DOE2 Dry-Bulb Temperature Precision Level Impact on Sensible Economizer Performance

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Abstract

Weather files are used with building simulation tools to calculate the impact of local climate on energy use. In DOE2, the dry-bulb temperature (DBT) is one of the internal variables initialized from weather file data. A discrepancy in the precision level of the DOE2 air-side sensible economizer high limit shutoff temperature and the weather file DBT was found to affect simulation results. This paper first details the origins of the economizer-related energy use variations due to this discrepancy. The findings were then evaluated in terms of energy simulation results for a peer-reviewed energy model. Finally the same model was run with weather files for various climates to evaluate the importance of the discrepancy based on the building location. The purpose of this paper is to make DOE2 users aware of the discrepancy and suggest ways to achieve more accurate simulation results.

1 Introduction

DOE2 was developed by James J. Hirsch & Associates (JJH) in collaboration with Lawrence Berkeley National Laboratory (LBNL) (Hirsch 2009). This building simulation program was first released in 1978 and originally "created to develop and support energy standards" (Mills 1995). DOE2 is now used internationally to evaluate energy performance and costs.

The energy performance of a building may vary substantially with geographic location since climate and sun exposure greatly affect building loads (Rock and Wu 1998). To account for location, annual climate files are used. These include one of 1) actual weather data, for example when "calibrating" a simulation model with data from utility records or monitoring, 2) projected weather data (Jentsch et al. 2008), and, 3) most commonly, representative historic weather data.

Weather files created by the National Renewable Energy Laboratory (NREL) are commonly used in the research community (e.g., Rock and Wu 1998). These files include one year of hourly climate and solar radiation data, using monthly information extracted from a 30 year site history of meteorological conditions (Wilcox and Marion 2008). Weather file formats such as TMY2, TMY3, or WYEC2 were developed to accommodate the simulation of new technologies requiring additional data. These data sets are based either in Inch-Pound (I-P) or International System (SI) units and are derived using various algorithms to generate weather years representative of the local climate. According to the DOE2 user's manual (Lawrence Berkeley Laboratory and Los Alamos National Laboratory 1981), in 1981, 12 weather variables were included in weather files for use with DOE2. The dry-bulb temperature (DBT) was one of these variables; DBT affects multiple aspects of building performance, from the heat flow through walls to the performance of the HVAC system.

For DOE2 to internally initialize variables based on weather file data, these files must be converted to a machine language using the DOE2 weather processor. Independently of the initial format (e.g., TMY2 or TMY3), all files, once converted to a binary format, contain the same level of precision and are based in the I-P system. The weather processor source code shows decimal values are converted I-P values and rounded to integers (Buhl 1999, VIII.8).

At the time of writing, whether DOE2.1E or DOE2.2 is used and CTMY2, TMY3 or any other type of weather files, the precision level is the same. The goal of this paper is to report the impact this precision level has on energy simulation results. Although the precision level affects several aspects of a simulation, the focus of this study is on the use of the weather file DBT and the high limit shutoff temperature of the air-side economizer in a few climate types.

2 Methods

A typical weather file was initially analyzed to understand the effect of precision on building energy use estimates when running a simulation. An energy analysis was then performed using an existing peer-reviewed model of a building to illustrate the effect of the weather file on energy use results. Finally, the importance of the precision relative to location was calculated by running simulations with weather files for a range of climates.

2.1 Weather File Analysis

The Calgary CTMY2 weather file was analyzed to understand the ways precision could impact the energy simulation results. CTMY2 weather files are the Canadian version of TMY2 files created by the NREL and provided with the EE4 simulation package (NRCan 2008), which uses DOE2.1 as the simulation engine. The number of hours each DBT value was represented in the CTMY2 file was compiled and separated in temperature bins.

Weather files are initially composed in text format and then converted to binary format using the DOE-2 weather processor "FMTWTH2.EXE". Similarly, binary files can be converted to text format using WTHFMT2.EXE (Buhl 1999). The weather processor was used to convert the Calgary weather binary file downloaded from the DOE2 web site (Hirsch 2009) to text format. The DBT column was extracted from the text file. The number of hours each DBT value was recorded was determined and plotted.

2.2 Energy Use Analysis

The same CMYT2 Calgary weather file was used for a DOE2.1E energy simulation of the Child Development Center (CDC), located near the University of Calgary. Considerable effort was devoted to minimizing the internal loads of this high efficiency building (Tian et al. 2009). System-1 and System-2 (the auto-defined system names generated by the EE4 interface) in the DOE2 energy model are the two main air handling units serving, respectively, the first floor and floors two to four of the CDC. The present study was conducted on the cooling energy use of System-2, which handles a larger cooling load than System-1. The larger cooling loads of System-2 offer greater economizer energy efficiency potential than System-1 hence better highlighting the concepts presented in this project.

