A Simplified Method for Estimating Cooling Energy Savings Due To Passive Strategies for Indian Cities

Arjun Desai¹, Prasad Vaidya¹, Sanchi Pathella¹

¹CEPT University, Ahmedabad, India

Abstract

Different methods are used for calculating the energy consumption of buildings. While the heat balance method, weighing factor method and thermal network methods are complex and require intense computing power, the degree-day and the BIN methods are relatively simple. In this study, we have used the degree-day approach published in CIBSE TM-41 to develop a Python tool to calculate the energy consumption of energy buildings on an hourly basis. The tool calculates the building energy for 59 Indian cities for five different cases: 1) fully air-conditioned, 2) with evaporative pre cooling, 3) evaporative cooling, 4) with comfort cooling and 5) with night ventilation with five different thermal comfort models. These cases are run for two building versions: 1) Business as Usual and 2) Energy Conservation Building Code compliant, and the study resulted in two realistic versions of Balance Point Temperatures for these cases. In total these add up to 2900 simulation which the Python tool completes within 1 hour. The results are shown in an excel dashboard.

The results indicate the cooling energy reduction possible due to the three passive design strategies. The CDD-based results are compared with EnergyPlus results. The Normalised Mean Biased Error is 4.6% while the Root Mean Squared Error value is 15%.

Introduction

The global energy consumption is expected to rise from 13.2 Gtoe in 2010 to 20.7 Gtoe in 2040 following a growth in energy consumption of 56% between 2010 and 2040 (Berardi, 2017). And in India, the growth in commercial sector energy consumption is growing at a rate of 5.4% per year. Cooling energy accounts for about 40-60% of the total energy consumption of buildings (Berardi, 2017; Clean Energy Ministerial, 2014). The total floor area in India was expected to increase by about 400% between 2005 and 2030 (Kumar, Kapoor, Deshmukh, & Kamath, 2010).

Passive cooling techniques reject heat from the building with architectural design strategies using a naturally available heat sink. Passive cooling techniques can be combined with active cooling. This approach is termed as mixed mode. Operating the building in mixed mode greatly help reduce the space cooling demand as the space cooling is only turned on when it is required and for the rest of the time the building operates in natural

ventilation. The India Model for Adaptive thermal Comfort (IMAC) (Manu, Shukla, Rawal, Dear, & Thomas, 2014), is now a part of the National Building Code of India, and provides a standard for the building to be operated in mixed mode, and most Indian building are operated in a seasonal mixed mode. However, while simulating for new construction, buildings are most typically simulated in fully air conditioned mode. The Energy Conservation Building Code (ECBC) 2017, in its whole building performance approach, also suggests the building be simulated in fully air conditioned mode and gives no credit to passive design strategies.

Passive strategies are climate dependent and each location 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 (Bhadra, Vaidya, & Sarraf, 2017). The Thermal Autonomy and DDH are calculated for 5 passive cooling strategies for 59 cities in India. However, that study does not quantify the amount of cooling energy that can be reduced by the passive strategies. His method implies that comfort can be achieved with a BPT equal to the thermostat set point, which 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. Their 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), their method implies that comfort can be achieved with a BPT equal to the thermostat setpoint, which does not take in to account internal and solar thermal gains in the building.

This study takes that work further to quantify the reduction in the cooling energy due to passive cooling strategies. A preliminary estimate of reduction in the cooling energy by various passive strategies for different climate locations can help 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.

Each passive cooling strategy has different heat sinks. Givoni, (1994) has classified passive strategies based on natural heat sinks available such as ambient air, soil mass,

and moisture for natural ventilation, ground cooling, and evaporative cooling respectively. The effectiveness of each strategy needs to be estimated based on the amount of heat transfer possible between the building and the heat sink, which can also be climate or location dependent.

