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QUANTIFYING THE REDUCTION IN COOLING ENERGY DUE TO PASSIVE COOLING TECHNIQUES FOR INDIAN CITIES

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ABSTRACT

Past studies have quantified the potential of various passive design strategies to achieve thermal autonomy. Bhadra, Vaidya, & Sarraf (2017) have shown that for 60 cities in India, minimum thermal autonomy calculated by using the thermostat set point as the benchmark, is at 12% for night cooling, 75% for evaporative cooling, 28% for ground cooling and 32% for radiant cooling. This paper takes that approach further and quantifies the reduction in cooling energy due to three passive strategies, using the CIBSE method with Cooling Degree Days (CDD) for 60 Indian cities.

Three passive strategies: night ventilation, comfort ventilation and evaporative cooling are considered for mixed mode institutional buildings in India. Using the CIBSE TM41 , the Balance Point Temperature (BPT) for two different versions of Indian buildings is established; 1) buildings complying with the latest energy code i.e. Energy Conservation Building Code (ECBC 2017), and 2) business-as-usual buildings in India. Using these BPT values and the latest TMY files, the residual CDD for the three passive design strategies and the CDD for buildings without passive strategies are calculated. Cooling energy consumption is then calculated for all the cases for the 60 cities.

The study provides two versions of BPT for Indian buildings, which are more realistic that those published in the past. The results indicate the cooling energy reduction possible due to three common passive design strategies. The results state that the CDD calculated by using ASHRAE 55 adaptive comfort model is almost twice than that of the published values. For Ahmedabad, the value of base temperature ranges between 16-25°C for a BAU building as compared to 18.3°C constant base temperature considered by ASHRAE. Cooling energy can be reduced by upto 80% just by using passive strategies in BAU buildings and upto 86% in ECBC compliant buildings.

INTRODUCTION

Cooling energy accounts for about 40-60% of the total energy consumption of buildings (Clean Energy Ministerial, 2014). The total floor area in India is expected to increase by about 400% by the year 2030 Kumar, Kapoor, Deshmukh, & Kamath (2010). This will create a huge stress on the energy sector for cooling these buildings. Cooling energy can be reduced by using various passive cooling strategies. These passive strategies are climate dependent and each climate will have different potential for different strategies. Past studies have quantified the potential of passive cooling strategies to achieve Thermal Autonomy, and the Degree Discomfort Hours (DDH) using the thermostat set point as the base temperature. This study takes that work further to quantify the reduction in the cooling energy due to passive cooling strategies. These estimates can provide additional information about the effectiveness of these strategies. The methods used today for predicting energy with simulation tools are complex and need intensive training to use. A preliminary estimate of reduction in the cooling energy by various passive strategies for different climate locations would help the designers select suitable passive strategies in the early design stages. Also planners and policymakers can use this to estimate the energy consumption and savings at a larger scale to formulate and implement new policies. Bhadra, (2017) has calculated the Thermal Autonomy for 5 passive cooling strategies for 60 cities in India. However, this study does not quantify the amount of cooling energy that can be reduced by the passive strategies. This study assumes that comfort can be achieved with a BPT equal to the thermostat setpoint, and does not take in to account internal and solar thermal gains in the building. Chiesa & Grosso (2015) quantified the potential of controlled natural ventilation in reducing the cooling energy for Mediterranean area using the residual cooling degree hours. The study has used two different comfort models, fixed set point temperature and adaptive comfort, for calculating the residual cooling degree hours. Similar to Bhadra (2017), this study assumes that comfort can be achieved with a BPT equal to the thermostat setpoint, and does not take in to account internal and solar thermal gains in the building.

Passive cooling techniques reject heat from the building just by using natural energy sources (Givoni, 1994). Buildings are cooled naturally with architectural design strategies to use any natural heat sink available. Passive cooling techniques provide active cooling in naturally ventilated and mixed mode buildings. Givoni, (1994) has classified passive strategies based on natural heat sinks available such as ambient air, soil mass, and moisture.

Each passive cooling strategy has different heat sinks. Hence there is no single way to define their effectiveness.