When the air-side economizer with dry-bulb temperature control is modeled with DOE2, the HVAC system attempts to maintain the mixed air temperature as specified in the schedules by modulating the outdoor air (OA) damper. The dampers are controlled based on the mixed air and the OA DBTs. The economizer control is enabled until the OA DBT reaches the high limit shutoff temperature. This shutoff temperature is explicitly entered by the user as a floating point value variable named "DRYBULB-LIMIT" in the BDL file (BDL is Building Description Language, the programming language developed to model buildings in DOE2).

In the present research, the “DRYBULB-LIMIT” variable was increased by 1 ºC, from 10 ºC to 25 ºC, between each run. In order to do so, the user did a manual conversion to I-P units and entered these high limit shutoff temperatures as a one decimal place precision Fahrenheit value. For each simulation run, the resulting System-2 energy use was recorded and plotted in relation to the shutoff temperature.

The study was repeated by increasing the shutoff temperature of both systems by one degree Fahrenheit from 50 ºF to 77 ºF. The energy use of System-2 was plotted on the same graph as when it was increased by 1 ºC to show the energy use curve at the finest available precision.

2.3 Degree of Error in Various Climates

The magnitude of the impact when economizer shutoff temperatures were entered as floating point values versus integer values was explored for different climates. The CDC model was first simulated with whole value shutoff temperatures and then at the same temperature to which 0.01 was added. This very small increment was sufficient to generate different energy use values. The two curves obtained were then plotted on the same graph and identified respectively as the integer and floating point curves. The degree of discrepancy for each climate was determined by calculating the differential values between the two curves.

3 Results

Energy simulation models are increasingly used both at the design phase and after buildings have been built, in the latter case to evaluate the previously estimated performance. Models are also used to evaluate energy reductions for potential retrofit scenarios. In either case, the models must be as accurate as possible and any potential error must be eliminated. Following the methods described above, the impact of the discrepancy in the precision of the air-side economizer shutoff temperature variable and the DBT available from the weather file was determined and is addressed in this section.

3.1 Weather File Analysis

Using metric DBT values to be compared with the weather file DBT data in DOE2 requires a conversion followed by rounding of the value, either by the user or within the software, since binary weather data against which the DBT is compared are composed of integers based on the I-P system. Rounding errors occur when the precision level of a converted number is greater than that available in the weather file. The magnitude of the rounding error will vary with the approach used to determine the closest integer value. As shown in Table 1, once a Celsius value is converted to Fahrenheit, the floating point value can either be rounded up or down or a ceiling function can be applied where any decimal will move the value to the next closest whole number.

Table 1 - Celsius to Fahrenheit conversion, corresponding rounded and ceiling values

°C	°F	Rounded	Ceiling	°C	°F	Rounded	Ceiling
10	50	50	50	**18**	64.4	64	65
11	51.8	52	52	**19**	66.2	66	67
12	53.6	54	54	**20**	68	68	68
13	55.4	55	56	**21**	69.8	70	70
14	57.2	57	58	**22**	71.6	72	72
15	59	59	59	**23**	73.4	73	74
16	60.8	61	61	**24**	75.2	75	76
17	62.6	63	63	**25**	77	77	77

As a result, as it is the case for values such as 13°C in Table 1, the same Celsius value may correspond to different Fahrenheit values, depending on the rounding approach.

When using an air-side economizer, the number of hours at which free cooling is enabled will impact the building energy use estimate. Figure 1 shows the compilation, from the Calgary CTMY2 weather file, of the number of hours at the Celsius temperature on the x-axis when this Celsius value was converted to a Fahrenheit integer value based on two different rounding approaches. The left most column in Table 1 corresponds to the x-axis in Figure 1. Every bin, identified as a degree Celsius, represents a range of equivalent Fahrenheit values. This range varied based on the rounding approach used. As an example, in the "rounded" column of Table 1, between 12°C and 13°C, the gap for the equivalent degree Fahrenheit value is 1°F while using the ceiling function, the gap was 2°F. As a result, the number of hours recorded as 13°C varied based on the rounding approach. When using the "rounded" approach, temperatures at 55°F were considered equivalent to 13°C while the sum of temperatures at 55°F and 56°F were considered equivalent to 13°C when using the ceiling function.

