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Analytical Assessment of Cooling Degree-Days for Estimating Energy Consumption in Building Sector During Cooling Season in Belgrade

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Abstract: Although the degree-day method for heating is classified as a single-parameter method, as it only accounts for daily changes in outdoor air temperature to estimate the heating demand of a building due to climatic influences, it has proven to be highly reliable over decades of practice and is now widely regarded as a standard method for determining heating requirements. However, due to evident climate changes and rising outdoor air temperatures, treating the heating degree days as a prescribed constant value for the specified location, leads to significantly inaccurate results, as demonstrated in this paper through an analysis of data from the Republic Hydrometeorological Service. Meanwhile, the use of the cooling degree days method to determine cooling demand has proven to be highly unreliable. This is because the method does not account for solar radiation, which, during the summer months, is as significant a factor as outdoor air temperature. To address this issue, while preserving the core concept of the method the heat load to be removed from a cooled space is proportional to the difference between the average daily outdoor air temperature and the base indoor temperature, a considerably lower base indoor temperature can be used in place of the internal design (reference) temperature. This paper presents the corrected method, along with international experiences and best practices, and includes data from the Republic Hydrometeorological Service. Additionally, cooling degree days for Belgrade have been calculated and presented, providing more accurate and reliable cooling demand forecasts.

Keywords: Cooling degree-days; Avarage daily outside temperature; Annual energy consumption; Climate change

1. Introduction

Climate change is ongoing and will likely continue in the coming decades. Globally, an increase in average air temperature during both summer and winter months has been observed. In Serbia's building sector, heating and cooling currently account for about 45% of total energy consumption according to official data [1]. The forecasted climate changes will significantly alter this balance. Specifically, higher temperatures are expected to reduce energy demand for heating during the winter period and increase energy consumption for cooling during the summer months.

Computer simulations are continuously being improved to provide support in assessing energy consumption in the building sector. However, in addition to complex simulations, simpler and well-established tools, such as the degree-day method and the bin method, are also used [2]. Cooling degree days (*CDD*) and heating degree days (*HDD*) are often used as climate indicators to assess heating and cooling needs. This stationary, single-parameter method allows for the evaluation of a building's energy performance and is based on current or averaged differences between the reference indoor air temperature and the daily mean outdoor air temperature.

Therefore, the degree-day method is relevant when the thermophysical properties of building structures can be considered constant. This method assumes no heat accumulation in building structures during the analyzed period. Using the degree-day concept, it is possible to estimate monthly or annual heating and cooling requirements of buildings at various locations.

The average heating degree day value currently used in the "*Regulation on Energy Efficiency of Buildings*" [3] for Belgrade is $HDD = 2520$ [3, 4, 5]. This value was obtained using meteorological data from the period 1925 to 1968. Since the "*Regulation on the Methodology for Calculating the Number of Degree Days for Heating and Cooling*" [6] prescribes the determination of degree days over the last 25 years, the study [7] found that the heating degree day value for Belgrade during this heating period is $HDD = 2179.7$.

The newly obtained value is 13.5% lower than the value currently used in the "*Regulation on Energy Efficiency of Buildings*." In Table 1, θ_h [°C] represents the average temperature of the heating season, and Z is the number of days in the heating season.

Table 1. Comparison of currently used heating degree day values with newly obtained results from study [7]

Belgrade model 12/19			
Period	$HDD_{average}$	Z [day]	θ_h [°C]
1925-1968.	2520	175	4,6
1998-2022.	2179,7	152	4,66

The currently applicable "*Regulation on Energy Efficiency of Buildings*" [3] only takes into account the annual heating energy demand. Due to the intensifying climate changes during the summer period, which lead to increased energy consumption for cooling, the aim of this paper is to determine the number of cooling degree days, which will be used to calculate the annual cooling energy demand, $Q_{c,nd}$ [kWh/month].

2. Methodology for calculating cooling degree days

The methodology according to ASHRAE guidelines [2] is widely accepted for calculating the number of cooling degree days (*CDD*), using the following equation:

$$CDD_{\text{annual}} = \sum_{j=1}^{N} cc \cdot (\theta_{\text{average,i}} - \theta_{\text{b}}) \tag{1}$$

where N represents the number of days in the year (365 or 366), θaverage,i [°C] denotes the daily average outdoor air temperature, and θb [°C] is the base (reference) temperature for cooling. If the daily average outdoor air temperature is higher than the base temperature, *c*c equals 1; otherwise, *cc* equals 0.

