Cooling Degree Days for Quick Energy Consumption Estimation in the GCC Countries

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Abstract: One of the most useful and simplified approaches in assessing building energy estimates is the degree days method. The heating and cooling requirements can be easily compared for different locations as well as system trends. In this paper, the cooling degree day values for the capitals of the Gulf Cooperation Council (GCC) are presented. Degree day values at different base temperatures are also produced for these locations. These values are useful for engineers and policy makers for evaluating energy demands and their cost for these countries. A typical two-story residential building is considered here and its yearly cooling load is evaluated. The total cooling energy is compared based on the energy cost of the respective GCC countries. The results presented in this investigation illustrated that the cooling load, based on the cooling degree days (CDDs) at a 23 °C base temperature, agrees well with the detailed hourly cooling load simulated by eQuest software. Additionally, the highest CDDs value of 2589 was observed in the city of Doha and the lowest value of 2037 was seen in Riyadh city. The lowest cooling cost of USD 492 corresponds to Muscat, while the highest value of USD 1672 belong to Abu Dhabi, partially due to a higher tariff of 0.081 USD/kWh.

Keywords: building cooling; building heating; degree days; gcc countries; variable-base temperature

1. Introduction

One of the major challenges of our time is climate change and its irreversible transformation of the planet. The consumption of energy for heating and cooling purposes has put more pressure on the environment. Harsh climate conditions have also led to high demands for air conditioning, which account for 70% of the annual peak electricity consumption in the Gulf Cooperation Council (GCC) [1]. The GCC was established in Riyadh, Saudi Arabia, in May 1981 [2] and represents a political and economic alliance of six Middle Eastern countries—Saudi Arabia, Kuwait, the United Arab Emirates, Qatar, Bahrain, and Oman.

Additionally, the lack of building codes, the use of low efficiency appliances, and high living standards have resulted in the GCC region being one of the highest for electricity consumption per capita in the world [3]. It is also expected that the total electrical energy consumption of the GCC countries will jump to 1094 TWh by 2025 [4]. In the GCC countries, summer temperatures frequently exceed 45 °C with high relative humidity. The cooling capacity in this region has cost approximately USD 50 billion to install. However, governments have not regarded the provision of air-conditioning as a matter requiring public policy and planning as they have with other utilities such as power and water [5].

Building energy analyses are of two types, the simplified and the detailed analyses. Each project has different requirements and depending on the accuracy, speed, cost, sensitivity, ease of use as well as the availability of data, a certain analysis can be adopted [6]. One of the simplest and fastest methods in analyzing building energy demands is the degree days method. It measures the variations of the outdoor temperature with respect
to a base temperature. The base temperature is the temperature at which no heating or cooling is required. Many countries use 18.3 °C as a base temperature ($T_b$) [6]. This base temperature is traditionally used, but the actual balance temperature depends on many factors such as solar heat gains, thermostat settings, insulation levels, internal and solar heat gains, and the type of construction [7]. This indicates that 18.3 °C an unreliable base temperature. Therefore, several base temperatures are used to assess the cooling degree days in this study. In such hot climates as the GCC countries, cooling degree days are commonly used. Several methods can be applied to calculate the cooling degree days (CDDs), such as the hourly method [8], Erbs method [9], Schoenau and Kehrig (S–K) method [10], and hybrid S–K method [11]. If hourly temperature data are available, accurate CDDs can be calculated; however, in this study, the average monthly temperatures are adopted since the goal is to compare the required cooling load that increases with the number of CDDs. Al Houmod presented graphical heating and cooling degree day values at different base temperatures for different cities in Saudi Arabia [12]. Al-Saadi et al. used five different methods to calculate the CDDs for different cities in Oman to classify Omani climates based on the calculated CDDs values [13].

Building performance has been extensively studied using simulation tools, such as eQuest (the Quick Energy Simulation Tool) and TRANSYS (Transient Systems Simulation Program). To simulate the energy efficiency of an existing four-star hotel in Tianjin, China, Xing et al. [14] used eQuest. In their investigation, the authors looked at the degree to which the key variables influencing hotel buildings’ energy use might be predicted. Their research demonstrated that the internal load schedule had the greatest influence on the model’s accuracy. Using TRNSYS 16, Terziotti et al. [15] modeled a building using seasonal solar thermal energy. In their investigation, building efficiencies and various storage bed placements and structures were simulated in order to determine whether a system is practical in an urban setting. Considerable energy savings were found possible within the small footprint required by city lots.

A comparison between the energy analysis model established for buildings by eQuest and the actual energy consumption (IPMVP—International Performance Measurement and Verification Protocol—method D) of an actual office building in Taiwan was made by Kea et al. [16] and the final results had errors from 0.5% to 27%. The loads of a typical building in Athens were calculated by TRNSYS and eQuest [17]. The results showed that TRNSYS provides greater loads of about 5% in the study case and in most cases of the parametrical analysis TRNSYS gives greater loads. The monthly load comparison proved that the results were close to each other.