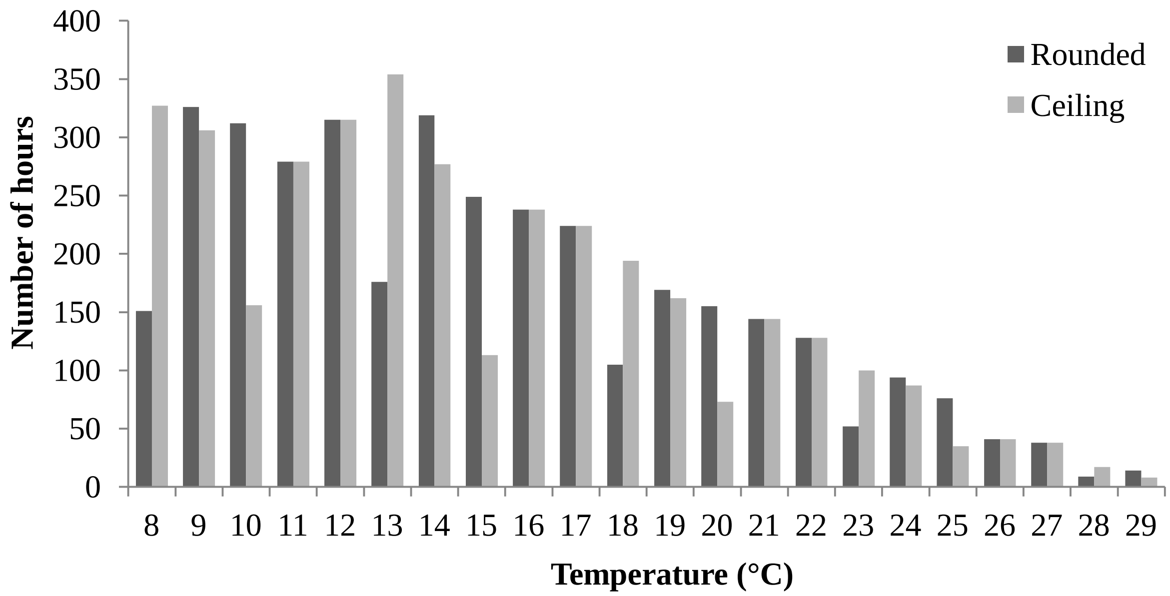

Figure 1 - Calgary CTMY2 weather file DBT distribution based on the rounding approach

Figure 1 graphically demonstrates the phenomenon described in Table 1. The darker columns show the number of hours corresponding to Celsius temperatures when the rounding function was used to obtain an integer Fahrenheit corresponding value while the lighter columns represent using a ceiling function. Picking one or the other rounding approach determined the number of hours assigned to that temperature. As an example, approximately 175 hours were assigned to 13°C based on the rounding function while approximately 355 hours are considered at the same temperature when using the ceiling function. Although the total number of hours is the same over a year, the distribution of hours across temperatures varied.

When using DOE2, the number of hours at which free cooling can be used in a year will affect the energy use. One of the factors that will affect the total number of hours in economizer mode is the economizer shutoff temperature. Although integrating the number of hours below a given temperature in a weather file cannot be an indicator of the effectiveness of an economizer for a given climate, it gives insight into the effect of the rounding of the shutoff temperature on the economizer energy reduction estimate.

Figure 2 shows the total number of hours below the Celsius temperatures shown on the x-axis.

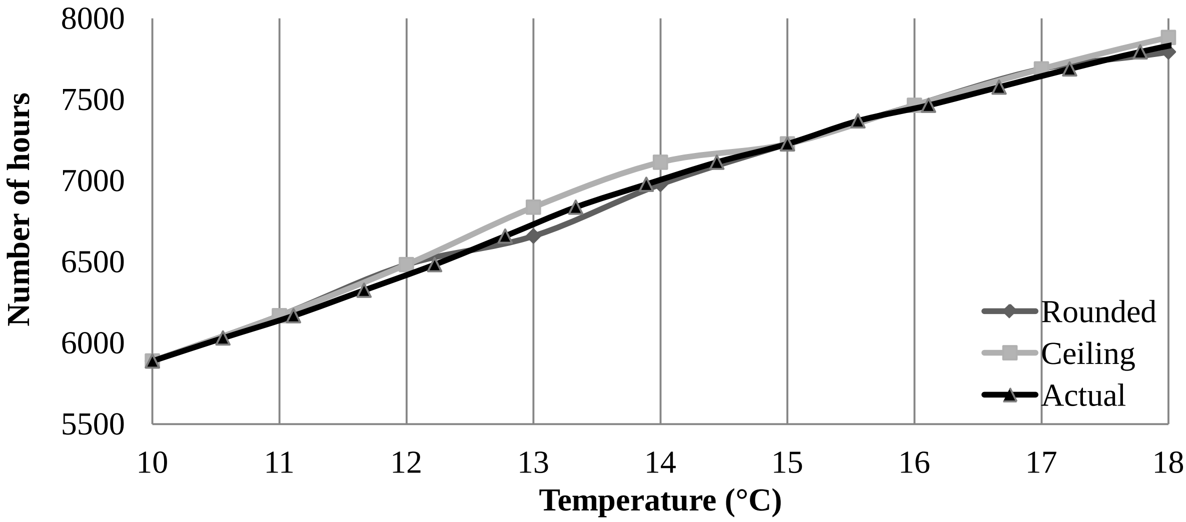

Figure 2 – Total number of hours at and below each shutoff temperature as per the Calgary CTMY2 weather file

Each marker represents the cumulative number of hours starting at the lowest temperature available in the weather file up to the high limit value shown on the x-axis. The “actual” curve corresponds to integer Fahrenheit values which did not require any rounding while the two other curves used different rounding approaches. All series converged to the total number of hours in the Calgary CTMY2 weather file, 8760 hours. The results show that at 13°C, the rounded value equalled the closest marker of the actual curve on the left while the ceiling value equalled the closest marker of the actual curve on the right. Hence, at 13°C there was a difference of approximately180 hours depending on the rounding approach used, correlating with the results found in Figure 1. Figure 2 also shows that when a ceiling function was used, the error was always on a single side of the actual curve while the rounding function error was smaller in absolute value but located on both sides of the actual curve.