There are different methods to calculate energy consumption such as Heat Balance Method, Weighing factor method, Thermal network method, Degree Day method and BIN method ASHRAE (2013) (Reddy, Kreider, Curtiss, & Rabl, 2017). The Heat Balance method is a rigorous approach and has been used in many energy analysis programs like NBSLD and TARP (ASHRAE Fundamentals, 2013). Weighting-Factor method is used to calculate instantaneous space sensible loads. The third method used to calculate energy consumption is the Thermal-Network methods where the building is represented into a network of thermal nodes (ASHRAE Fundamentals, 2013). Degree-days method is the simplest method for annual energy estimation (ASHRAE Fundamentals, 2013). There are various approaches to the Degree Days method for annual energy estimation. This study uses the CIBSE CDD method to calculate the cooling energy consumption.

CDD for any location can be calculated by subtracting the hourly outside dry bulb temperature from a base temperature and summing up the difference for all the hours for entire day. Degree-days are versatile climatic indicators, used in building design and operation to estimate the heating and cooling energy consumption (Borah, Singh, & Mahapatra, 2015 as cited in Aktacir, Büyükalaca, Bulut, & Yilmaz, 2008; Mourshed, 2012). Different approaches are taken to calculate degree-days based on the availability of the data (Day, 2006). The mean degree hour method is the most rigorous method to calculate degree-days. In this method, hourly temperature difference between the outdoor air DBT and base temperature as summed up and divided by the time step of the available data. For hourly data, the sum of the temperature difference is divided by 24. In the other method called The Meteorological Office equation, daily maximum and minimum air temperature is used to calculate degree-days. This method assumes a quasi-sinusoidal pattern in the diurnal temperature. ASHRAE Fundamentals (2013) uses the daily mean air temperature to calculate the degree-days. This makes the calculation for calculating degree-days simpler.

The base temperature, also called the Balance Point Temperature (BPT) and is a building specific temperature based on building envelope, building form, internal loads and solar gains. BPT is that outdoor temperature at which heating or cooling systems need not operate inside the building to maintain thermal comfort inside (ASHRAE, 2013). This makes BPT a building property. Different researchers have used different approaches to calculate BPT. Traditionally used base temperatures to calculate HDD and CDD are 18.38°C in the United States, 15.58°C in the United Kingdom, and 15.08°C in Germany (Carbon Trust, 2012). Apart from this, different researchers have used different approaches to find the BPT.

Golden, Woodbury, Carpenter, & O'Neill (2017) used indoor thermostat set point temperature as the BPT for the calculation of CDD.

Two widely methods used for find BPT is energy signature method and performance line method (Lee, Baek, & Cho, 2014). In the energy signature method, daily energy consumption is plotted against daily mean outdoor air temperature (Fazeli, Ruth, & Davidsdottir, 2016). This gives a "U" shaped curve. The lowest point (temperature) of this curve is the BPT. This means that above that temperature, cooling will be required and below that temperature, heating will be required. In this curve, the intercept of temperature dependent and temperature independent function gives the balance point temperature. In the performance line method, daily energy consumption is plotted against CDD or HDD (Carbon Trust, 2012). This yields a straight line with two components- a slope and an intercept in the form of a straight equation $y = mx + c$. The slope and the intercept can be found by linear regression analysis. Day (2006) gives a detailed method to calculate the balance point temperature based on the internal loads of the building, solar gains, building envelope characteristics, etc.

In this study, BPT suitable for Indian context is calculated for two building versions: the Energy Conservation Building Code (ECBC) 2017 compliant buildings and business as usual (BAU) buildings. Thus, we calculate CDD values that are more accurate for India than those currently published, which use 18.3°C as base temperature for calculation of CDD. We also calculate the cooling energy based on CDD for the two buildings version for 60 Indian cities for four different cases; case one, where no passive strategies are applied; case two, when evaporative cooling is used; case three, when night ventilation is used; and case four, where comfort ventilation is used. These calculations are done for for mixed mode operated buildings using the ASHRAE Standard 55 Adaptive Thermal Comfort Model.

METHODOLOGY

This study uses the TMY weather files for Indian cities.

