Thermal Energy Storage System Sizing[1]

Dominique DUMORTIER, Ron KAMMERUD, Bruce BIRDSALL
Brandt ANDERSSON, Joe ETO, William L. CARROLL, Fred WINKELMANN
Lawrence Berkeley Laboratory
Cyclotron Road
Berkeley, CA 94720, USA.

ABSTRACT

This paper describes results from a larger project [11 which investigated the sizing of Thermal Energy Storage (TES) systems used as part of the cooling system in buildings. The study was based on DOE-2 simulations; daily integrated cooling coil energy requirements for office and retail buildings in the Chicago, Fort Worth, and Miami climates were examined in relation to climate and operational parameters. Based on these studies, it was concluded that the peak daily integrated coil load, which determines the storage capacity, occurs during multiday periods of severe weather that do not necessarily include the most severe day or the most severe hour in a particular climate. A significant component of the peak daily integrated coil load is due to energy accumulated during periods when the building is not cooled, and stored in building materials and furnishings; ultimately the stored energy must be removed by the cooling system in order to satisfy comfort requirements during occupied periods. The magnitude of the stored energy component of the peak depends on the lengths of the uncooled period and of the severe climate period, and on a host of building design parameters relating to its thermal capacity and its interactions with the climate.

Sizing calculations that use instantaneous peak climate conditions and that do not take into account the storage effect cannot be recommended for TES design. The only sizing calculations believed to account adequately for the full range of variables that affect peak integrated loads are based on hourly simulations. Suggestions are made for insuring that such simulations provide technically sound estimates of peak daily integrated coil loads on which to base the storage capacity calculation. Recommendations are also made for development of new sizing tools.

I. INTRODUCTION

Thermal Energy Storage (TES) is becoming widely recognized as a viable load management technique. Electric utilities are providing favorable off-peak rates to encourage adoption of TES technology and of other strategies that shift air conditioning loads away from on-peak periods. Utilities benefit by deferring addition of new generation capacity and by making better use of efficient base load plants. The customer benefits by having lower electricity bills. A useful summary of TES systems design, operation and performance characteristics has recently been completed by Piette et al [2].

To maximize these benefits, it is essential that the TES system be correctly sized: undersizing could have a dramatic impact on the comfort and productivity of a building's occupants under severe weather conditions, and oversizing increases first costs. It is believed that most TES systems in place have been oversized, but this is difficult to confirm because the literature does not assess TES systems effectiveness in terms of sizing procedures. For the same reason, no clear conclusions can be drawn regarding the adequacy of existing sizing calculation tools.

This paper describes partial results from a broader project [1] that was undertaken to: identify the major problems with sizing cool storage systems, develop a preliminary sizing methodology, identify long-term research issues relating to thermal energy storage in buildings, and develop a plan for addressing these issues. This paper provides a basic understanding of the conditions under which peak storage capacity is required and an assessment of the adequacy of the existing engineering calculations to meaningfully estimate this peak.

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II. APPROACH

Conventional cooling equipment size is determined by the peak rate of extraction of thermal energy from the air stream at the cooling coil. TES systems must be sized based on estimates of peak extraction requirements for all zones integrated over the operating cycle. For a full storage system, the storage capacity is equal to the peak daily integrated coil load. For demand-limiting or partial storage system, the storage capacity is smaller than the peak daily integrated load by an amount equal to the cooling provided by the chiller.

In order to examine the hourly and daily cooling coil requirements during the cooling season, we simulated two prototypical buildings in various climates using DOE-2.1C as the hourly simulation program[2]. DOE-2.1C conveniently produces daily integrated or hour-by-hour cooling coil load over any period of time. Two additional sets of simulations were performed with BLAST-3.0[3] and DOE-2.1D to confirm selected project results.

Table 1: Office Building Description

Floor area	20,000 ft^2
Configuration	One Story
Maximum Occupancy	108
Lighting/Equipment	2.18 W/ft^2 of floor area
Glazing	Single Pane 25% of the ext. wall Equally Distributed
Roof	U=0.099 $Btu/hr.ft^2.°F$
Wall	U=0.077 $Btu/hr.ft^2.°F$
Total Building Mass	110 Lb/ft^2 of floor area
Equipment	Variable Air Volume System
System Operation	8:00 to 17:00 on Weekdays No Operation on Weekends

The prototype buildings analyzed were: an office and a retail building. They are distinctly dissimilar in design and each represents a significant fraction of the non residential sector. Results obtained for the retail building were similar to those for the office building. Only results for the office building are presented here; results for the retail prototype can be found in Ref. [1]. The office building characteristics are given in Table 1.