The base temperature refers to the outdoor air temperature at which no additional heating or cooling is needed, meaning it is the temperature within the range of comfortable conditions for the occupant, without the need for mechanical heating or cooling systems. During the summer period, when the average daily outdoor temperature exceeds the base temperature, cooling systems need to be activated to maintain comfortable indoor conditions. Determining the base temperature requires a detailed consideration of specific factors, such as: thermal characteristics of the construction, internal heat sources, heat gains through the thermal envelope of the building, and the desired indoor air temperature [9,10]. Therefore, the base temperature should be individually determined based on the specific case for accurate energy consumption estimation.

Many countries use 18.3°C as the base temperature for calculating cooling degree days [9]. However, the base temperatures used for calculating *CDD* vary across different countries, for example: 18.3°C in the United States and Saudi Arabia, 15.5°C in the United Kingdom, and 15.0°C in Germany.

In study [8], the calculation of cooling degree days for Belgrade was carried out for the reference period from 1971 to 2000, based on a base temperature of 18.3°C. According to this study, the obtained value for cooling degree days is *CDD* = 432.

On the other hand, in Serbia, the methodology for calculating degree days was prescribed in 2021 by the "Regulation on the Methodology for Calculating Degree Days for Heating and Cooling" [6]. According to this methodology, the daily, monthly, and annual number of cooling degree days is calculated using expressions (2-5) as follows:

$$CDD_{\text{daily}} = \begin{cases} (\theta_{\text{average},i} - \theta_{\text{in}}) & \text{if} \quad \theta_{\text{average},i} \geq 24°\text{C} \\ 0 & \text{if} \quad \theta_{\text{average},i} < 24°\text{C} \end{cases} \tag{2}$$

$$CDD_{\text{monthly}} = \sum_{i=1}^{z} CDD_{\text{daily}} \tag{3}$$

$$CDD_{\text{annual}} = \sum_{j=1}^{12} CDD_{\text{monthly}} \tag{4}$$

$$CDD_{\text{average}} = \frac{\sum_{i=1}^{z} CDD_{\text{annual}}}{25} \tag{5}$$

According to the Regulation [6], the number of cooling degree days for a calendar year is determined using the 24/21 model. In the model name, the number 21 represents the indoor reference air temperature θ_{in} [°C], while the number 24 represents the base temperature, which is the average daily outdoor air temperature at which the cooling system begins to operate. Additionally, the average number of cooling degree days ($CDD_{average}$) refers to the arithmetic mean of the number of cooling degree days over the past 25 years. If this value is not available, data from a shorter period can be used, but not less than 15 years.

To determine *CDD* according to the specified expressions, it is necessary to have data on the average daily outdoor air temperatures at a given location. As shown in equation (6), there are three different methods for calculating the average daily outdoor air temperature. This value can be obtained as the arithmetic mean of the maximum and minimum daily outdoor air temperatures, using measured air temperatures at three intervals: 7, 14, and 21 hours local time, or using average daily outdoor air temperatures measured every hour.

$$\theta_{\mathrm{average},i} = \begin{cases} \dfrac{\theta_{\max,i} + \theta_{\min,i}}{2} \\ \dfrac{\theta_{7,i} + \theta_{14,i} + 2 \cdot \theta_{21,i}}{4} \\ \dfrac{\sum_{k=1}^{24} \theta_{\mathrm{sr},k}}{24} \end{cases} \tag{6}$$

3. Results

In accordance with the prescribed Regulation [6], the average number of cooling degree days for Belgrade ($CDD_{average}$) is determined as the arithmetic mean of the number of cooling degree days over the past 25 years, i.e., for the period from 1998 to 2022. The data on average daily outdoor air temperatures were obtained based on climatological measurements and observations at measuring stations at three intervals: 7, 14, and 21 hours local time. These values were provided by the Republic Hydrometeorological Institute of Serbia (RHMZ) - from the automatic meteorological station at the Vračar Observatory, Belgrade (44°48' N, 20°28' E, 132 m above sea level).

For the period from 1998 to 2022, the average annual number of cooling degree days for the calendar year and the average annual number of cooling degree days for the cooling period (from May 15 to September 15) are presented in Tables 2 and 3. Additionally, the table shows the number of days during the cooling period (*Z*), the average temperature during that period (θ_c), as well as the differences in the number of cooling degree days for each year compared to the average value over the observed interval. These differences are presented as absolute and relative deviations.