Building details

The building used in this study is a 5000m^2 hypothetical building oriented in E-W elongated axis and an aspect ratio of 1:2. The construction assembly for the building is assumed to be 230 mm uninsulated masonry walls for BAU case and insulated masonry walls for ECBC 2017 compliant case (Rawal & Shukla, 2014). The roof construction assembly is assumed as 150mm concrete slab for BAU case and insulated 150mm concrete slab. Window assembly is assumed as single clear glazing for BAU and double clear for ECBC compliant case. The window to wall ratio (WWR) is taken as 40% distributed evenly on each side for both BAU and ECBC 2017 compliant case. The system CoP is assumed as 3.1, which is for the common split AC units available in the market.

Cooling Degree Days

Since hourly weather data was available, the mean degree hour method is used to calculate the CDD. The BPT was subtracted from the outdoor air temperature for all the 8760 hours in a year. Equation (1) is used to calculate the CDD.

$$CDD = \frac{\sum(\theta_o - \theta_b)}{24} \quad (1)$$

Where, θ_o is the outside air temperature and θ_b is the base temperature.

Balance point temperature

Day (2006) in his report Degree-days: theory and application TM41: 2006, described a method to calculate the balance point temperature (BPT) for a building. This method takes into account the internal loads (occupancy, lighting and equipment), envelope load, solar gains and latent loads into consideration to calculate the BPT. Equation (2) is used to calculate the BPT:

$$\theta_b = \theta_{sp} - \left[\frac{\dot{v}\Delta P}{\dot{m}c_p\eta_{fan}} + \frac{Q_s}{\dot{m}c_p} + \frac{\sum(UA)\times(\theta_{out}-\theta_{sp})}{\dot{m}c_p} + 2400(g_o - g_s) - \frac{Q_c}{\dot{m}c_p}\right] \quad (2)$$

Where, θ_{sp} is the indoor set point temperature

$\frac{\dot{v}\Delta P}{\dot{m}c_p\eta_{fan}}$ is the temperature rise due to fan gains

$\frac{Q_s}{\dot{m}c_p}$ is the temperature rise due to sensible loads which include the lighting loads, equipment loads, occupancy loads and the loads due to solar gains through windows

$\frac{\sum(UA)\times(\theta_{out}-\theta_{sp})}{\dot{m}c_p}$ is the temperature rise due to gains through envelope

$2400(g_o - g_s)$ is the notional temperature rise due to latent load

$\frac{Q_c}{\dot{m}c_p}$ is the mitigation of heat gain due to heat loss at night

Heat gain due to fans

The heat generated by the fans is calculated by:

$$Q_{fan} = \frac{\dot{v}\Delta P}{\eta_{fan}} \quad (3)$$

The heat generated by the fans is also calculated by:

$$Q_{fan} = \dot{m}c_p(\theta_s - \theta_c) \quad (4)$$

Combining the equation (3) and (4) gives the temperature rise due to fan gain, which can be given as

$$(\theta_s - \theta_c) = \frac{\dot{v}\Delta P}{\eta_{fan}\dot{m}c_p} \quad (5)$$

Where, Q_{fan} is the heat gain through the fan and is given in (W) $\dot{v}$ is the volume flow rate through the fan (m^3/s), ΔP is the pressure rise across the fan kPa, η_{fan} is the efficiency of the fan, $\dot{m}$ is the mass flow rate, c_p is the specific heat of the air, θ_s is the supply air temperature θ_c is the off-coil air temperature

Temperature rise due to sensible heat gain

The sensible heat gain involves heat gain from lighting, equipment, occupants and radiant gain through windows. Hence Q_s can be written as:

$$Q_s = Q_L + Q_E + Q_o + Q_{sol} \quad (6)$$

Where, Q_L is the heat gain through lighting (W), Q_E is the heat gain through equipment (W), Q_o is the sensible heat gain through occupants (W) and Q_s is the solar heat gain through window (W).

$$Q_L = LPD \times A \times \%_L \quad (7)$$

Where, LPD (Lighting Power Density) is taken as per ECBC for ECBC compliant buildings and BAU for BAU buildings, A is the area of building, $\%_L$ is the percentage light turned on during that hour

$$Q_E = EPD \times A \times \%_E \quad (8)$$

Where, EPD (Equipment Power Density) is taken as BAU and is kept same for both versions of buildings, A is the area of building, $\%_E$ is the percentage equipment turned on at that hour

$$Q_o = n \times q_o \quad (9)$$

Where, n is the number of occupants, q_o is the heat generated by each occupants

$$Q_{sol} = I \times A_w \times SHGC \quad (10)$$

Where, I is the incident solar radiation on the window, A_w is the area of window, SHGC is the Solar Heat Gain Co-efficient of the window