Typical Meteorological Year (TMY) [3] climate data was used in the simulations. Three locations were chosen as relative extremes:

- Chicago, IL, typical of cool northern regions.
- Fort Worth, TX, a hot climate where cooling is a consideration but where humidity conditions are not too severe.
- Miami, FL, representative of hot and humid regions where cooling requirements dominate and where latent effects are maximized.

Although we were studying thermal energy storage requirements, we did not simulate a specific storage system. Rather, we analyzed the building with a conventional cooling system. The hourly coil energy requirements integrated over the day were interpreted as the capacity that must be available from the cooling system as a whole. The peak of the daily integrated coil energy requirement defines the maximum storage capacity which is of interest in TES design. However, because specific storage and operation configurations were not examined, other TES system design issues such as storage charging, storage losses, and storage-to-coil transfer were not accounted for in the results.

Typically, when sizing a conventional system with a simulation program such as DOE-2, a few hours of unmet loads that occur under peak conditions are tolerated. Under these conditions, there is some rise in space temperature and a corresponding reduction in comfort levels. However, when the peak has passed the chiller is able to "catch" up as long as the undersizing is not too severe in degree or duration. In contrast, a storage system has different limitations in terms of capacity. The supply temperature of a TES system typically is not affected when the return water from the coil exceeds the design temperature; the storage system has an apparent "unlimited" capacity and continues to remove heat to meet the load until the storage is depleted. In order to correctly simulate the heat removal characteristics of a storage system, the conventional system used for the study was intentionally oversized by sizing the air system for space temperatures lower than the upper limit of the comfort range (assumed here to be 76°F) until unmet loads were eliminated.

2 DOE-2. Simulation Research Group, Lawrence Berkeley Laboratory, Berkeley, California.

3 BLAST-3.0 (Building Loads Analysis and Systems Thermodynamics). Corps of Engineers, US Army Construction Engineering Research Laboratory, Champaign, Illinois.

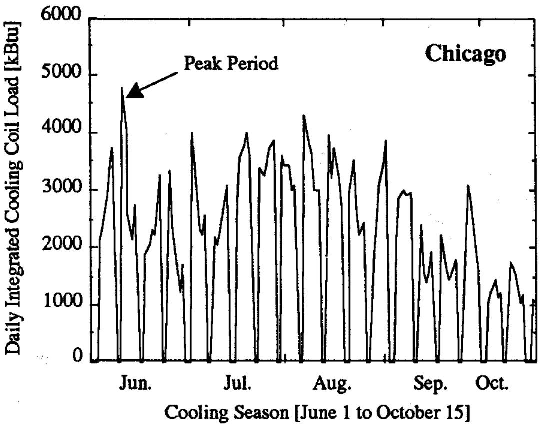

Figure 1.a: Daily Integrated Cooling Coil Loads in Chicago.

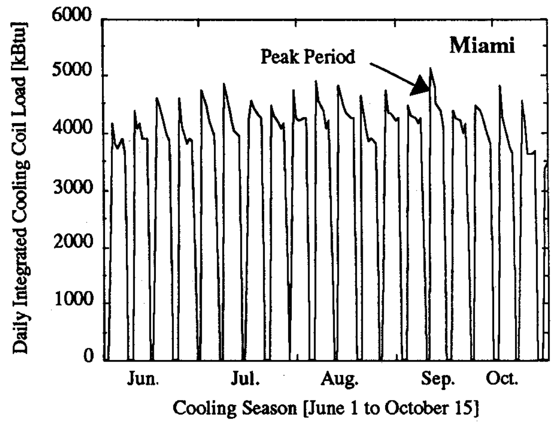

Figure 1.b: Daily Integrated Cooling Coil Loads in Miami.

III. DAILY INTEGRATED COOLING COIL LOAD ANALYSIS

Cooling Season Analysis

Simulations of the office building were performed for the cooling season (June 1 through October 15) in Chicago, Fort Worth, and Miami, in order to examine the characteristics of daily integrated loads and their relationship with climate variables. Figures 1.a and 1.b show the daily integrated cooling coil loads in Chicago and Miami respectively.