Table 2. The number of annual cooling degree days for the calendar year in Belgrade, determined by the 24/21 model

Model 24/21					
Year	Z	θ_c	$CDD_{24/21}$	$\Delta CDD_{24/21}$	$\Delta CDD_{r\ 24/21}$
–	day	°C	°C-day	°C-day	%
1998.	49	26,96	291,8	5,0	1,76
1999.	24	26,1	122	-164,8	-57,46
2000.	55	27,19	340,5	53,7	18,74
2001.	34	26,42	184,4	-102,4	-35,70
2002.	36	26,54	199,4	-87,4	-30,47
2003.	60	26,6	335,7	48,9	17,06
2004.	25	26,54	138,4	-148,4	-51,74
2005.	24	26,14	123,4	-163,4	-56,97
2006.	42	26,6	235,2	-51,6	-17,98
2007.	56	27,39	357,7	70,9	24,74
2008.	52	26,9	307	20,2	7,06

2009.	47	26,21	245,1	-41,7	-14,53
2010.	44	26,7	251	-35,8	-12,47
2011.	51	27,12	312,2	25,4	8,87
2012.	79	27,42	507,5	220,7	76,97
2013.	51	27,09	310,5	23,7	8,28
2014.	29	25,82	139,8	-147,0	-51,25
2015.	65	27,66	432,7	145,9	50,89
2016.	45	25,99	224,4	-62,4	-21,75
2017.	59	28,02	414,3	127,5	44,47
2018.	59	25,91	289,5	2,7	0,95
2019.	65	26,83	378,8	92,0	32,09
2020.	52	26,09	264,7	-22,1	-7,69
2021.	55	28	387,5	100,7	35,13
2022.	64	26,9	375,6	88,8	30,98

Table 3. The number of annual cooling degree days for the cooling season in Belgrade, determined by the 24/20 model

Model 24/21					
Cooling season	Z	θ_c	$CDD_{24/21}$	$\Delta CDD_{24/21}$	$\Delta CDDr_{24/21}$
–	day	°C	°C-dan	°C-dan	%
1998.	49	26,96	291,8	13,4	4,82
1999.	23	26,1	117,2	-161,2	-57,90
2000.	53	27,3	334	55,6	19,97
2001.	34	26,42	184,4	-94,0	-33,76
2002.	36	26,54	199,4	-79,0	-28,37
2003.	50	26,85	292,5	14,1	5,07
2004.	25	26,54	138,4	-140,0	-50,29
2005.	24	26,14	123,4	-155,0	-55,67
2006.	42	26,6	235,2	-43,2	-15,51
2007.	53	27,55	347,4	69,0	24,79
2008.	52	26,9	307	28,6	10,28
2009.	46	26,17	242	-36,4	-13,07
2010.	44	26,7	251	-27,4	-9,84
2011.	48	27,23	299,8	21,4	7,69
2012.	71	27,7	476	197,6	70,98
2013.	44	27,46	284	5,6	2,01
2014.	29	25,82	139,8	-138,6	-49,78
2015.	59	27,78	400	121,6	43,68
2016.	43	26,07	218,1	-60,3	-21,66
2017.	58	28,06	409,4	131,0	47,06
2018.	57	25,96	282,8	4,4	1,58
2019.	65	26,83	378,8	100,4	36,07
2020.	49	26,17	253,3	-25,1	-9,01
2021.	54	28,1	382,7	104,3	37,47
2022.	63	26,9	371,4	93,0	33,41

Taking into account the observed period over 25 years, Table 4 shows the average number of cooling degree days, the number of days during the cooling period, and the average temperatures for the cooling season for both the calendar year and the entire cooling season.

Table 4. Presentation of the obtained results

1998. – 2022.			
	$CDD_{average}$ model 24/21	Z [day]	θ_c [°C]
Calendar year	286,8	49	26,77
Cooling season	278,4	47	26,83

Figures 1 and 2 graphically present the number of cooling degree days determined by the 24/21 model, for the entire calendar year and the cooling season, compared to the average number of cooling degree days from Table 4. The smallest relative deviation of the number of cooling degree days from the average value over 25 years for the cooling season is 0.95% (cooling season 2018), while for the calendar year it is 1.58% (2018).