In our study, a comparison between eQuest and the simple degree days method to estimate the monthly and seasonal cooling loads of a residential building in the GCC capitals is made to predict how close the results of those methods are. The data can be useful for designers and policy makers as well as the public of those countries that witness one of the highest energy demands in the world.

2. Materials and Methods

The simplest method to evaluate the degree days is achieved by using the following equation,

$$CDD = \frac{(T_{\text{max}} + T_{\text{min}})}{2} - T_b$$

(1)

For the sake of comparison purposes, this simple approach is believed to be sufficient. The degree days are evaluated for the years (2017–2021) in the capitals of the GCC countries with base temperatures of 18, 20, 22, 24, and 26 °C. The average monthly temperatures for the capitals of the GCC countries were derived from the NASA (National Aeronautics and Space Administration) power website [18]. The base temperature 26 °C is associated with lower cooling degree days and better cooling energy consumption.
Residential Building Example

A two-story residential building shown in Figure 1 is considered for simulation with an eQuest software package [19]. The building dimensions and U-values are given in Table 1. The typical two-story residential house has a total floor area of 1366 ft² (127 m²) and it was suggested for this study to indicate how much energy is needed to cool such an envelope in these cities. The building is also assumed to have 196.48 ft² (18.25 m²) of windows and 5939.52 ft² (552 m²) of walls. All the walls are exposed to the external and the floor and ceiling are assumed to be adiabatic (see Figure 1).

Figure 1. The simulated two-story residential building.

Table 1. The two-story building dimensions and thermal characteristics.

|        | Average U-Value Windows (BTU/h ft²·F) | Average U-Value Walls (BTU/h ft²·F) | Average U-Value Windows + Walls (BTU/h ft²·F) | Window Area (ft²) | Wall Area (ft²) | Window + Wall Area (ft²) |
|--------|--------------------------------------|-------------------------------------|-----------------------------------------------|-------------------|----------------|-------------------------|
| North  | 0.00                                 | 0.403                               | 0.403                                         | 0.00              | 1200.00        | 1200.00                 |
| East   | 0.00                                 | 0.403                               | 0.403                                         | 0.00              | 502.00         | 502.00                  |
| South  | 1.005                                | 0.403                               | 0.478                                         | 148.33            | 1051.67        | 1200.00                 |
| West   | 1.005                                | 0.403                               | 0.461                                         | 48.15             | 453.85         | 502.00                  |
| Roof   | 0.000                                | 0.195                               | 0.195                                         | 0.00              | 1366.00        | 1366.00                 |
| All Walls | 1.005                               | 0.403                               | 0.438                                         | 196.48            | 3207.52        | 3404.00                 |
| Walls + Roofs | 1.005                             | 0.341                               | 0.368                                         | 196.48            | 4573.52        | 4770.00                 |
| Underground | 0.000                              | 0.139                               | 0.139                                         | 0.00              | 1366.00        | 1366.00                 |
| Building | 1.005                               | 0.294                               | 0.317                                         | 196.48            | 5939.52        | 6136.00                 |

The total cooling load required is calculated by the following equation,

\[ Q = 24 \cdot UA \cdot CDD \] (2)

The CDD at a base temperature of 18.3 °C is usually considered for load calculations. The total energy consumption is amongst the highest at this base temperature. It should also be noted that the base temperature will be different for different locations, building orientations, thermostat setups as well as other factors that should be taken into consideration. The U-values were selected based on Kuwait Ministry of Electricity and Water recommendations for residential buildings [20].
3. Results

Figure 2 shows the average monthly temperatures for the GCC capitals. The figure shows that the lowest temperature is for the month of January, while the highest are in the month of June for Muscat, July for Kuwait City, Doha, Manama, and Riyadh, and August for Abu Dhabi. Kuwait has the highest temperature of 38.5 °C as well as the lowest of 16.7 °C in January. When comparing the total CDDs for these capitals in Figure 3, Riyadh has the lowest number of CDDs regardless of the base temperature used and Abu Dhabi has the highest CDDs, especially at lower base temperatures. Although Kuwait is considered one of the hottest cities on the planet, it is interesting to notice that its CDDs are not the highest in the region. This is due to the fact that it has the coldest weather for the period between January and April.
To check the reliability of the degree days method in assessing residential building cooling loads, a detailed hourly cooling load was conducted with eQuest software. Solar gain, air infiltration, occupancy, and other parameters were set in the software. Since Abu Dhabi and Riyadh represent the highest and lowest loads, respectively, eQuest was chosen to evaluate the hourly cooling load for these two cities to compare their seasonal cooling loads with ones derived from the simple degree days method. Figure 4 shows the monthly cooling loads for Abu Dhabi and Riyadh for the residential building under consideration. The cooling load is always larger for Abu Dhabi. The highest monthly load is seen in August and the lowest is in January for both cities.