Hence, the temperature rise due to all the gains is calculated by

$$\Delta\theta = \frac{Q_s}{\dot{m}c_p} \quad (11)$$

Temperature rise due to envelope gain

The heat gain due to envelope is given by:

$$Q_E = \sum(UA) \times (\theta_{out} - \theta_{sp}) \quad (12)$$

Also,

$$Q_E = \dot{m}c_p(\theta_{out} - \theta_{sp}) \quad (13)$$

Combining the two equations gives the temperature rise due to envelope,

$$\frac{\sum(UA)\times(\theta_{out}-\theta_{sp})}{\dot{m}c_p} \quad (14)$$

Where, U is the U-value of the component of envelope, A is the area of component, θ_{out} is the outside air temperature, θ_{sp} is the indoor set point temperature

Notional temperature rise due to latent load

The latent load is treated as equivalent sensible load, and the moisture difference is converted into notional difference in the air temperature across the coil

$$\Delta\theta_L = 2400(g_o - g_s) \quad (15)$$

Where, g_o is the moisture content (kg/kg) on the coil and is the summation of moisture released by occupants, moisture in the infiltrated air and the moisture content of the supply air g_s is the moisture content (kg/kg) after the coil.

Mitigation of gains due to night time cooling

Depending on the thermal capacity of the exposed mass, the load on the cooling system can be mitigated if these gains can be stored and effectively released outside of occupancy hours. This is the principle of night-time cooling in which the building fabric cools overnight such that it can absorb heat the next day when the occupants arrive. The building fabric then warms up slowly during the day

(staying below the room temperature) — heat is only released from the structure (becoming a gain to the space) when the ambient air temperature falls below the fabric temperature. This effect is accounted for by using a form of the solution for equation

$$\frac{Q_c}{\dot{m}c_p} = \frac{(e^{\frac{t_3-t_1}{\tau}}-1)(\theta_{sp}-\theta'_{ao(night)})}{24\times3600\times\dot{m}c_p} \quad (16)$$

Where, $(t_3 - t_1)$ is the unoccupied period, τ is the building time constant, $\theta'_{ao(night)}$ is the night time outdoor air temperature

$$\tau = \frac{C}{3600U} \quad (17)$$

Where U is the U value of envelope and C is the building thermal capacity

Cooling energy

Cooling energy is calculated by the following equation:

$$F_{chiller} = \frac{24\times\dot{m}c_pD_m}{COP} \quad (18)$$

Effect of evaporative cooling

Givoni (1994) stated that the air exiting from the evaporative cooling device is always 2 to 3 °C higher than the actual wet bulb temperature of the air. Hence, the efficiency of evaporative cooling devices is not 100%. The decrease in the dry bulb temperature depends upon the humidifying efficiency. Givoni (1994) defines humidifying efficiency as "*the ratio between the temperature drop by the air exiting from the evporative device and the wet bulb depression".* The author has calculated the efficiency of single stage direct evaporative cooling system to be between 60 to 80%. However, Patel (2017) has done a survey on the availability of evaporative cooling systems available in Indian market. The efficiency of current available direct evaporative cooling systems ranges from 88% to 97%. The actual temperature drop is calculated as

Wet Bulb Depression = (DBT – WBT)×η (19)

Effect of comfort cooling

Chiesa & Grosso (2015) studied the geo-climatic potential of controlled natural ventilation. They studied the natural ventilative cooling potential of 50 cities of Mediterranean region by using climate dependent variables. They calculated the residual cooling degree hours for the evaluating the potential of natural ventilative cooling. They considered indoor airspeed as 30% of the outdoor airspeed. Hence, the effectiveness of this passive strategy depends on the indoor air speed and the moisture carrying capacity of air which can be measured by RH. They derived an equation for decrease in the air temperature perceived by a person due to increased air velocity.

$$\Delta\theta_{v,air} = 2.319V_{air} + 0.4816 \quad (20)$$

Where,

$\Delta\theta_{v,air}$ is the air temperature decrease percieved by a person as the effect of air movement