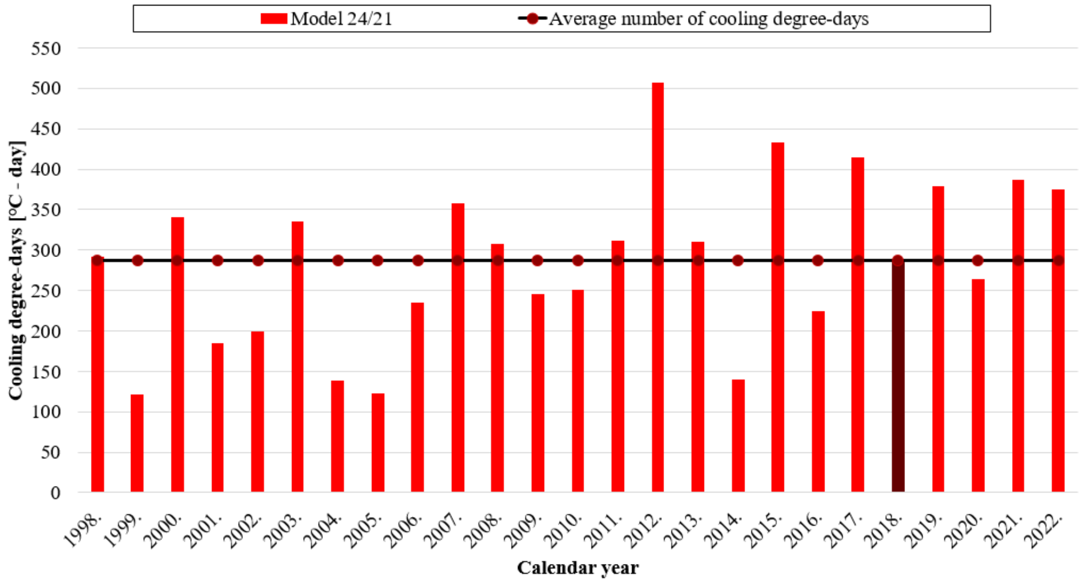

Figure 1: Graphical representation of the annual number of cooling degree days for the period from 1998 to 2022, determined by the 24/20 model, compared to the overall average number of cooling degree days for calendar year

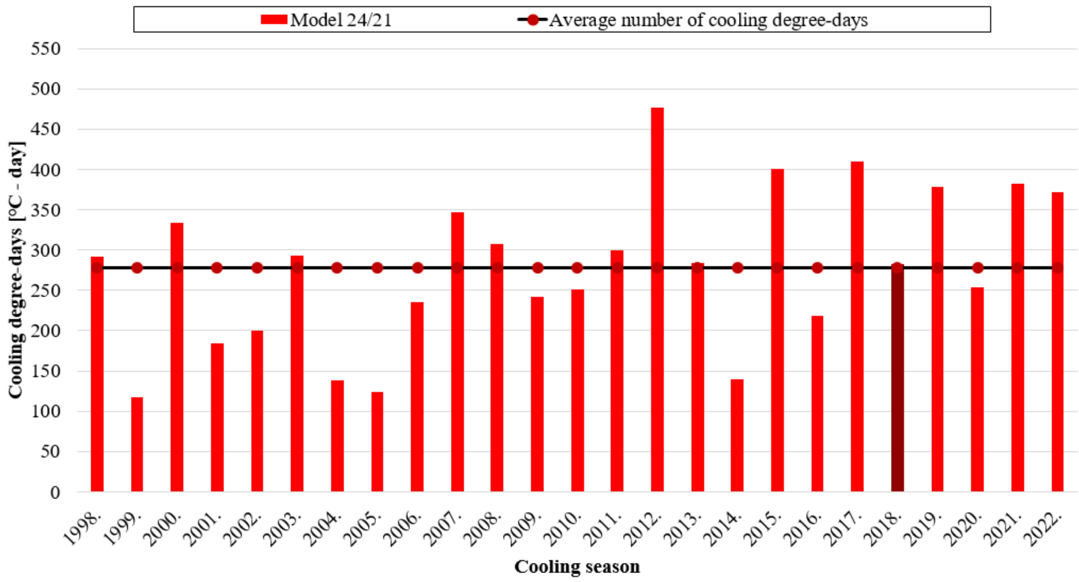

Figure 2. Graphical representation of the annual number of cooling degree days for the period from 1998 to 2022, determined by the 24/20 model, compared to the overall average number of cooling degree days for cooling season

Based on the data shown in Tables 2 and 3, diagrams have been created to illustrate the variation in the average number of cooling degree days throughout the calendar year (Figure 3) and during the cooling season (Figure 4) over the past 25 years.

