated to enforce Minimum Energy Performance Standards (MEPS) to identify and eliminate worst performing appliances and also providing the consumer an informed choice about energy and cost saving potential through the energy labelling programmes. However, setting and rating RACs (both fixed speed and inverter types) at 'locked' conditions, as specified in the test standards, fails to accurately reflect how RACs operate in real life situations, where the unit operates for its lifetime, to match the room (end user home or office) load. Hence AEEE developed a customised test procedure in consultation with a NABL[2] certified, international RAC testing facility in India.

The tests are carried out on three RACs as mentioned in Table 2. For the two inverter type RAC Units, a total of 18 tests were carried out at three indoor set-points (22 °C, 24 °C and 27 °C) for three outdoor temperatures (30 °C, 35 °C, and 40 °C); and for the fixed speed type RAC Unit, 3 tests were carried out at the three indoor set-points at 35 °C outdoor temperature. A three-year-old fixed speed RAC unit was selected to assess RAC operation, at mid-point of their life, accounting for derating to get a realistic idea of lifecycle energy savings potential.

2. National Accreditation Board for Testing and Calibration Laboratories.

EXPERIMENTAL PROCEDURE

A 2,000 W convection heater is introduced into the indoor chamber to ensure constant heat load (emulating human and climatic load typically encountered in a residential setting) during the experimental run time. The indoor and outdoor chamber equipment of the balanced heat calorimeter facility are run till the desired outdoor conditions are reached in both outdoor and indoor units, following which the test RAC in the indoor unit is turned on along with the convection heater. The indoor chamber equipment is then turned off, once the steady state is reached, i.e. indoor and outdoor are at same desired outdoor temperature with the heater and the AC unit on. From this point data of the controlled variables are logged every 5 minutes till the indoor temperature gradually reaches (approaches) the indoor set point condition. This unique testing design employed helps capture the differential energy consumption of RACs at different thermostat settings at varying ambient conditions depicting real-world conditions. The electrical parameters viz. voltage, current, power and energy consumption are monitored, and data logged every 5 minutes (Table 3). The indoor chamber temperature depicting effective room temperature being maintained by test RAC is monitored and logged at two points in the room; one at the air sampler unit (both DBT & WBT) and other at the return grill of the indoor RAC.

Results and Observations

The test results for 4-hour monitoring (Figure 2 – left side), show that as the room temperature (secondary Y-axis) approaches the indoor set-point conditions, the energy consumption (at 5-minute duration) depicted by the area graphs (primary Y-axis) decreases due to ramping down to lower fre-

Table 3. Specifications of lab apparatus used for monitoring and data logging.

S. No.	Instrument/Equipment	Accuracy	Measured parameters (unit)
1	Digital Power Meter	± 0.5 %	Voltage (Volts), Current (Ampere), Power Factor, Power (W), Energy Consumption (kWh)
2	Resistance temperature detectors	± 0.1 °C	Indoor/Outdoor room air DBT (°C), WBT (°C)
3	T-type thermocouple	± 0.3 °C	Indoor return/supply air DBT (°C)

quency operation in case of inverter RAC Units 1 & 2 and the beginning of cycling (intermittent ON/OFF operation) in case of fixed speed RAC Unit 3. A comparison of the three indoor conditions at 35 °C outdoor condition reveal that as the indoor set-point increases from 22 °C to 24 °C and 24 °C to 27 °C, the decrease in energy consumption not only begins early but also stabilises at comparatively lower energy consumption rates with the increasing indoor setpoints. Similar trends were observed for the other two tested outdoor conditions as well. Understandably, the energy consumption increases with the increase in outdoor temperature condition for all indoor conditions.

For the fixed speed RAC Unit 3, the monitored room temperature is much above the reference temperature set-point condition even at the beginning of cycling operation of compressor. This could be attributed to the following two reasons – capacity degradation of RAC unit due to three years of usage; and, constraints of fixed speed RACs in closely regulating indoor set-point conditions as compared to the inverter technology. The cumulative energy consumption graphs (Figure 2 – right side) show that as the room temperature approaches the indoor set-point condition (compare from Figure 2 – left side), the energy consumption rate decreases. As evident from the slopes of representative curves, the inflection point is more pronounced in case of inverter RAC Units 1 & 2 while in the case of fixed speed RAC Unit 3, the change in energy consumption rate is comparably very small.

Data Analysis

DEVELOPMENT OF ENERGY SAVING EVALUATION METHODOLOGY

The customised lab tests presented in this paper were designed to investigate the energy consumption trends of RACs at different thermostat settings in real-world operation emulated by different test indoor/outdoor conditions. In order to estimate the annual energy consumption under different scenarios, the representative trends emerging in the lab test results were analysed and a methodology was devised to extrapolate the available test data into daily and annual energy consumption estimates. AEEE's methodology for energy saving estimation through adoption of ATC comprises of three chronological steps. First, establishing the energy consumption trends for different combinations of test indoor and outdoor conditions; second, aggregating the trends into representative daily energy consumption; and third, aggregating the daily energy consumption for respective outdoor conditions' test results to comprise representative annual energy consumption.