Since the shutoff temperature is converted to a floating point value in DOE2 while the weather file is composed of integer values, a rounding error, as illustrated in this section, was bound to occur. This rounding error was observed in the energy estimate when attempting to use weather file data at a finer precision level than that available, as will be shown in the next section.

3.2 Energy Use Analysis

The same DOE2.1E model was repeatedly run increasing only System-2 air-side economizer high limit shutoff temperatures. The simulations were based on 1) entering Fahrenheit values with one place decimal precision equivalent to integer metric values and then 2) entering integer I-P values directly to verify the effect of temperature rounding on energy simulation results. Even though the simulation model was originally built using the EE4 interface, the simulations in this research were done using the DOE2 code directly. Doing so limited potential issues to the simulation engine itself. Figure 3 shows the energy use curve based on decimal Fahrenheit values equivalent to degrees Celsius and then the curve based on whole degree Fahrenheit values.

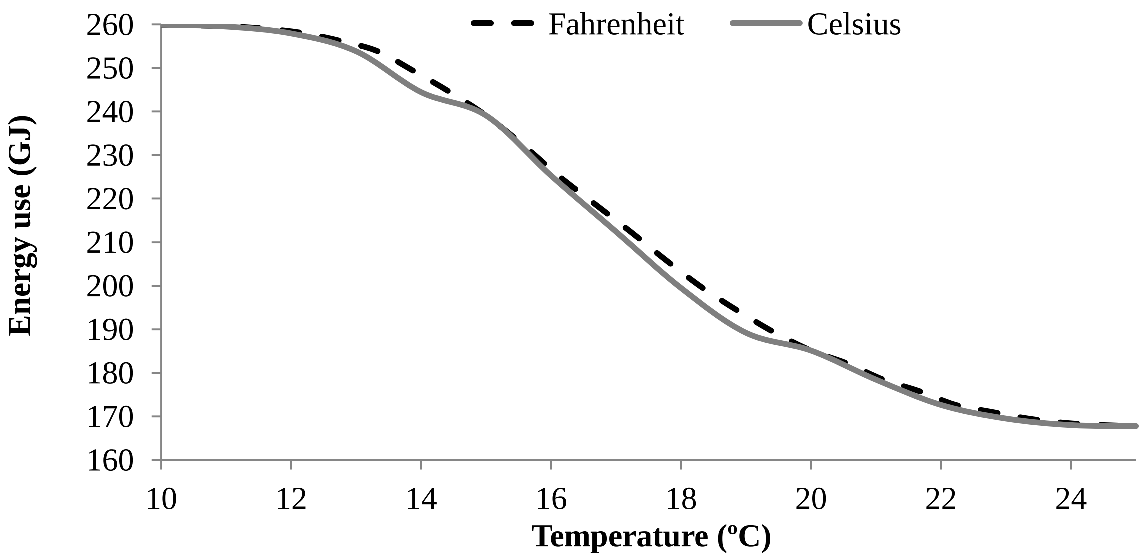

Figure 3 - CDC System-2 Calgary modeled cooling energy use as a function of the air-side economizer shutoff temperature

Figure 3 shows that without an economizer, or when the shutoff temperature was set to a point before the economizer is enabled, the energy use of the system was close to 260 GJ. When the economizer was set to shut off at 24ºC, the energy use was close to 170 GJ. The economizer energy reductions were therefore substantial, close to 35% over one year. The transitions between the two plateaus common to both data sets were nonlinear curves meeting at 15ºC (59°F) and 20ºC (68°F). The Celsius curve in Figure 3 always remained on one side of the Fahrenheit curve which shows the equivalent of a ceiling function was applied to the shutoff temperatures entered in DOE2.

Rounding the value to the nearest integer would cut the absolute value of the error by half but would, in some cases overestimate the energy use. Currently, when there is error, the energy use is always underestimated. The error for a given model will depend on the location, which is represented by the weather file.

3.3 Error in Various Climates

The number of hours available for free cooling changes with the economizer shutoff temperature as explained in section 3.1. The time of the day when these temperatures occur also affects the impact on the energy reduction. That is, if temperatures favourable to free cooling occur at times when the building cooling loads are at the lowest, e.g. during the night, and/or the system is off, the impact of the economizer energy reduction will be smaller. For this reason, simply analyzing weather files may provide a sense of the climate but not of the energy reductions provided by the economizer. To fully understand the economizer energy reductions a building simulation should be run. This section focuses on the impact of building location on energy use to compare the importance of the round off error when using decimal values for the air-side economizer shutoff temperature.

Based on Rock and Wu (1998), cities where the air is generally cooler offer more opportunities for dry-bulb air-side economizers to reduce energy use. The authors compiled the number of hours available for free cooling for various cities in the United States. A city from each of the top, middle and bottom of the list was selected. The CDC System-2 was simulated with the weather files for the three cities listed in Table 2 to determine the importance of the rounding error in various climates.