V_{air} is the indoor air speed with $V_{air} = 0.3 \times V_{wind}$

V_{wind} is the outdoor air speed

Night ventilation

Givoni (1998) conducted measurements to check the effectiveness of night ventilation in hot and dry climate and derived a formula for the indoor maximum temperature. The equation derived by the author is as follows:

$$T_{in\ max} = GT_{avg} + \mathrm{DEL}T + k(T_{avg} - GT_{avg}) \quad (21)$$

where: $T_{in\ max}$ = Indoor maximum temperature in a particular day; GT_{avg} = 'Grand average' of the outdoor temperature, the average of the whole period of a given experimental series; DELT = Average elevation of the indoor maximum above the outdoor average. T_{avg}=Outdoor temperature average in a particular day; k = Ratio of the rates of daily changes of the indoor maximum to the rate of change of the outdoor average, depending on the mass level.

RESULTS AND DISCUSSION

Since Indian buildings have different loads than the buildings in US, it is important to consider the loads in calculating the base temperature. Figure 1 shows the values of CDD published by ASHRAE considering 18.3°C as the base temperature and CDD calculated in this study for two versions of Indian buildings: BAU buildings and ECBC 2017 compliant buildings and using ASHRAE standard 55 as thermal comfort model. The results shows that the CDD values for Indian buildings are almost twice than the values published by ASHRAE. This mean that the cooling energy estimated by using the published CDD values is seriously underestimated. The Figure 1 shows the CDD values for five different cities representing five different climate zones of India. Ahmedabad represents hot & dry climate, Bangalore represents temperate climate, Chennai represents warm & humid climate, Delhi represents composite climate and Sundernagar represents cold climate. For all the climate zones the CDD calculated by using the variable base temperature is almost twice than the values published by ASHRAE by using 18.3°C in case of BAU buildings. In case of ECBC compliant buildings, the CDD values are 5-7% lower than the values for BAU buildings for all five cities.

Figure 2 shows the impact of adaptive comfort model on CDD values. Since the base temperature depends on the internal loads and the set point temperature, the CDD values change with change in set point temperature. For adaptive comfort model, the upper band of the comfort temperature is considered as the set point temperature. It was assumed that the CDD values should decrease by using adaptive comfort model as the set point temperature are higher. However, the results show that by using adaptive comfort model, the CDD values increases for all the five cities. Even for ECBC compliant buildings, the CDD increases by 9% in Ahmedabad, 12% in Bangalore, 21% in Chennai, 12% in Delhi and 5% in Sundernagar. For BAU buildings, this increase is 22% in Ahmedabad, 26% in Bangalore, 23% in Chennai and 18% in Sundernagar.

The amount of cooling energy reduced by the using passive strategies in building needs to be looked at before using them in buildings. Each passive strategy has different impact on building energy consumption depending on the climatic condition of the location. Figure 3 shows the cooling energy reduction by using passive strategies. The comfort model used here is ASHRAE 55 adaptive model. For Ahmedabad (hot &dry climate), HVAC energy is reduced by about 40%. Note that, in this study only the energy of HVAC system is considered and not the energy of evaporative cooling system. However, if the energy of evaporative system is considered then the total reduction in HVAC energy can go down to 20-25 %. This result matches with the study done by Patel (2017). Lowest reduction in cooling energy demand is seen in Chennai (warm & humid) of 28%. Eaporative cooling gives the second highest number of savings which ranges from 22-26% across the climate zones. Maximum reduction of 26% is seen in the case of Bangalore while least reduction is seen in case of Chennai. Overall night ventilation gives the least reduction. The potential of night ventilation in reducing the cooling energy demand remains between 5% to 10% across the climate zones.

Figure 4 shows that for buildings with ECBC 2017 compliant building envelope, the reduction in cooling energy requirement due to evaporative precooling system ranges from 50% to 60% across all climate zones. The higher savings is due to lower envelope loads in the ECBC 2017 compliant building envelope. Also since the evaporative cooled air is already cooled, the mechanical cooling system requires less energy to further cool the air. Also the BPT for the occupied period remains between 12 to 18°C throughout the year. Hence, air temperature due to evaporative precooling remains below the BPT during winter months and shoulder periods. During the summer months, however, as the cooling loads are higher, BPT goes lower to in the range of 12 to 15°C. Hence during this period, the evaporative cooling is not able to lower the air temperature to BPT. Hence the mechanical cooling systems are started. But the inlet temperature of the mechanical systems is already lower due to evaporative precooling, hence the energy requirement for further cooling the air is lower. The reduction in mechanical cooling energy requirement due to evaporative cooling ranges from 20% to 25%. The results suggest that comfort cooling is even more effective than evaporative cooling system for all climate zones.