The test results for both inverter RACs showed a marked deflection in energy consumption trends while arriving close to the set indoor condition. The inflection point to define change in energy consumption rate at each test condition was established by carefully examining the energy consumption at each 5-minute bin and the instantaneous power draw at each 5-minute time step. Two separate trend lines were plotted for each test condition on either side of the inflection point representing the initial higher energy consumption rate while the monitored room temperature is approaching the indoor set-point condition, and subsequent lower energy consumption rate (lower frequency operation for inverter RACs and cycling for fixed speed RAC) while the monitored room temperature is close to (or achieved) the indoor set-point condition. For each such linear regression, an R^2 value of greater than 0.9 was observed as illustrated for one test condition in Figure 3.

The Bureau of Energy Efficiency (BEE) in its testing method for calculating ISEER has suggested the reference outdoor temperature bin distribution representing typical Indian climates. The suggested bin hours for outdoor temperature ranging from 24 to 43 °C have been consolidated for the tested outdoor conditions of 30 °C, 35 °C, and 40 °C (Table 4). For fixed speed RAC, the annual energy consumption projections have been made only considering 35 °C outdoor condition.

It was assumed that for each day of RAC operation, out of the total 200 days (at 8 hours per day) in a year, the unit goes through initial higher energy consumption rate twice. The daily energy consumption calculation for all three tested RACs are summarised in Table 5 and should be read, along columns, under each outdoor temperature condition of 30 °C, 35 °C, and 40 °C for inverter RAC Units 1 & 2 and 35 °C for fixed speed RAC Unit 3. The annual energy consumption estimates are first calculated for each outdoor condition individually. The summation of all outdoor conditions gives the annual energy consumption for tested RAC units for the three indoor temperature set-points.

SUMMARY OF ENERGY SAVINGS THROUGH ADOPTION OF ATC

Table 6 summarises the annual energy consumption estimates for the tested RACs. For inverter RACs the energy savings through adoption of ATC ranges from 8 to 10 % per °C increase in temperature set-point from 22 °C to 24 °C and 24 °C to 27 °C. For the fixed speed RAC unit, there is negligible energy saving with set-point increase from 22 °C to 24 °C, while a saving of 4 % per °C was observed with set-point increase from 24 °C to 27 °C.

Conclusion and Recommendations

The test results show a strong correlation between indoor thermostat setting and the RAC energy consumption with inverter RACs being more responsive to change in temperature set-point. With the significant uptake of inverters replacing the share of fixed speed RACs (Kumar *et al* (2018a)), the energy