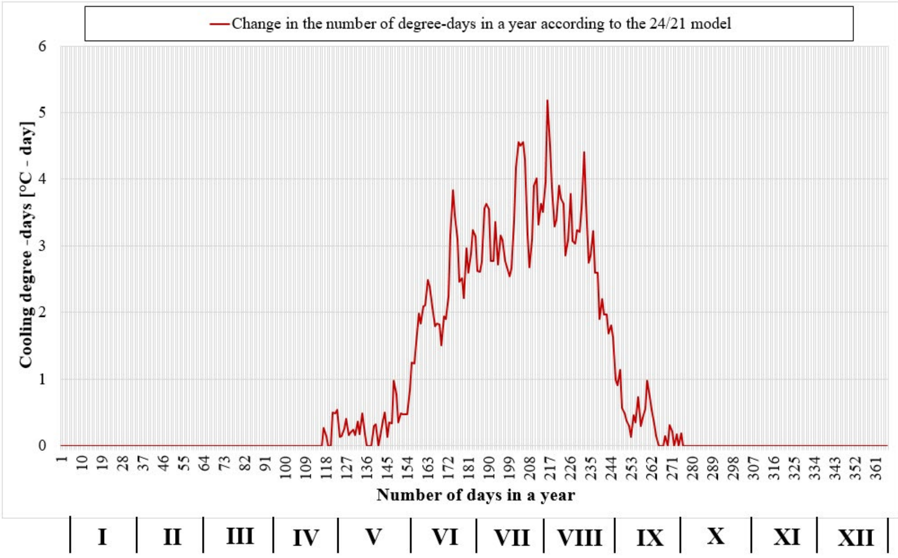

Figure 3. Diagram showing the change in cooling degree days during the calendar year from 1998 to 2022.

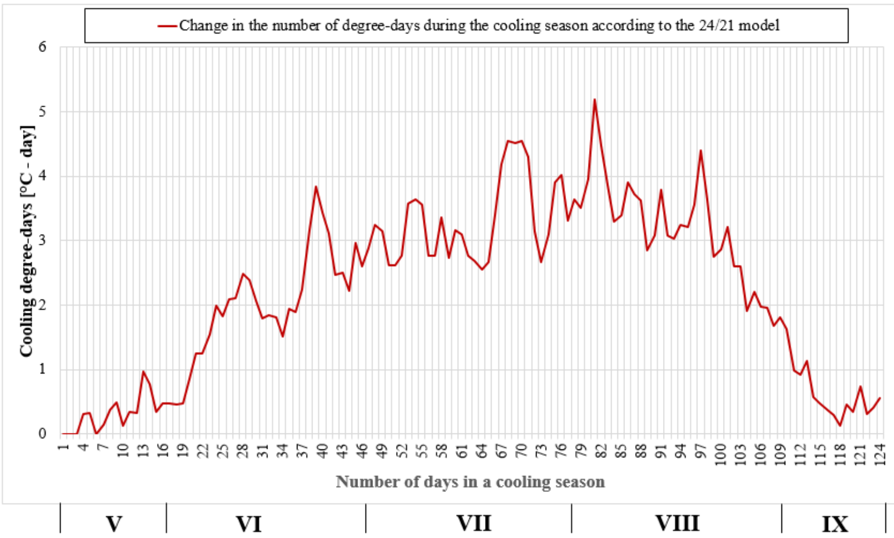

Figure 4: Diagram showing the change in cooling degree days during the cooling season from 1998 to 2022.

The number of cooling degree days (CDD_{annual}) can also be expressed graphically as a function of the number of days during the cooling period (Z), according to the following equation:

$$CDD_{\text{annual}} = \underbrace{Z(\theta_{\text{b}} - \theta_{\text{in}})}_{A_1} + \underbrace{\sum_{n=1}^{Z}(\theta_{\text{average},i} - \theta_{\text{b}})}_{A_2} \tag{7}$$

By applying equation (7), the number of cooling degree days is determined as the sum of area A_1, which corresponds to the first term of the equation, and area A2, which corresponds to the second term. The graphs allow for the determination of the number of days in the cooling period (Z) obtained from the intersection of the average monthly air temperature profile curve and the cooling isotherm boundary curve.