Table 2 – Number of hours available for free cooling, zone number based on location and required economizer shutoff temperatures for three US cities

City	Free cooling (hours) (Rock and Wu 1998)	Zone	High limit shutoff temperature(°C/°F) (ASHRAE 2010)
Kodiak (AK)	2379	7	24 / 75.2
Madison (WI)	1303	5A	21 / 69.8
Miami (FL)	294	1	18 / 64.4

The required shutoff temperature in Table 2 is that required by Standard 90.1-2010 (ASHRAE 2010). These temperatures are specific to dry-bulb air-side economizer control. The same type of economizer was used for all cities to allow comparison even though an enthalpy-based economizer or simply no economizer might have been a more practical choice for certain locations.

Figures 4 to 6 show the CDC modeled energy use in the climates listed in Table 2. The dotted line results from shutoff temperatures entered as integers while the solid line represents the same shutoff value to which 0.01°F was added. As an example, 69 °F was entered as the air-side economizer shutoff temperature to obtain the dotted line while 69.01 °F was entered to get the solid line. The vertical line indicates the required shutoff temperature.

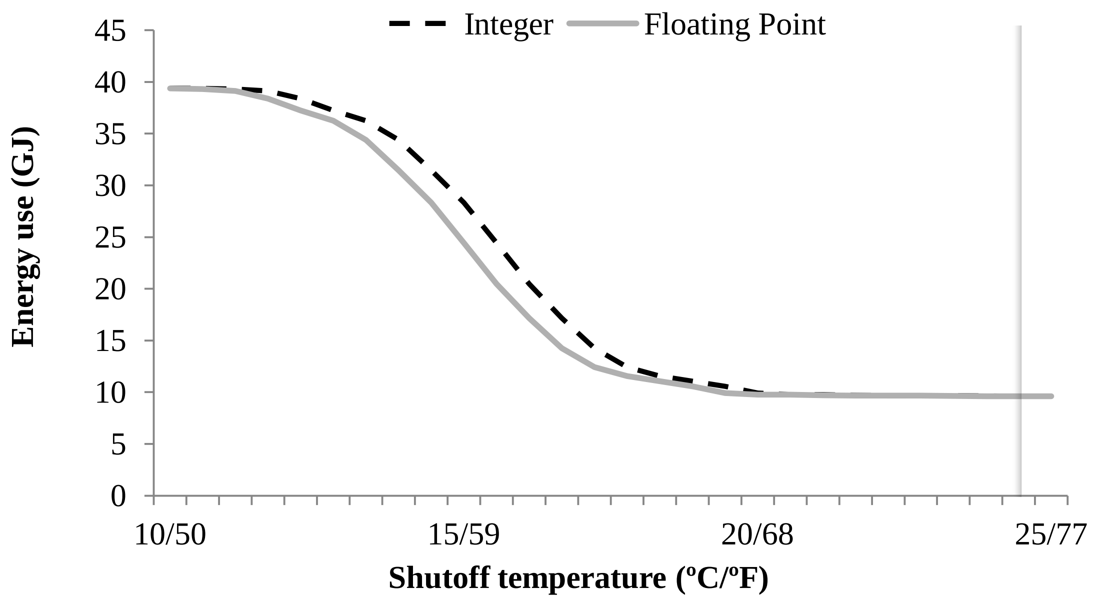

Figure 4 – Cooling energy use versus economizer high limit shutoff temperature, Kodiak, Alaska

As expected, the amount of energy required for cooling in Kodiak, Alaska, was generally much lower than in warmer regions. Given the lower energy use for cooling, a slight variation in cooling energy use would be relatively large in percentage. The largest cooling energy reduction was 75% and occurred around 72°F. At the required shutoff temperature of 75.2°F, little error would be introduced by the rounding error. If one were to explore lower floating point shutoff temperatures, Figure 4 showed the error would be largest, up to 16%, around 60°F.