Weekend shutdowns, when daily integrated coil loads are zero, can easily be seen on these figures. These weekly profiles, especially in Miami, suggest a pattern. For many weeks, the daily integrated coil load on Monday is substantially larger than those for the rest of the week; this is observed for about half of the weeks in Chicago and Fort Worth. In Miami, only one Monday during the entire cooling season does not produce the peak daily integrated coil load for the week. This **Monday startup** follows the shutdown of the cooling system during the weekend. Furthermore, the startup effect is not limited to Monday; the patterns show that it lasts **several days**. Note that the Monday startup following the weekend shutdown of office buildings had been observed earlier [4].

The largest daily integrated coil loads occur during the weeks of June 10, July 8, and September 9 in Chicago, Fort Worth, and Miami, respectively. These peaks were all on Monday and in all cases the daily integrated coil loads are relatively large for the entire week. The following weeks were selected for more detailed examination: June 6 to June 12 in Chicago, July 4 to July 10 in Fort Worth, and September 5 to September 11 in Miami.

Peak Period Weather Profiles Analysis

Figures 2.a and 2.b show the dry bulb temperature profiles for Chicago and Miami for the peak periods. In all climates, daily integrated cooling coil loads were examined in relation to indicators of climate severity. This is fully described in Ref. [1], which showed that the influence of the average dry bulb temperature is much stronger than either average wet bulb temperature or total daily insolation.

The common features of these peak-producing periods are that they are **multi-day hot spells** that do not include the most severe day during the cooling season. The daily average dry bulb temperature in Miami is below the 2.5% ASHRAE [5] design temperature typically used for sizing. The peak periods are also characterized by **small daily temperature swings**. The difference between the maximum and the minimum temperature is around 18ºF and 12ºF in Chicago and Miami, respectively. Results were identical for the Fort Worth location. During these multi-day hot spells, at night the building is unable to dissipate the heat stored during the day.

In order to assess the extent to which the TMY data meaningfully represents peak conditions, long-term weather data analysis was performed for the Fort Worth climate. In this analysis, the average daily dry bulb temperature over a three-day period was used as a measure of climate severity. These three-day weather patterns were identified for each of the 20 years for which SOLMET [6] data were available for Fort Worth (1954-1973).

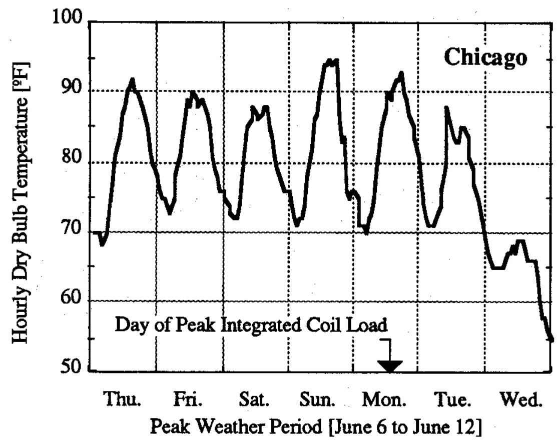

Figure 2.a: Hourly Dry Bulb Temperature for the TMY Peak Weather Period in Chicago.

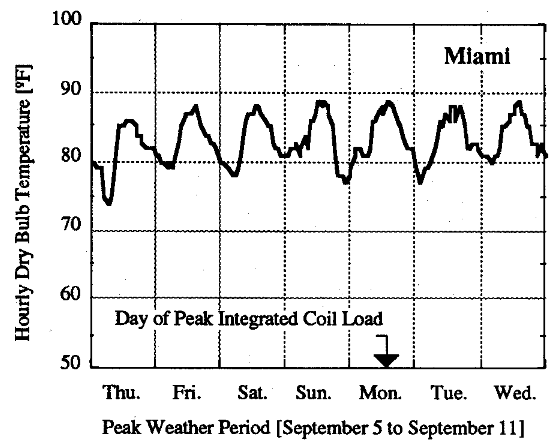

Figure 2.b: Hourly Dry Bulb Temperature for the TMY Peak Weather Period in Miami.