The energy reduction by night ventilation remains in the range of 13-25% for all cities. Form the results, it is seen that evaporative cooling works best for Ahmedabad, which is a hot & dry climate while comfort cooling works best for Chennai, which is a warm & humid climate.

CONCLUSION

The CDD published by ASHRAE using 18.3°C as the base temperature underestimates the cooling energy in Indian buildings, as the loads in Indian buildings are different. It is better to calculate CDD for buildings as compared to CDD for a location as published by ASHRAE. The CDD values depend on the base temperature and the base temperature are different for different buildings and hence the CDD will also change with buildings. And hence, the cooling energy will also change for different buildings. The results shows that passive strategies can reduce the cooling energy requirement upto 30% for a BAU building and upto

50% in ECBC compliant building. ECBC 2017 compliant buildings shows higher savings as the cooling loads from the envelope are already reduced by tighter envelope. Climate zones should not be used to delineate the potential of passive strategies in reduction the cooling energy requirement. Even cities within the same climate zones vary in the potential of different strategies. And the cities from different climate zones have the same potential of passive strategies in reducing the cooling energy requirement.

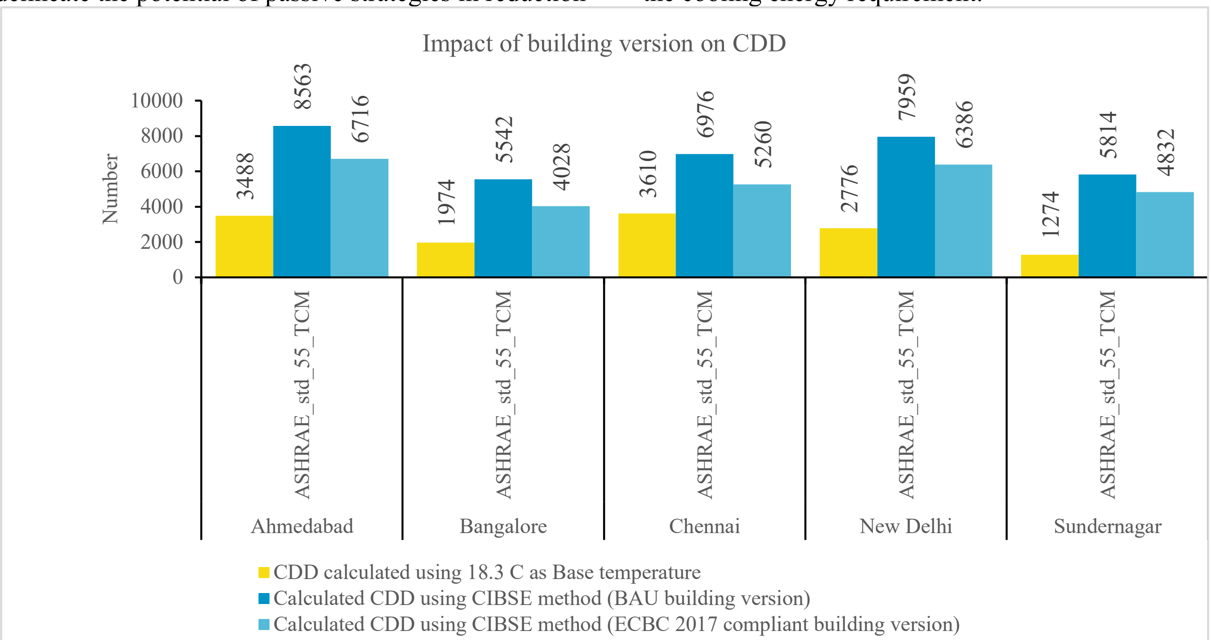

Figure 1: CDD comparison between constant base temperature and variable base temperature for five different Indian cities representing five different climates