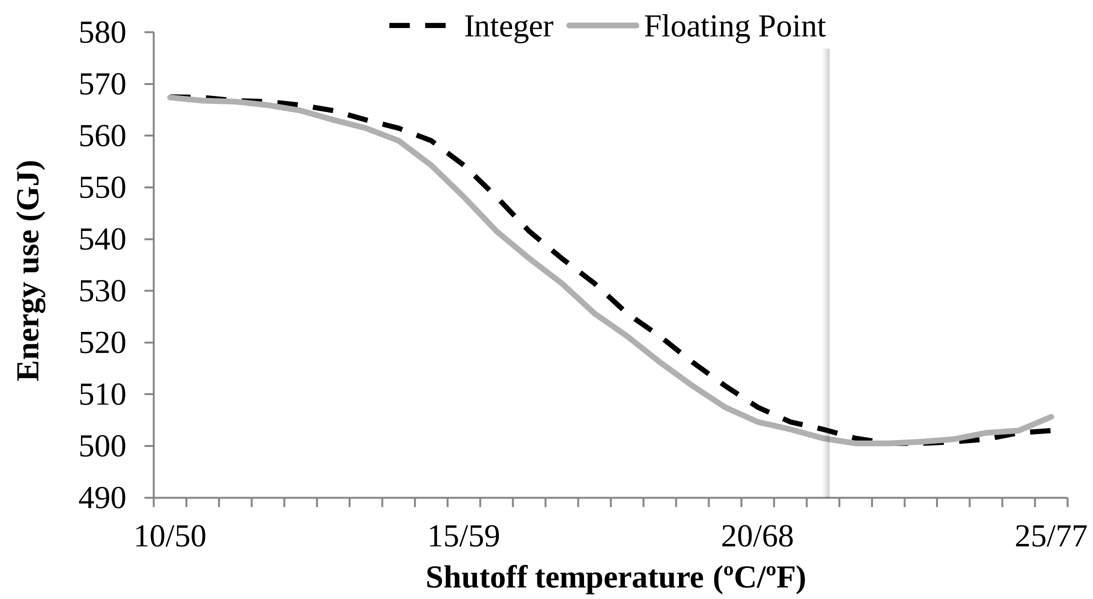

Figure 5 - Cooling energy use versus economizer high limit shutoff temperature Madison, Wisconsin

Although more humid, Madison, Wisconsin, has a similar climate to Calgary. Unlike Kodiak, keeping the OA damper open at warmer temperatures increased the energy use. The largest energy reduction, 11%, occurred between 70°F and 75°F, where the two curves in

Figure 5 meet. With the Madison weather file, up to 1% error in cooling energy use could be introduced by the rounding error.

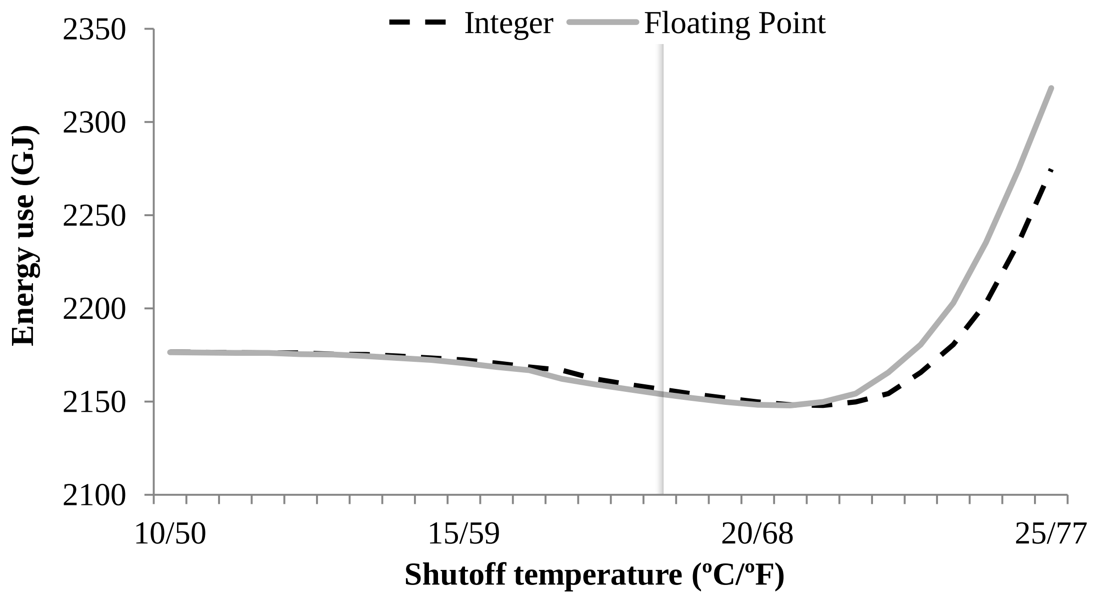

Figure 6 - Cooling energy use versus economizer high limit shutoff temperature Miami, Florida

With the Miami, Florida, weather file, the largest energy reduction occurred between 65°F and 70°F. Figure 6 shows that a defective OA damper that fails to close completely would substantially increase energy use. The largest energy reduction was barely perceptible at 1%, while the potential error was less than 0.5%. In a warm and humid climate such as that of Miami, the use of a dry-bulb air-side economizer is unlikely.

The same diagram was plotted for the city of Calgary, the actual location of the CDC, which is located in climate zone 7 and for which the ASHRAE required shutoff temperature is 24°C or 75.2°F.