Results indicate that in any given year there is high probability of encountering hot spells with durations of three or more days that are more severe (i.e., with higher average dry bulb temperature) than the ones given by TMY data and used in this study. For Fort Worth, the most severe conditions have average temperatures about 5ºF higher than those found in TMY data. This modest temperature increment increases the daily integrated coil loads by about 10%.

To further examine climate sensitivity of the peak integrated coil load and to facilitate examination of its sensitivity to operation and design variables, a more systematic definition of peak climate conditions was used. The worst case scenario for a TES system-i.e., the conditions that maximize the startup effects and therefore define capacity requirements- was taken to be a multi-day pattern in which **24-hour profiles for each of the climate variables were simply repeated from day to day**. This was suggested by the consistent pattern observed in Miami for both the weather characteristics and the daily integrated cooling coil loads. For consistency with the previous results, the 24-hour profiles for each climate variable were taken from the TMY weather day on which the peak daily integrated coil load had been obtained in the earlier simulation: June 10 in Chicago, July 8 in Fort Worth, and September 9 in Miami. A week of synthetic weather was then created for each of the three climates.

Peak Period Daily Integrated Coil Load Profile

Figure 3 shows the daily integrated coil loads calculated using the synthetic weather for Chicago and Miami for 5-day and 7-day cooling system operations. The 7-day operation assumed occupancy and internal load schedules identical to those for the normal 5-day operation. Weekend operation of the cooling system was examined in order to reduce and eliminate accumulation and storage of heat during the weekend that is responsible for the startup effect. Note that the curves for each climate are similar in shape and that similar results were obtained for Fort Worth.

For a normal 5-day operation, the cooling system is turned off during the weekend and the daily integrated coil load becomes zero on Saturday and Sunday. As shown in Figure 3, during the week there is a monotonic decrease in daily integrated coil loads for both Chicago and Miami; this implies that, contrary to expectations, the startup effect is not limited to a few hours on Monday morning. Rather, several days are required for the cooling system to remove heat accumulated over the weekend so that the building come into a quasi-steady-state equilibrium with the climate. At this equilibrium, there is a balance between overall daily thermal gains (including, but not limited to, gains during occupied hours) and overall daily thermal losses. This equilibrium condition defines the minimum cooling capacity required to insure that design comfort levels are maintained, assuming that the startup loads earlier in the week can be eliminated. The minimum cooling capacity is represented by the daily integrated coil load for the day where the equilibrium is reached-typically Friday for the three climates and the office building used in this study. The maximum cooling capacity requirement is represented by the daily integrated coil load on Monday, assuming that the cooling system is sized to meet the full startup load. Capacity requirements based on the Friday equilibrium are 15% to 20% smaller than those based on the Monday startup.

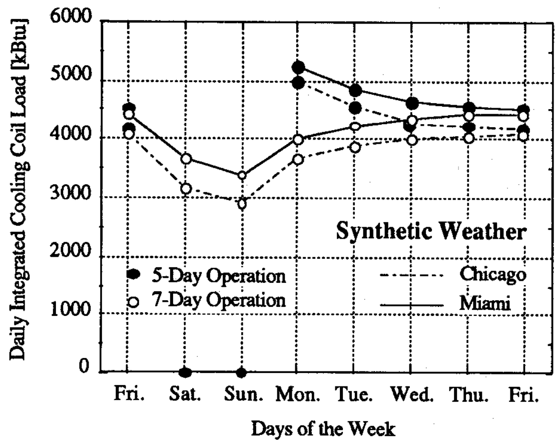

Figure 3: Daily Integrated Cooling Coil Loads for a Week of Synthetic Weather in Chicago and Miami.

On weekends, internal loads are limited to a small standby lighting level, so one expects smaller daily integrated cooling coil loads on Saturday and Sunday for the 7-day system operation schedule. As shown by Figure 3, for both Chicago and Miami the daily integrated coil loads decrease from Friday to Saturday and Sunday, but the storage effect is still evident. On Sunday, the cooling requirement is 25% smaller than on Friday. On Monday, the internal loads increase to the level used through the occupied period and the daily integrated cooling coil load begins to increase, but only reaches its maximum later in the week on Friday, where it is essentially the same as that for the normal 5-day operation. During this severe weather period, the near monotonic increase in the capacity requirement indicates that starting on Monday, the building is accumulating and storing heat each day, over and above that removed by the cooling system during the operating cycle, until the quasi steady-state condition observed under normal 5-day operating schedules is reached late in the week.

