Assessing the Actual Energy Efficiency of Building Scale Cooling Systems

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Summary

When comparing the economics and efficiency of district cooling service to in-building air conditioning systems, it is important to consider the full operating costs of in-building equipment over a range of load conditions; with chillers operating at part loads; auxiliaries designed for peak conditions; and in-building systems often over-sized for safety factors and impacted by various performance degradation and depreciation.

This project sought to collect data on actual operating costs and performance of in-building chiller plants in order to better understand cooling requirements, costs and efficiencies in comparison to district cooling service. The project team found very limited data of relevance on actual building system performance that included operating costs for full systems related to cooling requirements. Data tended to focus on chiller electricity performance but did not consider the full systems involved in cooling output and did not measure actual cooling delivered for comfort or process to the building space. Industry data on buildings that had converted to district cooling provided a before/after scenario to analyze the building chiller system performance.

Background
The costs, energy efficiency and environmental impacts of District Cooling (DC) are often compared to those of building-scale cooling systems. In such comparisons, the assumptions regarding the efficiency of building-scale systems have a significant impact on the comparative economic conclusions as well as the analysis of efficiency and the related environmental impacts. Generally, the assumptions for building systems are based on theoretical values or chiller equipment ratings based on static laboratory conditions rather than “real world” data reflecting part load operations, weather variations, operator inputs, full system operation (including auxiliaries); actual cooling loads and system depreciation. This may result in underestimation of the economic, efficiency and environmental benefits of district cooling service.

Intent of the Report
This project set out to develop more realistic data on building-scale air conditioning system efficiencies, by investigating the actual annual efficiency of building cooling systems and determining how this differs from the theoretical annual efficiency using values based on test conditions. Particularly when considering all auxiliaries (e.g. cooling tower fans, pumps) and the relative frequency of part load vs. full load operating conditions, the annual operating efficiency could differ dramatically from the stated efficiency at design conditions.

The objective of this project was to 1) conduct a literature search to find documentation of real world air conditioning system operations; 2) to collect data from multiple sources and variety of building types; and 3) to evaluate “before/after” conditions in buildings converted to district cooling service. The report was intended to be useful for realistic comparisons of DC to building-scale systems in a number of contexts, including:

- marketing of DC service to prospective customers by DC utility companies;
- municipal planning for a development area;
- private sector planning for multi-building developments; and
- local, national or EU energy/environmental policy analysis.

The fundamental question this project attempted to answer is “What is the total real-world annual electrical efficiency of building-scale chiller systems?” The investigation was focused on larger buildings (peak cooling load >200 tons or 700 kW), although some data on smaller systems was obtained and is presented.

Content of the Report

The report contains the following main sections:

Introduction - provides an overview of the project hypothesis and the background for the project.

Key Technical Variables and Measures - discusses basic efficiency measures such as Coefficient of Performance (COP) and KW/Ton efficiency. Coefficient of Performance (COP) is the ratio of the rate of heat removal to the rate of energy input at a specific set of load and condensing conditions. More efficient systems have a higher COP. Since this parameter is a ratio, consistent application of any unit of energy can be used, e.g., COP = kilowatts (kW) cooling output / kW power input. kW/ton Efficiency is another measure of cooling system efficiency and is often used in the USA. One ton of cooling is equal to the removal of 3.516 kW (12,000 Btu per hour) of heat.

This section of the report reviews the key variables affecting system efficiency, in order to provide a context for the later discussion of data. These variables include but are not limited to:

- Type of chiller equipment
- Sizing of chiller(s) and cooling tower(s) relative to seasonal loads
- Condenser temperature
- Chilled water supply temperature
- Use of variable frequency drives (VFDs)
- Age of equipment and maintenance history

The report looks at annual efficiency comparison measures used for chiller selections including ARI 550 (IPLV and NPLV) and other technical guidance including ESEER; ASHRAE Guideline GPC 22 and ASHRAE Standards 90.1 and the Energy Performance of Buildings Directive (EPBD).

Modelling has the advantage that it is known that the comparison is between exactly similar situations, except for those aspects that have been deliberately changed. It also allows comparable results to be produced for different climates and systems. The disadvantage is that the results are only as good as the models used, and the models do not capture the negative impacts of performance degradation due to suboptimal operation and maintenance practices.

Prior Studies - looks at search results for similar studies performed in North America and Europe and finds limited relevant data that properly tracks building cooling loads relative to equipment energy consumption. While a great deal of attention is given to the efficiency of the chiller itself, we have found very few studies or data relating to the total plant efficiency including the auxiliaries (cooling tower fans, condenser water pumps). Auxiliaries can have a significant negative impact on annual efficiency, particularly if fans and pumps are driven by fixed speed motors rather than variable frequency drives. The chiller plant equipment of interest is that required to produce cooling, i.e. chillers, cooling towers, condenser pumps, and in some cases chilled water pumps* along with special equipment such as cooling tower sump heaters and water conditioning equipment. Chilled water pumps are asterisked because they are not part of the equipment that produces the cooling in these chiller plants. They move the chilled water from the plant to the terminal equipment in the building HVAC system. The primary pumps in primary/secondary pumping may be an exception, since they are there to pump constant flow through each chiller.