Figure 5 graphically presents the daily cooling degree day profile for an exceptionally warm cooling season (2012), while Figure 6 provides a graphical representation for an exceptionally cold cooling season (1999) during the observed period.

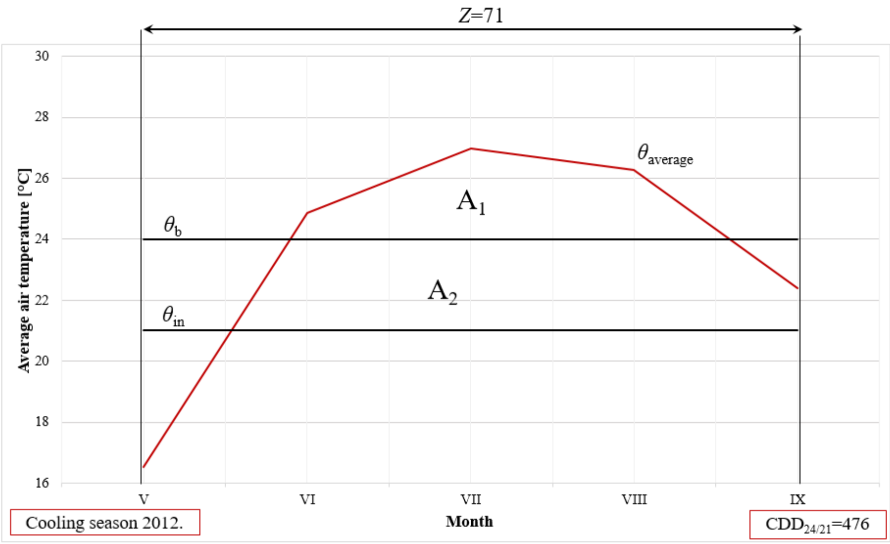

Figure 5. Graphical representation of cooling degree days for Belgrade during the exceptionally warm cooling season (2012) over the observed 25 years, based on average monthly outdoor air temperatures

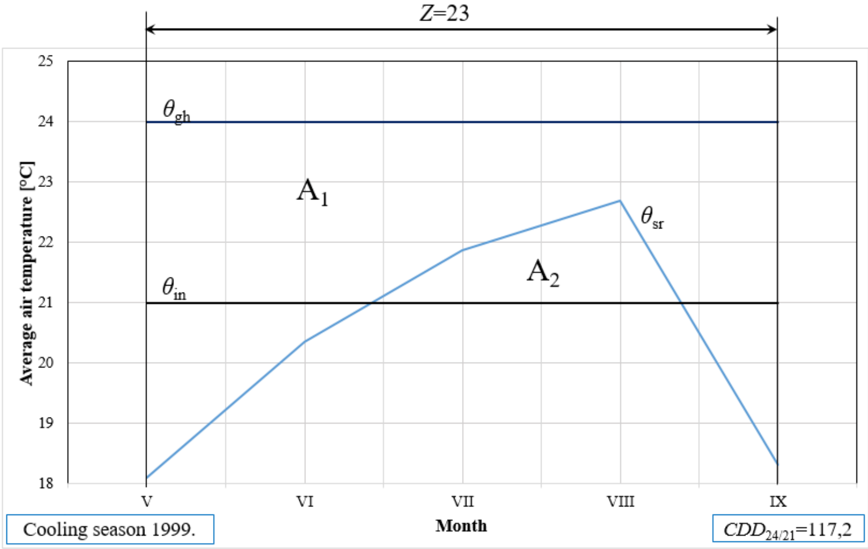

Figure 6. Graphical representation of cooling degree days for Belgrade during the exceptionally cold cooling season (1999) over the observed 25 years, based on average monthly outdoor air temperatures

In addition, the number of cooling degree days can also be graphically represented using average daily outdoor air temperatures. Figure 7 shows the exceptionally warm cooling season (2012), while Figure 8 illustrates the exceptionally cold cooling season (1999) over the observed period. During the exceptionally warm cooling season, the lowest average daily temperature (May 17) was 11.4°C, while the highest (August 6) was 32.6°C. In contrast, during the exceptionally cold cooling season, the lowest average daily temperature (June 22) was 11.1°C, and the highest (August 10) was 30.5°C.