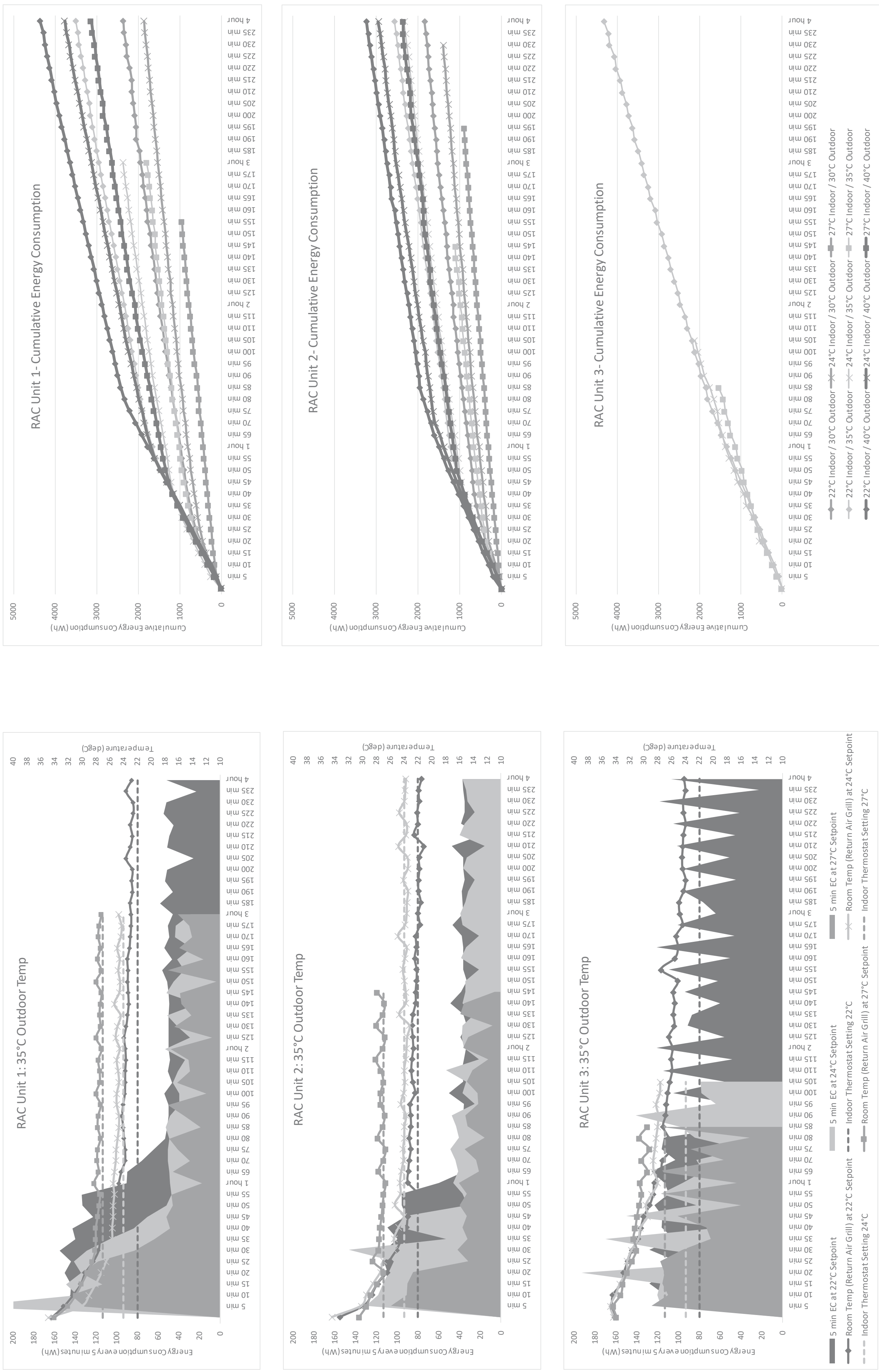

Figure 2. Monitored room temperatures and corresponding energy consumption (left); Cumulative energy consumption (right).

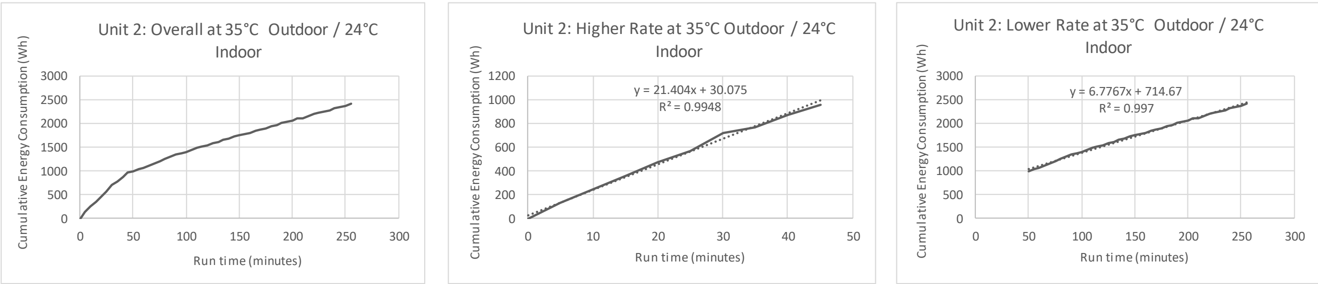

Figure 3. Energy consumption trends for RAC Unit 2 at 35 °C outdoor/24 °C indoor test condition.

Table 4. Outdoor temperature bin distribution for Inverter RACs.

				Total
Tested Outdoor Temp (°C)	30 °C	35 °C	40 °C	
ISEER Outdoor Temperature (°C)	≤30 °C	31 °C to 35 °C	36 °C to 43 °C	
Average Annual Hours	4,013	1,287	474	5,774
Fraction	69 %	22 %	8 %	100 %
Bin Hours	1,111	357	132	1,600
Days (at 8 hours per day)	139	45	17	200

Table 5. Daily and Annual Energy Consumption Calculations for the Tested RACs.