Data Obtained in this Study - explores challenges involved in collecting relevant data and the complexity and costs associated with data gathering; storage and analysis. Indirect measurement has the advantage of reflecting actual rather than theoretical conditions, but it is difficult to ensure that conditions are truly the same for the pre-connection and post-connection measurements (or to reliably compensate for any differences). Such differences may arise, for example, because of weather or changing occupancy. Direct measurement is best, but it is expensive and time-consuming to implement. The scope of this study did not provide adequate budget for installation and monitoring of metering equipment in test settings.

Findings

There are three basic approaches to assessing chiller system efficiency:

- Modelling, typically using detailed building and system simulation;
- Indirect measurement (monitor changes in total building electricity consumption after a building is connected to district cooling, and compare the reduction to the measured chilled water consumption following connection); and
- Direct measurement (submetering) of chiller system components and chilled water production.

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Many variables affect the efficiency of building chiller systems, including type of chiller equipment, size of chillers and cooling towers relative to seasonal loads, condenser temperatures, chilled water supply temperatures, use of variable frequency drives (VFDs) and the age and maintenance history of the equipment.

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Very few data are available that directly quantify the actual annual efficiency of building-scale chiller systems through sub-metering, and some of the data obtained had gaps or flaws that constrain their usefulness. Limited case study data on submetered building chiller systems are reported in the literature.

Sizing of Chillers and Cooling Towers Relative to Load

The experience of the international district cooling industry over the past 30 years is clear: conventional load estimation methodologies and software tend to overstate peak loads. This is understandable, given the consequences of underestimating loads for the purposes for which these methods are used. The last thing a consulting engineer wants is to be blamed for inadequate capacity. Consequently, typical load estimation methodologies tend to result in unrealistically high load estimates. Design practices that contribute to high load estimates include:

- Using inappropriately high design temperatures for wet bulb and dry bulb;
- Assuming the peak dry bulb and wet bulb temperatures are coincident;
- Compounding multiple safety factors; and
- Inadequate recognition of load diversity within the building.

The result of overestimation of load is oversizing of chillers and cooling towers, which contributes to operation of systems at suboptimal levels during much of the year. Poor operations, particularly lack of attention to chiller staging, can exacerbate this problem.

Part Load Performance

During the last 15 years, great improvements have been made in part-load efficiency of commercially available chillers. "Part-load performance" of chillers is usually presented based on corresponding decreases in entering condenser water temperature (ECWT) as the load decreases. At a fixed ECWT, the efficiency of older chiller compressors dropped significantly at lower loads. With today's state-of-the-art chillers, constant-speed chiller efficiency degrades very little until load drops below about 40%. With variable-speed chillers, efficiency is actually maximized at about 50% loading, with kW/ton increasing as load goes up or down from that level. Below 40% loading the efficiency of even variable-speed compressors degrades significantly.

Other Performance Factors

Other variables affecting system performance include condenser temperatures; chilled water supply temperatures; application of variable speed drives on pumps and motors; and the age and maintenance of systems. Isolating these variables to determine relative impact on cost and efficiency is a challenging endeavour.

Although it is possible to obtain very high seasonal efficiencies (less than 0.65 kW/ton) with well-designed, well-operated all-VFD plants operating in favorable climate conditions, during the course of this study we were unable to obtain primary data documenting such performance.

There were also very few data available for the indirect analytical approach to quantifying building chiller efficiency – by comparing building electricity consumption before and after connection to district cooling, and using post-connection cooling consumption data to estimate the efficiency of the building chiller system operations thus eliminated.

Conclusions

Many variables affect the efficiency of building chiller systems, including type of chiller equipment, size of chillers and cooling towers relative to seasonal loads, condenser temperature, chilled water supply temperature, use of variable frequency drives (VFDs) and the age and maintenance history of the equipment.

Very few data are available that directly quantify the actual annual efficiency of building-scale chiller systems through sub-metering, and some of the data obtained had gaps or flaws that constrain their usefulness. Limited case study data on submetered building chiller systems showed the following annual average kW/ton: air cooled 1.50, variable speed screw 1.20, ultra-efficient all variable speed with oil-less compressors 0.55, and district cooling plant 0.85 kW/ton.

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Limited case study data on electricity consumption before and after connection to district cooling yielded calculated annual efficiencies as summarized below.

Building Name	Location	Chiller type	Calculation method	Average annual kW/ton
Gross Chemistry	Duke University, NC	Water-cooled	1	1.33
(Confidential)	Phoenix, AZ	Water-cooled	1	1.25
ITS Franklin	UNC Chapel Hill, NC	Air-cooled	2	1.21
Cheek Clark	UNC Chapel Hill, NC	Air-cooled	1	0.92

Calculation Methods

1. Based on electricity consumption before and after connection to district cooling, and cooling consumption following connection.
2. Submetering of chiller system.

Reference

Robert Thornton, et al: Assessing the Actual Energy Efficiency of Building Scale Cooling Systems, IEA-Report. IEA-DHC Annex VIII, 2008:8 DHC- 08-04.