There are different methods to calculate energy consumption such as Heat Balance method, Weighting 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 used in many energy analysis programs like NBSLD and TARP (ASHRAE, 2013). Weighting Factor method is used to calculate instantaneous space sensible loads. The Thermal Network method represents the building in a network of thermal nodes (ASHRAE Fundamentals, 2013). The Degree Day method is the simplest method for annual energy estimation (ASHRAE Fundamentals, 2013). Of the various approaches for Degree Days method our study uses the CIBSE Technical Memorandum 41 (TM41)s (Day, 2006) to calculate the cooling energy consumption.

The Cooling Degree Days (CDD) for any location are 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 (Aktacir, Büyükalaca, Bulut, & Yilmaz, 2008; Mourshed, 2012).

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). To simplify the process, most approaches assume a common BPT for all buildings and building types. 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). Golden, Woodbury, Carpenter, & O'Neill (2017) used indoor thermostat set point temperature as the BPT for the calculation of CDD.

The energy signature method and performance line method are widely used to estimate BPT (Lee, Baek, & Cho, 2014). Both methods use actual energy consumption of existing buildings which is plotted against daily mean outdoor air temperature or CDD or HDD values (Fazeli, Ruth, & Davidsdottir, 2016), (Carbon Trust, 2012). CIBSE TM-41 gives a detailed method to calculate the BPT based on the temperature set point, and estimates of internal loads of the building, solar gains, building envelope characteristics, etc. This method is suitable for calculating BPT for buildings that are not yet built.

In our study, we calculate BPT suitable for Indian context for two building versions: the Energy Conservation Building Code (ECBC) 2017 compliant buildings and non-compliant business as usual (BAU) buildings. These two versions give 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 further calculate the cooling energy based on CDD for the two building versions for 59 Indian cities for five different cases: 1) fully air-conditioned, 2) with evaporative pre cooling, 3) evaporative cooling, 4) with comfort cooling and 5) with night ventilation with five different thermal comfort models. In total, these add up to 2900 cases. As a part of the study, we have developed a python based tool that calculates the cooling energy and CDD for all these cases.

Research objectives

- Finding the efficiency of passive strategies based on literature
- Calculating the BPT and CDD values based on Indian building conditions.
- Develop a tool to view the results and facilitate analysis and decision-making.

Methodology

The methodology discusses the equations and algorithms used to develop the python based energy estimation tool called BQEET.

Cooling Degree Days

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 BPT temperature.

Balance point temperature

The TM41: 2006 method to calculate the balance point temperature (BPT) 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

Cooling energy

Hourly Cooling energy is calculated by the following equation:

$$F_{chiller} = \frac{24 \times \dot{m} c_p CDD}{COP} \quad (3)$$

Passive cooling effectiveness

There are 3 different methods used to calculate the indoor temperature achieved by the following 3 passive strategies. Residual cooling load, or Residual Cooling Degree Hour (CDH) is calculated as the difference (if greater than zero) between the indoor temperature and the BPT for that hour.

Effect of evaporative cooling

Patel (2017) has done a survey on the availability of evaporative cooling systems in the Indian market. The efficiency of direct evaporative cooling systems used in this study is 90%

The actual temperature drop is calculated as

$$\text{Wet Bulb Depression} = (DBT - WBT) \times \eta \quad (4)$$

After using the evaporative cooling, we calculated the Residual Cooling Degree Hours (RCDH) for all the hours that are still outside the comfort hour as per the selected comfort model.

Figure 1: RCDH logic for Evaporative pre-cooling

Figure 2: RCDH logic for using Evaporative cooling and mechanical cooling separately

Figure 1 explains the control logic used for calculating the RCDH after using the evaporative precooling technique. While Figure 2 explains the control logic for calculating the RCDH for evaporative cooling.

Effect of comfort cooling

Chiesa & Grosso (2015) derived equation-20 for decrease in the air temperature perceived by a person due to increased air velocity. 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.

$$\Delta\theta_{v,air} = 2.319V_{air} + 0.4816 \quad (5)$$

Where,

$\Delta\theta_{v,air}$ is the air temperature decrease perceived 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

After calculating the perceived air temperature, we calculated the RCHD for the hours that are outside of the comfort hours. The control logic used for the calculation of RCDH after using the comfort cooling is explained in the Figure 3.