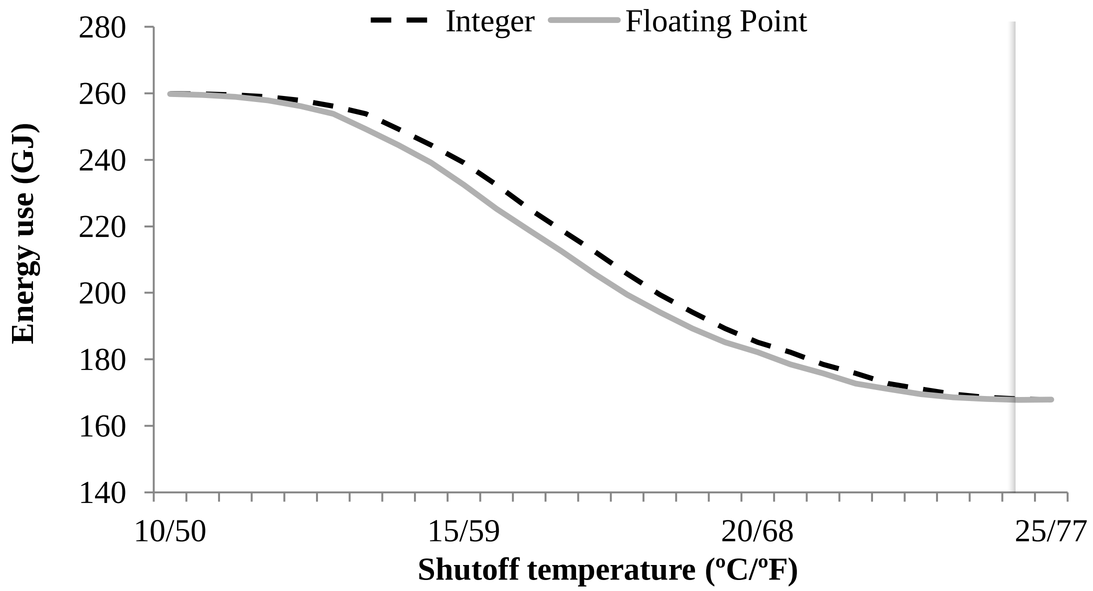

Figure 7 - Cooling energy use versus economizer high limit shutoff temperature Calgary, Alberta

The largest economizer energy reduction, 35%, occurred around 75°F. However, if one were to explore “what if?” scenarios, entering floating point shutoff temperatures, the error could be as substantial, as much as 3% around 64°F.

Overall, one can see that the ASHRAE specified high limit temperatures are located where the largest economizer reductions were found. The points where the curves separate show the temperatures at which entering a floating point value as the shutoff temperature may generate an error. Figure 8 shows a summary of the relative error on the total cooling energy usage for various locations while Figure 9 shows the absolute value of the error.

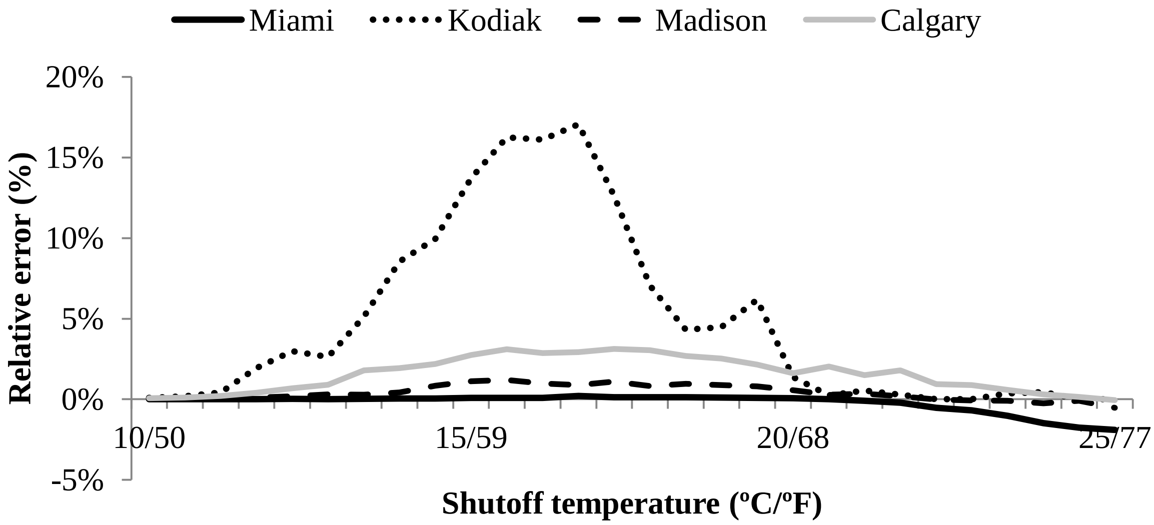

Figure 8 – Error relative to total cooling energy use for various locations based on the air-side economizer shutoff temperature