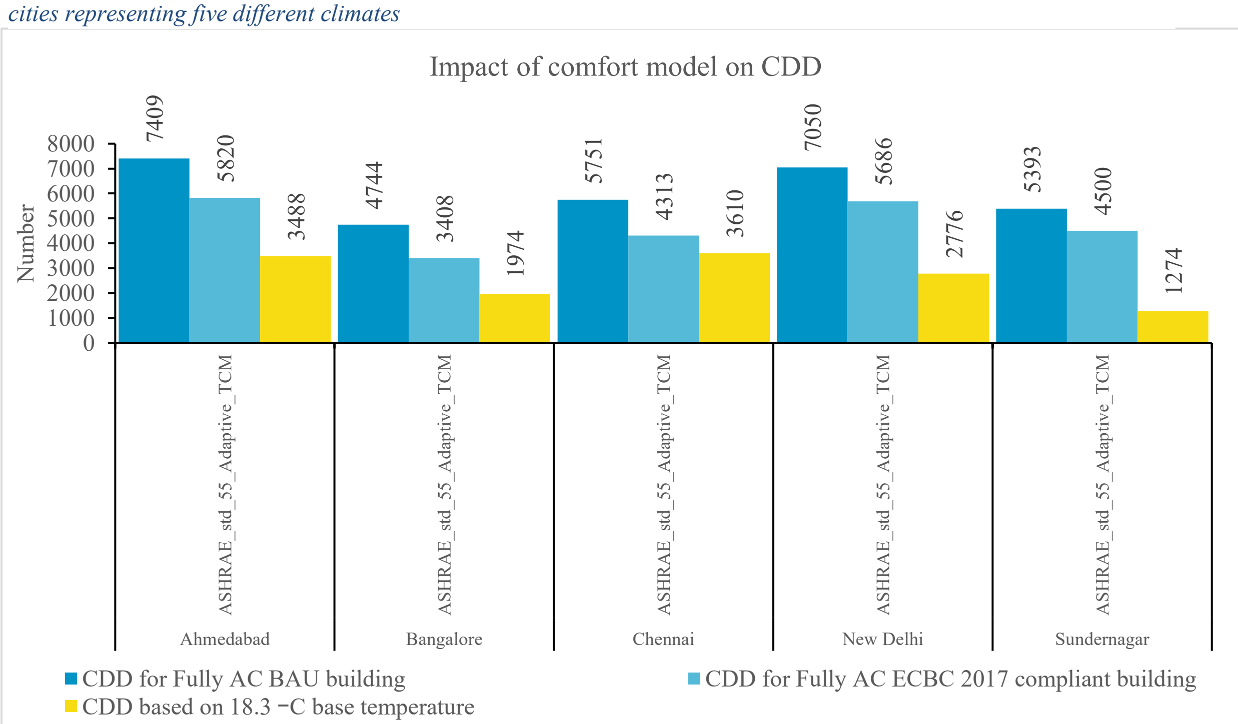

Figure 2: Impact of adaptive comfort model on CDD values

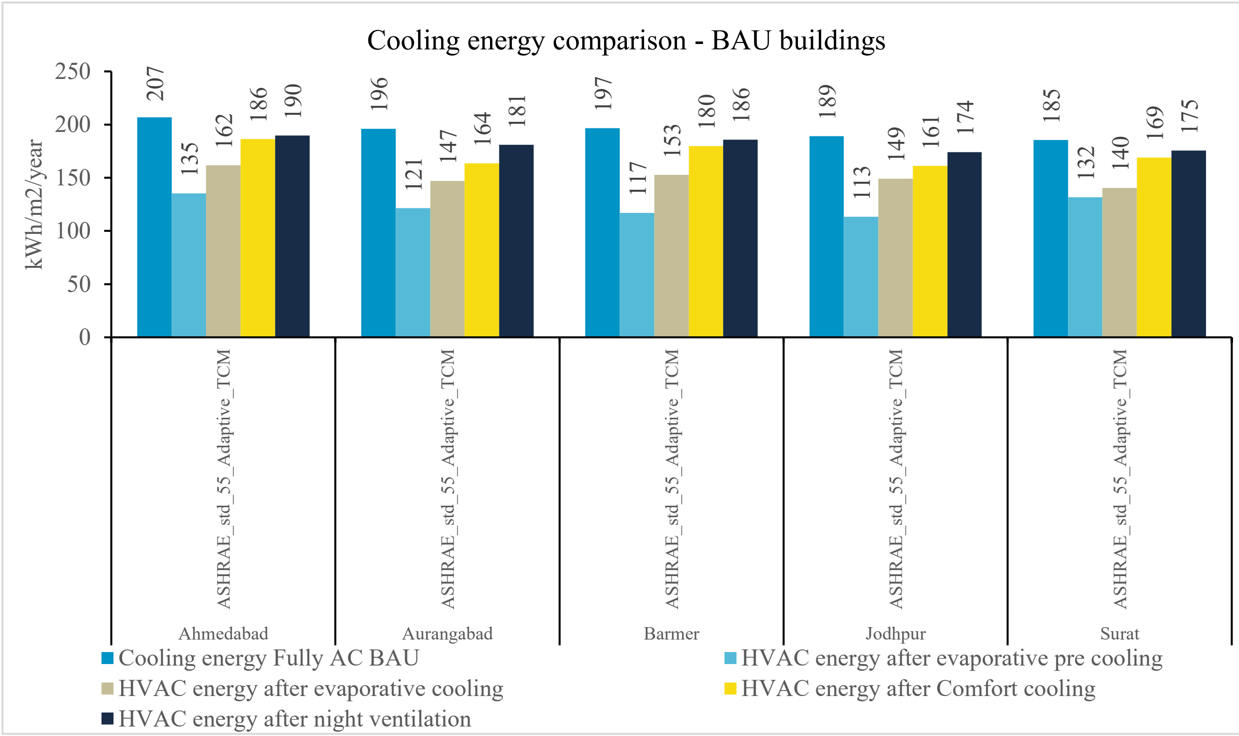

Figure 3: Annual cooling energy estimation of BAU buildings