Figure 3: RCDH logic for comfort cooling

Night ventilation

To calculate the indoor air temperature after using the night purge ventilation, we used the following equation developed by Bhadra (2017):

$$T_{IndoorHourly} = \frac{T_{in(max)} - T_{in(min)}}{2 \sin(-\theta)} + \frac{T_{in(max)} + T_{in(min)}}{2} \quad (6)$$

The equations for $T_{in(min)}$ and $T_{in(max)}$ are derived by Givoni (1998)

After calculating the hourly indoor air temperature, we calculated the RCDH for the remaining the uncomfortable hours. For calculating the RCDH for the remaining hours, we used the control logic as shown in the

Figure 4: RCDH logic for night ventilation

The example case and validation

The building example used in this study is a single-storied 5000m² hypothetical institutional building oriented in E-W elongated axis with a plan aspect ratio of 1:2. The construction assembly for the building is assumed to be typical uninsulated masonry walls and concrete roof for BAU case and insulated for ECBC 2017 compliant case (Rawal & Shukla, 2014). Window assembly is assumed as single clear glazing for BAU and as required for the ECBC compliant case. The window to wall ratio (WWR) is 40%, distributed evenly on each side for both BAU and ECBC 2017 compliant cases. The cooling system COP is assumed as 3.1, representing commonly available split AC units available in the market. The Lighting Power Density (LPD) of the building is 11.2 W/m² based on the building area method of ECBC 2017. The Equipment Power Density is 11.1 W/m².

Figure 5: Example EnergyPlus model used for study

A five zone energy model in EnergyPlus with same building and weather inputs was simulated, and the results were compared with the CDD method described above. The cooling system used in EnergyPlus was a PTAC system with a CoP of 3.1 and the flow rate was set to 1 CFM/ft², which equals 2.37 m³/s for a 5000m² building. The simulation was carried out for Amritsar, which is a composite climate.

For both the cases, ASHRAE standard-55 comfort model was used for calculating the CDD and energy consumption.

Results and discussions

Figure 6: Comparison of monthly energy estimation for BAU building between EnergyPlus results and the results obtained by the method described in the study

The Figure 6 shows the monthly energy results for BAU building version using the two methods. From the figure it can be seen that the energy results of the CDD method deviate slightly from the EnergyPlus results. In the summer months, the estimation done by the CIBSE method is on an average 16.2% higher than the results obtained from EnergyPlus. However, in winter months, the estimation is on an average 23% lower than the EnergyPlus results.

Figure 7: Annual EPI comparison for CDD method and EnergyPlus results

The Figure 7 shows the cooling EUI calculated by the CIBSE method and the EUI obtained by the EnergyPlus. The annual EUI calculated by using the CIBSE TM41 method is 199 kWh/m²/year while that with the EnergyPlus is at 191 kWh/m²/year. Then annual EUI calculated by using the CIBSE method is 4.6% higher than the EUI calculated using EnergyPlus.

Figure 8: Comparison of monthly energy estimation for ECBC 2017 building between EnergyPlus results and the results obtained by the method described in the study

Figure 8 compares the monthly results for ECBC 2017 compliant building version. In the summer months, the estimation done by the CIBSE method is on an average 38% higher than the results obtained from EnergyPlus. However, in winter months, the estimation is on an average 23% lower than the EnergyPlus results. Then annual EUI calculated by using the CIBSE method is 4.6 % higher than the EUI calculated using EnergyPlus (Figure 4). Figure 9 shows the end use split for the energy calculated by the using the CIBSE method and energy calculated using EnergyPlus. From the figure, it is seen that the cooling energy varies slightly but the lighting and equipment energy values do not. The Normalised Mean Biased Error is 4.6% while the Root Mean Squared Error value is 15%. Lighting and Equipment loads and energy use are calculated in BQEET using the total installed watts and use schedule for the respective end uses. 100% of the lighting and equipment loads contribute to the cooling load in the space. Beyond the schedule which can be edited by the user, the tool does not account for any additional occupancy or daylighting control of the loads.