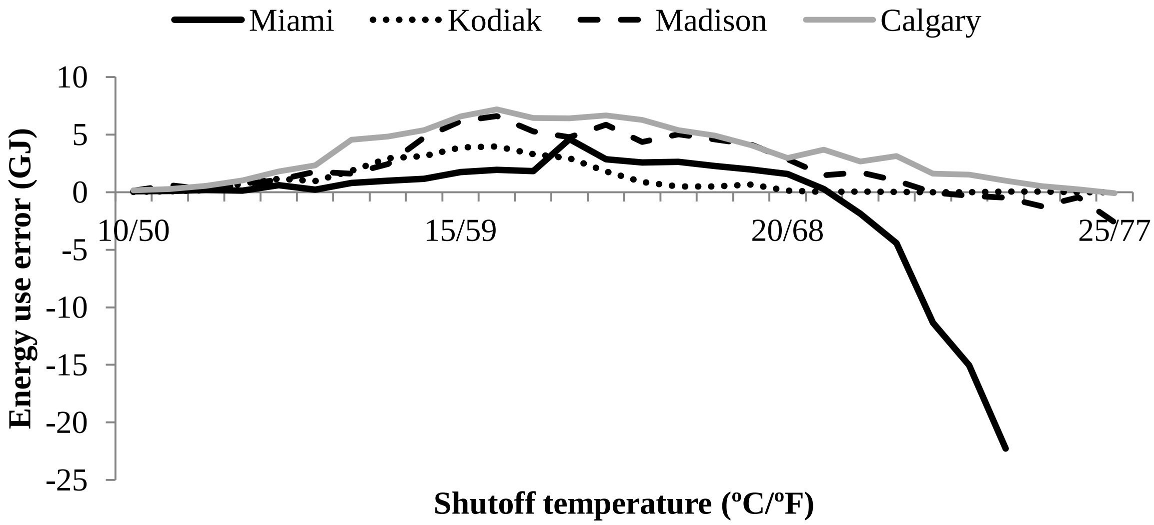

Figure 9 – Absolute value of error on cooling energy use based on the economizer shutoff temperature for different climates

As shown in Figure 8, the less the free cooling potential, the more important the error relative to the total cooling energy use. In contrast, Figure 9 shows the absolute value of the error is greater in warmer climates, which could translate into greater cost errors, assuming utility costs are similar between locations.

The simulation work presented in this paper confirms the air-side economizer shutoff temperatures should be set as per the required Standard 90.1-2010 (ASHRAE 2010) values for optimum performance. These shutoff values should be entered as whole numbers to eliminate any rounding errors.

4 Discussion

The issue outlined in this paper resides in the fact that the air-side economizer DBT shutoff temperature can be entered as a decimal number while the weather file DBT is an integer. As a result, rounding errors affect the DOE2 energy use estimate.

The precision used in the current weather files would be sufficient for energy analysis at the early design phase or models to be submitted for accreditation since the weather file is a best estimate of a typical weather year which itself contains a great deal of uncertainty. Moreover, the base model uses exactly the same data as the proposed one and therefore, the error would be applied to both the base and the submitted model. However, it is now more common for simulation models to be calibrated after the fact. The calibration process requires the use of a weather file generated by the user; the simulation model is verified based on measured weather conditions. When attempting to verify that a model is within 15% of the in situ energy use (Department of Energy 2008, 4-22), a 3% error in cooling due to rounding can be very large.

Addressing the issue presented in this paper could be approached in three ways. The most complex and most accurate solution would be to generate binary files containing data of a greater precision level and ensure DOE2 keeps this precision through its calculations, while ensuring files are backward compatible. Currently, all files are converted to a binary format into which the precision level is limited to the nearest degree Fahrenheit. Since the internal DOE2 code has the ability to handle a floating point value for its global DBT (Hirsch 2011), the work remains to generate binary files with greater precision levels that could be read by DOE2. The integer precision level was originally based on computer performance, at times when the use of floating points would substantially increase simulation time (Lawrence Berkeley Laboratory and Los Alamos National Laboratory 1981, III.17). Nowadays, as computers are faster and research is ongoing to increase the accuracy of simulation tools, this added precision could be computed in a timely manner.

As a temporary solution, the DOE2 compiler could be modified so the air-side economizer shutoff temperature would simply be limited to an integer value, identifying a floating point value as a compiling error. However this solution may not be satisfactory to some users who may have the impression of loosing some level of precision and to the community of simulators working towards increasing simulation model precision.

Finally, the simplest solution is the status quo, relying on users to be aware of the issue and always enter integer Fahrenheit values to ensure the expected shutoff temperature is used.

5 Conclusion

To summarize, the DOE2 weather file converter limits the DBT value to an integer value for all weather file types when they are converted to binary format. Since the air-side economizer shutoff temperature can be entered as a decimal value, rounding errors occur in the simulated energy use. This paper first explained why this rounding error occurs. Secondly, based on a peer-reviewed building simulation model, the type of rounding used was found to be equivalent to a ceiling function. Lastly, the same simulation was run to identify the importance of this rounding error for various climates. Possible solutions were then proposed to address the issue.

This paper has established an approach to evaluating the importance of the rounding error due to a given parameter. Although not explored in this project, the same could be done with the enthalpy based economizer, which is most likely to present the same issue. Further work should be done to understand if DOE2 has other components that present the same issue of coordinating the precision level between the weather file and the user entered values. Further work could also be done to evaluate the rounding error impact when using metric input and output values with DOE2 by entering the command line “INPUT=METRIC OUTPUT-METRIC“.

6 Acknowledgements

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