			Unit 1				Unit 2				Unit 3
Outdoor Temp			30 °C	35 °C	40 °C	Total	30 °C	35 °C	40 °C	Total	35 °C
Bin Hours			1,111	357	132	1,600	1,111	357	132	1,600	1,600
Days (at 8 hours per day)			139	45	17	200	139	45	17	200	200
Daily Calculation	Energy consumption at higher rate (kWh)	22 °C	1.4	3.6	5.0		1.2	2.5	4.0		3.6
		24 °C	1.1	2.0	3.5		0.6	2.0	3.2		2.1
		27 °C	0.2	1.5	2.8		0.1	0.9	2.2		1.2
	Energy consumption at lower rate (kWh)	22 °C	3.7	4.5	5.1		2.8	3.4	3.7		5.5
		24 °C	3.1	4.4	5.0		2.5	3.4	3.7		7.0
		27 °C	2.7	3.4	4.5		2.1	2.7	3.3		6.9
	Daily energy consumption (kWh)	22 °C	5.1	8.1	10.1		4.0	5.9	7.7		9.2
		24 °C	4.1	6.4	8.5		3.1	5.3	6.9		9.1
		27 °C	2.9	4.9	7.2		2.2	3.6	5.5		8.0
Annual Calculation	Annual energy consumption (kWh)	22 °C	710	362	166	1,239	560	264	127	952	1,837
		24 °C	570	286	141	997	430	237	114	782	1,826
		27 °C	407	218	119	744	306	160	91	556	1,605

Table 6. Summary of energy savings through adoption of ATC.

	Annual Energy consumption at different Indoor Set-point			Energy Saving from 22 °C to 24 °C			Energy Saving from 24 °C to 27 °C			Energy Saving from 22 °C to 27 °C		
	22 °C	24 °C	27 °C	overall		% / °C	overall		% / °C	overall		% / °C
Unit 1 (kWh)	1,239	997	744	242	19.5 %	9.8 %	253	25.4 %	8.5 %	495	40.0 %	8.0 %
Unit 2 (kWh)	952	782	556	170	17.9 %	8.9 %	225	28.8 %	9.6 %	395	41.5 %	8.3 %
Unit 3 (kWh)	1,837	1,826	1,605	12	0.6 %	0.3 %	220	12.1 %	4.0 %	232	12.6 %	2.5 %

saving potential through ATC is also growing corresponding to the growth of RAC sales in India. Operating the RACs in homes and offices at higher temperature set-points conforming to ATC (up to 27 °C or beyond) guidelines in tropical climates like India shall not only enhance the building occupants' thermal comfort and health but also lead to substantial energy and cost savings. The Government of India has already shown commitment to drive a national campaign to increase awareness about the benefits of ATC based AC operation (MoP (2018)). The energy saving estimates through ATC adoption, shall help the policy makers to frame definitive guidelines for all stakeholders encompassing building occupants and facility management personnel to operate the ACs as per ATC based standards; and AC manufacturers to build design features in ACs preventing the thermostat setting below a certain threshold and setting default thermostat setting to 24 °C or above. However, large scale implementation of these guidelines in individual residences and offices to realise the potential energy savings and enhanced thermal comfort, requires more research particularly exploring behavioural science. The study findings are applicable for all tropical countries with similar temperature and humidity conditions as prevalent in India.

References

de Dear, R.J., and G.S. Brager. 1998. Developing an adaptive model of thermal comfort and preference. *ASHRAE Transactions* 104 (1a): 145–167.

Ghawghawe, K., Manu, S., Shukla, Y. (2014) Determining the Trade-offs between Thermal Comfort and Cooling Consumption in Indian Office Buildings. Proceedings of 30th International PLEA Conference, Ahmedabad.

ISO (2013). ISO 16358-1: Air-cooled air conditioners and air-to-air heat pumps – Testing and calculating methods for seasonal performance factors – Part 1: Cooling seasonal performance factor.

ISO (2017). ISO 5151: Non-ducted air conditioners and heat pumps – Testing and rating for performance

Kumar, S., Sachar, S., Kachhawa, S., Goenka, A., Kasamsetty, S., George, G. (2018). Demand Analysis of Cooling by Sector in India in 2027. New Delhi: Alliance for an Energy Efficient Economy.

Kumar, S., Sachar, S., Kachhawa, S., Singh, M., Goenka, A., Kasamsetty, S., George, G., Rawal, R., Shukla, Y. (2018). Projecting National Energy Saving Estimate from the Adoption of Adaptive Thermal Comfort Standards in 2030. New Delhi: Alliance for an Energy Efficient Economy.

Manu, S., Shukla, Y., Rawal, R., Thomas, L., & de Dear, R. (2016). Lab studies of thermal comfort across multiple climate zones for the subcontinent: India Model for Adaptive Comfort (IMAC). Building and Environment, 98, 55–70.

MoP (2018). Energy Conservation in Building Space Cooling through recommended optimum temperature setting: D.O. No. 11/3/2018-EC. http://www.mca.gov.in/Ministry/pdf/AcTempNotice_21082018.pdf

Nicol, Fergus & Humphreys, Michael. (2002). Adaptive Thermal Comfort and Sustainable Thermal Standards for Buildings. Energy and Buildings. 34. 563–572. 10.1016/S0378-7788(02)00006-3.

Sachar, S., Goenka, A., Kumar, S. (2018). Leveraging an Understanding of RAC Usage in the Residential Sector to Support India's Climate Change Commitment. Presented at ACEEE Summer Study 2018, California, US.

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