Figure 9: End use split comparison

Both the Energy Plus and BQEET models use schedules to compute the lighting and equipment loads and energy. Unlike Energy Plus, BQEET converts 100% of the lighting and equipment load in to a cooling load.

The Table 1 compares the model set up and run time for simulating 2900 cases in EnergyPlus and BQEET which is the tool developed in this study. To set up so many cases in EnergyPlus will take an average modeller more than a week, as it requires very detailed inputs. Whereas it takes only 1 minute to set up all the cases in BQEET. Similarly, simulation of 2900 cases in EnergyPlus take at least 3 days in running batch simulation. Whereas, BQEET takes only 55 minutes to run all the cases.

Table 1: Comparison of simulation time

	EnergyPlus	BQEET
Model set up	1 week	1 minute
simulation	3 days	55 minute

Although, BQEET is not a replacement of EnergyPlus or conventional energy simulation software, it gives a fairly accurate result for using it during the early design stage of a project. For studies related to policy making decisions, this tool can be used to estimate the energy consumption of similar kind of buildings across a larger regions.

Figure 10: Impact of building version on CDD

The Figure 10 shows the impact of building version on the CDD values. 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. The reason for higher CDD values are the load conditions for Indian buildings. Since Indian buildings have different load conditions than western countries, the CDD values are higher. The higher values of CDD are mostly due to the solar loads and the envelope loads. Since in the ECBC 2017 compliant building

version, the building envelope has a lower U values, the CDD value is also lower as compared to BAU building envelope. In case of ECBC compliant buildings, the CDD values are 5-7% lower than the values for BAU buildings for all five cities.

Since Indian buildings have different envelope conditions and loads than the buildings in the USA, it is important to consider those in calculating the BPT and the CDD values. Figure 11 shows the values of CDD published by ASHRAE considering 18.3°C as the base temperature and CDD calculated in this study for two 2017 compliant buildings and using ASHRAE standard 55 as thermal comfort model.

Figure 11: Impact of adaptive comfort model on CDD values

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 underestimated.

Figure 11 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.

Figure 12: Cooling energy of building after using various passive design strategies

Figure 8 shows the cooling energy reduction by using passive strategies. The comfort model used here is ASHRAE 55 adaptive model. It is clear from the figure,

that for Sundernagar, night ventilation is the most effective passive strategy while it is least effective for Chennai.

Figure 13: Cooling energy of building after using various passive design strategies

For ECBC compliant buildings, envelope has a better thermal performance and hence the envelope loads are reduced. This reduces the cooling need in buildings. Figure 10 shows the reduction in cooling energy if the building is ECBC 2017 compliant and uses ASHRAE 55 adaptive comfort.

Further validation of this tool is being done using the HERS BESTEST method. HERS BESTEST seems to be an appropriate method for the comparative testing of a simplified tool like BQEET. But the HERS BESTEST testing procedure for an air-conditioned building has been designed for fully conditioned typical US residential buildings, whereas the BQEET tool has been designed for single zone Indian buildings operating in Mixed Mode. So reference building models developed previously for India need to be used to modify the HERS BESTEST L100AL case. Additional HERS BESTEST cases that vary loads also need to be modified to develop cases that are relevant for mixed mode buildings.

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. Since the CDD based energy estimation method is often used for policy analysis, this study provides a more accurate method for determining the BPT, CDD and estimating the energy use. Cooling energy can be greatly reduced by using passive strategies in buildings. However, the amount of reduction is dependent on climatic potential of passive strategy. The method developed can help calculate building specific CDD for any location in the world. The Python based tool BQEET is able to simulate a large number of cases in a short amount of time, and can make early design or policy analysis energy estimation accessible to non-simulation experts. The limited validation of the tool has shown promising results.

Application and limitation of study

This method can be used only during the early design stage when details of all the components of building is not available in detail. The degree day method cannot be used during the detail design stage.

At macro level, because of the lower simulation time this method can be used for planning and policy decisions.

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