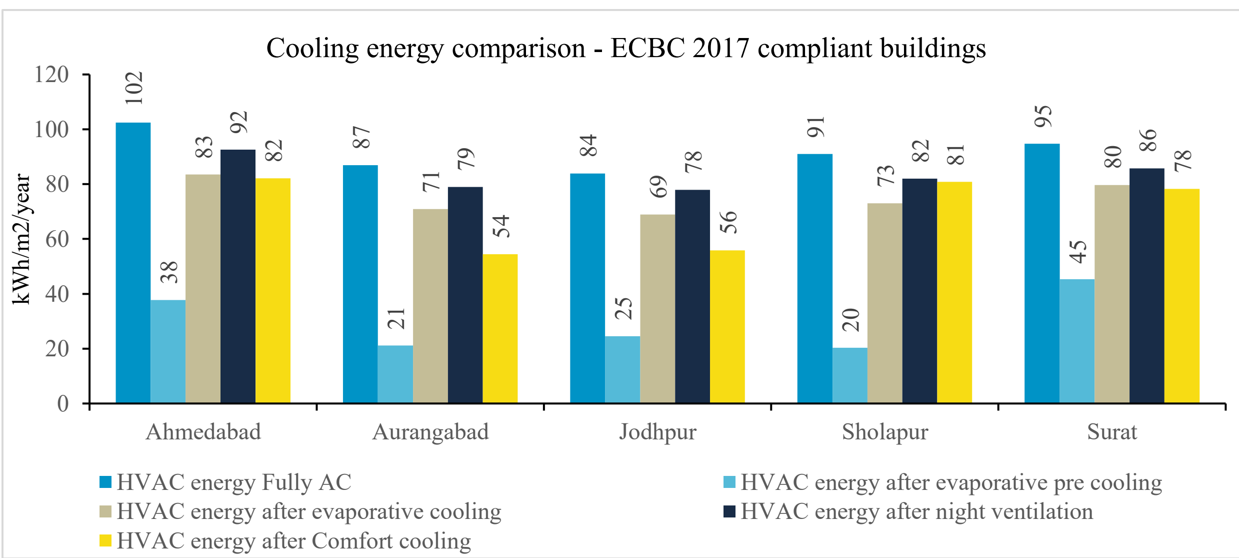

Figure 4: Annual cooling energy for ECBC 2017 compliant building after applying passive strategy

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