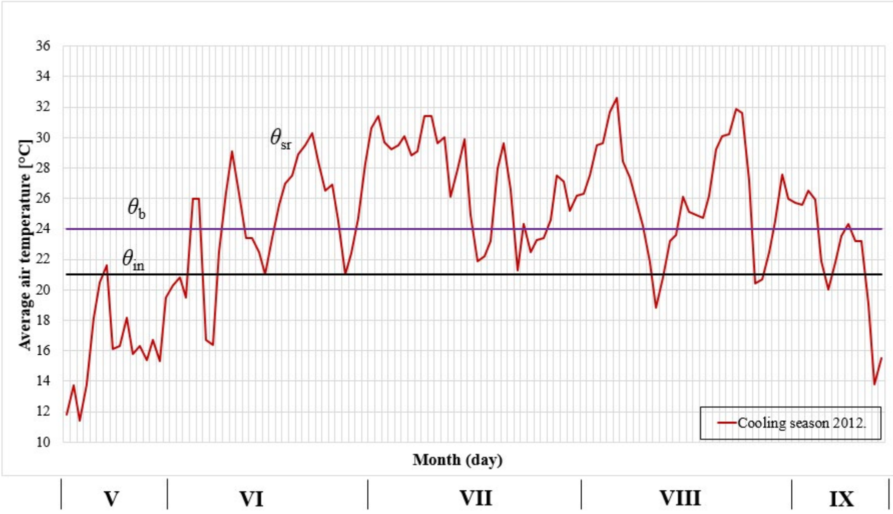

Figure 7. Graphical representation of cooling degree days for Belgrade during the exceptionally warm cooling season (2012) over the observed 25 years, based on average daily outdoor air temperatures

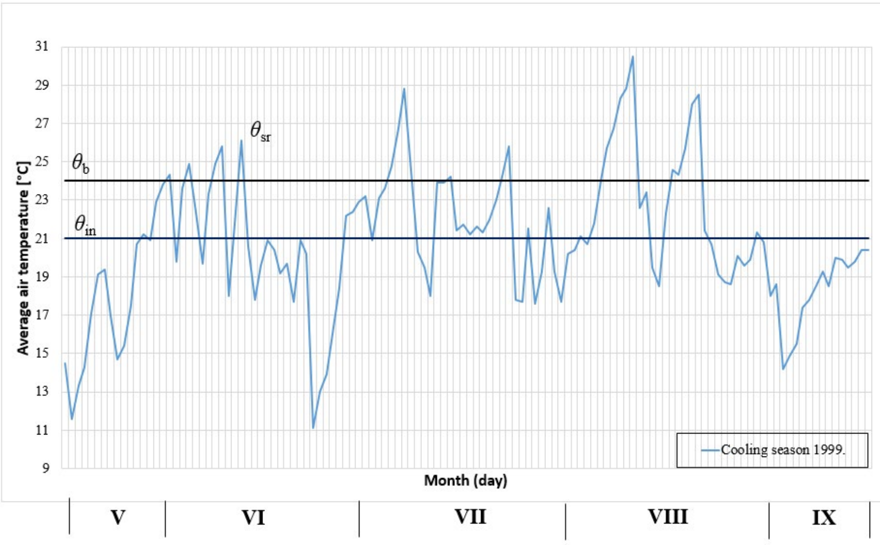

Figure 8. Graphical representation of cooling degree days for Belgrade during the exceptionally cold cooling season (1999) over the observed 25 years, based on average daily outdoor air temperatures

4. Conclusion

Cooling degree days (*CDD*) is an important climatic parameter used to estimate energy consumption in buildings during the summer period. This method represents the cumulative difference between the outdoor air temperature and a reference (base) temperature over a specified time period. The base temperature is crucial in determining *CDD* and represents the temperature at which cooling systems are not needed to maintain the desired indoor air temperature. Using a base temperature of 24°C, as established by the "*Methodology for Calculating Degree Days for Heating and Cooling*," the average cooling degree days values obtained are *CDD*=286.8 (for the calendar year) and *CDD*=278.4 (for the cooling season). In contrast to the proposed regulation that specifies a base temperature of 24°C, many countries use a base temperature of 18.3°C for calculations. Based on a base temperature of 18.3°C, the study [8] calculated the cooling degree days for Belgrade for the reference period (1971–2000), yielding a value of *CDD*=432.

The significant differences in the average cooling degree days values, considering base temperatures of 24°C and 18.3°C, highlight the importance of carefully selecting the base temperature. Further research should focus on accurately defining the base temperature to obtain more precise estimates of cooling degree days, which is essential for determining the required cooling energy.

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