Shutdown Effect on Startup

As evidenced in the daily integrated cooling coil loads analysis, startup loads following a period of hot weather when the cooling system is not operated can be significant and must be considered as part of TES system design. Startup loads can be dealt with either by providing adequate storage system capacity or by implementing operating strategies that mitigate the startup effect. In order to determine the extent to which operating schedules affect peak daily integrated coil loads, a series of parametrics were performed for the office building prototype using the synthetic weather data. Table 2 shows these results for Fort Worth.

Table 2: Parametrics on System Operation Synthetic Weather Fort Worth.

Cooling System Operation	Daily Integrated Load [kBtu]
No Shutdown	4,960
2-Day Shutdown	5,717
3- Day Shutdown	5,947
4-Day Shutdown	6,128
2-Day Shutdown with Sunday Operation	
18:00 to 22:00	5,250
16:00 to 22:00	5,028

These parametrics showed a strong dependence of the daily integrated coil load on the duration of the shutdown. Startup loads are substantially aggravated by the longer than normal three- and four-day weekend shutdowns, leading to startup loads that are larger by 20% to 24%, respectively. Cooling system operation for a few hours on the day preceding the 5-day work week shows that the startup effect is substantially reduced with 4 hours of operation on the last day of the shutdown, and is essentially eliminated with the 6 hours of operation. Note that the energy consumption penalty associated with operating the system during 6 hours on Sunday is small. The total coil load for the week in that case is only 5% larger than for the normal 5-day operation.

IV. IMPLICATIONS

As we saw from the results presented in Section III, design conditions are not defined by "instantaneous" occurrences of climate extremes. The peak daily integrated coil load occurs during multi-day periods of severe weather characterized by high average temperatures and small daily temperature swings. The period may not include the most severe day or the most severe hour in a particular climate, and for this reason, sizing methods that use "instantaneous" peak climate characteristics are inadequate.

Building dynamics can no longer be ignored in sizing. On the peak day, a significant component of the daily integrated coil load is due to energy accumulated during periods when the building is not cooled and is allowed to reach space temperatures above the design temperature. Under these conditions, energy is stored in building materials and furnishings and ultimately must be removed by the cooling system in order to satisfy comfort requirements during occupied periods. The magnitude of the stored energy component of the peak depends on the length of the uncooled period and of the severe climate period, and on a host of building design parameters relating to its thermal capacity and its interactions with the climate. Sizing methods that do not take into account multi-day building system operation such as weekend shutdown are therefore inadequate. Referring back to Figure 3, many of these methods assume steady periodic operation, consistent with calculation of an integrated coil load on Friday when the building is in equilibrium with the climate; these methods miss the startup load effect, which is about 20% of the required storage capacity.

We believe that only hourly simulation programs can be used reliably for TES sizing if "unmet loads" are eliminated. This requires deliberate "oversizing" during the sizing calculations: the conventional sizing procedure would lead to a TES system design that would not provide the cooling capacity necessary to meet startup requirements. Since the startup effect would not be anticipated, the design probably would not provide operation strategies effective in mitigating the startup load. We conclude that in using a detailed simulation tool such as DOE-2 to size a cool storage system, care must be exercised to insure that the simulation is providing a meaningful representation of the dynamic response of the storage system to the space load.

V. CONCLUSION

The peak daily integrated cooling coil load appears on the day of system startup and is the result of a multi-day severe weather period that occurs during the shutdown period. Note that these conditions also should be expected to produce the peak hourly cooling coil load used for sizing conventional systems. Existing sizing methods that use "instantaneous" weather conditions or "instantaneous" calculation methods are not adequate for TES sizing. Although hourly simulation programs such as DOE-2 can be used for TES sizing, they are not design tools and they should only be used with proper attention to building dynamics.

There is a need to develop a specialized sizing tool which could be based on existing hourly simulation programs, but which would correct the inherent deficiencies of the actual methods by including:

- An improved calculation of the energy stored in materials and furnishings.
- Severe weather data selected from real data on the basis of high average temperatures and small daily temperature swings.
- Multi-day simulation period to appropriately take into account startup loads created by system shutdowns.

Additionally, because system sizing is an iterative process, the sizing tool should allow convenient alteration of equipment characteristics, and operation and control assumptions; it should also include more detailed analysis of space comfort conditions and equipment performance.

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