Figure 4. Monthly cooling load for the residential building evaluated by eQuest.

The total cooling load was found by eQuest to be 60 MWh for Abu Dhabi and 50.5 MWh for Riyadh. When comparing the former values with the ones evaluated by the simple degree days method, one can find that the total load changes with the base temperatures and that the higher the base temperature, the lower the cooling loads are. Figure 5 shows the change of cooling loads as a function of the base temperature. When a curve fitting is used, a linear relationship is found for all cities. From those lines, a base temperature at which the DD load is equal to the hourly simulated cooling load can be found. From Figure 5, the base temperature that gives a CDD load equal to the hourly simulated load of the residential building is 23.1 °C for Riyadh and 23.5 °C for Abu Dhabi. These values are much higher than the traditional 18.3 °C base temperate used for other parts of the world. The error in evaluating the yearly cooling load is 64% for Riyadh and 75% for Abu Dhabi when choosing this value. It is, however, recommended here to use the value 23 °C for the base temperature, especially for comparison studies. The error drops to less than 10% when selecting this value of temperature. Obviously, the higher the base temperature, the lower the cooling load needed.
The total cooling load was found by eQuest to be 60 MWh for Abu Dhabi and 50.5 MWh for Riyadh. When comparing the former values with the ones evaluated by the simple degree days method, one can find that the total load changes with the base temperatures and that the higher the base temperature, the lower the cooling loads are. Figure 5 shows the change of cooling loads as a function of the base temperature. When a curve fitting is used, a linear relationship is found for all cities. From those lines, a base temperature at which the DD load is equal to the hourly simulated cooling load can be found. From Figure 5, the base temperature that gives a CDD load equal to the hourly simulated load of the residential building is 23.1 °C for Riyadh and 23.5 °C for Abu Dhabi. These values are much higher than the traditional 18.3 °C base temperature used for other parts of the world. The error in evaluating the yearly cooling load is 64% for Riyadh and 75% for Abu Dhabi when choosing this value. It is, however, recommended here to use the value 23 °C for the base temperature, especially for comparison studies. The error drops to less than 10% when selecting this value of temperature. Obviously, the higher the base temperature, the lower the cooling load needed.

Before concluding this work, it is interesting to provide an example of the cooling load cost for this building in the region with the new recommended base temperature, i.e., 23 °C. Table 2 shows the estimated degree day cooling load at this temperature for the GCC capitals and their respective tariffs [21] for electricity consumption in residential buildings. The table shows that the cost of cooling is the lowest in Doha and the highest in Abu Dhabi. A standard efficiency coefficient of performance (COP = 3) was chosen for the residence air cooling system. Table 2 shows the cooling cost in USD for the residence at the capitals of the GCC. The highest electricity bill is found in Abu Dhabi, while the lowest is in Muscat. Abu Dhabi’s electricity bill is more than twice the one in Doha even though they have closer cooling loads.

Table 2. Cooling load cost in the GCC capitals for the model Residence ($T_b = 23\degree C$, COP = 3).

| Capital   | CDD   | Tariff (USD/kWh) | Cooling Load (kWh) | Electric Consumption (kWh) | Cooling Cost (USD) |
|-----------|-------|------------------|--------------------|---------------------------|--------------------|
| Doha      | 2589  | 0.032            | 63,937.944         | 21,312.648                | 682                |
| Kuwait    | 2393  | 0.029            | 59,097.528         | 19,699.176                | 571                |
| Riyadh    | 2037  | 0.048            | 50,305.752         | 16,768.584                | 805                |
| Manama    | 2334  | 0.048            | 57,640.464         | 19,213.488                | 922                |
| Abu Dhabi | 2508  | 0.081            | 61,937.568         | 20,645.856                | 1672               |
| Muscat    | 2299  | 0.026            | 56,776.104         | 18,925.368                | 492                |

4. Conclusions

The objective of this study was to compare the cooling load trend for the GCC capitals by comparing the seasonal CDDs. Average monthly temperatures over the last five years were used in calculating these values. The cooling degree days were determined at 18, 20, 22, 24, and 26 °C base temperatures. The findings of this study are summarized as follows:

- The highest CDDs values of 2589 were seen in Doha.
- The lowest CDDs values of 2037 were found in Riyadh, Saudi Arabia.
- The cost of cooling a single home in Abu Dhabi was the highest at USD 1672, partially due to it having the highest tariff of 0.081 USD/kWh.
- The cost of cooling was the lowest at USD 492 in Muscat, partially due to it having the lowest tariff of 0.026 USD/kWh.

Figure 5. Seasonal cooling load for the residential building at different base temperatures.
• It is found that 23 °C is a good temperature for cooling load evaluation for the degree days method.

The simple CDD method is a quick tool for estimating the cost of cooling and can help customers and policy makers in regions have better and quicker future planning.

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